HYBRID III 95th PERCENTILE LARGE MALE FINITE ELEMENT MODEL NECK ALTERATION

A Thesis
presented to
California Polytechnic State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Mechanical Engineering

by
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December 2019
COMMITTEE MEMBERSHIP

TITLE: Hybrid III 95th Percentile Large Male Finite Element Model Neck Alteration

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ABSTRACT

Hybrid III 95th Percentile Large Male Finite Element Model Neck Alteration

Eric Day

The motivation behind the project was to update the Livermore Software Technology Corporation (LSTC) Hybrid III 95th percentile finite element model, such that the neck assembly response under varying simulated loading conditions equals that of the federally regulated Hybrid III 95th percentile anthropomorphic testing device (ATD).

The family of Hybrid III crash test dummies approximate the physical properties and response of the human body in a frontal automotive crash. The Hybrid III is used to assess the effectiveness of vehicle restraint systems. LSTC offers Hybrid III finite element models for use in their Multiphysics simulation software package, LS-DYNA. The Hybrid III models are used as cost-effective alternative to physical crash tests in the development of vehicle crashworthiness. However, the neck response of the LSTC Hybrid III 95th percentile model in simulation was poorly correlated to that of the physical Hybrid III neck in corresponding tests. The source of the dissimilarity was inadequate dimensions, element behavior, and material properties of the neck. To improve correlation to the physical ATD, a number of modifications were made to the LSTC Hybrid III 95th percentile neck.

Development of the neck model began with improvements in mass and geometry. Element formulation and element discretization were altered to improve model durability and accuracy. A mesh convergence study and simulation under extreme-severity loading were completed to validate the foregoing model alterations. Test data from a physical compression test and NASA-performed Neck Sled Tests were collated with data from simulation to adjust material type and material properties. The model was further calibrated according to Code of Federal Regulations neck calibration test response requirements.

The resulting neck model developed in LS-DYNA exhibited improved dynamic characteristics and reliability under both low and high-severity loading. Computational efficiency was enhanced along with model tendency to normally terminate under excessive loading. The updated model moreover demonstrated consistent element behavior and realistic feedback in bending. The revised neck model will be adopted by NASA for use in predicting potential occupant injury during spacecraft landing. A similar model with reworked material properties attuned to higher loading will be implemented into the full consumer version of the Hybrid III 95th percentile model for employment in high-severity frontal crash simulation.
ACKNOWLEDGMENTS

Thank you to:

Christoph Maurath Sommer for providing LS-DYNA help, writing recommendations, and overall direction throughout the project. Your guidance has been vital for the completion of this thesis.

Lauren Cooper for project council, coordinating my timeline, and ensuring that I graduate.

Livermore Software Technology Corporation for providing the research opportunity and for financial support.

Mike Burger for generating the mesh on a number of neck models.

Jim Day, Christoph, Peter Schuster, and Garrett Hall for sharing their knowledge in finite element analysis and LS-DYNA.
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1. INTRODUCTION

1.1 Hybrid III

The family of Hybrid III crash test dummies are anthropomorphic testing devices (ATD) that approximate the physical properties and dynamic response of the human body in a frontal automotive crash. Vehicle compliance to Federal Motor Vehicle Safety Standard (FMVSS) No. 208 is dependent on its ability to protect the Hybrid III from potential injury (Hollowell, William T., Gabler, Stucki, Summers, & James R., 1999). The federally regulated Hybrid III is crucial in the assessment and development of restraint systems for vehicle crashworthiness.

The Hybrid series of crash test dummies were first developed in the 1970’s by General Motors (Backaitis & Mertz, 1994). Each ATD developed during this time period possessed the physical attributes of an average-sized male in the United States. Three generations of dummies: Hybrid I, Hybrid II, and GM-ATD 502 were created before the first Hybrid III. The Hybrid I and Hybrid II were created in 1971 and 1972 respectively, with the Hybrid II having increased durability and performance over the Hybrid I (Backaitis & Mertz, 1994). In 1972, the ATD 502 dummy was constructed under contract with the National Highway Traffic Safety Administration (NHTSA), the Federal agency in charge of Federal Motor Vehicle Safety Standards (Backaitis & Mertz, 1994). The ATD 502 had updated biofidelity, dynamic response, and geometry of the head, shoulders, lumbar spine, and joints (Backaitis & Mertz, 1994). However, the ATD 502 lacked anthropomorphic attributes of the neck and chest structures, which are essential in properly assessing potential occupant injury (Backaitis & Mertz, 1994).

The deficiencies of the past General Motors ATD’s led to the development of the Hybrid III in 1975 (Backaitis & Mertz, 1994). The aim of the Hybrid III was to improve its biomechanical response and repeatability, while preserving the best qualities of past generations (Backaitis &
The key structure and head of the ATD502 was adopted into the Hybrid III. The response improvements of the Hybrid III were concentrated on the neck, knees, and chest (Backaitis & Mertz, 1994). Adjustments to the listed areas were completed based on biofidelity data from literature. Increased instrumentation including accelerometers and load cells were added to the Hybrid III to measure internal forces, moments, and reactions (Backaitis & Mertz, 1994). Being repeatable involved better documentation of dummy manufacture and certification processes, as well as developing the Hybrid III to be more serviceable. In addition, General Motors established Injury Assessment Reference Values (IARV’s) appointed to the Hybrid III 50th percentile that coincided with biofidelity data and physical tests (Backaitis & Mertz, 1994). The resulting ATD had increased lifetime, biofidelic performance, and documentation.

In 1986, NHTSA incorporated the Hybrid III Average Male into FMVSS 208, which is defined in the United States Code of Federal Regulations (CFR), Title 49, Part 571 and 572 (Backaitis & Mertz, 1994). The vehicle safety standards No. 208 outline certification tests and assessment for vehicle frontal crashworthiness (Hollowell, William T., Gabler, Stucki, Summers, & James R., 1999). Certification test procedures for inspection and calibration of the Hybrid III are listed in CFR to achieve repeatable, reciprocal results (Backaitis & Mertz, 1994). The standard involves measuring the occupant deceleration and crush of the occupant compartment during severe frontal crashes (Hollowell, William T., Gabler, Stucki, Summers, & James R., 1999). The accelerometers of the Hybrid III Head and Torso measure potential occupant injury due to deceleration, while the transducers of the knee, femur, chest, and lumbar spine measure impact, crush, and trauma sustained during crash. Additional instrumentation is included in the Hybrid III for supplemental occupant injury measurements.

In 1993 the Hybrid III became the mandatory dummy used in FVMSS 208 compliance testing (Backaitis & Mertz, 1994). The performance requirements and structural properties of the
Hybrid III are stated in CFR Title 49 (Electronic Code of Federal Regulations, 2019). Part and assembly drawings, as well as material specifications are federally regulated and are currently maintained by the Society of Automotive Engineers' (SAE), Biomechanics Committees, and NHTSA (Saul, Pritz, Backaitis, & Hallenbeck, n.d.). The Hybrid III 50th percentile Male is now manufactured by Humanetics in accordance to CFR standards (Saul, Pritz, Backaitis, & Hallenbeck, n.d.). The characteristic of the Hybrid III to produce repeatable, correlative, biofidelic response in frontal automotive crashes has made it the most widely-adopted dummy for domestic and foreign testing of vehicle crashworthiness (Saul, Pritz, Backaitis, & Hallenbeck, n.d.).

1.2 Hybrid III 95th percentile

The Hybrid III 95th percentile Large Male ATD represents the upper extreme of American adult males (User’s Manual for the Hybrid III Large Male Test Dummy, n.d.). Development of the Hybrid III 95th percentile began at Ohio State University in 1997 (User’s Manual for the Hybrid III Large Male Test Dummy, n.d.). The project was funded in part by the Center of Disease Control and overseen by SAE International Mechanical Human Simulation Subcommittee of the Human Biomechanics and Simulation Standards Committee (User’s Manual for the Hybrid III Large Male Test Dummy, n.d.). The model was created to assess the potential injury that an occupant with the size, weight and biofidelic characteristics of a large male would sustain in a frontal automotive crash.

The Hybrid III 50th and 5th percentile dummies are part of CFR, Title 49, Part 572, while the 95th percentile dummy is not. The Hybrid III 95th percentile is not yet regulated by Federal code. However, SAE has established documentation that outlines Hybrid III 95th percentile regulations. SAE J2860 Surface Vehicle Report – User’s Manual for the Hybrid III Large Male Test Dummy describes the part assembly descriptions, measurement specifications, calibration, and
certification test procedures of the Hybrid III Large Male (User’s Manual for the Hybrid III Large Male Test Dummy, n.d.). SAE founded the 95th percentile geometry and biofidelic characteristics from scaled values of the federally regulated 50th percentile male (User’s Manual for the Hybrid III Large Male Test Dummy, n.d.). Vehicle compliance specifications for the 95th percentile originate from CFR 49 requirements for the 50th percentile. Similarly, calibration specifications and supplemental test procedures are based off those of the average-sized male. Although the 95th percentile Hybrid III is not required for vehicle compliance to Federal Motor Vehicle Safety Standards, many car manufactures use the dummy in testing for vehicle crashworthiness.

1.3 LSTC
Livermore Software Technology Corporation (LSTC) develops and supports LS-DYNA, a Multiphysics finite element program. LS-DYNA offers solution methods for many types of problems; however, its most widely used application is high-energy transient problems. This is due to the software’s exceptional explicit solver. This attribute of LS-DYNA and its capabilities for server scalability make it ideal for simulating vehicle crash tests.

Advances in LS-DYNA and computer clusters have made it possible to integrate occupant models in with vehicle and restraint system models for analysis of vehicle crashworthiness (Kan, Marzougui, & Bedewi, 2003). LSTC offers Hybrid III finite element models for customer use in LS-DYNA. The LSTC Hybrid III models were originally created in cooperation with the George Washington University’s National Crash Analysis Center, but are now solely developed by LSTC (“Hybrid III 50th percentile Male,” n.d.). The highly detailed models simulate the dimensions, weight proportions, material properties, component connectivity, and dynamic characteristics of the federally regulated Hybrid III (Kan, Marzougui, & Bedewi, 2003). When positioned inside vehicle models, the LSTC Hybrid III models offer a cost-effective, accurate alternative to
physical crash tests. The Hybrid III models are crucial in the development of vehicles, vehicle restraint systems, and protective vehicle barriers (Kan, Marzougui, & Bedewi, 2003). The models assist in vehicle conformance to Federal Motor Vehicle Safety Standards, allowing car manufactures to avoid excessive, extortionate physical crash tests.

1.4 NASA Updated Hybrid III 95th Percentile

The LSTC Hybrid III models, originally developed for automotive crash simulation, have been adopted by NASA to predict potential occupant injury in simulated spacecraft landing. Specifically, NASA is investigating the passenger protection capabilities of three new spacecrafts: Boeing CST-100 Starliner, SpaceX Dragon, and NASA/Lockheed Martin Orion (Somers, Putnam, Greenhalgh, & Lawrence, 2019). Unlike the high-severity accelerations faced during FVMSS 208 vehicle compliance testing, NASA is using the LSTC dummies in low-impact landing simulations. NASA is currently using the LSTC Hybrid III 5th, 50th and 95th percentile dummy models in testing.

To validate the use of the LSTC models, NASA contrasts Hybrid III physical tests with corresponding Hybrid III simulations. In the Neck Sled Test, NASA found that the LSTC Hybrid III 95th percentile finite element model performance in simulation was not equivalent to the physical ATD in testing. This result is unlike that of the 5th and 50th percentile dummies, where the physical and simulated tests produced similar responses. On further examination of the physical Hybrid III Large Male, NASA found that the LSTC model neck differed in geometry (Somers, Putnam, Greenhalgh, & Lawrence, 2019). LSTC’s 95th percentile model is a scaled version of the LSTC 50th percentile model. In most cases, the part scaling between models parallels the scaling on the physical 95th percentile dummy; however, this is not the case for the neck assembly. The physical 95th percentile neck is geometrically equal to that of the physical 50th percentile, other than the addition of two metal spacers that increase neck length (Somers,
Putnam, Greenhalgh, & Lawrence, 2019). The incorrect neck geometry of the LSTC 95th percentile finite element model prevented NASA from obtaining accurate head and neck injury data through test simulation.

NASA performed an in-house fix of the LSTC 95th percentile neck. A new 95th percentile neck model was made from the 50th percentile neck model. Additional neck pucks were fitted on the model and the neck cable was lengthened (Somers, Putnam, Greenhalgh, & Lawrence, 2019a). An Additional 0.3 kg of mass was added to the head to meet CFR requirements (Somers, Putnam, Greenhalgh, & Lawrence, 2019a). The neck rubber element formulation was set to fully integrated solid (Somers, Putnam, Greenhalgh, & Lawrence, 2019a). The variables on the neck rubber material card were also adjusted. NASA executed an optimization procedure using LS-Opt in order to determine values for the material properties (Somers, Putnam, Greenhalgh, & Lawrence, 2019a). LS- Opt was used on the 6G and 12G Lateral Impact and 6G and 16G Rearward Impact Neck Sled Tests. Finally, a manual optimization was completed in order to determine the final material property values listed in Table 1 (Somers, Putnam, Greenhalgh, & Lawrence, 2019a).

Table 1. Original and optimized material property values for neck rubber

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Original Value</th>
<th>Optimized Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO</td>
<td>Mass Density</td>
<td>1.1 E-6</td>
<td>1.1 E-6</td>
</tr>
<tr>
<td>BULK</td>
<td>Elastic Bulk Modulus</td>
<td>0.1128</td>
<td>0.1128</td>
</tr>
<tr>
<td>G0</td>
<td>Short-Time Shear Modulus</td>
<td>0.0046</td>
<td>0.0079</td>
</tr>
<tr>
<td>GI</td>
<td>Long-Time (infinite) Shear Modulus</td>
<td>0.001</td>
<td>0.0025</td>
</tr>
<tr>
<td>BETA</td>
<td>Decay Constant</td>
<td>0.11</td>
<td>0.116</td>
</tr>
</tbody>
</table>

Performance of the model was measured through a rating scale created by the International Organization of Standards: ISO scores. This rating scale was used to evaluate the sameness of corridor, phase, magnitude, and slope between the data from the physical and simulated tests.
(Somers, Putnam, Greenhalgh, & Lawrence, 2019). A passing rating for any given test was set by NASA as 0.5 or greater in a scale of 0 to 1. The NASA Neck Sled Tests consist of 24 runs, differing in head position and magnitude of acceleration. NASA selected six of these runs to assess the improvement of the LSTC 95th percentile model. In the original model, only 16 of the 42 performance criteria were of passing grade. The NASA updated model had 40 of 42 measurements of passing grade. Results are available in Table 2.

Table 2. Original versus optimized model ISO scores for selected test cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Head_Ax</th>
<th>Head_Ay</th>
<th>Head_Az</th>
<th>Head_Rx</th>
<th>Head_RY</th>
<th>Unneck_Fx</th>
<th>Unneck_Fy</th>
<th>Unneck_Fz</th>
<th>Unneck_Mx</th>
<th>Unneck_My</th>
<th>NiJ</th>
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</thead>
<tbody>
<tr>
<td>Lateral 6G_100ms</td>
<td>0.5795</td>
<td>0.5977</td>
<td>0.4927</td>
<td>0.5453</td>
<td>0.4104</td>
<td>0.4676</td>
<td>0.5406</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral 12G_50ms</td>
<td>0.5206</td>
<td>0.5893</td>
<td>0.5265</td>
<td>0.4867</td>
<td>0.6245</td>
<td>0.4899</td>
<td>0.5268</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Frontal 6G_100ms</td>
<td>0.5552</td>
<td>0.5309</td>
<td>0.5502</td>
<td>0.5261</td>
<td>0.7452</td>
<td>0.4497</td>
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<td></td>
</tr>
<tr>
<td>Frontal 16G_50ms</td>
<td>0.5729</td>
<td>0.4271</td>
<td>0.5987</td>
<td>0.5143</td>
<td>0.7685</td>
<td>0.5115</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.53427</td>
<td>0.55033</td>
<td>0.443397</td>
<td>0.327503</td>
<td>0.50294</td>
<td>0.51603</td>
<td>0.43023</td>
<td>0.46823</td>
<td>0.418687</td>
<td>0.526473</td>
<td></td>
</tr>
</tbody>
</table>

**Green** – ISO > 0.5  
**Red** – ISO < 0.5  
**Orange** – Rounded ISO = 0.5


NASA greatly improved the LSTC 95th percentile neck model with the adjustments and optimization they ran. However, the performance of the model was only characterized by response in the low-severity NASA Neck Sled Simulations. The motivation of the thesis was to further evaluate the NASA Updated neck model under high-severity loading. Model modifications would be made according to performance in a number of simulated real-world
tests. A revised 95th percentile neck model would be produced and implemented into the working Beta of the LSTC 95th percentile model. NASA would be sent the revised Hybrid III model for further use in space craft landing simulation.

1.5 Viscoelastic Materials

The Hybrid III neck is comprised of rubber cylinders layered between pucks of 6061 T6 Aluminum (H-III 95M Drawing Package Draft, 2010). A pre-stressed neck cable runs through the neck to give increased resistance to axial tension (Backaitis & Mertz, 1994). The skewed geometry of the rubber cylinders allows for increased bending in extension than flexion (Backaitis & Mertz, 1994). Figure 1 displays the 95th percentile neck. The rubber is made of isobutylene-isoprene (butyl rubber), which possesses the high damping and hysteresis characteristics needed to model the neck defined in biofidelity literature (Backaitis & Mertz, 1994). Rubber butyl is viscoelastic.

![Figure 1. Lateral view of Hybrid III 95th percentile neck](image)

Viscoelastic materials hold properties of both viscous and elastic materials. The viscous property includes time dependent resistance to loading, while the elastic property includes material tendency to return to its original state (Yang, 2017). Elastomers, such as rubber butyl, are viscoelastic (Gauthier & Tuszynski, 1995). Viscoelastic materials possess properties of creep,
stress relaxation, and hysteresis (Yang, 2017). The loading and unloading curves of viscoelastic materials differ due to the dissipation of heat while stressed, or hysteresis. Additionally, properties of creep and stress infer that viscoelastic materials have time dependent stress and strain under load.

Viscoelastic materials are generally modeled as a spring and damper (Yang, 2017). The spring attempts to bring the system back to its unstressed state, while the damper resists abrupt motion. These properties show how viscoelastic materials relax under prolonged deformation.

The LS-DYNA material model: MAT_006, Viscoelastic, is used to model the viscoelastic behavior of the Hybrid III neck rubber solid elements. The material is defined by a single card with variables: mass density, elastic bulk modulus, short-time shear modulus, long-time shear modulus, and decay constant (LS-DYNA Keyword User’s Manual Volume II Material Models, 2014). The decay constant constitutes the dissipation of energy. The bulk modulus is a measure of a material’s resistance to volumetric compression, while the shear modulus is a measure of material’s resistance to transverse deformation (Imaoka, 2008). The shear and bulk modulus make up the system stiffness. Unlike in elastic materials, viscoelastic shear modulus and bulk modulus are not constant but are defined as a decaying function of time. The shear relaxation of the material with respect to time is defined by Hermann and Peterson (LS-DYNA Keyword User’s Manual Volume II Material Models, 2014):

$$G(t) = G_\infty + (G_0 - G_\infty) \exp(-\beta t)$$  \hspace{1cm} \text{(Eq. 1)}$$

Where $G(t)$ is the shear relaxation, $G_\infty$ is the long-time shear modulus, $G_0$ is the short-time shear modulus, and $\beta$ is the decay constant (LS-DYNA Keyword User’s Manual Volume II Material Models, 2014). The short-time shear modulus is the instantaneous stiffness of the model. While
the long-time modulus is the stiffness at infinite time, or the remaining stiffness after decay. The shear relaxation is used to measure the stress rate. The deviatoric part of the stress rate is defined by the Jaumann rate (*LS-DYNA Keyword User’s Manual Volume II Material Models*, 2014):

\[ \dot{\sigma}'_{ij} = 2 \int_0^t G(t - \tau) D'_{ij}(\tau) \, d\tau \]  

(Eq. 2)

Where \( G \) is the shear modulus as defined by Hermann and Peterson, and \( D' \) is the deviatoric part of the strain rate (*LS-DYNA Keyword User’s Manual Volume II Material Models*, 2014). The MAT_006 material card variables: mass density, elastic bulk modulus, short-time shear modulus, long-time shear modulus, and decay constant, define the stress rate and hence performance of the neck model. A major portion of the project was spent contrasting physical data to data from simulation to ultimately define the viscoelastic material properties of the Hybrid III neck model.

1.6 Project Significance

The LSTC Hybrid III models are used by a number of large clients including Ford, Toyota, and NASA. These companies rely on the accuracy of the LSTC Hybrid III models when designing restraint systems for occupant protection. The neck of the current downloadable version of the LSTC 95th percentile model is faulty. Head deceleration of the Hybrid III 95th percentile model cannot be measured accurately in simulation for vehicle compliance without a biofidelic modelled neck. Inaccurate results from simulation builds a poor foundation for vehicle design for crashworthiness. This leads to under or over engineered vehicle restraint systems that inevitably will not meet FMVSS.

Simulation for vehicle crashworthiness is more and more common because it is far too expensive to blindly build and test vehicle prototypes until safety standards are met. Hybrid III dummies are
priced around $125,000, while vehicle prototypes may cost upwards of $250,000 (Hoffman, 2007). Each individual crash test costs about $100,000 (Hoffman, 2007). To ensure vehicles pass FMVSS the first time, simulation using Hybrid III models becomes necessary. If the Hybrid III models are inaccurate, a large amount of time and money would be spent on failed compliance testing and vehicle development trying to engineer for unreliable simulation results.

By the end of the project, the refined Hybrid III 95th percentile model will be sent back to NASA for further use in spacecraft landing simulation. The refined 95th percentile model will help NASA to efficiently assess occupant injury potential. Furthermore, the updated geometry and material model of the neck will be integrated in with the other in-progress updates of the LSTC 95th percentile to help progress the model to its BETA version. The simulation data collected from the Hybrid III 95th percentile BETA version will assist engineers in more efficient and more accurate computer-aided design for occupant protection.

1.7 Project Outline

This subsection will briefly outline the order of events of the thesis. The Project Outline may be beneficial in better understanding the direction of the project.

Proceeding the Introduction begins Chapter 2: Preliminary Evaluation of NASA Updated Model. The chapter describes assessment procedures and conclusions made about the NASA Updated neck model in high-severity loading conditions. The material properties of the NASA Updated model were then adjusted to tailor for high-severity loading according to Hybrid III certification procedures. Following this initial model calibration, Chapter 3 presents a synopsis of the project and its main conclusions. Chapter 3 offers a concise alternative to reading the entire thesis.
Chapters 4, 5, and 6 describe the process required to complete the compression experiment and simulation. The compression experiment and simulation were used to identify the 95th percentile neck material properties, specifically the long-time shear modulus. Chapter 4 defines the initial development of the compression simulation. The simulation was created before the actual experiment was carried out due to inaccessibility of material testing resources. The simulation is presented before the experiment in the thesis because it leads to the development of a new neck model, which is used for the remainder of the project. Chapter 5 defines the new model. The new model possesses a new mesh and element formulation. The chapter describes these model changes and their implementation into the head and lower neck assembly. The mesh is evaluated in a mesh convergence study, while the element formulation is evaluated in extreme-severity loading simulation. Chapter 6 then outlines the compression experiment and results. The compression simulation was altered to include the new neck model. The load data from experiment was then used as the basis to alter material properties in the model to achieve equal response between necks under physical and simulated compression. The long-time shear modulus model material property was identified in this chapter.

Chapters 7 and 8 describe supplemental tests used to find the remaining material properties of the neck model: bulk modulus, short-time shear modulus, and decay constant. Chapter 7 defines the NASA Neck Sled Tests. The physical data from these tests was obtained by NASA and shared for the purpose of improving the LSTC 95th percentile neck model. Corresponding LS-DYNA simulation files replicated the sled tests. Just as is in the compression tests, model material properties were adjusted to match the neck responses described by the physical data. The NASA Neck Sled Simulations and CFR neck calibration simulations were utilized to ultimately define the remaining material properties of the neck model. Chapter 8 presents the finalized neck models. One neck model was produced solely for NASA use in low-severity space craft landing.
simulation. A supplemental neck model was produced for consumer use in high-severity car crash simulation. Chapter 9 outlines project conclusions.
2. PRELIMINARY EVALUATION OF NASA UPDATED MODEL

Hybrid III Large Male certification procedures are provided by SAE. Vehicle conformance to FMVSS 208 is defined by scaled Hybrid III average male response characteristics (Backaitis & Mertz, 1994). The Hybrid III 95th percentile must meet SAE calibration standards to be used as a compliance test tool (Backaitis & Mertz, 1994). Hybrid III calibration tests ensure that all dummies produce repetitive and correlative responses during compliance testing (Backaitis & Mertz, 1994).

LSTC uses simulated certification tests to calibrate their Hybrid III models. Model response measurements collected during post processing must comply to CFR performance specifications. The calibration simulations used in LS-DYNA ensure that the Hybrid III model performance is as equal to that of the physical Hybrid III as possible. Calibration of the Hybrid III models allow for accurate performance during simulation for crashworthiness.

Two of the calibration simulations used on the LSTC Hybrid III models include the Neck Extension and Neck Flexion Simulations. The Neck Extension and Neck Flexion Test are federally regulated certification tests, as of CFR49. The tests ensure that dummies have biofidelic neck characteristics before being certified as FMVSS compliance test tools. The Neck Extension and Flexion test setup includes fixing the Hybrid III head and lower neck assembly to the end of a pendulum. The pendulum is dropped from a specified height and strikes an aluminum honeycomb stop. The inertial characteristics of the head cause the neck to bend on impact. Hybrid III neck calibration is determined by conformance to neck response requirements. Plane-D rotation, maximum moment about the occipital condyle, and negative moment decay response requirements are federally regulated. The pendulum velocity at impact and time of pendulum stoppage is regulated by CFR49 according to the test: extension or flexion. Head and neck
orientation are also dependent on the type of test. The Neck Extension Test setup specifications are available in Figure 2.

Figure 2. Neck Extension Test Setup Specifications. Adapted from ‘PART 572—ANTHROPOMORPHIC TEST DEVICES’ by United States, Code of Federal Regulations. Title 49, Subtitle B, Chapter V, 2019, Government Publishing Office.

Components necessary for the physical neck calibration tests include the head assembly, neck assembly, upper neck bracket, lower neck bracket, bib simulator, six-channel transducers, and three head accelerometers (Electronic Code of Federal Regulations, 2019). The transducers measure the Plane-D rotation, as well as upper neck force and moment. The LSTC Hybrid III models imitate the neck transducer with the input file keyword *CONSTRAINED_JOINT_STIFFNESS, which can be used to measure joint forces between the head and neck during post processing. The head accelerometer is modeled with the input file keyword *DATABASE_HISTORY_NODE, which can be used to track the acceleration of a node belonging to the model’s head accelerometer block.
2.1 Neck Extension Simulation

The NASA Updated Hybrid III neck model was assessed using the explicit LSTC neck calibration simulations. The calibration simulations were provided by LSTC. A few adjustments were made to the simulation setup to agree with the 95th percentile certification test SAE specifications. To be more computationally efficient, the pendulum is prescribed an initial rotational velocity, millimeters from the honeycomb stop, rather than having to simulate the entirety of the pendulum dropping from the specified height. The NASA updated neck was included into the main file. The head and neck assembly were translated and rotated in line with the pendulum. The lower neck bracket and pendulum interface were rigidly constrained using *CONSTRAINED_RIGID_BODIES.

The pendulum rotational velocity was set to -3.6784E-3 rad/ms about the y-axis using two *INITIAL_VELOCITY_GENERATION keywords. Two keywords were used to prescribe velocity because rigid body velocities are always set to the value used prior to dynamic relaxation (H-III 95M Drawing Package Draft, 2010). A dynamic relaxation phase was initialized in the simulation; therefore, two velocity generation cards are needed, one with the phase variable set to 0: velocities applied immediately, and one with the phase variable set to 1: velocities applied after dynamic relaxation (H-III 95M Drawing Package Draft, 2010). The two velocity generation cards allow LS-DYNA to find dynamic equilibrium before dynamic analysis, and then prescribe initial velocity to all rigid and deformable bodies during dynamic analysis.

The prescribed initial rotational velocity at impact was found using the SAE specified Neck Extension Test drop height, the conservation of energy, and the definition of angular velocity. The honeycomb barrier longitudinal stress in the x-direction was adjusted by scaling the load curve of sigma-aa versus volumetric strain to give the pendulum the SAE indicated change in
velocity during impact. Figure 3 displays the NASA Updated Hybrid III Large Male neck at peak extension.

![Figure 3. Neck Assembly at Peak Extension](image)

The pendulum impact velocity and pendulum change in velocity was measured in the `nodout` file by tracking node 1000399, the pendulum accelerometer. A plot of the pendulum velocity as a function of time is available in Appendix A. The orientation of plane-D was measured using the Element Tool during post-processing. A plot of the plane-D rotation in the xz-direction is available in Appendix A. The moment experienced by the neck assembly about the occipital condyle was monitored in the `jntforce` file at the joint 50100001. Plotting the theta-moment-total data produces the plot in Appendix A. The maximum moment and negative moment decay are visible in the plot.

The Hybrid III 95th percentile performance specifications in the Neck Extension Test are provided by SAE and are listed in Table 3, along with the results from the Extension Simulation. Results in green are acceptable, while those in orange do not meet calibration requirements.
Table 3. Neck Extension Test specifications and NASA updated model simulated results

<table>
<thead>
<tr>
<th></th>
<th>Lower Corridor</th>
<th>Upper Corridor</th>
<th>Units</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>20.6</td>
<td>22.2</td>
<td>C</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>69.1</td>
<td>72.0</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>Humidity</td>
<td>10.0</td>
<td>70.0</td>
<td>% RH</td>
<td>N/A</td>
</tr>
<tr>
<td>Velocity</td>
<td>5.95</td>
<td>6.19</td>
<td>m/s</td>
<td>6.07 m/s</td>
</tr>
<tr>
<td></td>
<td>19.52</td>
<td>20.31</td>
<td>ft/s</td>
<td></td>
</tr>
<tr>
<td>Pendulum Pulse at 10 ms</td>
<td>1.8</td>
<td>2.2</td>
<td>m/s</td>
<td>1.90 m/s</td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>7.2</td>
<td>ft/s</td>
<td></td>
</tr>
<tr>
<td>Pendulum Pulse at 20 ms</td>
<td>3.4</td>
<td>4.2</td>
<td>m/s</td>
<td>3.90 m/s</td>
</tr>
<tr>
<td></td>
<td>11.2</td>
<td>13.8</td>
<td>ft/s</td>
<td></td>
</tr>
<tr>
<td>Pendulum Pulse at 30 ms</td>
<td>4.8</td>
<td>5.8</td>
<td>m/s</td>
<td>5.66 m/s</td>
</tr>
<tr>
<td></td>
<td>15.7</td>
<td>19.0</td>
<td>ft/s</td>
<td></td>
</tr>
<tr>
<td>Plane-D Rotation</td>
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<td>98</td>
<td>deg</td>
<td>79.15°</td>
</tr>
<tr>
<td>Moment During Rotation</td>
<td>66</td>
<td>84</td>
<td>N-m</td>
<td>70.51 N-m</td>
</tr>
<tr>
<td>Interval</td>
<td>49</td>
<td>62</td>
<td>lbf-ft</td>
<td></td>
</tr>
<tr>
<td>Moment Decay to -10N-m</td>
<td>100</td>
<td>120</td>
<td>ms</td>
<td>107.56 ms</td>
</tr>
</tbody>
</table>

Note. Corridor data adapted from “User's Manual for the Hybrid III Large Male Test Dummy.”

SAE International, Copyright Sept. 2012 by SAE International

2.2 Neck Flexion Simulation

The concept of the Neck Flexion Test is equal to that of the Neck Extension Test; however, the head and neck assembly in flexion faces the opposite direction. The head and neck assembly face the x-direction in flexion, and negative x-direction in extension. Additionally, the pendulum drop height and hence pendulum impact velocity is larger in the Flexion Test. The calculated prescribed rotational velocity of the pendulum was equal to -4.245E-3 rad/ms. Again, the honeycomb Barrier longitudinal stress in the x-direction was altered to match the pendulum velocity stoppage to the prescribed values listed by SAE. Figure 4 displays the NASA Updated Hybrid III Large Male neck assembly at peak flexion.
The same areas of neck response are measured in the Flexion Simulation as in the Extension Simulation, although the SAE performance corridors change. Plots of the plane-D rotation, maximum moment and negative moment decay are available in Appendix A. The Hybrid III 95th percentile performance specifications in the Neck Flexion Test are provided by SAE and are listed in Table 4, along with the results from the Flexion Simulation. Results in green are acceptable, while those in orange do not meet calibration requirements.

Table 4. Neck Flexion Simulation specifications and NASA updated model simulated results

<table>
<thead>
<tr>
<th></th>
<th>Lower Corridor</th>
<th>Upper Corridor</th>
<th>Units</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>20.6</td>
<td>22.2</td>
<td>°C</td>
<td>N/A</td>
</tr>
<tr>
<td>Humidity</td>
<td>10.0</td>
<td>70.0</td>
<td>% RH</td>
<td>N/A</td>
</tr>
<tr>
<td>Velocity</td>
<td>6.89</td>
<td>7.13</td>
<td>m/s</td>
<td>7.01 m/s</td>
</tr>
<tr>
<td>Pendulum Pulse at 10 ms</td>
<td>2.2</td>
<td>2.7</td>
<td>m/s</td>
<td>2.32 m/s</td>
</tr>
<tr>
<td></td>
<td>7.2</td>
<td>8.9</td>
<td>ft/s</td>
<td></td>
</tr>
<tr>
<td>Pendulum Pulse at 20 ms</td>
<td>4.0</td>
<td>5.0</td>
<td>m/s</td>
<td>4.58 m/s</td>
</tr>
<tr>
<td></td>
<td>13.1</td>
<td>16.4</td>
<td>ft/s</td>
<td></td>
</tr>
<tr>
<td>Pendulum Pulse at 30 ms</td>
<td>5.7</td>
<td>6.9</td>
<td>m/s</td>
<td>6.29 m/s</td>
</tr>
<tr>
<td></td>
<td>18.7</td>
<td>22.6</td>
<td>ft/s</td>
<td></td>
</tr>
<tr>
<td>Plane-D Rotation</td>
<td>61</td>
<td>75</td>
<td>Deg</td>
<td>55.11°</td>
</tr>
<tr>
<td>Moment During Rotation Interval</td>
<td>110</td>
<td>130</td>
<td>N-m</td>
<td>103 N-m</td>
</tr>
<tr>
<td></td>
<td>81</td>
<td>96</td>
<td>lbf-ft</td>
<td></td>
</tr>
<tr>
<td>Moment Decay to 10N-m</td>
<td>77</td>
<td>97</td>
<td>ms</td>
<td>75.62 ms</td>
</tr>
</tbody>
</table>

Note. Corridor data adapted from “User's Manual for the Hybrid III Large Male Test Dummy.”

SAE International, Copyright Sept. 2012 by SAE International
2.3 Preliminary Model Calibration

From the initial neck calibration simulations, the NASA Updated LSTC 95\textsuperscript{th} percentile model does not meet SAE specified standards. The plane-D rotation of the head and neck assembly in the Neck Extension Simulation was not within the required corridor. The Plane-D rotation, maximum moment, and moment decay to 10 N-m of the head and neck assembly in the Neck Flexion Simulation was not within the required corridor.

The NASA Updated Hybrid III model is not calibrated as a compliance test tool for vehicle safety standards. Although NASA reports that the model performs well in the sled simulations under low-level loading (6 – 16 G’s), the model does not perform accurately under the high-level loading of the neck calibration simulations (40+ G’s). It is important to properly calibrate the neck to not only meet SAE Hybrid III certification standards, but also to ensure that the LSTC Hybrid III model performs accurately in its primary application: automotive crash simulation.

To properly calibrate the neck, material properties of the neck rubber material card were altered. The material properties belonging to the viscoelastic material include: density, bulk modulus, short-time shear modulus, long-time shear modulus, and decay constant. Density was not changed because the model neck assembly mass already conformed to the mass listed in the 95\textsuperscript{th} percentile Drawing Package. Material properties were individually, arbitrarily altered to see its effect on neck performance. The decay constant and long-time shear modulus were not adjusted much because the calibration simulations are transient. The material model was altered until performance specifications were well-within the SAE regulated corridors. The resulting material properties are listed in Table 5. The neck calibration performance of the revised model is compared to the NASA Updated model in Table 6. The plots of neck response characteristics of the calibrated and uncalibrated models are compared side-by-side in Appendix B.
Table 5. Hybrid III 95th percentile model revised viscoelastic material properties

<table>
<thead>
<tr>
<th>Ro</th>
<th>Bulk</th>
<th>G0</th>
<th>GI</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1E-6</td>
<td>0.0728</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.116</td>
</tr>
</tbody>
</table>

Table 6. Neck calibration simulation NASA updated and revised model simulated results

<table>
<thead>
<tr>
<th>Response Criterion</th>
<th>SAE Corridors</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extension Test:</td>
<td>SAE Corridors</td>
<td>Performance</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>Plane-D Rotation [deg]</td>
<td>81</td>
<td>98</td>
</tr>
<tr>
<td>Moment During Rotation Interval [N-m]</td>
<td>66</td>
<td>84</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m [ms]</td>
<td>100</td>
<td>120</td>
</tr>
<tr>
<td>Flexion Test:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plane-D Rotation [deg]</td>
<td>61</td>
<td>75</td>
</tr>
<tr>
<td>Moment During Rotation Interval [N-m]</td>
<td>110</td>
<td>130</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m [ms]</td>
<td>77</td>
<td>97</td>
</tr>
</tbody>
</table>

Adjustments made to the Hybrid III material allowed the model to conform to SAE standards in the CFR calibration simulations. However, model performance beyond just the calibration simulations are pertinent. Later model modifications were made to improve element behavior and increase performance in the NASA Neck Sled Simulations, and neck compression simulations. Further work is summarized in the following section: Preview of Work.
3. PREVIEW OF WORK

This section will provide a concise outline of the proceeding sections and the main takeaways of the project. There are four main segments to the project: Model Mesh and Element Testing, Compression Testing, Calibration Testing, and NASA Neck Sled Testing. Results of each segment build off each other to produce an ultimate neck model. Results below correspond to the ultimate model.

3.1 Model Mesh and Element Testing

Results from various simulation led to remeshing the neck model and altering the element formulation of the neck rubber. A mesh convergence study was completed on the neck in the Neck Extension Simulation to select element size based on computational efficiency and deflection-based convergence. The convergence is visible in Figure 5. The computation time is shown in Table 7. The mesh selected shows results in green.

![Figure 5. Maximum plane-D rotation for models v099, v100, v103, and v104](image-url)
Table 7. Mesh influence CPU timing information

<table>
<thead>
<tr>
<th>Model</th>
<th>Element Count Normalized over v100</th>
<th>Factor of Elements per Dimension</th>
<th>50200001 Smallest Time step [ms]</th>
<th>Total CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>v099</td>
<td>0.125</td>
<td>1</td>
<td>5.0738E-03</td>
<td>13 mins 12 sec</td>
</tr>
<tr>
<td>v100</td>
<td>1</td>
<td>2</td>
<td>1.7175E-03</td>
<td>20 mins 19 sec</td>
</tr>
<tr>
<td>v103</td>
<td>8</td>
<td>4</td>
<td>4.9164E-04</td>
<td>1 hr 26 min 38 sec</td>
</tr>
<tr>
<td>v104</td>
<td>64</td>
<td>8</td>
<td>1.6713E-04</td>
<td>35 hr 1 min 21 sec</td>
</tr>
</tbody>
</table>

The element formulation was changed to constant stress solid with hourglass control 7. Extreme conditions testing was completed to show improvement in element tendency to normally terminate. The study largely evaluated the models’ element formulation. Scaled rotational velocities of the pendulum were used in the Neck Extension Simulation, as well as scaled rod velocities in the Rod Impact Simulation to find where the NASA model and the ultimate model failed. The results are compiled in Table 8. Through extreme conditions testing, it was found that the NASA model was artificially stiff in bending. The elements of the ultimate model had more consistent deformation and were less likely to prompt negative volume errors.

Table 8. Neck Extension Simulation extreme condition testing results

<table>
<thead>
<tr>
<th>Model</th>
<th>Velocity Multiplier</th>
<th>Head Maximum Acceleration [G’s]</th>
<th>Termination</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA updated</td>
<td>1x</td>
<td>38</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>1.2x</td>
<td>51</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>1.5x</td>
<td>N/A</td>
<td>Error</td>
</tr>
<tr>
<td>Ultimate Model</td>
<td>1x</td>
<td>50</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>1.2x</td>
<td>82</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>1.5x</td>
<td>360</td>
<td>Normal</td>
</tr>
</tbody>
</table>
Table 9. Rod Impact Simulation maximum acceptable rod velocity without model failure

<table>
<thead>
<tr>
<th>Model</th>
<th>Rod velocity at failure [m/s]</th>
<th>Rod to rubber maximum resultant force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA modified</td>
<td>12</td>
<td>1.26</td>
</tr>
<tr>
<td>New Model</td>
<td>24</td>
<td>4.58</td>
</tr>
</tbody>
</table>

3.2 Compression Test and Simulation

The Compression experiment compressed the Hybrid III 95th percentile and 50th percentile neck assemblies using a Lloyd Instruments LD50 tester. Individual quasi-static tests loaded each neck at a constant head rate to a deflection of about 10mm. The force-deflection data obtained through testing was used as a template for modeling neck response in simulated compression. Figure 6 displays the load curves of 50th and 95th percentile necks under equal head rate. It was determined that the neck rubber material between the differing percentile necks is virtually identical.

![Graph showing load curves for 50th and 95th percentiles](image)

Figure 6. Compression Test 95th and 50th load curves without initial low-level loading

The compression simulations were made to replicate the compression test experiment. An explicit and implicit simulation were created and performed. Results varied based on the solver selected. The implicit simulation was determined as the more accurate simulation because the load rate was equal to the experiment, while time step restrictions of the explicit solver made replicating
experimental boundary conditions not viable. The neck rubber is prone to the viscoelastic effect, so rate of force is an important variable. The material properties of the model were adjusted to best match the implicit simulation response to the experimental load data. The magnitude of load could not be replicated. Instead, the slope, or rate of reaction force under load, was matched as seen in Figure 7.

![Figure 7. Implicit Compression Simulation: experiment and usimcurve19 data](image)

### 3.3 CFR Calibration Simulations

The model was intermittently evaluated in the CFR Calibration Simulations: Neck Extension and Neck Flexion. The simulations replicated the federally regulated calibration tests used for the Hybrid III head and neck assembly. Material property adjustments completed in the NASA Neck Sled Simulations were further evaluated in the calibration simulations to ensure that neck model response was still within the CFR specified corridors. The improvement in model calibration from the NASA model to ultimate model is seen in Table 10. The improvement in computational efficiency is seen in Table 11.
Table 10. Neck Calibration Simulation performance of NASA updated model and usimcurve19

<table>
<thead>
<tr>
<th>Neck Extension</th>
<th>Lower Corridor</th>
<th>Upper Corridor</th>
<th>NASA updated</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane-D Rotation [deg]</td>
<td>81</td>
<td>98</td>
<td>79.15</td>
<td>91.29</td>
</tr>
<tr>
<td>Maximum Moment [N-m]</td>
<td>66</td>
<td>84</td>
<td>70.51</td>
<td>68.50</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m [ms]</td>
<td>100</td>
<td>120</td>
<td>107.56</td>
<td>109.86</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neck Flexion</th>
<th>Lower Corridor</th>
<th>Upper Corridor</th>
<th>NASA updated</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane-D Rotation [deg]</td>
<td>61</td>
<td>75</td>
<td>55.11</td>
<td>63.52</td>
</tr>
<tr>
<td>Maximum Moment [N-m]</td>
<td>110</td>
<td>130</td>
<td>103</td>
<td>111.44</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m [ms]</td>
<td>77</td>
<td>97</td>
<td>75.62</td>
<td>77.64</td>
</tr>
</tbody>
</table>

Table 11. Neck Extension Simulation computational efficiency

<table>
<thead>
<tr>
<th>Model</th>
<th>Total CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA Updated</td>
<td>1 hour, 12 min, 59 sec</td>
</tr>
<tr>
<td>Ultimate</td>
<td>20 min, 19 sec</td>
</tr>
</tbody>
</table>

3.4 NASA Neck Sled Simulations

The working model was evaluated in the NASA Neck Sled Simulations along with intermittent evaluations in the CFR Calibration Simulations. The NASA Neck Sled Tests consisted of mounting the 95th percentile head and lower neck assembly on a rigid sled that was then accelerated from zero velocity. Material properties were further adjusted to match response of the neck model to that of the physical 95th percentile. Response was judged based on sameness of injury criterion data from simulation to data from NASA-performed tests. Sameness of response was quantified using International Organization for Standardization (ISO) ratings. The ultimate model was CFR calibrated and also possessed improved ISO scores in the Neck Sled Simulations. The ultimate material properties of the viscoelastic material model are available in Table 12. The
ISO ratings for the NASA model and ultimate model in each of the four sled cases is listed in Table 13.

Table 12. Usimcurve19 viscoelastic material properties

<table>
<thead>
<tr>
<th>Version</th>
<th>Ro</th>
<th>Bulk</th>
<th>G0</th>
<th>GI</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate</td>
<td>1.175E-6</td>
<td>0.0500</td>
<td>0.0055</td>
<td>0.0205</td>
<td>0.043</td>
</tr>
</tbody>
</table>

Table 13. NASA Neck Sled Test 300ms ISO18571 scores: NASA model and ultimate model

<table>
<thead>
<tr>
<th></th>
<th>Lateral 12G</th>
<th>Frontal 6G</th>
<th>Frontal 16G</th>
<th>Rearward 6G</th>
<th>Combined Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA model</td>
<td>0.786</td>
<td>0.675</td>
<td>0.651</td>
<td>0.639</td>
<td>0.688</td>
</tr>
<tr>
<td>Ultimate</td>
<td>0.818</td>
<td>0.672</td>
<td>0.765</td>
<td>0.613</td>
<td>0.717</td>
</tr>
</tbody>
</table>

The ultimate material model was greatly improved from the NASA model in the Lateral 12G and Frontal 16G sled cases. The performance increase in the 12G and 16G simulations was attributed to the model’s calibration at high-severity loads.

3.5 Project Conclusions

The resulting neck model developed in LS-DYNA exhibited improved dynamic characteristics and reliability under both low and high-severity loading. Computational efficiency was enhanced along with model tendency to normally terminate under excessive loading. The ultimate model moreover demonstrated consistent element behavior and realistic feedback in bending. The ultimate model had the highest combined ISO18571 rating in the Neck Sled Simulations, while still meeting CFR Neck Calibration test corridor requirements. The revised neck model will be adopted by NASA for use in predicting potential occupant injury during spacecraft landing. A similar model with reworked material properties attuned to higher loading will be implemented.
into the full consumer version of the LSTC Hybrid III 95th percentile model for employment in high-severity frontal crash simulation.

Succeeding sections of the thesis go in much greater detail of how simulations and tests were constructed, how results were obtained and analyzed, and problems confronted during testing and their corresponding solutions. Supplemental simulations, studies, and neck models are presented in the proceeding text.
4. COMPRESSION SIMULATION DEVELOPMENT

The compression simulation was made to replicate the ensuing compression test experiment. The compression simulation was built prior to the experiment since the required lab equipment for compression was not available until later in the project. The projected outcome of the experiment was created in LS-DYNA. It was anticipated that changes to the simulation would be implemented according to the boundary conditions established during the actual experiment.

The experiment would consist of the compression of the Hybrid III 95\textsuperscript{th} percentile and 50\textsuperscript{th} percentile neck assemblies. Individual quasi-static tests would load each neck at a constant head rate to a deflection of about 10mm. Testing would conform to ASTM standards for compression of rubber. The force-deflection data obtained through testing would be used as a template for model neck assembly response in simulated compression. The intension of the study was to adjust model material properties to match the simulated neck reaction force to the physical loading data from experiment.

4.1 Form of Analysis

In linear static problems, the applied load is not time dependent, and the assumption of linearity implies, that is, materials, boundary conditions, and displacements are all linear. The model response is assumed to be purely elastic. In LS-DYNA, static analysis is completed using implicit analysis (“What are the differences between implicit and explicit?,” 2014). Implicit solvers use a stiffness matrix and residual vector to compute nodal displacement. In implicit static analysis, only one tangent, stiffness matrix, is required to solve the problem with no increment in time. In this analysis, velocity and acceleration are neglected and deformation has no effect on model behavior. Effectively, static implicit analysis does not take into effect mass inertia nor plastic behavior (“What are the differences between implicit and explicit?,” 2014).
Dynamic analysis is implemented to account for acceleration and inertial characteristics of mass. Nonlinear analysis is implemented when there is a nonlinear relationship in the material or between loading and displacement. In nonlinear implicit analysis loads are applied in increments within a single step to find the solution path (Steps, increments, and iterations, 2017). Multiple iterations are required to find the equilibrium solution of each increment (Steps, increments, and iterations, 2017). Each iteration requires forming new stiffness and residual matrices. The previous solution is used to calculate a new stiffness matrix each subsequent iteration until the residual is small enough to indicate a solution. In dynamic nonlinear implicit analysis, nonlinearities and inertial forces are captured, however multiple iterations, increments, and matrix inversions make analysis computationally expensive (“What are the differences between implicit and explicit?,” 2014). Consequently, implicit solvers are typically limited to simpler problems to avoid inversion of large stiffness matrices.

By contrast, explicit analysis only requires large inversions of diagonal matrices, which are computationally inexpensive. In explicit analysis, the nodal force vector and mass matrix are used to directly solve for nodal accelerations. Nodal accelerations at the current time step are then used to solve for nodal velocities and nodal displacements at the next time step (“What are the differences between implicit and explicit?,” 2014). In explicit analysis, boundary condition and displacement nonlinearities are automatically captured, as well as inertial forces; however, many small time steps are necessary to find an end solution. Explicit time steps are limited by the courant time step: “the time it takes a sound wave to travel across an element” (“What are the differences between implicit and explicit?,” 2014). Because of this, Explicit analysis is limited to transient problems to keep solutions computationally efficient.
Selection of the most efficient solver depends on problem termination time and complexity. Nonlinearities and inertial forces are captured by explicit solvers, while that is not always the case for implicit solvers. Explicit analysis does not require iterative methods like implicit analysis but does require many small time steps to be accurate. Explicit solvers are typically used for short time dynamics when velocity or deformation experienced is high (Stuttgart, 2016). Examples of uses for explicit analysis include simulation for drop tests and automotive crashes. The advantage of implicit solvers is that they have the ability to have large time steps, though they may have difficulty converging when there are high inertial forces or extreme nonlinearities. Implicit analysis is typically used for long-duration problems when the effects of acceleration are insignificant (Stuttgart, 2016). Examples of uses for implicit solvers include small model structural analysis or quasi-static loading.

Although the compression experiment will be non-destructive, the response of the neck cannot be modeled as linear. The displacements will be small, and boundary conditions will remain the same throughout simulation. Therefore, geometric and boundary conditions will be linear for the most part. However, there will be strong material nonlinearities. This is because of the viscoelastic material model. Viscoelastic materials have nonlinear behavior under loading, meaning that its stiffness is time-dependent. The material nonlinearities of the neck rubber make it necessary to use nonlinear analysis. Dynamic analysis will also be necessary, as the time history simulation data will be required to compare model response to physical response.

To simulate the compression test experiment, the LSTC 95th percentile model neck assembly will undergo a nonlinear implicit and explicit dynamic analysis. Explicit analysis will be used because LS-DYNA has a powerful explicit solver. Furthermore, the Hybrid III models are exclusively used in explicit analysis. A downfall of this simulation will be the time step limitations of explicit solvers. Because the explicit time step is restricted by the courant time step, the simulation will
either be extremely expensive, or require modifications to boundary conditions. Implicit analysis will also be used as an alternative to the explicit simulation. Implicit analysis will be a viable solution method due to the quasi-static nature of the experiment. The lack of time step constraints will allow all boundary conditions to remain equal to the those in the experiment. A downfall of the implicit solver will be the large matrix inversions that will take place. This and difficulties in convergence may lead to a computationally inefficient simulation. Nonetheless, both solvers will be used to simulate the neck compression experiment. Solutions obtained from both solvers will be compared, as they should arrive at the same result.

4.2 Explicit Simulation

The first compression simulation was made with an explicit solver. To begin, the 95th percentile neck file was produced. The head and neck assembly file was modified so only parts and entities pertaining to the neck were left. The Element Tool in LS-PrePost was used to delete all other elements and nodes. All constraints, including nodal rigid bodies, extra nodes, and joints were removed. Contacts that were not between parts, node sets, or segment sets of the neck rubber and neck disks were removed from the keyword file. Extraneous parts were deleted in the keyword file. A model check was run in LS-PrePost to remove any keyword warnings caused by unreferenced nodes, node sets, and database history nodes.

To ensure the neck assembly contacts remained unchanged, the neck assembly was assigned an arbitrary velocity to view its response. The neck rubber and neck pucks were given transnational and rotational velocities differing in direction and magnitude. The reaction of the neck was observed. The intuitive response suggested that there were proper contacts between parts and there were no hidden constraints. The resulting keyword file was named 95neck.k.
The next step was to create the main keyword, or input, file to simulate compression. Input files used in LS-DYNA require a set of keywords to define the problem. The keywords all begin with an asterisk. Additional definitions of the problem are set in variables listed under its corresponding keyword. All keywords and variables are defined in the LS-DYNA Keyword User’s Manual. According to the LS-DYNA Course Notes, all input files must include commands: *KEYWORD, *CONTROL_TERMINATION, *NODE, *ELEMENT, *SECTION, *MAT, *PART, *DATABASE_BINARY_D3PLOT, and *END. Node, element, section, material, and part keywords were already contained in the 95neck.k file. Additional requirements of the main file were as follows: include the 95neck.k file, reposition the neck, establish boundary conditions, form referenced node sets, and establish a means of obtaining response data. Table 14 lists select keywords that were used in the explicit compression simulation input file.

Table 14. Compression Simulation input deck notable keywords

<table>
<thead>
<tr>
<th>KEYWORD</th>
<th>Output file</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>*DEFINE_TRANSFORMATION</td>
<td></td>
<td>Define a rotation such that the neck assembly length is parallel with the global z-axis.</td>
</tr>
<tr>
<td>*INCLUDE_TRANSFORMATION</td>
<td></td>
<td>Insert the neck assembly under the defined transformation into the main_comp.k file.</td>
</tr>
<tr>
<td>*DEFINE_CURVE</td>
<td></td>
<td>Define a load curve that constitutes the acceleration of gravity. Define a load curve that constitutes the neck rate of displacement.</td>
</tr>
<tr>
<td>*BOUNDARY_PRESCRIBED_MOTION_SET_ID</td>
<td></td>
<td>Prescribe the rate of displacement established in *DEFINE_CURVE to the set of nodes on the top-most plane of the top neck puck in the global z-direction.</td>
</tr>
<tr>
<td>*BOUNDARY_SPC_SET</td>
<td></td>
<td>Create a fixed-fixed connection to the set of nodes on the bottom-most plane of the bottom neck puck.</td>
</tr>
<tr>
<td>*LOAD_BODY_Z</td>
<td></td>
<td>Prescribe the acceleration due to gravity established in *DEFINE_CURVE to all parts in the file.</td>
</tr>
<tr>
<td>*CONTROL_TERMINATION</td>
<td></td>
<td>Set the termination time for the job.</td>
</tr>
</tbody>
</table>
Table 14. Compression Simulation input deck notable keywords, Continued

<table>
<thead>
<tr>
<th>KEYWORD</th>
<th>Output file</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>*CONTROL_TIMESTEP</td>
<td></td>
<td>Set the minimum time step size. This is necessary to view the added mass output during simulation.</td>
</tr>
<tr>
<td>*DATABASE_HISTORY_NODE_SET</td>
<td>nodout</td>
<td>Track the acceleration, velocity, and displacement of the set of nodes on the top-most plane of the top neck puck. The nodout file will confirm the displacement of the model under compression.</td>
</tr>
<tr>
<td>*DATABASE_BNDOUT</td>
<td>bndout</td>
<td>Track boundary condition forces and energy (<em>LS-DYNA Keyword User’s Manual</em>, 2007). The bndout file will measure the reaction force of the neck assembly on the *BOUNDARY_PRESCRIBED_MOTION set of nodes.</td>
</tr>
<tr>
<td>*DATABASE_SPCFORC</td>
<td>spcforc</td>
<td>Track SPC Boundary forces. The spcforc file will confirm the reaction forces measured in the bndout file.</td>
</tr>
<tr>
<td>*DATABASE_MATSUM</td>
<td>matsum</td>
<td>View hourglass energy, internal energy, and added mass.</td>
</tr>
</tbody>
</table>

The prescribed motion was set at a constant head rate of 12mm/min according to ASTM D575 Test Method A – Compression Test of Specified Deflection of Rubber. The deflection of the neck was limited to the arbitrary termination time of the model. The correct deflection was established in the input file after the actual experiment was completed.

The complete input file for the explicit compression simulation is available in Appendix C. MPP LS-DYNA version R9.0.1 on Red Hat 5.4 for Linux was used to run the file. Single precision was used to keep the simulation computationally efficient. MPP was selected to use large scale
parallel data processing on multiple processors. The server used to run the simulation was located on site at LSTC. The explicit simulation normally terminated when run.

### 4.3 Implicit Simulation

The compression simulation with implicit solver possesses a similar input deck to the explicit solver. All keywords used in the explicit input deck were reused in the implicit input deck except for *DATABASE_EXTENT_BINARY, as there is no mass scaling in implicit analysis. A number of control cards were added to the input file to activate and manage the implicit solver in LS-DYNA. The following additional keywords were implemented into the input deck:

Table 15. Implicit Compression Simulation additional control cards

<table>
<thead>
<tr>
<th>KEYWORD</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>*CONTROL_IMPLICIT_DYNAMIC</td>
<td>Activate dynamic analysis.</td>
</tr>
<tr>
<td>*CONTROL_IMPLICIT_EIGENVALUE</td>
<td>Activate eigenvalue analysis.</td>
</tr>
</tbody>
</table>

The added control cards with defined variables for the implicit compression simulation are available in Appendix D. Imflag was set to one on *CONTROL_IMPLICIT_GENERAL to activate implicit analysis. DT0 was set to 500 to set an initial timestep of 500ms. The variable ialut on the implicit auto card was set to one to automatically adjust the time step (LS-DYNA Keyword User’s Manual, 2007). IMASS was set to one on *CONTROL_IMPLICIT_DYNAMIC to activate dynamic analysis with Newark time integration (LS-DYNA Keyword User’s Manual, 2007). The time integration constants were left as default. Ilimit and maxref were set to 11 and 15.
respectively as the iteration limit and stiffness reformation limit per time step. The displacement relative convergence tolerance, $\text{dctol}$, was set to 0.01 mm. $\text{Nlprint}$ on the implicit solution card was set to two to print iteration information for transnational degrees of freedom in the output file.

The LSTC Checklist for Implicit Modeling was used to help produce a functioning, accurate implicit simulation. $\text{Nsolvr}$ 12 was selected on the *CONTROL_IMPLICIT_SOLUTION card to activate a nonlinear solution with Broyden–Fletcher–Goldfarb–Shanno iterative updates (LS-DYNA Keyword User’s Manual, 2007). This is the recommended solver for nonlinear problems and introduces different integration methods than $\text{nsolvr}$ two (“Checklist for Implicit Modeling,” n.d.). $\text{LSMTD}$ was set to 4 to put the line search convergence method to, “energy method using sum of transnational and rotational degrees of freedom” (LS-DYNA Keyword User’s Manual, 2007). The strategy attempts to reduce potential energy in the line search direction (Johansen, 2016). $\text{Abstol}$, the absolute convergence tolerance, was set to $10E^{-20}$ to prevent early convergence (“Checklist for Implicit Modeling,” n.d.). Shell elements were set to the recommended element formulation -16 with hourglass type 8 (“Checklist for Implicit Modeling,” n.d.). Element formulation -16 is a fully integrated shell specifically made for implicit analysis with large deformations and rotations (LS-DYNA Keyword User's Manual, 2007). Solid elements were set to element formulation -2: fully integrated eight-point hexahedron for elements with poor aspect ratios (LS-DYNA Keyword User's Manual, 2007).

The control card *CONTROL_IMPLICIT_EIGENVALUE was only temporarily added. The keyword disables dynamic analysis, but was used to check for rigid body modes. Mode shapes and eigenfrequencies are seen in the animation of the $d3eigv$ binary plot file. The eigenmode shows the shape of the deformation when the model is vibrating at its natural frequency (Eigenfrequency Analysis, 2018). Three modes were shown with natural frequencies 0.11312,
0.11667, and 0.23947. In each eigenmode, the bottom puck did not move, confirming that the puck was correctly constrained. Rigid body modes would be present if there was motion in any degree of freedom without internal deformation (Eigenfrequency Analysis, 2018). The non-zero eigenfrequencies suggest that the model was not completely free in translation or rotation. The eigenvalue analysis confirms that the model is properly constrained and that there are no rigid body modes present in the defined job.

MPP LS-DYNA version R9.2.0 on Red Hat 5.4 for Linux was used to run the input file. A different version of LS-DYNA was downloaded to run the implicit compression in double precision rather than single. The double precision executable takes longer to run; however, double precision significantly reduces numerical round off and provides better convergence for nonlinear implicit problems (LS-DYNA Keyword User’s Manual, 2007). Double precision is also mandatory when running implicit analysis on MPP databases. The server used to run the simulation was located on site at LSTC. The implicit simulation, however, did not terminate normally.

4.4 Evaluation of Neck Discretization

The explicit simulation successfully terminated, while the implicit solver was unable to converge on a solution. Figure 8 displays the Von Mises stress plot of the neck assembly in the explicit simulation at peak deflection. Figure 9 shows the neck assembly in the implicit simulation at the final converged state before the induced error termination.
An error was encountered in the implicit simulation at 5% of the prescribed termination time. The model was compressed by 0.4 mm at this time. The *d3hsp* output file revealed that the fatal error was due to negative volumes in solid elements. Negative volume errors occur when the volume of an element is calculated as negative. These errors typically arise in elements that undergo large deformations. The negative volume of elements prompted a non-positive definite stiffness matrix, which is evident in the negative eigenvalue warnings. Negative eigenvalues are typical among systems that experience instability.
Figures 10-13 show the Von Mises stress progression in the model in sequential states. The figures show that the negative volume in elements occurs as soon as a non-zero stress was present in the elements around the neck rubber hole. Figure 13 shows no stress concentration at the rubber neck hole that would suggest element singularities.

Figure 10. Implicit Compression Simulation old mesh Von Mises stress at state 3

Figure 11. Implicit Compression Simulation old mesh Von Mises stress at state 4

Figure 12. Implicit Compression Simulation old mesh Von Mises stress at state 5
Negative volume errors usually happen in soft materials under extreme distortions ("Negative volume in soft materials," 2015). However, surrounding elements are not largely deformed. To negate the negative volume errors, a number of techniques were attempted. The timestep factor was reduced to avoid numerical instabilities, the element formulation of the rubber was changed to the more robust reduced integration formulation, and various recommendations from the LSTC Checklist for Implicit Modeling were implemented ("Negative volume in soft materials," 2015). However, the negative volume errors were still present.

The odd element behavior was attributed to poor meshing around the neck rubber hole. The discretization created sharp internal corners in each hole, which may cause model instability. Figure 14 displays one of the neck rubber holes.

Figure 13. Implicit Compression Simulation old mesh Von Mises stress at state 6

Figure 14. Neck assembly neck rubber hole
The hole is poorly shaped for how fine the mesh is. There are two elements per side, creating five internal edges. With equal mesh size, one element per side would produce a neck rubber hole with less severe internal angles. Tailoring the mesh in consideration of the deformation field can discourage negative volume errors ("Negative volume in soft materials," 2015). In order to prevent model instability, the neck assembly was re-meshed.
5. MODEL DISCRETIZATION EVALUATION

5.1.1 Model Re-Meshing

The failure to converge in the implicit compression simulation seeded the re-meshing of the LSTC 95th percentile neck pucks and neck rubber. Model discretization was completed by Mike Burger using TrueGrid mesh generator.

Because the neck assembly would be re-meshed, further adjustments to the neck geometry were subsequently set. All changes in geometry were made based off the federally regulated Hybrid III 95th percentile drawing package. The old mesh and newly meshed neck assembly is shown in Figure 15.

Changes in the mesh began at the neck rubber holes. The holes were re-shaped from pentagons to 14-sided tetradecagons. The minimum interior angle of the neck rubber hole was increased from 103° to 152°. Sharp interior angles may produce singularities. Increasing the minimum interior angle of elements creates a model that is less likely to produce errors or have odd behavior under loading. The new neck rubber hole is pictured in Figure 16.

Further adjustments in model geometry were completed on the neck disks. The neck cable through-hole was enlarged from 0.31” to 0.62” in diameter in accordance to the intervertebral disk part drawing (H-III 95M Drawing Package Draft, 2010). A neck bushing was added to the upper neck plate with geometry agreeing to the upper neck mount plate part drawing (H-III 95M Drawing Package Draft, 2010). The neck disk elements were changed from a mix of pentahedrons and hexahedrons to uniformly positioned hexahedrons. The foregoing changes are seen in Figure 17, the former and updated meshed upper neck mount plate. The changes to the neck should make for a more accurate model.
Figure 15. Former and updated neck assembly mesh

Figure 16. Updated mesh neck rubber hole
Although the neck assembly updated mesh appears finer than the previous mesh, the total number of nodes and elements had decreased from the previous mesh. Entity count is available under Model Info in LS-PrePost. The number of nodes in the updated mesh decreased by 14.1% from 57,590 to 49,460 nodes. The number of elements decreased by 12.9% from 69,776 to 60,776 elements. The loss of nodes and elements is due to the increased neck cable hole diameter, as well as the more efficient meshing of the neck rubber. The decrease in number of elements of the updated mesh becomes more evident when noting Figure 18, the top view of the neck rubber.
After updating the model mesh, the neck rubber and neck disk corresponding shell parts were deleted. In the past, it was difficult to specify contact between solid elements. The solution was to create null shell elements around the solid part, merge their nodes, and specify contact between shells. Advances in LS-DYNA have made it so coincident shell parts are no longer required for solid contact. Because they serve no purpose, the shells elements were deleted in LS-PrePost. The part, material, and segment cards of the shells were deleted in the keyword file. Node set and segment set 50200001, the contacting surfaces of the neck pucks and neck rubber, were re-created. The sets had to be recreated because the previous defined sets contained the massless nodes of the deleted shell elements. The sets are used to constrain the parts together and are referenced in the *CONTACT_TIED_NODES_TO_SURFACE.

Alterations in the neck keyword file were made to properly integrate the neck in with the rest of the dummy. Massless nodes of the deleted shell elements were removed in LS-PrePost. The addition of nodes and elements in the new mesh and the removal of shells made part, node, and element numbering counterintuitive. Part ID’s, node ID’s, and element ID’s of the neck were renumbered to coincide with the numbering scheme of the rest of the Hybrid III model. Furthermore, the addition of new nodes made it necessary to recreate existing node and segment sets involving the neck. All contact cards from the previous model were copy-pasted into the new keyword file.

Enlarging the neck cable hole removed mass from the neck assembly. The 95th percentile Drawing Package lists the neck assembly weight as 2.10 +/- 0.10lbs or 1.10 +/- 0.045kg (H-III 95M Drawing Package Draft, 2010). The mass of the neck pucks was calculated using the part geometry and density of 6061 T6 Aluminum. The mass of the neck rubber is equal to the difference between the neck assembly mass and neck puck mass.

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From the produced $d3hsp$ file, the mass of the former neck model was equal to 1.104kg. The mass of the newly sized neck was 1.075kg, which was too small. The known density and geometry of the aluminum pucks suggests that the additional mass should be added to the neck rubber, where the required density is unknown. The previous neck rubber density was $1.100 \times 10^{-6}$kg/mm$^3$. The density was raised to $1.175 \times 10^{-6}$kg/mm$^3$. This produced a neck assembly mass of 1.100kg, which is well within the regulated tolerance. Moreover, the increase in density also puts the neck rubber within the density tolerance of rubber butyl shore A 35-95 density: 1.15 – 1.35g/cc (“Butyl Rubber (IIR),” 1960).

5.1.2 Mass Scaling

The performance of the new mesh was evaluated in the compression simulations. The neck assembly was compressed to 10mm using the implicit and then explicit solver. The alterations to the mesh permitted the implicit simulation to normally terminate. The neck was compressed 10mm without negative volume errors or signs of odd element behavior. The implicit solver converged in each state within two to three iterations at an absolute convergence tolerance set to $10^{-20}$.

Similarly, the explicit simulation was able to terminate normally; however, a new problem arose with the new mesh: mass-scaling. Mass-scaling is only prevalent in explicit analysis, in which it may be necessary to add nonphysical mass to entities that are controlling the times step (“Mass Scaling,” n.d.). The process involves scaling density in small elements in order to meet time step criterion (“Mass Scaling,” n.d.). Mass scaling is necessary to avoid many, tiny time steps that would ergo cause lengthy computation time.
The addition of *DATABASE_EXTENT_BINARY to the keyword file allows the user to view the added mass of parts during simulation. The added mass is pulled from the *matsum file. Figure 19 displays the added mass of parts during the explicit compression simulation.

![Figure 19. Explicit Compression Simulation new mesh mass scaling](image)

The figure shows that the neck pucks have an added mass of about 0.7kg during simulation. The updated discretization of the neck pucks introduced elements that were too small to meet the minimum time step criterion. Hence, the mass-scaling of these small elements. An additional 0.7kg of mass in the quasi-static compression simulation is unlikely to cause problems; however, the inertial characteristics of the added mass become largely significant in high speed crash simulations.

One fix to the mass-scaling issue could be lowering the minimum explicit time step. The minimum time step size used in the dummy model is 5.0E-4ms. However, lowering the minimum time step is not an option because it would cause an increase in computation time. Customers would not appreciate a more computationally expensive model.
Instead of again, re-meshing the neck pucks, the neck puck material type was changed from *MAT_ELASTIC to *MAT_RIGID. Rigid parts do not control the time step because they are bypassed in element processing (*LS-DYNA Keyword User’s Manual, 2007). Changing the neck pucks to rigid will therefore eliminate mass scaling. However, disjoint groups of elements defined in a rigid part are not able to deform or bend (*LS-DYNA KEYWORD USER’S MANUAL VOLUME II Material Models, 2014). This means that the space between neck pucks was invariant. Separate rigid parts had to be generated so that each puck could move independently. Part 50200005 was split up into five separate parts using the move-copy tool in LS-PrePost.

An additional benefit of rigid bodies is their computational efficiency. Rigid part calculations do not rely on the elements and nodes of the body (*Determining when to use a rigid body, n.d.). Instead, rigid body movement is defined by just six degrees of freedom, making the motion calculation inexpensive (*Determining when to use a rigid body, n.d.).

Changing the neck puck material to rigid is justifiable because the aluminum neck pucks will never significantly deform in crash tests. Other aluminum and steel parts of the complete dummy model will likely be changed to *MAT_RIGID in future releases to further increase model computational efficiency.

5.2.1 Neck Calibration Simulations: Re-visited

The adjustments made to the neck model material and discretization suggest that the model would no longer have the same response as it once did. Consequently, the working model required re-calibration in the CFR Neck Extension and Flexion Simulations. Before calibration could begin, the simulation input files had to be adjusted to account for the new nodes, elements, and rigid neck pucks.
To begin, the former neck model was replaced with the new neck model in the head-and-lower-neck assembly file. The elements and nodes of the former-meshed neck rubber and neck pucks were deleted in the head-and-lower-neck assembly file using LS-PrePost. The input deck of the new neck assembly was read into the head-and-lower-neck assembly file. Because the working model was re-meshed in equal global coordinates to the old model, the neck did not have to be transformed when added to the file.

The addition of independent rigid neck puck parts made part itemizing inconsistent. Part, material, and section ID’s were renumbered in LS-PrePost. The neck puck part ID’s from top to bottom were 50200005, 50200006, 50200007, 50200008, and 50200009. All shell part ID’s in the full neck assembly were placed after all solid part ID’s to keep part numbering consistent with the rest of the model. The new part ID’s were added to the part set referenced in the initial velocity generation card in the main_ext.k file. The lower neck bracket part ID listed in the rigid body constraint to the pendulum was changed to the new, correct part ID.

Changing the neck pucks to separate rigid parts meant that node sets, contacts, and constraints had to be regenerated. Previously, *CONSTRAINED_EXTRA_NODES was used to tie the rigid upper neck bracket to four sets of evenly spaced nodes on the neck bib and bottom neck puck. However, the extra-nodes keyword option cannot be used to constrain two rigid bodies together. Changing the neck puck material type made it necessary to replace the keyword with *CONSTRAINED_RIGID_BODIES to connect the rigid parts. The upper neck bracket was set as the master part and neck puck 5 as the slave. A uniformly spaced set of nodes on the neck bib were constrained to the rigid bottom neck puck using *CONSTRAINED_EXTRA_NODES. The constrained set of nodes is considered part of the rigid body. A limited number of nodes were defined in the node set to admit the neck bib to deform.
Previously, constrained nodal rigid bodies (CNRB) were used to rigidly connect the upper neck disk and top neck disk deformable parts. Altering material type rendered the connection useless. The constraint was replaced with a *CONSTRAINED_EXTRA_NODES, which tied the rigid neck disk 1 to an evenly dispersed set of nodes on the top face of the upper neck disk. The connections between the neck rubber and individual neck pucks were not touched, as the connection was changed during the implementation of the new neck into the compression simulations.

The CNRB connecting the top edges of the neck cable to the cable beam and top neck puck was replaced by *CONSTRAINED_EXTRA_NODES_SET. The nodes on the top edge of the neck cable and the top-most node on the cable beam were constrained to the top puck rigid body.

The *AUTOMATIC_SURFACE_TO_SURFACE contact definitions between the neck cable and neck disks, as well as the neck rubber and neck disks were replaced by ten *AUTOMATIC_SURFACE_TO_SURFACE contacts. Node sets for each neck puck and neck rubber contacting surfaces were created to make the contacts and constraints possible.

Following the changes, the head and neck assembly was ready for evaluation in the CFR neck calibration simulations. The Neck Extension Simulation was run with the new neck; however, errors plagued the model. Most likely, the reworking of element size and location had introduced smaller elements in locations of large deformations. The large deformation of small elements caused element volumes to be calculated as negative.

To fix the element errors, the element formulation of the neck rubber solids was changed from fully integrated to under-integrated. Linear fully integrated elements, elform 2, are typically unstable under great deformations, such as the ones produced during the CFR neck calibration.
simulations. The reduced integration solid linear element, *elform* 1, is typically a more robust element under great deformations. The increased number of integration points in a fully integrated element formulation makes the element more prone to negative Jacobians and negative stiffness than under-integrated elements (“Negative volume in soft materials,” 2015).

Another consequence of fully integrated elements is shear locking. Fully integrated elements exhibit spurious shear energy caused by their inability to capture curvature under bending (“What is shear locking?,” n.d.). The higher shear stress accordingly triggers a smaller nodal displacement. The resulting element is stiffer than it should be. Changing the neck rubber element formulation to constant stress, *elform* 1, prevents shear locking. This is significant because bending of the neck is prevalent in car crash simulations.

The neck assembly with element formulation type 1 was able to terminate normally in the CFR neck calibration simulations. However, an additional problem was introduced with the reduced integration element formulation: hourglass modes. Hourglassing is frequent in reduced integration hex elements as a result of its single integration point. Certain bending deformations of the element cause an incorrect report of zero strain energy at the integration point (*Hourglass (HG) Modes*, 2012). As is, the constant stress element is unable to capture strain and stress under this non-physical form of deformation, producing unreliable results. Figure 20 shows the neck assembly at peak extension. The neck elements exhibit severe hourglass modes under compression. During unloading of the neck, the hourglass effect grew increasingly larger in the elements affected.
Keyword *CONTROL_ENERGY was added to the input deck to calculate the hourglass energy of the system. *DATABASE_MATSUM was added to the input deck to retrieve the calculated hourglass energy from the produced matsum file. Hourglass energy is equal to the work of internal forces to oppose hourglassing (Hourglass (HG) Modes, 2012). Figure 21 displays the hourglass energy and internal energy of the neck rubber in the current model.

Figure 20. Neck Extension Simulation hourglass modes at peak extension

Figure 21. Neck Extension Test neck rubber internal and hourglass energies
The hourglass modes in the neck elements are evident in the hourglass energy. Generally, the hourglass energy should be less than 10% of the internal energy at any given point in time (Hourglass (HG) Modes, 2012). The hourglass energy in the model is much larger than the 10% threshold. In this case, the hourglass modes of the model became unstable, which is why the hourglass energy was measured as high as it was. The instability shown in the plot was also observed in the model.

Hourglass modes can be lessened or completely avoided in a few ways. One way could be using fully integrated elements; however, it was already discovered that fully integrated elements were not robust enough under large deformations. Another solution would be refining the mesh, but further refinement would require a smaller time step and therefore lead to computational inefficiency. Another option could be using tetrahedral elements over hexahedral elements. However, tetrahedranes are prone to shear locking and replacing the current hex elements would require another time-consuming re-mesh (Hourglass (HG) Modes, 2012). One last solution, and the solution that was chosen, was introducing hourglass control.

There are two forms of hourglass control: viscous and stiffness. Both forms solve the issue of hourglass modes by introducing internal forces that artificially stiffen response (Hourglass (HG) Modes, 2012). Viscous hourglass stabilization produces internal forces relative to nodal velocities that are causing hourglass modes (Hourglass (HG) Modes, 2012). Viscous forms of hourglass control are best used in high-rate dynamic simulations, such as those using explosives (Hourglass (HG) Modes, 2012). Stiffness hourglass stabilization produces internal forces relative to nodal displacements that are causing hourglass modes (Hourglass (HG) Modes, 2012). Stiffness forms of hourglass control are best used in static or low-rate dynamic simulations (Hourglass (HG) Modes, 2012). Stiffness forms are ideal for crash simulation (Hourglass (HG) Modes, 2012).
The default hourglass control: type 1, and an hourglass coefficient of 0.1 was previously used in the model that exhibited severe hourglass modes. Type 1 is the standard hourglass viscous form (LS-DYNA Keyword User’s Manual, 2007). LS-DYNA has a number of well-developed hourglass control algorithms. The one settled on was type 7: Linear total strain form. Type 7 hourglass control is a stiffness form and variant of type 6: Belytschko-Bindeman assumed strain corotational stiffness (LS-DYNA Keyword User’s Manual, 2007). Type 7 is an expensive hourglass control but works well with foams and viscoelastic materials (Hourglass (HG) Modes, 2012). The resolved hourglass coefficient to go with type 7 was 1.0. Figure 22 displays the neck with type 7 hourglass control at peak extension. Figure 23 displays the hourglass energy and internal energy of the neck rubber in the model with updated hourglass control.

Figure 22. Neck Extension Simulation HG control type 7, HG coefficient 1.0
Changing the hourglass type significantly impacted the model. The resulting hourglass energy was just below 3% of the internal energy at any point throughout simulation. The 3% value is well below the 10% threshold for acceptable hourglass energy. Visually, the elements in the model exhibited little to no hourglass modes in each state of simulation.

### 5.2.2 Model Re-Calibration

Following adjustments to element formulation, the working model was calibrated in the CFR neck calibration simulations. The material properties selected in this section of testing were not precisely dialed in on because the properties would ultimately change during the NASA Neck Sled Simulations. The properties were adjusted until the model met the CFR specified calibration standards.

Table 16 presents the material properties of models referred to as A, B, and C. Model A is equal to the calibrated former-meshed model found in Section 2.3. Model B is the working model with material properties equal to that of the formerly calibrated Model A. Model C is the working model with adjusted material properties. The response of Model C falls within the SAE specified
corridors. Table 16 lists the material properties of models A, B, and C. Table 17 presents the Neck Extension and Neck Flexion Calibration Simulation results of each model.

Table 16. CFR Neck Calibration Simulation material model properties of Models A, B, and C

<table>
<thead>
<tr>
<th>Model</th>
<th>Mesh</th>
<th>Calibrated</th>
<th>Bulk</th>
<th>G0</th>
<th>GI</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>old</td>
<td>yes</td>
<td>0.0728</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.116</td>
</tr>
<tr>
<td>B</td>
<td>new</td>
<td>no</td>
<td>0.0728</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.116</td>
</tr>
<tr>
<td>C</td>
<td>new</td>
<td>yes</td>
<td>0.0728</td>
<td>0.0049</td>
<td>0.0025</td>
<td>0.040</td>
</tr>
</tbody>
</table>

Table 17. CFR Neck Calibration Simulation results for models A, B, and C

<table>
<thead>
<tr>
<th>Neck Extension</th>
<th>Lower Corridor</th>
<th>Upper Corridor</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane-D Rotation [deg]</td>
<td>81</td>
<td>98</td>
<td>87.7</td>
<td>79.9</td>
<td>89.96</td>
</tr>
<tr>
<td>Maximum Moment [N-m]</td>
<td>66</td>
<td>84</td>
<td>71.3</td>
<td>75.6</td>
<td>72.38</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m [ms]</td>
<td>100</td>
<td>120</td>
<td>112.4</td>
<td>109.5</td>
<td>111.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neck Flexion</th>
<th>Lower Corridor</th>
<th>Upper Corridor</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane-D Rotation [deg]</td>
<td>61</td>
<td>75</td>
<td>62.7</td>
<td>54.8</td>
<td>63.23</td>
</tr>
<tr>
<td>Maximum Moment [N-m]</td>
<td>110</td>
<td>130</td>
<td>113.2</td>
<td>110.7</td>
<td>117.3</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m [ms]</td>
<td>77</td>
<td>97</td>
<td>80.6</td>
<td>75.9</td>
<td>77.3</td>
</tr>
</tbody>
</table>

The cell color differentiates model performance. Green cells classify injury criterion that adheres to the CFR corridor requirements, while orange does not meet the SAE corridor requirements.

The adjustments to the mesh and neck pucks seemed to give the neck a slightly stiffer response. Material properties in the former-meshed model that satisfied SAE corridors did not properly calibrate the latter-meshed neck. However, minor adjustments to the long-time shear modulus and decay constant did calibrate the model.
The material model found in this section was later modified according to model response in the compression simulations and NASA Neck Sled Simulation. But first, studies of the working model were completed to view the effect of model discretization and element formulation on model durability, convergence, and computational efficiency.

5.2.3 Neck Calibration Simulation: Model Effect on Computational Efficiency

The computation time of the working neck model was compared to the neck model provided by NASA. The NASA Updated model was version 95_HB_Opt_v002.k. The new model developed was version 95_HB_Opt_v009.k. The CPU timing comparison was made in the Neck Extension CFR calibration simulation. For these simulations the *CONTROL_TIMESTEP card was removed in the main file to allow LS-DYNA to automatically set the time step size, rather than it be limited by an input minimum time step. A lack of minimum time step will resolve all mass scaling in small elements, but may increase computation time due to the removal of timestep restrictions. The Neck Extension Simulation was run with both neck models with an equal control termination time: 125ms. Notable CPU timing information taken from the d3hsp file is compiled in Table 18.

<table>
<thead>
<tr>
<th>Model</th>
<th>Average required memory to complete solution per processor</th>
<th>Smallest Time Step [ms]</th>
<th>Total CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>v002.k</td>
<td>807k</td>
<td>3.6484E-04</td>
<td>1 hour, 12 min, 59 sec</td>
</tr>
<tr>
<td>v009.k</td>
<td>569k</td>
<td>3.6484E-04</td>
<td>20 min, 19 sec</td>
</tr>
</tbody>
</table>

The total run time for the Neck Extension Simulation with the old neck was 1 hour and 13 mins. The total run time for the Neck Extension Simulation with the new neck was about 21 minutes. The smallest time step in each model was 3.6484E-04ms. The timestep belongs to elements in part 50100003: Head Skull Cap. Part 50100003 is dictating the timestep size in each model.
Because the value is lower than the prescribed value when the *CONTROL_TIMESTEP card is present, minor mass-scaling would occur in part 50100003. Re-discretization of this part would likely be necessary if the added mass was significant to the model. This finding, however, is not relevant to my project, but will be relayed to LSTC.

The decrease in total CPU timing between models is due to a number of benefits of the new neck model. First, the fewer number of nodes and elements introduced from the new mesh of the neck assembly entails fewer degrees of freedom and therefore fewer calculations. Additionally, changing the neck pucks from a deformable body to a rigid part allows LS-DYNA to lump all part masses into a single node. The combined mass is then used with the part moment of inertia and nodal locations to solve for the part acceleration, velocity, and orientation ("Rigid Body Definition," n.d.). Lumping all nodes of each neck puck to a single node greatly reduces computation time, especially considering the rigid parts have a relatively fine mesh. Finally, and likely the biggest contributor to the increased computational efficiency, the neck rubber element formulation was changed from fully integrated to reduced integration. The number of integration points in each individual element of the neck rubber was reduced from eight to just one. This greatly reduces the number of calculations required for solution, and hence the large reduction in CPU timing.

5.3.1 Mesh Convergence Study
As in any model, it is valuable to evaluate the performance of a new mesh to understand its influence on results. A mesh convergence study was completed on the working neck model to do just that. The convergence study completed involved adjusting element size, rather than adjusting the order of the elements. Typically, a model will become more and more accurate as element size is reduced. This is because the model gets closer to the continuous domain when element size shrinks. Element size also has an influence on model stiffness. In displacement-based and force-
based elements, coarser meshed models have a stiffer response than finer meshed models. A consequence of a finer mesh is the increase in CPU timing. A mesh convergence study is beneficial to selecting a mesh size that will produce an accurate model, while remaining computationally efficient.

Four models were studied for mesh convergence. The model meshed by Mike Burger and used in the previous sections is referred to as model version 100. The neck rubber elements in version 100 were split at the midpoint of each element by three orthogonal planes using the element edit interface in LS-PrePost. The resulting model, version 103, had eight elements per single element of version 100. Following the split of elements, all duplicate nodes of the mesh had to be merged to ensure that the newly formed elements were connected to each other. Node sets to constrain the neck rubber to the neck pucks were recreated due to the introduction and renumbering of nodes. The process was completed again on version 103 to produce an even finer mesh: version 104. The resulting models: 100, 103, and 104, had an increased factor of elements of 1, 8, and 64 respectively from version 100.

The last model produced was a re-meshed model of version 100. The new model, version 99, had its elements merged by a factor of 8 by Mike Burger using TrueGrid mesh generator. Merging solid elements in LS-PrePost is not possible, which is why Mike had to generate a completely new mesh for version 99. The resulting model had a decrease in total elements by a factor of 8, or an “increased” factor of elements of 0.125. Again, the node sets to constrain the neck rubber to neck pucks were recreated due to the introduction and renumbering of nodes.

The elements in each model were split or merged in multiples of eight, that is, two elements per dimension, to ensure that all elements produced had similar if not equal aspect ratios. Splitting or merging elements in any other way would introduce bias to the mesh convergence due to the
varying element aspect ratios. The four neck models used in the mesh convergence study are pictured in Figures 24-27. Table 19 displays the number of elements and nodes of the neck rubber in each model.

Figure 24. 95th percentile neck with element factor 0.125: 95_HB_Opt_v099.k

Figure 25. 95th percentile neck with element factor 1: 95_HB_Opt_v100.k
Figure 26. 95th percentile neck with element factor 8: 95_HB_Opt_v103.k

Figure 27. 95th percentile neck with element factor 64: 95_HB_Opt_v104.k

Table 19. Neck rubber model element count

<table>
<thead>
<tr>
<th>Model</th>
<th>Split/Merge</th>
<th>Normalized Element Count</th>
<th>Total Element Count</th>
<th>Total Node Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>v099</td>
<td>Merge</td>
<td>0.125</td>
<td>4256</td>
<td>6772</td>
</tr>
<tr>
<td>v100</td>
<td>N/A</td>
<td>1</td>
<td>30592</td>
<td>39652</td>
</tr>
<tr>
<td>v103</td>
<td>Split</td>
<td>8</td>
<td>244736</td>
<td>280440</td>
</tr>
<tr>
<td>v104</td>
<td>Split</td>
<td>64</td>
<td>1957888</td>
<td>2099632</td>
</tr>
</tbody>
</table>

Each model was tested in the Neck Extension calibration simulation. Performance of the model was based off of its CPU timing, plane-D rotation, and maximum moment about the occipital
condyle. The *CONTROL_TIMESTEP card was removed from each model to remove minimum time step constraints that would otherwise cause mass scaling. Removing the minimum time step allows LS-DYNA to control the time step based on element size. By default, the smallest 100 timesteps are reported in the d3hsp file. Earlier it was found that part 50100003 determined the governing timestep in most states. In order to see the smallest time step produced by the neck rubber, ipnint was set to 1000 to see possible neck rubber elements that may control the time step. Viewing 1000 of the smallest time steps was not necessary to get the neck rubber smallest element time step in each test but was still inserted in each model to prevent bias in CPU timing. Table 20 displays the neck rubber smallest time steps and total CPU timing of each model in the Neck Extension Simulation. The LS-DYNA version and number of compute nodes remained constant in each simulation.

<table>
<thead>
<tr>
<th>Model</th>
<th>Element Count Normalized over v100</th>
<th>Factor of Elements per Dimension</th>
<th>50200001 Smallest Time step [ms]</th>
<th>Total CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>v099</td>
<td>0.125</td>
<td>1</td>
<td>5.0738E-03</td>
<td>13 mins 12 sec</td>
</tr>
<tr>
<td>v100</td>
<td>1</td>
<td>2</td>
<td>1.7175E-03</td>
<td>20 mins 19 sec</td>
</tr>
<tr>
<td>v103</td>
<td>8</td>
<td>4</td>
<td>4.9164E-04</td>
<td>1 hr 26 min 38 sec</td>
</tr>
<tr>
<td>v104</td>
<td>64</td>
<td>8</td>
<td>1.6713E-04</td>
<td>35 hr 1 min 21 sec</td>
</tr>
</tbody>
</table>

The Von Mises stress between varying numbers of elements gives a good indication of mesh size. The similar location and magnitude of stress between the coarser meshes and the 64-element split mesh suggests that the models with larger element size are acceptable representation of the continuous model. The Von Mises stress plot for the model with normalized element count 0.125, 1, 8, and 64 is available in Figures 28-31 respectively.
Figure 28. Neck Extension Simulation Von Mises stress for normalized element count 0.125

Figure 29. Neck Extension Simulation Von Mises stress for normalized element count 1

Figure 30. Neck Extension Simulation Von Mises stress for normalized element count 8
A better depiction of mesh influence in the Neck Extension Simulation can be seen in the plots of plane-D rotation and moment. All models were run in the same simulation with equal material properties. Figure 32 shows the plane-D rotation of the model with normalized element count 0.125, 1, 8, and 64. Figure 33 shows the rotation for each model normalized over version 100.
Plane-D rotation for each model is similar up until about 40ms into simulation. At this point, the coarsest meshed model deviates from the rest of the models. The maximum rotation of version 99 was significantly less than the other models at 75ms. The response of versions 100 and 103 were comparable throughout the simulation. The finest meshed model had a slightly higher rotation and longer time to settle than the other models.

The mesh influence is also visible in the moment about the occipital condyle. Figure 34 and 35 display the moment and normalized moment measured in the Neck Extension Simulation for models with normalized element count 0.125, 1, 8, and 64.
Figure 34. Neck Extension Simulation moment: v099, v100, v103, v104

Figure 35. Neck Extension Simulation normalized moment: v099, v100, v103, v104

It is easiest to review results in Figure 34. The finest meshed model had a slightly lower maximum moment than the coarsest meshed model. Versions 100 and 103 had similar maximum moments to version 104. The moment decay was comparable between versions 100, 103, and 104. The moment decay of version 99 to not coincide with the rest of the models.

The mesh convergence is visible in the following figures. Figure 36 shows the log plot of maximum plane-D rotation. Figure 37 displays the log plot of maximum moment about the
Occipital Condyle. Figure 38 shows the log plot of moment decay to -10N-m. The abscissa value of each point in the plot is equal to the total nodal degrees of freedom of the neck rubber.

Figure 36. Maximum plane-D rotation for models v099, v100, v103, and v104

Figure 37. Maximum moment for models v099, v100, v103, and v104
Convergence is visible in each of the above figures. Typically, convergence is achieved when there is a 5% difference between maximum deflection, stress or strain energy (“Introduction to Meshing,” 2012). For the neck model, the factor of interest was occupant injury criterion, rather than stress or strain. Version 99 had a 5.6% difference in maximum plane-D rotation from version 104. This is close to the 5% rule of convergence; however, according to Figure 36, the continuous model would likely have a higher rotation than what version 104 predicted. It would be safe to assume that version 100 has converged, as it has just a 1.9% difference in rotation from version 104.

The maximum moment and moment decay convergence plots are about inverse of each other. Convergence was further evaluated in just the maximum moment plot. Version 99 exhibits a 4.6% difference in maximum moment from the finest meshed model, version 104. Version 100 exhibits about a 0.1% difference in maximum moment from version 104.
The general findings from the convergence study were expected. The plot of plane-D rotation follows the trend of displacement convergence in displacement-based and force-based elements. That is, the displacement of a coarsely mesh model will be less than the displacement of a finer meshed model under equal loading. As a result, the finest meshed neck had the largest plane-D rotation out of all models. The plane-D rotation and maximum moment about the occipital condyle is inversely proportional. This explains why the finest meshed model with the largest rotation experienced the smallest moment. Version 99, the coarsest model, appears to be nearly converged based on the percent differences of maximum rotation and moment. Version 100, however exhibits a much greater convergence on the true maximum values of rotation and moment based on the percent difference calculations.

Version 100 was selected as the ideal model based on mesh convergence and computational efficiency. The model would be further assessed and developed, as discussed in supplemental sections.

5.4.1 Extreme Conditions Testing: Neck Extension Simulation

Analysis of the ideal model continued in extreme conditions testing. Simulations were completed to access the stability of the LSTC 95th percentile model under rigorous loading conditions. The mesh and element formulation selected in the previous sections were evaluated here. The model’s ability to perform reasonably and avoid potential errors or crashing under extreme conditions will validate the durability and reliability of the model.

The first simulation run in extreme conditions was the Neck Extension Simulation. The performance of the NASA Updated and working model was evaluated under varying pendulum rotational velocities. Table 21 compiles the velocity increase and model performance in each simulation. The rotational velocity was set in *INITIAL VELOCITY GENERATION. The head
resultant acceleration was viewed in the nodout file and measured from the head accelerometer node: 52500001.

Table 21. Neck Extension Simulation extreme condition testing results

<table>
<thead>
<tr>
<th>Model</th>
<th>Velocity Multiplier</th>
<th>Rotational Vel [rad/ms]</th>
<th>Head maximum Acc [G’s]</th>
<th>Total CPU Timing</th>
<th>Termination</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA Updated</td>
<td>1x</td>
<td>-0.0036784</td>
<td>38</td>
<td>1 hr, 12 min, 59 sec</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>1.2x</td>
<td>-0.0044141</td>
<td>51</td>
<td>1 hr 12 min 31 sec</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>1.5x</td>
<td>-0.0055176</td>
<td>N/A</td>
<td>14 min 28 sec</td>
<td>Error</td>
</tr>
<tr>
<td>New Model</td>
<td>1x</td>
<td>-0.0036784</td>
<td>50</td>
<td>20 min 19 sec</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>1.2x</td>
<td>-0.0044141</td>
<td>82</td>
<td>20 mins 37 sec</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>1.5x</td>
<td>-0.0055176</td>
<td>360</td>
<td>22 min 12 sec</td>
<td>Normal</td>
</tr>
</tbody>
</table>

At 1.2x rotational velocity, the NASA modified model held up well. However, there was irregular element behavior at max extension. Elements in the neck rubber holes and on the neck cable hole experienced asymmetric, odd distortions. Figures 39-41 display the former-meshed model in the 1.2x velocity Neck Extension Simulation.

Figure 39. Neck Extension Simulation NASA model at 1.2x rotational velocity
Figures 40 and 41 exhibit the irregular element behavior of the NASA Updated model under high loads. Figure 40 shows adjacent elements stretching asymmetrically. The few largely distorted elements are likely absorbing greater load than neighboring elements. Figure 41 shows the Von Mises stress plot section view of the model. The stress experienced in the elements surrounding the neck cable hole is seen in red. The elements surrounding the neck cable hole appear oddly distorted.
The latter-meshed model performance in the 1.2x velocity Neck Extension Simulation was slightly improved. Figure 42 shows the working model at peak extension. There were hourglass modes present at peak extension, but the hourglass energy is reasonable. Figure 43 displays the hourglass and internal energy of the model. Figure 44 shows the neck cable hole on the working model neck rubber, as was shown in the old model in Figure 40. The distortion of elements in the working model neck rubber hole is not nearly as erratic as in the NASA updated model. Figure 45 shows the Von Mises fringe plot at the same location of the neck cable hole as Figure 41.

Figure 42. Neck Extension Simulation new model at 1.2x rotational velocity

Figure 43. Neck Extension Simulation new model hourglass and internal energy
The element behavior in the neck cable hole is more uniform in the working model, as seen in Figure 44. The deformation of elements is continuous across the neck cable hole. This suggests that the loading is more evenly dispersed across all elements, where this may not have been the case in the former model. Figure 45, the effective stress plot, shows less concentrated stress on the neck cable hole elements in the working model. The element behavior is more regular than was in the former-meshed model.
The working model experienced a greater load than the former model under equal pendulum velocities. Because the fully integrated elements in the former model are prone to shear locking, the neck is artificially stiff. The artificial stiffness was seen in the head accelerometer maximum load. The working model head accelerometer node reported an acceleration of 50 G’s, while only 38 G’s was reported in the former model.

At 1.5x rotational velocity, the NASA Updated model failed. Figure 46 displays the failure point of the model. The “notch” created by the neck rubber hole produced a geometric discontinuity, forming a stress concentration that lead to element failure.

Figure 46. Neck Extension Simulation NASA Updated model at 1.5x velocity Von Mises stress

The working model did not fail at 1.5x rotational velocity. However, the neck deformation was severe. Figure 47 displays the working model at maximum rotation. If the test was run again, additional contacts would have to be established between the head, lower neck bracket and pendulum. In the 1.5x test, the head accelerometer reached loads as high as 360 G’s. By contrast, the dummy faces just 50 G’s in the 1x Neck Extension Simulation.
Although loading of this caliber will be uncommon, it is useful to have the neck normally terminate. Allowing the simulation to run all the way through permits engineers to continue to take data on surrounding events. Likely occupant fatality can also be observed without causing an error in the program. The practicality of the robust model becomes even more significant in multiple-dummy car crashes, where occupants may suffer varying magnitudes of load.

5.4.2 Extreme Conditions Testing: Rod Impact Simulation

A second extreme conditions test simulated a rigid rod shot at the frontal surface of the neck. The simulation may represent occupant impact with steel debris in a frontal crash. The simulation confirms the increased durability of the latter-meshed model.

To begin, the main file was produced. The file included the head and neck assembly, as well as an impactor, which was reworked from the Hybrid III 50th percentile CFR chest deflection calibration simulation. The nodes, elements, part material, mesh, and accelerometer block of the impactor were readily available. The rod material is *MAT_RIGID with the density of general steel: 7813 kg/m³. The rod impact main file defined a transformation, which positioned and
scaled the impactor to a reasonable location and size. The resulting rod had a mass of 13.97 kg. Contacts between the rod and neck rubber, as well as rod and neck pucks were created using *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. Gravity was established using *LOAD_BODY_Z and a defined curve. The bottom plane of the lower neck bracket was constrained in all translational and rotational degrees of freedom by *BOUNDARY_SPC_SET. *DATABASE_RCFORC was included to track the contact forces between the rod and neck. *DATABASE_NODOUT was included to track the velocity and displacement of the rod. A termination time of 65ms was set.

Both the former and latter-meshed necks were evaluated. The main file for the latter-meshed neck required additional contact cards because the neck pucks were independent parts, whereas it is a single part in the older model. Figure 48 displays the initial state of the latter-meshed neck in the Rod Impact Simulation.

![Figure 48. Rod Impact Simulation initial state](image)

The initial velocity of the rod was adjusted in the impactor file. Multiple simulations with each neck were performed to find the minimum rod velocity that would induce an error termination.
Impactor initial velocity was increased or decreased by whole numbers until the velocity at model failure converged.

Table 22 lists the maximum allowable rod velocity and pertinent measurements for the NASA Updated and working model. Figure 49 and 50 show the neck reactions at maximum rod displacement. The figures display the simulation with rod initial velocity set to one integer below the velocity at model failure.

<table>
<thead>
<tr>
<th>Model</th>
<th>Rod velocity at failure [ms]</th>
<th>Maximum rod displacement [mm]</th>
<th>Rod to rubber maximum resultant force [kN]</th>
<th>Rod to puck maximum resultant force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA modified</td>
<td>12</td>
<td>36.42</td>
<td>1.26</td>
<td>5.85</td>
</tr>
<tr>
<td>New Model</td>
<td>24</td>
<td>51.97</td>
<td>4.58</td>
<td>9.97</td>
</tr>
</tbody>
</table>

Figure 49. Rod Impact Simulation NASA modified model maximum rod deflection at 11m/s
Termination in both cases occurred due to out-of-range forces in nodes. The error message signifies that instability had taken place. Under normal termination, the working model was able to endure the rigid rod at 2x impact velocity than the NASA Updated model. Compared to the former-meshed model, the working model experienced normal termination under a 70% increase in force to the neck pucks and a 260% increase in force to the neck rubber.

In both cases of extreme conditions simulation, the constant stress elements were able to endure larger deformation than the fully integrated elements. This is due to the number of integration points in each solid. When an element is largely distorted, the edges of the element may move closer and closer to the integration point. If the element edge reaches the integration point, it produces a singularity and hence the error: out-of-range forces in nodes. The fully integrated linear elements fail first because they have eight integration points throughout each element, while the linear reduced integration elements only have a single integration point at the center of the element. Therefore, a greater deformation is required to push the element edge to the integration point in reduced integration elements.
In extreme conditions testing, the working model was able to sustain greater injury without prompting an error in the simulation. Although the accuracy of the model under extreme loads is unknown, the robustness of the new model allows for more reliable simulation termination and more accurate measurement of surrounding events. Extreme conditions testing showed that the NASA Updated model was susceptible to locking and irregular element behavior. The working model’s ability to perform under extreme conditions will offer confidence in model accuracy and stability under normal loading conditions.
6. COMPRESSION TEST AND SIMULATION

6.1.1 Compression Experiment

At this point in the project, access to lab equipment for compression testing was granted. The experiment that followed evaluated the neck rubber material of the 50\textsuperscript{th} and 95\textsuperscript{th} percentile neck assemblies. The reaction force of the neck under constant head compression rate was monitored by the tester. The force-deflection curves obtained were used as a template in determining the material model for the LSTC Hybrid III 95\textsuperscript{th} percentile neck rubber.

LSTC allowed the use of their Hybrid III 50\textsuperscript{th} and 95\textsuperscript{th} percentile necks in a non-destructive test. The necks are comprised of rubber cylinders layered between pucks of 6061 T6 Aluminum (\textit{H-III 95M Drawing Package Draft}, 2010). The Hybrid III 95\textsuperscript{th} percentile neck is pictured in Figures 51 and 52. There are claims that the neck rubber differs in composition; however the SAE part drawings list both as the same material: rubber butyl 70-80 shore A durometer (\textit{H-III 95M Drawing Package Draft}, 2010). The two physical necks underwent the same compression test, to evaluate sameness of material.

Figure 51. Lateral view of Hybrid III 95th percentile neck
The experiment took place in the California Polytechnic Composites Laboratory. The compression tests were performed on a Lloyd Instruments LD50 tester in compression mode. The tester used can provide up to 50kN of force in either tension of compression (LD Series Operation Manual, n.d.). The system is compatible with NexyGen Plus software for regulating and monitoring material tests. Introduction to and supervision of the tester and software was provided by Dr. Eltahry Elghandour.

In accordance with CFR, the neck was soaked in an environment, “at any temperature between 18.9 and 25.6 °C (66 and 78 °F) and a relative humidity from 10 to 70 percent for at least four hours prior to a test” (Electronic Code of Federal Regulations, 2019).

Three tests were completed: A, B, and C. Test A assessed the 50th neck assembly under quasi-static loading, while Test B assessed the 95th percentile neck assembly under quasi-static loading. Both Tests A and B followed ASTM D575 Test Method A – Compression Test of Specified Deflection of Rubber. The head rate was equal to 12mm/min. Test C measured the 50th neck assembly at a different head rate than the previous tests. The head rate in Test C was equal to
4mm/min. Each of the three tests were non-destructive. Parameters recorded include neck geometry, time, compressive force and axial deflection.

The procedure of experiments A and B are equal other than the specimen tested. The procedure of experiment C is equal to that of experiment A other than the head rate input into the NexyGen Plus software. The 50th percentile neck was given 20 minutes to recover between experiments A and C. The procedure carried out during each experiment is as follows:

**Test A – Quasi-Static Loading**

1. Measure the height of the neck assembly using calipers.

2. Adjust the height of the LD50 console using the fast and slow jog up buttons of the hand held remote (*LD Series Operation Manual*, n.d.).

3. Fit the appropriate grips to the eye end of the load cell (*LD Series Operation Manual*, n.d.). The lower fixture was a standard compression plate. The upper fixture was a wedge grip in closed position. The wedge grip was used because it had a testing surface that was more normal to the specimen than the standard compression plate. Tighten each grip with the C-spanner.

4. Position the neck between the upper and lower grips, in line with the load cell axis (*LD Series Operation Manual*, n.d.). The neck was centered as best as possible to avoid side thrust.

5. Close the splinter shield. Lower the upper fixture using the hand held remote until it is millimeters away from the top neck puck.
6. Adjust the default settings in the NexyGen Plus software for Tension and Compression Test. The direction was set to compression. The extension rate was set to 12mm/min (0.5in/min) (“ASTM D575 Compression Test of Rubber,” n.d.). The preload stress and speed were kept as default: 5.6N at 21mm/min.


8. Begin loading by pressing the start button on the NexyGen Plus software. Observe the load curve generated by NexyGen Plus.

9. Strain the specimen to the desired load. Press the stop button on the NexyGen Plus Software to unload the specimen. The desired load was determined during testing as a force high enough to cause visual displacement without potential destruction of the specimen.

10. Remove the specimen. Measure the height using calipers

11. Set the data output to 1000 points. Save the time, extension, and force data monitored by NexyGen Plus to a text file. Stress and strain were recorded by the LD50 tester but were not saved because an extensometer was not used during testing.

The test setup directly before compression is available in Figure 53.
6.1.2 Compression Test Measurements

The pre-experiment and post-experiment caliper measurements of neck height are available in Table 23. The top and bottom neck pucks were not level on each neck, which made measuring the height difficult. The neck height was measured in several locations to find the maximum and minimum height between the top and bottom neck pucks. Table 24 gives the average neck height measurement and difference in average height between pre and post-experiment.
Table 23. Pre and Post-experiment 95th and 50th percentile neck assembly part dimensions

<table>
<thead>
<tr>
<th>Part</th>
<th>Drawing Package Part Thickness/Tolerance</th>
<th>Pre-Experiment Height Measurement</th>
<th>Post-Experiment Height Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[mm]</td>
<td>Min [mm]</td>
<td>Max [mm]</td>
</tr>
<tr>
<td>Mount Plate Lower Neck</td>
<td>7.9 +/- 0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Invertebral Disk Neck</td>
<td>6.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Mount Plate</td>
<td>9.53 - 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neck Rubber</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50th Total Neck Assembly</td>
<td>124 +/- 1</td>
<td>124.3</td>
<td>124.6</td>
</tr>
<tr>
<td>95th Total Neck Assembly</td>
<td>124 +/- 1</td>
<td>123.2</td>
<td>124.3</td>
</tr>
</tbody>
</table>

Table 24. Pre and Post-experiment 95th and 50th neck part dimensions average and difference

<table>
<thead>
<tr>
<th>Part</th>
<th>Pre-Experiment Average Caliper Measurement [mm]</th>
<th>Post-Experiment Average Caliper Measurement [mm]</th>
<th>Height / Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>50th Neck Assembly</td>
<td>124.45</td>
<td>124</td>
<td>-0.45 mm 0.36%</td>
</tr>
<tr>
<td>95th Neck Assembly</td>
<td>123.75</td>
<td>123.25</td>
<td>-0.5 mm 0.40%</td>
</tr>
</tbody>
</table>

The caliper measurements made after testing were completed within approximately 1-2 minutes after the peak load was removed. During the experiment, the neck deflection reached as high as 8mm. The deflection measured directly after compression was only about 0.5mm in Tests A and B. The rubber had nearly fully recovered by the time of post-experiment height measuring.

The extension and load tabulated below was read from the hand-held controller. The extension on the hand-held controller zeros after the preload stress is met. However, the force output on the hand-held controller does not zero after the preload stress is met. The extension and force reading on the hand-held controller is close to the data captured by the NexyGen Plus data output. The uncertainty of the LD50 extension is 0.00121 micron per encoder count (*LD Series Operation*...
Manual, n.d.). The uncertainty of the LD50 load cell is 0.5% of the reading. Figure 54 shows the 50\textsuperscript{th} percentile neck at peak deflection. Table 25 records the hand-held controller peak force and extension, as well as the peak force and extension reported in the data.

![Image of experiment setup](image.png)

Figure 54. Experiment A 50th percentile Neck at maximum extension: 7.4629mm

Table 25. Trial 1 Experiment A, 50th neck loading measurements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Model</th>
<th>Hand-Held Controller</th>
<th>Software Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Absolute Extension [mm]</td>
<td>Load [N]</td>
</tr>
<tr>
<td>A</td>
<td>50th</td>
<td>-7.463</td>
<td>3962.8</td>
</tr>
<tr>
<td>B</td>
<td>95th</td>
<td>-8.294</td>
<td>3910.1</td>
</tr>
<tr>
<td>C</td>
<td>50th</td>
<td>-6.494</td>
<td>3020.3</td>
</tr>
</tbody>
</table>

6.1.3 Compression Test Results

The data saved from Nexygen Plus was worked in Microsoft Excel. Test A includes the compression of the 95\textsuperscript{th} percentile neck at a rate of 12mm/min. The domain of the data was reduced to exclude the data from preload. The preload component of data was determined as all points below the set preload force: 5.6N. The time of preload for Experiment A was 1.5058
seconds. The machine extension during preload was 0.207 mm. The subsequent time and extension after preload were zeroed in Excel. Test A machine extension as a factor of time is available in Figure 55. The slope of the plot confirms the machine extension rate of 12mm/min.

![Graph](image)

**Figure 55. Test A, 95th percentile, machine extension**

Test B includes the compression of the 50th percentile neck at a rate of 12mm/min. The domain of the data was reduced to exclude the data from preload. The preload component of data was determined as all points below the set preload force: 5.6N. The time of preload for Experiment B was 2.6827 seconds. The machine extension during preload was 0.727mm. The subsequent time and extension after preload were zeroed. Test B machine extension as a factor of time is available in Figure 56. The slope of the plot confirms the machine extension rate of 12mm/min. Figure 57 displays the machine force output required to obtain the given machine extension rate in both tests.
Both necks demonstrate similar response under constant head rate loading. The 50th and 95th percentile necks exhibit an initial low-level load required to produce the set head rate. This load was prevalent up until an extension of about 1.3mm in the 50th percentile neck and 1.7mm in the 95th percentile neck. Thereafter, both curves appear mildly logarithmic. The curves have comparable slopes and magnitudes at any given moment in time. Although the stress and strain of
the neck rubber was not measured, it could be assumed that the stress-strain curve would look about the same as the load curve pictured. This is because the head rate is constant. Both necks exhibit a nonlinear elastic response. The nonlinearity of the load curve is characteristic of viscoelastic materials.

The initial low-level loading is likely due to the unequal orientation of the top and bottom surfaces of the neck. The failure of the surfaces to be parallel causes an uneven distribution of force across the neck. A smaller force is therefore required to deflect the top neck puck until the faces become parallel. The uneven surfaces of the neck were evident in the initial measurement of neck height. From the caliper measurements, the 50th neck height measured at minimum and maximum locations differed by 0.3mm. The 95th percentile neck height differed by 1.1mm. The difference in neck height variation between the 95th and 50th percentile is equal to 0.8mm.

The difference in neck height variation confirms the major differences in the 95th and 50th percentile load curve. Assuming the materials are the same, the deflection under of both necks under an equal load should be equivalent. But, observing Table 25, the 50th percentile neck deflected 7.4629mm and the 95th percentile neck deflected 8.2942mm under similar loads 3962.8N and 3910.1N respectively. The absolute extension difference is equal to 0.8313mm, which is very close to the difference in neck height variation: 0.8mm. It can be implied that the difference in absolute extension between the 50th and 95th percentile neck under equal loads is due to the unequal alignment of the top and bottom neck pucks.

It is likely that the load curves would have a much better alignment and a more comparable absolute extension if the preload stress was set higher. Raising the preload force from 5.6N to around 200N would greatly reduce or rid of the low-level initial loading. At a 200N preload stress, the top puck of the necks would likely be level with their bottom puck. At this point, the
timing difference during the initial low-level load would be removed. The lateral shift in the load
curve between the 50th and 95th percentile neck would be removed. The load curves would then
be overlapping and appear more equal. Figure 58 displays the machine load curve for both necks
with the initial low-level loading removed.

![95th vs 50th Machine Load](image)

Figure 58. Compression Test 95th and 50th percentile load curves, no initial low-level load

The constant head rate and assumed constant area during loading means that the engineering
stress-strain curve would roughly resemble the load curves pictured above. Figure 59 displays the
stress-strain curve of polymers of varying physical states. The 50th and 95th percentile neck load
curves are both characteristic of polymers that are in a rubbery physical state, as they should be.
Figure 59. Stress-strain curve for glassy, crystalline, and rubbery polymers in tension. Adapted from ‘Elastomers’ by Gauthier, M. M., & Tuszynski, R. 1995.

Figure 60 displays the polynomial trendline of the 50th and 95th percentile time derivative of force. The figure excludes the initial low-level loading. The slopes are equal around the 20ms mark. Both slopes are higher at the beginning of loading versus the end.

Figure 60. Compression Test 95th and 50th percentile load derivative
The SAE part drawings list the rubber material of the 50th and 95th percentile necks as equal. The 95th and 50th percentile drawing packages state that both models are made of rubber butyl 70-80 shore A durometer. The load curves appear roughly the same between necks. However, the slopes of the load curves do differ according to the load derivative plot. It is difficult to tell if the difference in rate of force between necks is due to the rubber composition material tolerance, or if the two necks are indeed different materials.

It should also be noted that the 50th and 95th percentile necks used during testing were given to LSTC because they were no longer suitable for dummy use. This may be because the necks no longer met calibration standards or because the rubber had expired. The 95th percentile neck has a stamped manufacture date from 2004. The 50th percentile neck, however does not have a stamped manufacture date. Rubber butyl has an average shelf life of 5-10 years in normal conditions (“Shelf Life vs. Service Life in Rubber Products,” n.d.). Differences in rate of force may also be due to the age of the neck rubber.

It was concluded that the necks are of equal material because the load curves between both neck parts are very comparable. The small differences in machine load rate are presumably due to leeway in manufacturing processes, hence the neck rubber material tolerances.

The 50th percentile Drawing Package, made by General Motors, is available to the public. The neck rubber is listed as shore A durometer 70-80. The 95th percentile is regulated by SAE. The SAE Drawing Package lists the 95th percentile neck rubber as shore A durometer 70-80. It is a safe assumption that those regulating the Hybrid III list the correct material.
6.1.4 Compression Test Varying Head Rate

A complimentary test was performed on the 50\textsuperscript{th} percentile neck to test the stiffness of the neck under differing head rate. The same procedure was used as the previous tests. The only difference was that the deflection rate was changed from 12 mm/min to 4 mm/min. Under varying head rate, the rubber may display the viscoelastic effect. The response of the neck at a head rate of 12mm/min and 4 mm/min, excluding the initial low-level loading is available in Figure 61.

![50th Varying Extension Rate](chart.png)

**Figure 61. 50th percentile neck compression at varying head rate**

The rate of applied force is near equal in both tests. There is no difference in machine load at 12mm/min versus 4mm/min until about 3mm of deflection. At this point, the neck reaction forces diverged. The slower head rate resulted in a lower reaction force, whereas a higher head rate resulted in a higher reaction force. The neck may have exhibited the viscoelastic effect under the differing head rate. The neck appears to stiffen under quick compression versus relaxing under slow compression.
6.2.1 Supplemental 95th and 50th Percentile Testing

A hardness test was attempted on the 50th and 95th percentile neck rubber. A shore D durometer was available for use in the Cal Poly Materials Lab. A durometer measures a materials resistance to indentation ("Shore Durometer Hardness Testing of Rubber and Plastics," n.d.). The resulting durometer hardness value is determined by the depth of penetration into the material. Typically, a durometer is used on rubbers, elastomers, and polymers ("Shore Durometer Hardness Testing of Rubber and Plastics," n.d.). Higher durometer hardness signifies higher resistance to penetration. The shore A durometer, which was used to classify the neck rubber, is used for softer rubbers. The Materials Lab only had to offer the shore D durometer, which applies more force and is used for harder rubbers. The shore type used in testing is not too significant. The goal was just to find if the rubber hardness differed between necks.

Unfortunately, the durometer hardness test could not be carried out. The clearance between the neck pucks was not large enough to fit the durometer testing surface against the neck rubber. The neck pucks would have to be torn off the rubber in order to get an acceptable testing surface.

Alternatively, an ORID 70-C bounce tester was used in determining material composition. The ORID 70-C is designed to test shore C durometer rubber O-rings ("The ORID," n.d.). A weight inside the device is dropped a controlled distance on top of a rubber surface ("The ORID," n.d.). The bounce height of the weight determines the material composition. The device has four predetermined height markings corresponding with four rubber compounds: Viton, Kalrez, Nitrile, and Ethylene Propylene ("The ORID," n.d.). The bounce tester was positioned in the same location on each of the necks. Magnitude of bounce height was assessed in the slow-motion video recorded during testing. The test is rudimentary, and measurement of bounce height was not exact. Figure 62 displays the ORID 70-C tester and the four compound height markings.
Results from the slow-motion video revealed that the rubber compounds were very similar. The bounce height of the weight in each test was just higher than the marking for Viton rubber. The test is not very scientific, but it did show a very similar response between the 50th and 95th percentile necks.

6.3.1 Compression Simulation Development Continued

With the experiment completed, the LSTC working neck model could be evaluated in the compression simulation. The model performance was gauged off of sameness of reaction force to the physical load data obtained through experiment. Material properties of the working model neck rubber were altered in an attempt to match the response to that of the physical neck.

Before evaluation, the explicit and implicit compression simulations were updated according to the adjustments made to the model. The change in neck puck material type to *MAT_RIGID prevented the previously made input files from running. A number of alterations were made to the main file and neck file.
In the neck file, separate rigid parts had previously been created for each individual neck puck to allow for independent movement. Part 50200005 was split up into five separate parts using the move-copy tool in LS-PrePost. The neck puck part, material, and section ID's were now renumbered in LS-PrePost. The neck puck part ID’s from top to bottom were 50200005, 50200006, 50200007, 50200008, and 50200009. In agreement with the working neck model, the neck rubber element formulation in the neck file was changed from -2 to 1, with hourglass control 7 and an hourglass coefficient of 1.

Five *CONSTRAINED_EXTRA_NODES_SETS were implemented to tie each individual neck puck to their respective contacting surface set of nodes on the neck rubber. These constraints were made to replace the *TIED_NODES_TO_SURFACE contact card. The tied contact card was replaced because it is based on constraint definitions that only work with deformable bodies (LS-DYNA Keyword User’s Manual, 2007). The respective node sets and segment sets necessary for the constraints were produced.

As for the main file, *BOUNDARY_SPC_SET was removed. This keyword only works on deformable bodies. Instead, to fix the bottom puck, the cmo variable was set to one on the bottom puck material card to constrain the part center of mass in global directions. Con1 and con2 were then set to seven to constrain x, y, and z displacements and rotations respectively.

The *BOUNDARY_PRESCRIBED_MOTION_SET keyword in the main file was replaced with six *BOUNDARY_PRESCRIBED_MOTION_RIGID keywords. One of the keywords was used to prescribe the z-displacement defined in *DEFINE_CURVE to the top neck puck. The five other keywords were used to constrain translation in the x and y global directions, and rotation in all directions.
With the listed changes, the explicit compression simulation experienced normal termination. The implicit simulation, however, was not able to normally terminate. There were no negative volume errors, as was the case with the former-meshed neck; however, the implicit solver instead was experiencing trouble converging on a solution. After a lot of researching and trial and error, the fix was found. The automatic contact cards had to end with the option MORTAR. Mortar contacts are the recommended, general purpose contact algorithm when using implicit solvers (Borrvall, 2012). “The Mortar contact is penalty-based segment-to-segment contact,” that couples elements of sliding surfaces (Borrvall, 2012). This contact algorithm is good for non-matching discretization, which occurs between the neck pucks and neck rubber (Borrvall, 2012). With the Mortar contact option added, the implicit solver was able to converge at each state within two to three iterations.

With the implicit convergence problem settled, the convergence tolerances could be tightened. The implicit convergence tolerances are defined in *CONTROL_IMPLICIT_SOLUTION. The displacement relative convergence tolerance as set to 0.001. The energy convergence tolerance was set to 0.01. Stricter convergence tolerances prevent premature convergence that may lead to an inaccurate solution over many steps.

With the changes completed, both explicit and implicit compression simulations normally terminated. The explicit compression simulation ran in parallel execution with 24 processors in 6 minutes and 43 seconds. The implicit compression simulation ran in parallel execution with 24 processors in 20 minutes and 49 seconds with 144 implicit dynamic steps.

6.3.2 Compression Simulation Sanity Check

To ensure the compression simulations were set up correctly, the energy data was evaluated. Checking the energy data will affirm model constraints, proper assembly connections, and
reaction forces per applied displacement. The Conservation of energy should hold true during analysis (“Energy Data,” n.d.):

\[ E_{\text{kin}} + E_{\text{int}} + E_{\text{si}} + E_{\text{rw}} + E_{\text{damp}} + E_{\text{hg}} = E_{\text{kin}}^0 + E_{\text{int}}^0 + W_{\text{ext}} \]  

(Eq. 3)

Where

- \( E_{\text{kin}} \) = kinetic energy
- \( E_{\text{int}} \) = internal energy
- \( E_{\text{si}} \) = sliding interface energy
- \( E_{\text{rw}} \) = rigid wall energy
- \( E_{\text{damp}} \) = damping energy
- \( E_{\text{hg}} \) = hourglass energy
- \( E_{\text{kin}}^0 \) = initial kinetic energy
- \( E_{\text{int}}^0 \) = initial internal energy
- \( W_{\text{ext}} \) = external work

If the equation does not hold true at any time, then there is an error. In the case of this model, there is no initial kinetic or internal energy. The external work applied should be equal to the elastic strain energy of the neck. The elastic strain energy is measured as the internal energy, and the external work is measured as the prescribed rigid body displacement.

If the internal energy is smaller than the external energy, then the model is absorbing energy that is not naturally occurring. The work energy might be absorbed due to high hourglassing (“Energy Data,” n.d.). If the internal energy is larger than the external energy, then artificial energy is being
introduced. This could be the case if there was false penetration of contacting bodies, or if there was a problem with the solver (“Energy Data,” n.d.).

A number of steps were taken to get the external work. To begin, the resultant displacement of a node on the top neck puck was tracked. The time history plot of the node was saved by evaluating the nodout file. The displacement of the node represents the distance traveled by the top neck puck under the load. Next, the rigid body z-force with respect to time was plotted using the data from the bndout file. The z-force represents the reaction force of the neck rubber on the neck puck due to the prescribed displacement. Next, a cross plot was created in LS-PrePost with displacement as the abscissa value and force as the ordinate. The area under the curve of displacement versus time is equal to the external work. The integral of the reaction force as a function of displacement is plotted against the neck rubber internal energy in Figure 63.

The equality of the strain energy and external work throughout the analysis shows that energy is conserved in the simulation. This is a good indication that there are no errors in the model, job, or solver because the load and reaction of the model match.
6.3.3 Compression Simulation: Evaluation of Old Mesh and New Mesh

The former-meshed neck response was compared to the latter-meshed neck response under equal displacement in the explicit compression simulation. As mentioned, the old meshed neck would not run to completion in the implicit simulation due to negative volume errors. Therefore, the working model could only be compared to the former-meshed model in the explicit compression simulation.

Running the explicit simulation with equal head rate to the experiment is far too expensive. Instead, the explicit simulations were run at 100x speed. Both models were loaded at a scaled head rate of 1200mm/min. The termination time was set to 400ms. At this time, both models reached a maximum deflection of 8mm. Figures 64 and 65 show the Von Mises stress plot of the former-meshed and latter-meshed models at maximum deflection.

![Figure 64. Explicit Compression Simulation old mesh model Von Mises stress](image)

Figure 64. Explicit Compression Simulation old mesh model Von Mises stress
From the fringe plots, the result of the rigid neck pucks is visible. The elastic pucks experience stress, while the rigid pucks experience zero stress. There is slightly less effective stress at the surface of the neck rubber cuts in the former mesh versus the latter mesh. Figures 66 and 67 show the section view of the models, where a larger difference in stress is visible. The former model has a higher stress than the working model at the contacting surfaces of the neck rubber and neck pucks. The high stress may be due to the model stiffness caused by fully integrated elements, or due to issues with the tied-nodes contact between a deformable body and a nearly rigid body.
Figure 67. Explicit Compression Simulation working model Von Mises stress

Figure 68 shows the neck rubber internal energy of the former model and working model under equal deflection. The higher strain energy of the former model implies a higher external work applied to achieve the prescribed head rate. The internal energies show that the old model is indeed stiffer than the new model.

Figure 68. Explicit Compression Simulation old and new mesh neck rubber internal energies
6.3.4 Compression Simulation New Model Mesh Analysis

To evaluate the mesh size of the new model, the nodal point stresses were compared to the integration point stresses. It is a good indication that the mesh is fine enough if the stresses in each contour plot are not significantly different.

To begin, *STRESS_RECOVERY_NODE was added to the main file to recover the stresses of solid elements at nodal points (Day, n.d.). The Zienkiewics-Zhu’s Super Convergent Patch Recovery method was selected to extrapolate nodal stress. The Super Convergent Patch Recovery method extrapolates elemental stress from a group of elements surrounding a node (*LS-DYNA Keyword User’s Manual, 2007). This method is superior to the elemental extrapolation method, which extrapolates stress from only a single element (*LS-DYNA Keyword User’s Manual, 2007).

The fringe plot of nodal stress using reduced integration is not obtainable. Although the nodal stress values are available for reduced integration elements, contour plots for these values cannot be produced. This is because, “results in eloutdet and d3plot are extrapolated based on the same shape function for nodal displacement” (Day, n.d.). To compare integration point and nodal stress values in a fringe plot, the element formulation of the neck rubber had to be increased to fully integrated. Elform 2 was chosen.

The keyword *DATABASE_BINARY_EXTENT was added to the main file. The variable nintsld was set to eight to save integration point data to the d3plot (Day, n.d.). The default stress fringe plot in LS-PrePost shows the integration point stress. Figure 69 displays the fringe plot of integration point Von Mises stress in the neck at maximum deflection. Under post settings in LS-PrePost, the extrapolate option was selected to extrapolate the gaussian point stress to nodes. Figure 70 displays the fringe plot of nodal Von Mises stress in the neck at maximum deflection.
The effective integration point stress and nodal stress fringe plots show that the stress is continuous across all elements. This is an indication of good mesh size. As expected, the nodal stress is higher than the integration point stress. Nodal stress is higher because it is the averaged value of the extrapolated nearest integration point stresses. The extrapolation to nodes typically makes stress appear higher at nodes than the true stress calculated at integration points. However,
the integration point stress is not significantly less than the nodal stress at any given location. This is also a good indication of discretization. The mesh does not need to be further refined.

After producing the contour plot, the nodal stress and element stress was evaluated at a single arbitrary element. The nodal values of stress were measured from the x, y, and z-acceleration time history components. These components represent Von Mises stress, yy-stress, and zz-stress respectively due to the addition of *STRESS_RECOVERY_NODE. Figure 71 shows the eight node values and single element value of z-stress for the hexahedral element.

![Implicit Compression Test Nodal and Elemental stress](image)

**Figure 71. Implicit Compression Simulation nodal values and elemental value of z-stress**

Elemental stress is typically calculated by again, extrapolating the integration point stresses to the nearest nodes. The stresses at the nodes are then averaged among the nodes of the element (“Nodal versus Elemental Stresses,” 2008). This is contrary to nodal stress, where stress is averaged at the node from its surrounding elements. The figure above shows how the elemental stress is interpolated from its nodes. This is also a good example of how extrapolation can cause nodal stress to be higher than integration point stress.
6.3.5 Compression Simulation: Explicit Time Effect

Explicit analysis is typically used for short time dynamics, but in the case of the experiment, the slow head rate makes simulation lengthy. Explicit time steps are limited by the courant time step, meaning that simulating the real time of the experiment would be extremely expensive. To save on CPU timing, the head rate of the simulation must be increased. The objective of increasing the head rate was to mimic the quasi-static nature of the experiment, while being far more computationally efficient. The effects of an increased head rate on the neck model are studied in this section.

Three tests were conducted to view the influence of simulation time on neck reaction force. Tests were run with equal deflection but with differing simulation times: 40, 400, and 4000 ms. The times correspond to 1/1000, 1/100, and 1/10 of the total time of experiment. Head rate of each simulation was scaled according to simulation time and the constant 8mm maximum deflection. Simulation with higher head rate may introduce inertial effects, which are captured by the explicit solver. Additionally, the viscoelastic material stiffness is dependent on the rate of applied force. These tests were intended to capture the change in material stiffness at differing head rates.

An explicit simulation with a head rate equal to the experiment was not completed because it would be too expensive. Nonetheless, the test was submitted just to get an estimated CPU time from the status file. This test was not allowed to run all the way through.

All tests were run in MPP with 24 processors. The total CPU timing is reported in Table 26. The boundary condition z-force on the top neck puck was tracked in the bndout file. The time history plots of z-force for each explicit compression simulation are compared in Figure 72.
Table 26. Explicit Compression Simulation varying simulation time and total CPU time

<table>
<thead>
<tr>
<th>Sim Time : Exp Time</th>
<th>Total Sim Time [ms]</th>
<th>Head rate</th>
<th>Total CPU Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1000</td>
<td>40</td>
<td>12000 mm/min</td>
<td>1 min 0 sec</td>
</tr>
<tr>
<td>1:100</td>
<td>400</td>
<td>1200 mm/min</td>
<td>6 min 43 sec</td>
</tr>
<tr>
<td>1:10</td>
<td>4000</td>
<td>120 mm/min</td>
<td>1 hour 32 min 24 sec</td>
</tr>
<tr>
<td>1:1</td>
<td>40,000</td>
<td>12 mm/min</td>
<td>298 hour 41 mins (estimated)</td>
</tr>
</tbody>
</table>

Figure 72. Compression Simulation explicit reaction force with varying simulation time

At a 40ms simulation time, the properties of viscoelastic materials are visible. Viscoelastic materials possess time-dependent strain under stress. The quick compression of the rubber causes it to stiffen. The resulting reaction force is higher than that of the other simulations with a smaller prescribed deflection rate. The tests run at 1/100 and 1/10 speed have more comparable reaction forces, however it cannot be concluded that the reaction force had converged at a head rate less than 120 mm/min.

At a 40ms simulation time, a large spike in force is present at the very beginning of the load curve. The initial force, although small, is also present in the 400ms simulation response. Likely, the force is instigated by a vibrational wave that resists the applied deflection. The spike is larger
with a faster head rate because the vibrational response of the rubber is larger with a faster deflection. The vibrational force is not seen in the implicit simulation, either because the head rate is too slow to cause significant vibrations in the neck, or because the implicit time step is too large to capture the immediate response of the rubber.

Not surprisingly, the explicit simulation gets more and more expensive the closer the simulation time gets to the true experimental time. Running an explicit simulation in real time is not a realistic option because it would take 12 days to run on a 24-processor computer. An implicit simulation is a better method to solve the problem because the time step is not limited by the courant time step. The time step size in implicit analysis can be set much larger than explicit time steps or can even be automatically calculated to provide best results.

6.3.6 Compression Test: Experiment, Explicit, and Implicit

Following the initial evaluation of the neck models, the working model performance in the explicit and implicit compression simulation was assessed. The working model material properties were later adjusted to match the simulated neck response to the physical 95th percentile neck response under compression.

The responses of the working model in the explicit and implicit simulations were compared. The Von Mises stress and parametric view of the working neck model at an 8mm deflection in the 400ms explicit and implicit compression simulations are shown in Appendix E. The model in the implicit and explicit simulation exhibits similar behavior and stress under loading. The only notable difference in Von Mises stress takes place in the neck rubber holes. Figures 73 and 74 show the section view of the working model under explicit and implicit compression.
The explicit and implicit model performance was further contrast against the physical force data from Test B: Compression of the 95th percentile neck. The physical data used to create the LS-PrePost load curve was taken from excel and saved as a .csv file. The domain of the excel data had already been adjusted to exclude the preload. Using LS-PrePost the curve was inverted over the y-axis to match the orientation of the simulation data. The experiment time data was adjusted.
to match the time of the explicit simulation. The experiment time data for the implicit simulation did not need to be adjusted.

The *bndout* file measures output forces and associated energy of rigid bodies. The file was used to obtain the z-force data for both simulations. A 1MHz filter was applied to the explicit data to filter out minor noise. The force time history data was saved as a curve file. The explicit and implicit load curve is compared to the experimental compression data in Figure 75.

![Figure 75. Compression Test Explicit, implicit, and experimental force versus time curve](image)

The two simulations show different results under equal deflection. Theoretically, both simulations should come to the same conclusion. Neck response in each simulation is comparable but not equal. The explicit simulation neck reaction force is greater than that of the implicit simulation. Most likely, the differences in response are due to the varying head rate between simulations. The implicit simulation was run with a head rate equal to the experimental head rate, 12mm/min. The explicit simulation was run at a head rate 100 times greater, 1200mm/min. Although the explicit simulation run at 10 times the true experimental head rate produced similar response to the
simulation at 100 times head rate, the load curves were not equal. This shows that the viscoelastic effect was still taking place. The viscoelastic neck rubber stiffens under quick compression. This explains why the explicit simulation produces higher load data than the implicit simulation under an equal deflection. The implicit solver was determined as the more accurate solution method because it could recreate the correct head rate, while the explicit solver could not due to time step restrictions.

6.4.1 Compression Simulation: Altering the Material Model

The working model material was altered in an attempt to match the model response to the physical neck response under compression. Material properties were adjusted to match the simulation boundary condition reaction force data to the experimental load data saved by the LD50 tester.

The experimental and simulation load curves were evaluated based on slope and magnitude. As discovered previously, the physical neck experienced a period of initial low-level loading. This period of loading occurred because the physical neck was not perfectly normal to the compression plate. Consequently, the experimental force values with respect to time are a little skewed because the entire neck was not being compressed at time zero. Beyond the initial low-level loading, the reaction of the entire neck under compression is captured. This section of the curve is concave but gets more linear with time. By contrast, the compression simulation replicates the experiment under ideal conditions, that is, the neck is perfectly normal throughout simulation. Hence, the entirety of the simulated load curves shows the full neck under compression. The magnitude of the load curve represents the reaction force of the rubber at a given deflection. The slope of the experimental load curve represents the change in force per change in deflection. Matching the simulation slope and magnitude to that of the experimental would best match the performance of the model to the physical neck under a compressive load.
The material model as is, is comparable to that of the physical neck, as seen in Figure 75. The adjustments necessary to correct the material model were unknown. A basic test was completed to view the effect that each material property had on model response. Figure 76 shows the result of raising each material property on the load curve during the explicit simulation. The abscissa is time in milliseconds. The ordinate is force in kN. The red line shows the starting point of the model with calibrated material properties. The black line shows the experimental data. All other lines show the performance of the model when a single material property was increased by 30%.

![Figure 76. Implicit Compression Simulation force performance varying material properties](image)

From the explicit force performance curve, Altering the bulk modulus had visibly no effect on force output. Raising the short-time shear modulus made the neck stiffer, shifting the curve down. Raising the long-time shear modulus gave the response a more cubic shape with a much higher force output with time. And finally, raising the decay constant shifted the curve upwards. This basic test shows the effect that individual material properties have on model response; however, does not show how material properties relate to one another.
Changes to the model were initially tested using the explicit solver because the CPU timing was much less than the implicit simulation. A number of runs were completed until the slope and magnitude of the explicit curve best-matched that of the experimental curve. Lowering the long-time shear modulus by about 33% produced the response in Figure 77, labeled exp_sim_FZ_08.

![Explicit Compression Test exp_sim_FZ_08](image)

**Figure 77.** Explicit Compression Simulation baseline, experimental, and altered response

The slope and magnitude of the simulation curve matches the experimental curve much better than the baseline model. The same material properties were tested in the implicit simulation. The resulting load curve is available in Figure 78.
The material model in the implicit simulation did not produce quite as good of results as in the explicit simulation. As discovered earlier, the implicit and explicit simulations did not have equal outcomes. The model material properties selected to represent the physical neck are dependent on the type of solver used. A model that performs well in the explicit simulation may not perform well in the implicit compression simulation.

### 6.4.2 Implicit Compression Simulation: Matching Physical Response

Further material properties were altered in the implicit simulation to achieve a good response; however, changes in the load curve per change in material property appeared less significant than in the explicit test. Altering the long-time shear modulus had the greatest effect on slope. Other parameters of the material card did not significantly change the response of the model. This may be because the viscoelastic effect is not as great in the implicit simulation, where the compression is quasi-static. The reaction force appears more dependent on the stiffness of the model after decay, rather than its initial stiffness. The convex curvature of the simulation load curve was unable to be changed with adjustments to material properties. Because of this, matching the slope
and magnitude from simulation to a mostly concave curve was difficult and moreover, not possible.

Figure 79 displays the resulting model that was determined to suit the experimental data well. The material properties used in this model are available in Table 27. The material model run in the implicit simulation generally matches the slope and magnitude of the experimental data. The response is by no means perfect, but is satisfactory.

Figure 79. Explicit Compression Simulation experimental and revised model force output

Table 27. Mat 006 material properties to best match experimental data

<table>
<thead>
<tr>
<th>Version</th>
<th>Bulk</th>
<th>G0</th>
<th>GI</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>FZ09</td>
<td>0.0428</td>
<td>0.0055</td>
<td>0.00205</td>
<td>0.04</td>
</tr>
</tbody>
</table>

The FZ09 model selected matches the raw data provided through the compression of the 95th percentile neck. However, it was concluded earlier that the initial low-level loading of the experimental load data was due to the failure of the neck pucks to be parallel. This period of loading is visible in the first eight to nine seconds of loading. The initial time and force required
to displace the model at 12mm/min was spent on correcting the nonparallel top and bottom surfaces of the neck assembly. If the physical neck was perfectly straight, as is in the model, the timing and force of the initial low-level loading would not be present. To correct for this, the abscissa and ordinate values of the physical data at the initial low-level loading were deleted. The force at the start of the loading was zeroed. The resulting load curve of the experimental data and FZ09 model data are available in Figure 80.

Figure 80. Implicit Compression Simulation adjusted time and load: experiment, FZ09 data

The resulting magnitude of the simulation model was not close to that of the physical model. The model slope, however, was generally close to that of the physical. Similar slopes suggest similar rate of reaction per change in time. The initial slopes could not be equal because the load curves have mirrored responses. The latter parts of both curves become more linear with time. The linear portions were easier to match. Figure 81 displays the derivative of each curve. The red values are the experimental data and green the simulation. The slopes in the latter half of simulation are alike.
It was attempted to match the magnitude of force in simulation to the physical data, but the shape of the simulation curve differed too greatly from the experimental curve to make this possible. Figure 82 displays an attempt to match the magnitude of force to the physical data. The long-time shear modulus was adjusted. Attempting to match the magnitude throws off the slope of the curve. Since the slope cannot be equal, the magnitude of the simulation curve cannot be constant with the physical curve with time.
The working model with the material properties listed as version FZ09 performed best in the implicit compression simulation. The long-time shear modulus was the largest contributor to performance in the compression simulation due to the quasi-static nature of the test. This value represents the remaining stiffness of the material after decay. The long-time shear modulus helps define the material models shear relaxation and hence stress rate. The long-time shear modulus defined from the experiment and corresponding simulation was kept constant throughout the remaining portion of the project. The other three material properties: short-time shear modulus, bulk modulus, and decay constant were later defined through analysis of model performance in the CFR calibration simulations and NASA Neck Sled simulations.
7. NASA NECK SLED TEST AND SIMULATION

7.1.1 NASA Neck Sled Test

Following model calibration and material property modifications in the Compression Simulation, the working model was evaluated in the NASA Neck Sled Simulations. Material properties were further adjusted to match response of the neck model to that of the physical 95th percentile. Response was judged based on sameness of injury criterion data from simulation to data from NASA-performed tests.

The NASA Neck Sled Tests consist of mounting the 95th percentile head and lower neck assembly on a rigid sled that is then accelerated from zero velocity. The sensors in the Hybrid III ATD measure the head and neck reaction to the sled acceleration. The head and neck acceleration, rotational velocities, forces, and moments are pertinent during analysis. There were five total head orientations tested by NASA with sled accelerations ranging from 6 to 16G’s. The test data for each sled test case was provided by NASA for use in this project.

7.1.2 NASA Neck Sled Simulation

Four sled test cases were selected to evaluate the performance of the NASA Updated neck model and the working model: Lateral 12G, Frontal 6G, Frontal 16G, and Rearward 6G. The four cases were selected because each of their individual orientations, loads, and original measured performances were well diversified. Only these four selected cases of the 24 total sled cases were examined due to time constraints. The measured injury criterion for each case includes head acceleration, head rotational velocity, upper neck force, and neck moment. The axis evaluated about for injury criterion is dependent on head orientation.
Performance of the model was gauged by sameness of simulation injury criterion data to its corresponding physical test data. The physical test data was collected by NASA in the physical Neck Sled Tests using a Hybrid III 95th percentile head and neck assembly. The physical acceleration of the sled in each load case was monitored at 10,000Hz. The sled acceleration pulse data was provided by NASA in individual MATLAB files and LS-DYNA keyword files. The physical injury criterion data recorded by the Hybrid III under each sled load case was provided by NASA in a MATLAB structure. The LS-DYNA keyword file used in simulating the NASA Neck Sled Tests was created and shared by NASA.

The LS-DYNA Sled Test keyword file was reworked into four separate files; one for each sled test case. Within each keyword file, the “zang” and “yang” parameters set the model orientation transformation by rotating the model about the y and z-axis respectively. The orientation for each sled case was designated by the Sled Reference pdf provided by NASA. The head orientation reference is available in Appendix F.

Each of the acceleration pulse keyword files were included into their corresponding sled test case keyword file. The pulse files were used to prescribe the acceleration of the rigid lower neck bracket. Prescribing the acceleration to this part is equivalent to rigidly connecting the bracket to an accelerating sled as is in the physical sled tests. The acceleration was prescribed using *BOUNDARY_PRESCRIBED_MOTION_RIGID. Six of these keywords were used: One to prescribe the acceleration defined in the pulse file, and five to constrain motion in all other degrees of freedom. *DATABASE_RBDOUT was included in the main file to confirm the prescribed rigid body motion during post processing. The figures below show the model initial state and reaction to the prescribed acceleration. The figures shown are the four sled cases simulated.
Figure 83. Neck Sled Simulation Frontal 6G initial state and state at max neck deflection

Figure 84. Neck Sled Simulation Frontal 16G initial state and state at max neck deflection

Figure 85. Neck Sled Simulation Lateral 12G initial state and state at max neck deflection
7.2.1 CORAplus

The performance of the working neck model in the NASA Neck Sled Simulation was determined using ISO scores. The ISO rating scale dictates the correlation between simulated and physical data. Unfortunately, NASA could not share their ISO function with me. Their ISO function was tied to a larger framework of functions and applications, which made retrieving it difficult. In place of the NASA ISO scoring system, ISO18571 ratings retrieved from CORAplus software were used to quantify the sameness of data. CORAplus 4.0.4 is a correlation and analysis software that produces an, "objective evaluation of time-history signals derived from test and simulation" ("CORA," n.d.). The newest version of CORAplus was downloaded, which has an option to compute a rating according to ISO18571 ("CORA," n.d.). The user-specified criterion used in the NASA ISO scoring system is unknown. However, it is known that the NASA ISO rating is based on the metrics CORrelation and Analysis (CORA) and Enhanced Error Assessment of Response Time Histories (EEARTH). The ISO18571 rating is based on the CORA corridor rating and CORA cross-correlation rating ("CORA," n.d.). Both ratings are used to calculate the correlation between simulation and test data intended for vehicle safety applications ("CORA," n.d.). The ISO18571 rating is not the exact same as the one used by NASA, but it is similar.
The CORAplus program flow is defined in the CORAplus User's Manual. First, the command line parameters are analyzed. The Linux command line used in C shell to execute CORAplus_4.0.4 is as follows:

```
@Path/cora.sh control.txt -b.
```

In this case, the command line parameter -b states that the browser defined in the configuration file is automatically started with the HTML results. The script, cora.sh, defined in the command line describes an environment variable and installation path of CORAplus:

```
#!/bin/csh -f
#
# CORAplus install directory
#setenv INST_PATH Installation_Path
#setenv INST_PATH /home/cday/CORA_examples/software/linux
#
# execute CORAplus
$INST_PATH/CORAplus_4.0.4 $argv[*]
#
```

Figure 87. CORAplus installation path and execution: Cora.sh

After analyzing the command line, the configuration file is read. CORAplus.cfg defines variables in ASCII format for creating the HTML report (Thunert, 2017). The configuration file was adopted and lightly modified from the Linux examples case provided by CORA with the download of CORAplus_4.0.4. The configuration file is available in Appendix G.

Lastly, the control file is read. Control.txt, is in ASCII format. The file includes global parameters and load cases. The global parameters define or adjust parameters to calculate the interval of evaluation, parameters to format the HTML report, parameters to control small signals, parameters to tune the corridor method, parameters to tune the cross-correlation method, and
weighting factors. The control file load case defines the method of rating, general parameter scaling, data files containing curves, and signal block parameters. The signal selected must be in ISOMME format and was determined by case through the filter specifications and extraction of occupant criteria, Table 28. The global settings were selected based on the proposed settings provided in the CORAplus User’s Manual. The control file used for the Frontal 6G Sled Test is available in Appendix H.

Table 28. Filter Specifications and extraction of occupant injury criteria

<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Filter</th>
<th>Finite Element Type</th>
<th>Element ID Number</th>
<th>ISOMME</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Acceleration</td>
<td>CFC 1000</td>
<td>Node</td>
<td>2400002</td>
<td>S1HEAD0000HFACOP</td>
</tr>
<tr>
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<td>Acceleration</td>
<td>CFC 180</td>
<td>Node</td>
<td>2401788</td>
<td>S1CHST0000HFACOP</td>
</tr>
<tr>
<td>Pelvis</td>
<td>Acceleration</td>
<td>CFC 180</td>
<td>Node</td>
<td>2403305</td>
<td>S1PELV0000HFACOP</td>
</tr>
<tr>
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<td>CFC 600</td>
<td>Node</td>
<td>511122</td>
<td>S1FEMRR0000HFACZ</td>
</tr>
<tr>
<td>Femur Left</td>
<td>Acceleration</td>
<td>CFC 600</td>
<td>Node</td>
<td>411122</td>
<td>S1FEMRL0000HFACZ</td>
</tr>
<tr>
<td>Chest Deflection</td>
<td>Relative Rot</td>
<td>CFC 180</td>
<td>Discrete</td>
<td>1</td>
<td>S1CHST0000HFDSXP</td>
</tr>
<tr>
<td>Upper Neck</td>
<td>Force</td>
<td>CFC 1000</td>
<td>Cross Section</td>
<td>1</td>
<td>S1NECKUP00001</td>
</tr>
<tr>
<td>Upper Neck</td>
<td>Moment</td>
<td>CFC 600</td>
<td>Cross Section</td>
<td>1</td>
<td>S1NECKUP00004</td>
</tr>
<tr>
<td>Femur Right</td>
<td>Force</td>
<td>CFC 600</td>
<td>Cross Section</td>
<td>5</td>
<td>S1FEMRR00001</td>
</tr>
<tr>
<td>Femur Left</td>
<td>Force</td>
<td>CFC 600</td>
<td>Cross Section</td>
<td>4</td>
<td>S1FEMRL00001</td>
</tr>
<tr>
<td>Upper Tibia Right</td>
<td>Force</td>
<td>Cross Section</td>
<td></td>
<td>9</td>
<td>S1TIBIR00009</td>
</tr>
<tr>
<td>Lower Tibia Right</td>
<td>Force</td>
<td>Cross Section</td>
<td></td>
<td>8</td>
<td>S1TIBIR00008</td>
</tr>
<tr>
<td>Upper Tibia Left</td>
<td>Force</td>
<td>Cross Section</td>
<td></td>
<td>7</td>
<td>S1TIBF00007</td>
</tr>
<tr>
<td>Lower Tibia Left</td>
<td>Force</td>
<td>Cross Section</td>
<td></td>
<td>6</td>
<td>S1TIBF00006</td>
</tr>
<tr>
<td>Iliac Crest Right</td>
<td>Force</td>
<td>Cross Section</td>
<td></td>
<td>3</td>
<td>S1ILACR00003</td>
</tr>
<tr>
<td>Iliac Crest Left</td>
<td>Force</td>
<td>Cross Section</td>
<td></td>
<td>4</td>
<td>S1ILACL00004</td>
</tr>
</tbody>
</table>

Following interpretation of the command line, CORAplus begins evaluating the data referenced in the control file. The global parameters are identified and the first load case is analyzed. In the control file, six load cases corresponding to an ISOMME occupant injury criterion were created from the list of ten: head x, y, and z acceleration, head x and y rotational velocity, upper neck x, y and z force, and upper neck x and y moment. Each load case lists the physical test and simulation datafiles as signals (Thunert, 2017). The datafiles are filtered, shifted, transformed, and re-sampled as described in the signal block definition (Thunert, 2017).
Reading the datafiles requires reference to dimension and units. The *output_units.txt* file was created with the specified dimensions provided by CORA. The units were selected based on the units used in the LS-DYNA model files: mm-kg-ms. The output units file is available in Appendix I.

After reading the database files, CORAplus generates corridor curves based on global parameters. The curves are used in the CORA corridor method to find a corridor rating. The cross-correlation rating is then calculated for each signal (Thunert, 2017). The ratings are weighted to find the signal rating, and the total rating thereafter. Finally, the HTML report and ASCII results file are created.

### 7.2.2 ISO18571 Rating

The ISO18571 method evaluates data through two unconnected means: a corridor and cross-corridor rating ("CORA," n.d.). The corridor rating assesses the fit of a curve within the user-specified corridor of a second curve. The cross-correlation rating, "evaluates phase shift, shape, and area below curves" ("CORA," n.d.). The methods combined compensate for limitations arising from each accompanying rating.

The ISO18571 cross-correlation rating uses a phase, magnitude, and slope scoring system (Thunert, 2017). The simulation curve is shifted by a specified multiple of the sampling interval (Thunert, 2017). The time shift at the maximum cross-correlation value creates the phase score (Thunert, 2017). The magnitude score is calculated on subsequent overlapping parts of the curves due to the time shift (Thunert, 2017). The slope score is calculated on the remaining part of the truncated simulation curve due to the time shift and slope of the test curve (Thunert, 2017).
The combined ISO rating is a weighted union of the corridor rating and each score from the cross-correlation method. The corridor method making up 40% of the weight, while the phase, magnitude, and slope of the cross-correlation method each making up 20% of the weight (Thunert, 2017).

7.2.3 Physical Datafiles

The physical test data for each sled test case was provided by NASA in MATLAB structures. Data for each sled case was available in separate MATLAB files. The structures contained fields for unfiltered data, filtered data, information, and results. The results field contained maximum and minimum values of the abscissa and ordinate terms. The unfiltered and filtered structures contained fields for head, neck, seat, and injury metric. The head and neck structures contained occupant injury data for each load case, as well as information on sampling rate, time of pulse, channel name, and units.

The filtered load case data was extracted from the structure by a MATLAB script. The data was shifted based on the time of pulse to zero the occupant injury response time. Much of the data was superfluous. The range was modified from 50000 points to 6000. With a sampling rate of 10000Hz, 6000 points is equal to 600ms of data, which is more than enough for the evaluation of occupant injury. The corresponding time in milliseconds was added as the abscissa values. The occupant injury data, ordinate values, were transformed from the raw units provided to the units used in the LS-DYNA Boundary_Condition.key file. The data was then exported as .csv file.

The physical data was then transferred from the local system to the remote server located at LSTC. The data was imported into LS-PrePost. The ordinate data was inverted to match the coordinate system used in the simulated sled test. The data could then be exported as xy-pairs.
The datafiles were further modified to the required format of CORAplus. The first line of the datafiles must begin with XYDATA, ISOMME NAME, followed by space-separated xy-pairs. The last line of each datafile must end with ENDATA.

### 7.2.4 Simulation Datafiles

The simulation datafiles were obtained using LS-PrePost. Each sled case was simulated separately. Following normal termination of the job, the *d3plot* binary file was opened in LS-PrePost. The binout interface was selected. The binary database output file was loaded to examine time history data. Acceleration and rotational velocity data was held in the nodout file, while force and moment data were held in the secforc file. Node 52500001-HeadAccel_INJURY was evaluated in the nodout file. Joint 50100001 was evaluated in the secforc file. The node and joint ID’s were selected based on the reference points and channels used by NASA, available in Table 29.

**Table 29. LSTC Hybrid III 95th percentile reference points and channels**

<table>
<thead>
<tr>
<th>Model</th>
<th>File Loc</th>
<th>loadstr</th>
<th>ID</th>
<th>SF</th>
<th>filtSpec</th>
<th>Region</th>
<th>Location</th>
<th>Type</th>
<th>Dir</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3 95TH</td>
<td>node</td>
<td>lin</td>
<td>52500001</td>
<td>1</td>
<td>108</td>
<td>head</td>
<td>CG</td>
<td>Acc,Vel,RotAcc,RotVel,x-y-z,reslt</td>
<td></td>
</tr>
<tr>
<td>H3 95TH</td>
<td>node</td>
<td>lin</td>
<td>52501787</td>
<td>1</td>
<td>108</td>
<td>chest</td>
<td>T6</td>
<td>Acc</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>deforc</td>
<td>rot</td>
<td>52500010</td>
<td>5.71</td>
<td>108</td>
<td>chest</td>
<td>sternum</td>
<td>Rot:Disp</td>
<td>rel</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>node</td>
<td>lin</td>
<td>52503304</td>
<td>1</td>
<td>108</td>
<td>pelvis</td>
<td>CG</td>
<td>Acc</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50500001</td>
<td>1</td>
<td>108</td>
<td>leg</td>
<td>Left Femur</td>
<td>Force</td>
<td>z</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50700002</td>
<td>1</td>
<td>108</td>
<td>leg</td>
<td>Left Lower Tibia</td>
<td>Force</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50700002</td>
<td>1</td>
<td>108</td>
<td>leg</td>
<td>Left Lower Tibia</td>
<td>Mom</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50700003</td>
<td>1</td>
<td>108</td>
<td>leg</td>
<td>Left Upper Tibia</td>
<td>Mom</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50600001</td>
<td>1</td>
<td>108</td>
<td>leg</td>
<td>Right Femur</td>
<td>Force</td>
<td>z</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50800002</td>
<td>1</td>
<td>108</td>
<td>leg</td>
<td>Right Lower Tibia</td>
<td>Force</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50800002</td>
<td>1</td>
<td>108</td>
<td>leg</td>
<td>Right Lower Tibia</td>
<td>Mom</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50800003</td>
<td>1</td>
<td>108</td>
<td>leg</td>
<td>Right Upper Tibia</td>
<td>Force</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50800003</td>
<td>1</td>
<td>108</td>
<td>leg</td>
<td>Right Upper Tibia</td>
<td>Mom</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50100001</td>
<td>1</td>
<td>108</td>
<td>neck</td>
<td>upper</td>
<td>Force</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>seeforc</td>
<td>lin</td>
<td>50100001</td>
<td>1</td>
<td>108</td>
<td>neck</td>
<td>upper</td>
<td>Mom</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>jntforc</td>
<td>lin</td>
<td>50100020</td>
<td>1</td>
<td>108</td>
<td>neck</td>
<td>lower</td>
<td>Force</td>
<td>x-y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>jntforc</td>
<td>rot</td>
<td>50100020</td>
<td>1</td>
<td>108</td>
<td>neck</td>
<td>lower</td>
<td>MomTot:Mom</td>
<td>phi,-,psi</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>jntforc</td>
<td>lin</td>
<td>52500038</td>
<td>1</td>
<td>108</td>
<td>spine</td>
<td>lumbar</td>
<td>Force</td>
<td>x,y,z,reslt</td>
</tr>
<tr>
<td>H3 95TH</td>
<td>jntforc</td>
<td>rot</td>
<td>52500015</td>
<td>1</td>
<td>108</td>
<td>spine</td>
<td>lumbar</td>
<td>MomTot:Mom</td>
<td>phi,0,psi,</td>
</tr>
</tbody>
</table>
After selecting the evaluation location, occupant injury criterion was chosen to produce a time history plot. The response characteristics measured for each sled test case was designated by the injury criterion test matrix provided by NASA. The ordinate data was filtered according to the filter specifications listed in its corresponding MATLAB structure for the given physical occupant injury criterion. The data was then saved as *xy-pairs*. Again, the datafiles were modified to the required format of CORAplus. The first line of the datafiles must begin with *XYDATA*, *ISOMME NAME*, followed by space-separated *xy-pairs*. The last line of each datafile must end with *ENDATA*.

Linux command lines were made to quickly transform the data output from LS-PrePost to the CORAplus-required format. For every material model tested, 24 injury criterion simulation datafiles had to be converted to get ISO scores. The command lines helped to avoid the need to go into each individual file and make changes one-by-one. The Linux command lines are available in Appendix J.

### 7.2.5 Executing CORAplus

The CORAplus software was not available on the LSTC Barstow remote server. The datafiles were moved using Secure File Transfer Protocol (SFTP) to the local computer where CORAplus was installed. For every material model tested, the simulation datafile names in each control file had to be updated. CORAplus_4.0.4 was executed using the previously mentioned command line. The HTML report with calculated ISO scores was automatically opened in the browser specified by the configuration file.

### 7.3.1 Neck Sled Simulation Dynamic Relaxation

The first neck model tested in the NASA Neck Sled Simulations was the model provided by NASA. A base evaluation of the NASA Updated neck model had to be made because the
ISO18571 rating used was not exactly equal to the ISO rating used by NASA. Following simulation of each sled case the injury criterion data was evaluated.

On evaluation, a number of injury criterion responses in the z-direction experienced a high initial noise. The noise lasted for about the first 150ms of the simulation. The noise was not located in the physical sled test datafiles nor the plots of injury criterion simulation data that were previously shared by NASA. The noise was unique to the immediate simulations.

It was found that the source of the noise was the neck cable vibrations caused by the prescribed neck cable pretension. In the physical Hybrid III dummies, the neck cable is always in tension. The tension in the Hybrid III model is imitated with the keyword *INITIAL_STRESS_BEAM. The keyword initializes stress in the neck cable beam elements. In the first time step of simulation, the neck cable beam elements are contracted according to the prescribed stress. The sudden tightening of the neck cable is opposed by the neck rubber, causing vibrations throughout the neck. The resulting noise is picked up in the injury criterion measurements.

NASA had acknowledged this problem in the unaltered neck sled simulation keyword file that was originally shared with me. The abscissa value of the simulation pulse data was offset by 0.25. The offset is imposed on the pulse data according to the equation (LS-DYNA Keyword User’s Manual, 2007):

\[
\text{Abscissa value} = SFA \times (\text{Defined value} + \text{OFFA}) \quad (\text{Eq. 4})
\]

The abscissa scale factor was equal to 1000 in order to transform the time from seconds to milliseconds. The resulting pulse was first offset and then scaled accordingly, meaning that the acceleration data was zero for the first 250ms of simulation. The zero acceleration wait time
allowed the neck cable to relax before the pulse was initiated. The pulse offset was originally removed because its purpose was ambiguous.

Instead of reestablishing the offset, a dynamic relaxation phase was activated. The zero acceleration 250ms wait time is a viable option for removing the vibrational effects of the prestressed beams, but it is computationally inefficient. Instead, the variable $sidr$ was set to two on a single *DEFINE_CURVE keyword card to initialize a dynamic relaxation phase in the model. Dynamic relaxation takes place before the dynamic analysis. In LS-DYNA explicit dynamic relaxation, the nodal velocities are essentially damped each time step until the kinetic energy of the model is near zero. At this point, the dynamic relaxation phase ends and the dynamic analysis begins at the first time step (Preloads in LS-DYNA, n.d.). Figure 88 shows the head z-acceleration of the model with and without a dynamic relaxation phase.

![Figure 88. Frontal 6G head z-acceleration noise due to pretension](image)

7.3.2 Neck Sled Simulation ISO18571 ISO Scores

The calculated combined ISO18571 score for the NASA model evaluated for 600ms was equal to 0.686. The ISO score calculated by NASA using their ISO function was equal to 0.823. Likely, the corridor and cross correlation settings are stricter on the ISO18571 rating versus the ISO
rating used by NASA. The difference in ratings will not affect the ultimate material model. The best representation of the physical Hybrid III will be selected as the model with the highest ISO18571 rating.

A wide range of models with varying material properties were executed in the simulated Neck Sled Test. The goal was to make a CFR calibrated Hybrid III neck model that also performed well in the NASA Sled Simulations. Accordingly, simulations were often alternated between the NASA Neck Sled Simulations and the CFR neck calibration simulations. The material model was adjusted to better match the injury criterion curves of the physical Hybrid III data in the sled test, while periodic simulations were completed in the CFR simulations to ensure the model response was still within the calibration corridors. Models that performed exceptionally well in the Neck Sled Simulation were evaluated using CORAplus to attain ISO scores.

Originally, the sameness of curves was evaluated at 600ms. 600ms was initially chosen because it was the default termination time of the simulated Neck Sled Test. The 600ms evaluation time contained several sinusoidal waves of neck response. Because there were so many curves produced, it was difficult to match the amplitude and period of each wave for each injury criterion response of each sled case. The domain of the CORAplus evaluation was ultimately changed to contain just the first period of the injury criterion data. The resulting domain was equal to 300ms. The first period of data contains the most important information when evaluating potential occupant injury. 300ms was long enough to view the maximum and minimum acceleration, force, and moment experienced by the dummy in each sled case simulation. CORAplus does not weight the initial peak of the wave greater than the subsequent peaks. The subsequent peaks are more than likely unimportant to NASA in testing for occupant injury. Significantly, the NASA injury criterion curves showed ISO evaluations between 250 to 350ms. The default 600ms termination time of the NASA Neck Sled Simulation was likely established
due to the 250ms zero acceleration time that was in place of the dynamic relaxation phase. It was determined that the first 300ms of simulation would be used to find a model that best matches the corridor and correlation of the physical data.

All further ISO score evaluations were set to 300ms in the CORAplus control file. The Neck Sled Simulation termination time was set to 300ms. The NASA Updated model, labeled as simcurve1, was re-evaluated in the 300ms domain. Table 30 displays the resulting ISO18571 scores for each injury criterion of the four sled cases.

Table 30. NASA Neck Sled Test 300ms ISO18571 scores: version simcurve01

<table>
<thead>
<tr>
<th>Case</th>
<th>Head Ax</th>
<th>Head Ay</th>
<th>Head Az</th>
<th>Head Rx</th>
<th>Head Ry</th>
<th>Unneck Fx</th>
<th>Unneck Fy</th>
<th>Unneck Fz</th>
<th>Unneck Mx</th>
<th>Unneck My</th>
<th>Nij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral 12 G</td>
<td>0.885</td>
<td>0.683</td>
<td>0.838</td>
<td></td>
<td></td>
<td>0.829</td>
<td>0.647</td>
<td>0.835</td>
<td></td>
<td>0.786</td>
<td></td>
</tr>
<tr>
<td>Frontal 6G</td>
<td>0.835</td>
<td>0.361</td>
<td></td>
<td>0.835</td>
<td>0.808</td>
<td>0.352</td>
<td></td>
<td>0.861</td>
<td>0.675</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal 16G</td>
<td>0.794</td>
<td>0.408</td>
<td></td>
<td>0.772</td>
<td>0.730</td>
<td>0.406</td>
<td></td>
<td>0.796</td>
<td>0.651</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rearward 6G</td>
<td>0.730</td>
<td>0.582</td>
<td></td>
<td>0.621</td>
<td>0.690</td>
<td>0.639</td>
<td></td>
<td>0.575</td>
<td>0.639</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.688</td>
<td></td>
</tr>
</tbody>
</table>

The calibrated model with updated mesh was run in the NASA Neck Sled Simulations and evaluated in CORAplus. This model was labeled as usimcurve01, for updated-simulation-curve-version01. The resulting ISO scores are presented in Table 31.
Table 31. NASA Neck Sled Test 300ms ISO18571 scores: version usimcurve01

<table>
<thead>
<tr>
<th>Case</th>
<th>Head Ax</th>
<th>Head Ay</th>
<th>Head Az</th>
<th>Head Rx</th>
<th>Head Ry</th>
<th>Uneck Fx</th>
<th>Uneck Fy</th>
<th>Uneck Fz</th>
<th>Uneck Mx</th>
<th>Uneck My</th>
<th>Nij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral 12 G</td>
<td>0.857</td>
<td>0.760</td>
<td>0.720</td>
<td></td>
<td></td>
<td>0.823</td>
<td>0.704</td>
<td>0.796</td>
<td>0.777</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal 6G</td>
<td>0.773</td>
<td>0.390</td>
<td>0.720</td>
<td>0.808</td>
<td></td>
<td>0.383</td>
<td>0.789</td>
<td></td>
<td>0.644</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal 16G</td>
<td>0.719</td>
<td>0.477</td>
<td>0.749</td>
<td>0.772</td>
<td></td>
<td>0.561</td>
<td>0.735</td>
<td></td>
<td>0.669</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rearward 6G</td>
<td>0.648</td>
<td>0.528</td>
<td>0.521</td>
<td>0.612</td>
<td></td>
<td>0.581</td>
<td>0.473</td>
<td>0.560</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.663</td>
<td></td>
</tr>
</tbody>
</table>

The combined ISO score of usimcurve01 was not adequate. The model did not match the physical response of the Hybrid III better than the NASA Updated model, simcurve1. The working model performed better in the frontal orientation simulations, but less well in the lateral and rearward simulations. Significantly, the model calibrated for high-severity frontal crash tests performed better in the Frontal 16G simulation, which exhibited the highest acceleration. Interestingly, both models performed poorly in the Frontal 6G simulation when evaluating the head z-acceleration and upper neck z-force. An example of the poor correlation is shown in the CORAplus generated graph, Figure 89.

![Graph](image-url)

Figure 89. Neck Sled Simulation simcurve1 upper neck z-force CORAplus generated graph
The figure shown displays the NASA Updated model without the dynamic relaxation phase initiated, although with or without dynamic relaxation is insignificant for the purpose of this paragraph. The red line is the simulation data, while the black line is the physical test data. The blue and green lines are the CORA generated corridors for the simulation and test data respectively. The figure reveals a difference in settling acceleration that is unique to the Frontal 6G head z-acceleration and upper neck z-force. The physical test data settles at around \(0.015\) mm/ms\(^2\). The simulation data settles at around \(-0.025\) mm/ms\(^2\). Both initial accelerations are equal to zero but settle at different magnitudes of acceleration. The difference in converged acceleration between the test and simulation data is the source of the poor ISO score ratings. The reason for the difference in settling acceleration was contemplated but was never found. The ISO scores for frontal 6G head z-acceleration and upper neck z-force, although poor, were still considered when choosing an ideal material model.

Changes in material properties were made to better match the response of select injury criterion. In the case of usimcurve01, the rearward response needed to be improved. Material model modifications were tested in the Neck Sled Simulation and intermittently in the CFR neck calibration simulations. Material model performance in the Neck Sled Simulation was initially judged by visually comparing the injury criterion time history plot to the test data. Select material models with good performance in the Neck Sled Simulation were evaluated using CORAplus. Appendix K contains the supplemental ISO scores of material models that did not meet the desired result.
8. FINALIZED NECK MODELS

8.1 Usimcurve19

Material properties were modified based on the response history of previous material models. However, predicting the ultimate model reaction to modifications was difficult as material card variables were each dependent, and the neck rubber response was nonlinear. Material properties were altered until material model performance could no longer be improved. The resulting material model was usimcurve19.

Usimcurve19 had the highest combined ISO18571 rating in the Neck Sled Simulations, while still meeting CFR Neck Calibration test corridor requirements. Moreover, usimcurve19 well approximated the response of the physical 95th percentile neck in the implicit compression simulation. The usimcurve19 material properties for MAT006 – Viscoelastic are presented in Table 32.

Table 32. Usimcurve19 viscoelastic material properties

<table>
<thead>
<tr>
<th>Version</th>
<th>Ro</th>
<th>Bulk</th>
<th>G0</th>
<th>GI</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>usimcurve19</td>
<td>1.175E-6</td>
<td>0.0500</td>
<td>0.0055</td>
<td>0.00205</td>
<td>0.043</td>
</tr>
</tbody>
</table>

The combined ISO18571 rating of 0.717 for the usimcurve19 material model was the highest of all models tested. The injury criterion curves best replicated the corridor and cross-correlation of the physical Hybrid III 95th percentile experimental data. The ISO scores of usimcurve19 are available in Table 33. For reference, the ISO scores of the NASA Updated model are available in Table 30. The combined ISO score of the NASA Updated model was 0.688.
The usimcurve19 material model was greatly improved from the NASA model in the Lateral 12G and Frontal 16G sled cases. Usimcurve19 response in the Frontal 6G sled case was equal to that of the NASA model. Usimcurve19 response in the Rearward 6G sled case was lesser than that of the NASA model. Because usimcurve19 is CFR calibrated for high-severity car crashes, the model exhibits better response in the higher load simulations: 12G and 16G. Response in the low-severity load cases is sufficient, but not improved from the NASA model. The combined ISO18571 rating for usimcurve19 has a 4.2% improvement over the rating for the NASA Updated model. The ISO rating improvement is not large, but it is notable when considering that NASA was content with their updated model. The usimcurve19 response is compared to the experimental data in the CORAplus generated graphs in Figures 90-93. The figures display select injury criterion data from each sled case. The complete record of usimcurve19 CORAplus generated graphs for each of the 24 evaluated injury criterion responses is available in Appendix L-O. The red line is the simulation data, while the black line is the physical test data. The blue and green lines are the CORA generated corridors for the simulation and test data respectively. The tan lines are the CORA generated simulation data shift. The tan vertical line displays the termination time of the CORAplus evaluation.
Figure 90. Neck Sled Simulation Frontal 6G Neck y-Moment usimcurve19

Figure 91. Neck Sled Simulation Frontal 16G Head y-Rotational velocity usimcurve19

Figure 92. Neck Sled Simulation Lateral 12G Head y-Acceleration usimcurve19
The magnitude of difference between the combined NASA ISO rating, using the NASA ISO function, and the combined ISO18571 rating for the NASA Updated model was 1.196.

Multiplying the usimcurve19 ISO18571 rating by this magnitude gives the working model a “NASA ISO rating” of 0.858. By contrast, the Hybrid III 5\textsuperscript{th} percentile and 50\textsuperscript{th} percentile LSTC dummy models received a combined NASA ISO rating of 0.721 and 0.809 respectively for the same four sled cases. The transformation of ISO18571 rating to the NASA ISO rating is approximated. Nonetheless, the transformation shows the 95\textsuperscript{th} percentile model as the highest correlated model to the physical experimental data out of all LSTC dummy models evaluated by NASA.

On top of the improved ISO rating, the usimcurve19 material model produces a 95\textsuperscript{th} percentile neck model that is CFR calibrated as a compliance test tool for FMVSS. The usimcurve19 material model performance in the CFR Neck Extension Simulation and Neck Flexion Simulation is available in Figures 94-97. The blue dashed lines represent the CFR established corridors. The maximum plane-D rotation and maximum moment about the occipital condyle fall within the
blue dashed lines. The blue solid line in the moment plots show the moment decay requirement to -10Nm and 10Nm for the extension and flexion simulations respectively. The moment response must cross the blue solid line to meet CFR requirements. Table 34 compares the CFR calibration test performance of usimcurve19 and the NASA Updated model.

Figure 94. Neck Extension Simulation Plane-D Rotation, NASA model vs usimcurve19

Figure 95. Neck Extension Simulation moment, NASA model vs usimcurve19
Figure 96. Neck Flexion Simulation Plane-D Rotation, NASA model vs usimcurve19

Figure 97. Neck Flexion Simulation moment, NASA model vs usimcurve19
Table 34. Neck Calibration Simulation performance of NASA model and usimcurve19

<table>
<thead>
<tr>
<th></th>
<th>Lower Corridor</th>
<th>Upper Corridor</th>
<th>NASA Updated (simcurve1)</th>
<th>usimcurve19</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neck Extension</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plane-D Rotation [deg]</td>
<td>81</td>
<td>98</td>
<td>79.15</td>
<td>91.29</td>
</tr>
<tr>
<td>Maximum Moment [N-m]</td>
<td>66</td>
<td>84</td>
<td>70.51</td>
<td>68.50</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m [ms]</td>
<td>100</td>
<td>120</td>
<td>107.56</td>
<td>109.86</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Lower Corridor</th>
<th>Upper Corridor</th>
<th>NASA Updated (simcurve1)</th>
<th>usimcurve19</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Neck Flexion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plane-D Rotation [deg]</td>
<td>61</td>
<td>75</td>
<td>55.11</td>
<td>63.52</td>
</tr>
<tr>
<td>Maximum Moment [N-m]</td>
<td>110</td>
<td>130</td>
<td>103</td>
<td>111.44</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m [ms]</td>
<td>77</td>
<td>97</td>
<td>75.62</td>
<td>77.64</td>
</tr>
</tbody>
</table>

The usimcurve19 performance in the Neck Extension Simulation and Neck Flexion Simulation is not ideal, but the measured injury criterion values still meet CFR requirements. Measured values were closer to the midpoint of the corridor domain in the Neck Extension Simulation versus in the Neck Flexion Simulation. The usimcurve19 model is regarded as calibrated for automobile crash tests, while the NASA Updated model is not.

Usimcurve19 performance in the Implicit Compression Simulation is good. The load curve produced by usimcurve19 under compression is available in Figure 98. The model load slope was generally close to that of the experimental data. Similar slopes suggest similar change in reaction force per change in time. Usimcurve19 is an adequate representation of the physical neck during compression. The NASA Updated model performance could not be compared to usimcurve19 in the implicit compression simulation due to the mesh induced error of the former-mesh model.
Figure 98. Implicit Compression Simulation: experiment and usimcurve19 data

8.2 Usimcurve27

A subsequent model was produced after usimcurve19 in an attempt to achieve the highest ISO rating possible regardless of performance in the CFR calibration simulations. Ideally, this model would only ever be used in low-severity loading simulations. The NASA Neck Sled Simulation termination time and CORAplus evaluation termination time was increased to 350ms. The slight bump in evaluation time was made to better match the decay of injury criterion data. Usimcurve19 well matched the initial wave of response but did not match the succeeding waves as well as it could.

The resulting material model from this study was usimcurve27. This model, however, did not have an improved ISO score from usimcurve19. Instead, its response was close to that of the NASA Updated model. The resulting material model properties and ISO18571 ISO scores are available in Table 35 and 36 respectively.
Table 35. Usimcurve27 viscoelastic material properties

<table>
<thead>
<tr>
<th>Version</th>
<th>Ro</th>
<th>Bulk</th>
<th>G0</th>
<th>GI</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usimcurve27</td>
<td>1.175E-6</td>
<td>0.0700</td>
<td>0.0100</td>
<td>0.0030</td>
<td>0.150</td>
</tr>
</tbody>
</table>

Table 36. NASA Neck Sled Test 350ms ISO18571 scores: usimcurve27

<table>
<thead>
<tr>
<th>Case</th>
<th>Head Ax</th>
<th>Head Ay</th>
<th>Head Az</th>
<th>Head Rx</th>
<th>Head Ry</th>
<th>Uneck Fx</th>
<th>Uneck Fy</th>
<th>Uneck Fz</th>
<th>Uneck Mx</th>
<th>Uneck My</th>
<th>Nij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral 12 G</td>
<td>0.895</td>
<td>0.729</td>
<td>0.833</td>
<td>0.890</td>
<td>0.700</td>
<td>0.857</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.817</td>
</tr>
<tr>
<td>Frontal 6G</td>
<td>0.812</td>
<td>0.336</td>
<td>0.788</td>
<td>0.808</td>
<td>0.359</td>
<td>0.855</td>
<td>0.660</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal 16G</td>
<td>0.795</td>
<td>0.505</td>
<td>0.734</td>
<td>0.820</td>
<td>0.515</td>
<td>0.782</td>
<td>0.692</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rearward 6G</td>
<td>0.704</td>
<td>0.581</td>
<td>0.572</td>
<td>0.676</td>
<td>0.655</td>
<td>0.578</td>
<td>0.628</td>
<td></td>
<td></td>
<td></td>
<td>0.699</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The combined ISO18571 score of usimcurve27, 0.699, is slightly better than the 0.686 score for the NASA Updated model run at 350ms. Even though the ISO scores are worse than usimcurve19, the model is still presented in the thesis because it has improved rearward loading response and better represents the decay of the physical response. The ISO18571 scores for the NASA Updated model and usimcurve19 at the 350ms extended evaluation time is available in Appendix L. The Rearward 6G response of usimcurve27 from usimcurve19 was improved by 6.4%. Additionally, the decay of usimcurve27 response better matches the physical dummy. The similarities in response between the NASA Updated model and usimcurve27 are seen in Figures 99-101.
Figure 99. Neck Sled Test Frontal 6G head x-Acc usimcurve27 and NASA model

Figure 100. Neck Sled Simulation Rearward 6G head x-Force usimcurve27 and NASA model

Figure 101. Neck Sled Simulation Lateral 12G head y-Acc usimcurve27 and NASA model
The usimcurve27 model may be beneficial to NASA for a few reasons. To begin, the period of response is near identical between usimcurve27 and the NASA Updated model. Matching the period of the NASA Updated model is relevant because the period matches the decay of the physical dummy response in testing relatively well. An additional reason is that NASA is content with the performance of the model they made. Usimcurve27 has an equal period to that model with the benefit of a slightly improve ISO rating. The last, and largest benefit of this model is its computational efficiency.

A few alterations to the neck and main file were completed to compare CPU timing between usimcurve27 and the NASA Updated model. The variable, $sidr$ was set to 2 on the NASA model to invoke dynamic relaxation, as is in the new model. The dynamic relaxation phase was added to replace the 250ms wait time that was initially defined in the NASA main file. The computation time of the models could be compared more clearly in jobs of equal prescribed termination time with dynamic relaxation.

A few simulations were submitted on different server types and with differing computation power. Each simulation tested the NASA Updated model and the usimcurve27 model in the Frontal 6G sled simulation. A simulation was submitted to the Cal Poly Aerospace Bishop Symmetric Multiprocessor (SMP) cluster run on 1 node and 12 cores. And two jobs were submitted to the LSTC Barstow Massively Parallel Processor (MPP) server run on 12 and 24 cores. Table 37 compares the total CPU timing between models in each job.
Different servers and computing power were used to solve the problems to see how results varied. LS-DYNA customers have varying server types, so LS-DYNA is offered in MPP and SMP versions. The CPU timing difference between the SMP cluster and MPP server run on the same number of cores is drastic. However, it is difficult to compare servers because the CPU’s and version of LS-DYNA are all different. Additionally, the job submitted to the Bishop cluster was set at 1 node and 12 cores, but it was unclear how many cores were available on 1 node of Bishop.

Timing information can be compared between like servers. The original neck model with original Neck Sled Simulation file was run in SMP. The file ran in 34 hours. Invoking a dynamic relaxation phase to the same file improved the CPU timing to 21 hours. Changing the model to usimcurve27 improved simulation time drastically, to just 10 hours. The results show that the CPU timing in the Frontal 6G Neck Sled Simulation was reduced by 70% by switching from the NASA Updated model to the usimcurve27 model.

The CPU timing decrease from the NASA Updated model with invoked dynamic relaxation to the usimcurve27 model in the Frontal 6G sled case was 29% and 28% when run in MPP with 12 and 24 cores respectively. A different number of CPU’s were tested in Barstow because 24 cores

<table>
<thead>
<tr>
<th>Model</th>
<th>Total CPU Timing</th>
<th>Bishop SMP 1 node</th>
<th>Barstow MPP 12 cores</th>
<th>Barstow MPP 24 cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA Updated (without DR)</td>
<td>34 hours 8 mins</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>NASA Updated</td>
<td>21 hrs 25 mins</td>
<td>2 hrs 22 mins</td>
<td>1 hrs 19 mins</td>
<td></td>
</tr>
<tr>
<td>Usimcurve27</td>
<td>10 hrs 6 mins</td>
<td>1 hrs 42 mins</td>
<td>57 mins</td>
<td></td>
</tr>
</tbody>
</table>
takes up two nodes, while 12 cores only takes up one node. Exchanging information between
nodes and using too many CPU’s sometimes adds to the CPU timing; however, this was hardly
the case when run at 12 and 24 cores.

Usimcurve27 provides NASA with a response near equivalent to the model they produced but
with much less expense. The magnitude of response characteristics in the usimcurve27 model is
not as accurate as usimcurve19. The peak-time, however, is more accurate throughout the time
domain. Usimcurve27 is a good model for obtaining relatively accurate timing and magnitude
values for extended periods under low-severity loading.

Usimcurve19, on the other hand is best for short-time performance. The usimcurve19 material
model matches the magnitude and peak-timing of the physical Hybrid III within 300ms of
simulation better than the NASA Updated model. After which, the magnitude of the response is
fairly accurate; however, the peak-timing is off. Typically, a 300ms explicit simulation is more
than enough to retrieve potential injury data. Usimcurve19 is best for obtaining peak occupant
injury information under low to mid-severity loading. A large majority of the time, usimcurve19
will be the preferred model for NASA use because it approximates the magnitude and timing of
maximum occupant injury potential better than any other model. In addition, usimcurve19 shares
equal computational efficiency to that of usimcurve27.

8.3 Downloadable LSTC Hybrid III model

One last model was created, aimed to produce the best response in the CFR calibration
simulations. Performance in the Neck Sled Simulations was disregarded. The neck model
developed in this section will be implemented into the downloadable version of the LSTC Hybrid
III 95th percentile finite element model. Customers will use the model in high-severity vehicle
crash simulations. Therefore, it is of greatest importance that the neck model be calibrated as a compliance test tool for Federal Motor Vehicle Safety Standards.

A number of material models for the latter-meshed neck were tested in the neck calibration simulations prior. The best calibrated material model from a selection of 25 was chosen to be tweaked. This model will be referred to as Model A. Slight material property modifications to Model A were completed to bring model response as close to the center of each injury criterion corridor as possible. Eight models were produced, labeled B though I.

A scoring system was introduced to judge occupant injury performance obtained from each material model. The formula used considers the deviation from the center of the regulated corridors, as well as the range between the upper and lower corridor. It is equal to the percent error of the upper corridor value minus the center corridor value. The percent error was calculated for each of the regulated response characteristics and averaged. The neck model with the lowest average percent error will be implemented into the Hybrid III 95th percentile finite element model. The formula used for each measured injury criterion is listed as equation 5.

\[
\text{Percent Error} = \left| \frac{(\text{upper} - \text{measured}) - (\text{upper} - \text{center})}{(\text{upper} - \text{center})} \right|
\]  

(Eq. 5)

Where upper is equal to the upper corridor value, and center is equal to the average of the upper and lower corridor values. The importance of each response characteristic is unknown, so each is weighted equally. The response characteristics measured include plane-D rotation, maximum moment, and moment decay. Material properties of models A-I are listed in Table 38. The measured injury criterion values for each model in the Neck Extension and Flexion Simulations is
listed in Table 39. The average percent error, or calibration score, of each model is listed in Table 40.

Table 38. Material properties models A-I

<table>
<thead>
<tr>
<th>Model</th>
<th>Bulk Modulus, K</th>
<th>Short-time Shear Modulus, G0</th>
<th>Long-time Shear Modulus, G1</th>
<th>Decay Constant, Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0728</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.080</td>
</tr>
<tr>
<td>B</td>
<td>0.0728</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.020</td>
</tr>
<tr>
<td>C</td>
<td>0.1528</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.400</td>
</tr>
<tr>
<td>D</td>
<td>0.0728</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.050</td>
</tr>
<tr>
<td>E</td>
<td>0.0528</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.050</td>
</tr>
<tr>
<td>F</td>
<td>0.0728</td>
<td>0.0039</td>
<td>0.0030</td>
<td>0.050</td>
</tr>
<tr>
<td>G</td>
<td>0.0228</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.030</td>
</tr>
<tr>
<td>H</td>
<td>0.0528</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.030</td>
</tr>
<tr>
<td>I</td>
<td>0.0378</td>
<td>0.0049</td>
<td>0.0030</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Table 39. Injury criterion response measurements models A-I

**Neck Ext, Injury Criterion:**

<table>
<thead>
<tr>
<th>Plane-D Rotation</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment During Rotation</td>
<td>91.45</td>
<td>85.02</td>
<td>95.46</td>
<td>88.79</td>
<td>90.81</td>
<td>94.86</td>
<td>97.29</td>
<td>88.45</td>
<td>91.51</td>
</tr>
<tr>
<td>Moment Decay to -10 N-m</td>
<td>115.7</td>
<td>109.0</td>
<td>124.1</td>
<td>111.5</td>
<td>113.5</td>
<td>120.2</td>
<td>114</td>
<td>110.0</td>
<td>115.3</td>
</tr>
</tbody>
</table>

**Neck Flex, Injury Criterion:**

<table>
<thead>
<tr>
<th>Plane-D Rotation</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment During Rotation</td>
<td>64.62</td>
<td>60.52</td>
<td>68.88</td>
<td>62.70</td>
<td>64.06</td>
<td>67.66</td>
<td>68.25</td>
<td>62.52</td>
<td>64.38</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m</td>
<td>83.5</td>
<td>74.88</td>
<td>85.94</td>
<td>77.32</td>
<td>78.3</td>
<td>81.66</td>
<td>80.1</td>
<td>76.18</td>
<td>77.37</td>
</tr>
</tbody>
</table>

Table 40. Calibration test scores models A-I

**Neck Ext, Scores:**

<table>
<thead>
<tr>
<th>Plane-D Rotation</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment During Rotation</td>
<td>0.229</td>
<td>0.526</td>
<td>0.701</td>
<td>0.083</td>
<td>0.155</td>
<td>0.632</td>
<td>0.916</td>
<td>0.124</td>
<td>0.237</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m</td>
<td>0.444</td>
<td>1.687</td>
<td>0.481</td>
<td>0.028</td>
<td>0.289</td>
<td>0.078</td>
<td>0.547</td>
<td>0.046</td>
<td>0.013</td>
</tr>
</tbody>
</table>

**Neck Flex, Scores:**

<table>
<thead>
<tr>
<th>Plane-D Rotation</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment During Rotation</td>
<td>0.483</td>
<td>1.068</td>
<td>0.126</td>
<td>0.756</td>
<td>0.562</td>
<td>0.049</td>
<td>0.036</td>
<td>0.782</td>
<td>0.518</td>
</tr>
<tr>
<td>Moment Decay to 10 N-m</td>
<td>0.350</td>
<td>1.212</td>
<td>0.106</td>
<td>0.968</td>
<td>0.870</td>
<td>0.534</td>
<td>0.690</td>
<td>1.082</td>
<td>0.963</td>
</tr>
</tbody>
</table>

**Calibration Score:**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.476</td>
<td>0.902</td>
<td>0.783</td>
<td>0.342</td>
<td>0.405</td>
<td>0.541</td>
<td>0.451</td>
<td>0.430</td>
<td>0.411</td>
</tr>
</tbody>
</table>
The model with the lowest average percent error was Model D with 34.2% error. According to the percent error, Model D performance was exceptional in the Neck Extension Simulation. Performance in the Neck Flexion Simulation plane-D rotation and moment decay to 10N-m was not as good. Overall, Model D had the closest measured response characteristic values to the ideal, center corridor. By contrast, the usimcurve19 model, which is also calibrated, had an average percent error of 56.3%.

Response characteristics of Model D can be seen in Figures 102-105. The blue dashed lines represent the CFR established corridors. The maximum plane-D rotation and maximum moment about the occipital condyle must fall within the blue dashed lines. The blue solid line in the moment plots show the moment decay requirement to -10N-m and 10N-m for the extension and flexion simulations respectively. The moment response must cross the blue solid line to be meet CFR requirements. The neck model developed in this section will be implemented into the downloadable version of the LSTC Hybrid III 95th percentile finite element model.

![Figure 102. Neck Extension Simulation plane-D rotation with specified corridors: Model D](image)
Figure 103. Neck Extension Simulation maximum moment and moment decay: Model D

Figure 104. Neck Flexion Simulation plane-D rotation with specified corridors: Model D

Figure 105. Neck Flexion Simulation maximum moment and moment decay: Model D
8.4 Impending Hybrid III Model Updates

The neck model performance was greater in extension than in flexion. Using CFR test procedures for each corresponding calibration simulation, the neck plane-D rotation in extension will always be greater than the rotation in flexion. This was not only the case in the calibration simulations, but also in the NASA Neck Sled Simulations, where bending was more significant when the head was in the rearward orientation than in the frontal.

The current material model: MAT_006 - Viscoelastic, does not have an option to adjust material response according to if loading is in compression or tension. Therefore, altering material properties will not change the bias in bending direction. One option to correct the bias may be to implement a new, more elaborate material model. Resistance to element compression could be decreased in a material model that has an option to define a stress-strain curve. Less compression resistance would allow for increased bending in flexion with little effect on bending in extension. A supplemental option to correct the bending bias, while also preserving the current material model is to alter the geometry of the neck. According to General Motors, the cuts in the Hybrid III neck from the outer surface of the rubber to the neck rubber holes lessens the amount of bending resistance in extension without influencing response in flexion (Backaitis & Mertz, 1994). The cuts in the neck model are visible in Figure 106.
A possible next step in neck enhancement would be offsetting the neck rubber holes closer to the front of the neck. This would increase resistance to bending in extension. In the calibration simulations, the plane-D rotation in extension would decrease, while the maximum moment would increase. The response in flexion would remain unchanged. The plane-D rotation in flexion and extension would be lesser than it should be according to CFR corridors. Adjusting material properties to reduce neck stiffness after shifting the neck rubber holes would likely influence neck response to be at the center of the corridors in both extension and flexion.

Offsetting the neck rubber holes would also increase performance of the usimcurve19 model in the NASA Neck Sled Simulations. In these simulations, acceleration in the frontal orientation results in bending in the same direction as the head and neck in the Neck Flexion Simulation. Usimcurve19 has an exceptional response in the frontal direction, while the head acceleration and neck forces in the rearward direction are too high. Offsetting the neck holes will have no impact on the neck response in the frontal orientation. The extension of the neck and therefore acceleration and forces in the rearward response will be lessened. Material properties of usimcurve19 will therefore not have to be adjusted after offsetting the neck rubber holes. The
rearward response of usimcurve19 held back its combined ISO rating. Offsetting the neck holes would increase performance in the rearward simulations and increase the combined ISO rating of the model. However, offsetting the neck rubber holes would go against the hole placement defined in the Hybrid III drawing package. Therefore, the more sensible option to correct the bias in bending may be the implementation of a more elaborate material model.
9. CONCLUSION

The neck model revised in this project exhibits greater performance than the former Hybrid III 95th percentile neck model in a variety of fields. The new model discretization creates a more uniform mesh and discourages irregular element behavior, while the rigid neck pucks eliminate neck element mass-scaling all together. The constant stress element formulation and hourglass control of the neck rubber improves model durability and avoids artificial stiffness, which plagued the former model. The new model exhibits more consistent element deformation and has greater tendency to terminate normally under excessive loading. Total CPU timing decreased by 30% in the NASA Neck Sled Simulations and by 70% in the Neck Extension Simulation. The viscoelastic material properties selected improve neck performance throughout the range of loading. The model is calibrated as a compliance test tool for Federal Motor Vehicle Safety Standards, and exhibits greater response characteristics in the NASA Neck Sled Simulations.

The usimcurve19 neck model will be adopted by NASA for use in predicting potential occupant injury during spacecraft landing. Results found using the Hybrid III models contribute to the design and regulation of spacecraft safety restraints. The neck model attuned to higher loading will be implemented into the full consumer version of the 50th and 95th percentile LSTC Hybrid III models. Further adjustments to the material models may be made according to the CFR certification procedures for each percentile of Hybrid III. The impending LSTC Hybrid III models will assist engineers in more efficient and more accurate computer-aided design for vehicle crashworthiness.
10. REFERENCES


Somers, J., Putnam, J., Greenhalgh, P., & Lawrence, C. (2019b). *Comparison of LSTC 5th, 50th and 95th percentile Anthropomorphic Test Dummy (ATD) LS-DYNA Finite Element (FE) Simulation Results to Sled Test Data*. NASA.


Appendix A: Preliminary Neck Extension and Flexion Simulation Plots
Appendix B: Preliminary Calibration Simulations, NASA Updated model before and after calibration
Appendix C: Explicit Compression Simulation Input File
Appendix D: Implicit Compression Simulation Added Keywords

```
*CONTROL_implicit_auto
  $#  1 auto  iteopt  itewin  dtmin  dtmax  dtexp
      1      5
  $
  $ Controls dynamic or static
  $
*CONTROL_implicit_dynamics
  $#  1 imass  gamma  beta  tdybirt  tdydh  tdybur  irate
      1
  $
*CONTROL_implicit_general
  $#  1 imflag  dt0  inform  nsbs  igs  cnstn  form  zero_v
      1    500      1
  $
*CONTROL_implicit_solution
  $#  1 nso1vr  ilimit  max-ref  dctlol  ectlol  rctlol  lstol  abstol
      12     11      15
  $  dnorm  diverg  istif  nlprint  nlnorm  d3itctrl
  $  arcctl  arcdir  arclen  arcmtth  arcdmp  arcpsi  arcall  arctim
  $
  $  1smtd
  $
*CONTROL_implicit_eigenvalue
  $#  3 neig  center  1flag  lftend  rflag  rhtend  eignth  shfscl
  $
```
Appendix E: Compression Simulation Implicit and Explicit Von Mises Integration Point Stress

Figure E-1. Explicit Compression Test
400ms termination time

Figure E-2. Explicit Compression Test
400ms termination time

Figure E-3. Implicit Compression Test

Figure E-4. Implicit Compression Test
Appendix F: NASA Neck Sled Test Head Orientation Reference

- **Lateral**
- **Rearward**

- **Frontal**
- **Rear-Lateral (45° in XY plane)**
Appendix G: CORAplus Configuration File, CORAplus.cfg

# Definition of colors used for drawing the diagrams
color black 0.00 0.00 0.00 1.00
color white 1.00 1.00 1.00 1.00
color red 1.00 0.00 0.00 1.00
color green 0.00 1.00 0.00 1.00
color blue 0.00 0.00 1.00 1.00
#
color cyan 0.00 1.00 1.00 1.00
color coral 1.00 0.50 0.31 1.00
color magenta 1.00 0.00 1.00 1.00
color yellow 1.00 1.00 0.00 1.00
color orange 1.00 0.65 0.00 1.00
#
color darkgoldenrod 0.72 0.53 0.04 1.00
#
# Usage of the defined colors
backgroundcolor white
foregroundcolor black
innercolor green
outercolor blue
experimentcolor black
simulationcolor red
intervalcolor darkgoldenrod
referencecolor orange
#
# Definition of colors used to draw the experimental curves
curvecolor magenta
curvecolor cyan
curvecolor yellow
curvecolor coral
#
# Linewidth for the small and large images
linewidth_small 1
linewidth_large 2
#
# Pointsize for signals consisting of a single supporting point
pointsize_small 4
pointsize_large 0
#
# obsolete
#CURVE_COLORS 6=magenta 5=yan 7=yellow 8=crimson 9=darkcyan 10=darkgreen
#LSP0ST 1spp
Appendix H: CORAplus Control File, control.txt

```plaintext
## 0/1/98 CONTROL FILE -- ERIC DAY
## Frontal 45
## ISO18871
##
## Global Parameters
##
BEGIN GLOBAL_PARAMETERS
DES Modal ISO18871
DES_UGL

## Interval Evaluation
A_nvars 0.09 ; (0,....,1)
A_nvars 0.99 ; (0,....,1)
A_nvars 0.403
T_DELTA_END 0.30
T_MIN/T_MAX automatic automatic ; length of time interval (automatic = calculate a range for each channel)

## Tune Corridor Method
## global parameters corridor correlation
K 2 ; Empirical factor for calculating the corridor setting [-]
G 1 0.8 ; Weighting factor of the corridor setting [-]
A_wb 0.5 0.85 ; inner and outer corridor width [-1]

## Tune Correlation
## global parameters cross correlation
D_MIN 0.000 ; inner corridor of phase shift in cross-correlation method (0,...,1) (NOT USED for ISO_18871)
D_MAX 0.18 ; outer corridor of phase shift in cross-correlation method (0,...,1) (NOT USED for ISO_18871)

## H/M
A 1 1.0 ; Maximum allowable percentage of time shift
M 0.5 ; Empirical factor for calculating the magnitude score [-]

## L/M
G 0.5 ; Weighting factor of the magnitude score [-]

## Z
0.25 ; Weighting factor of the phase score [-]

## E
0.1 ; Weighting factor of the cross-correlatio method (NOT USED for ISO_18871)

# normalising of the weighting factor ?
TRANSFORM NO ; should the Weighting factors be normalised ?

## Small signals
ISO8861-3-2/11-12 NO NO
MCH_SPEED 0.09
Y_SPEED extremum

## Format
OUTPUT_BSHAPE LISPLOT ; curve output format (LISPLOT, PARVIEW oder Hyp graph)

## Layout html-Report
PORT_HEIGHT 28 ; small font size in the html report

## Layout html-Report
PORT_FONT 28 ; large font size in the html report
Pref_LC/Post_LC -1 -1 ; enlargement of the shown time interval (-1: complete curve)

END GLOBAL_PARAMETERS

## LOADCASE

## LOADCASE

BEGIN LOADCASE
METHOD ISO18871
NAME LOADCASE Frontal 6G MAX
NAME LOADCASE Frontal 6G MAX
NAME LOADCASE Label Acceleration X
WEIGHT FACTOR OF THE LOADCASE

## Layout html-Report
PORT_HEIGHT 28
PORT_FONT X

## LOADCASE

## DATASETS
## Physical timeshift unit g

timecurve_F6_6G_MAX 0.0 ms-s-m-s NO

## Simulation

## Analysis

## Simulation

## Analysis

## Simulation

## Analysis

END DATASETS

## SIGNALS
##

## SIGNALS

## SIGNALS

## SIGNALS

END SIGNALS

END LOADCASE
```

167
END DATAPILES
BEGIN SIGNALS
$1=Name= WP  V_norm  t_min(NA)  t_max(NA)  g_1  g_2  g_3  g_4  a_0  b_0  a_7  a_8  a_9  b_9  D_min  D_max
SIGNALPROXY 1  x  0  500  x  x  x  x  x  x  x  x  x  x  x  x  x  x
END SIGNALS

END LOADCASE
$-------
BEGIN LOADCASE

METHOD  ISO18871  ; ISO18871
NUM_LC  Frontal 60_KMV  ; Loadcase_name
USE_LC  Upper Reck Moment  Y  ; Loadcase_description
WF LC  1  ; Weighting factor of the loadcase
##
## Layout html-report
P=WF_LC  x
Post_LC  x

BEGIN DATAPILES
## Physical  time-shift  unit  g
stresscurve_F60_KMV  0.0  mm-Ky-m  NO
## Simulation
##stresscurve_F60_KMV  0.0  mm-Ky-m  NO
END DATAPILES

BEGIN SIGNALS
$1=Name= WP  V_norm  t_min(NA)  t_max(NA)  g_1  g_2  g_3  g_4  a_0  b_0  a_7  a_8  a_9  b_9  D_min  D_max
SIGNALPROXY 1  x  0  500  x  x  x  x  x  x  x  x  x  x  x  x  x  x
END SIGNALS

END LOADCASE
$-------
Appendix I: CORAplus Output Units File, output_units.txt

# (ISO-Code); Unit; optional comment after #
00; 0 # Other dimension: not converted
AA; rad/(ms*ms) # Angle Acceleration, derived
AC; mm/(ms*ms) # Acceleration: derived or g = 9.81 m/s^2
AD; 0 # Auditory Damage Units
AH; rad # Angle: rad, grad or deg
AR; mm^2/mm # Area: not ISO conform, derived
AV; rad/ms # Angle Velocity, derived
CH; C # Charge: not converted
CU; A # Current: A, kA, mA
DB; dB # Decibel: dB
DC; mm # DISTANCE: km, m, cm, mm
DS; mm # Displacement: km, m, cm, mm
DV; mm # Displacement, integrated from Velocity: km, m, cm, mm
EN; J # Energy: mJ, J, kJ, MJ
EV; l # Event
FO; mN # Force: mN, N, KN
FR; l/ms # Frequency: Hz, kHz, MHz, GHz
HU; % # Humidity: %
IL; lx # Illuminance: not converted
IM; kg*mm/ns # Impulse
LE; mm # Lever Arm: mm, m
LF; lm # luminous flux: not converted
LI; cd # Luminous Intensity: not converted
LU; cd/(mm^2) # Luminance: not converted
MA; kg # Mass: kg, t, g, mg
MO; N*m # Moment
PO; W # Power: kW, W, kW
PR; Pa # Pressure: mPa, Pa, hPa, kPa, MPa
RE; V/A # Resistance, derived
SA; sr # Solid angle: not converted
SE; (Unit)/(Unit) # Sensitivity: not converted
SP; dB # Peak Sound Pressure Level: not converted
ST; mm/mm # Strain
TE; K # Temperature: C, K
TI; ms # Time: ms, s, min, h
VA; mm/ms # Velocity, Integr. from Acc., derived
VD; mm/ms # Velocity, Diff. from Displ., derived
VE; mm/mc # Velocity, derived
VO; V # Voltage: V, kV, mV
VU; mm*mm*mm # Volume: mm, cm, m, l, hl
Appendix J: Linux command lines to convert LS-PrePost xy-pairs to CORAplus-required format

```bash

sed -i -n -e '2,$p' usimcurve21_F16G_HAX usimcurve21_F16G_HAZ usimcurve21_F16G_RVY usimcurve21_F16G_NFX usimcurve21_F16G_NFZ usimcurve21_F16G_NMY ; sed -i '1i"XYDATA, S1HEAD0000HFACOP" usimcurve21_F16G_HAX usimcurve21_F16G_HAZ usimcurve21_F16G_RVY usimcurve21_F16G_NFX usimcurve21_F16G_NFZ usimcurve21_F16G_NMY ; sed -i '$a"ENDATA" usimcurve21_F16G_HAX usimcurve21_F16G_HAZ usimcurve21_F16G_RVY usimcurve21_F16G_NFX usimcurve21_F16G_NFZ usimcurve21_F16G_NMY

sed -i -n -e '2,$p' usimcurve21_L12G_HAY usimcurve21_L12G_HAZ usimcurve21_L12G_RVX usimcurve21_L12G_NFY usimcurve21_L12G_NFZ usimcurve21_L12G_NMX ; sed -i '1i"XYDATA, S1HEAD0000HFACOP" usimcurve21_L12G_HAY usimcurve21_L12G_HAZ usimcurve21_L12G_RVX usimcurve21_L12G_NFY usimcurve21_L12G_NFZ usimcurve21_L12G_NMX ; sed -i '$a"ENDATA" usimcurve21_L12G_HAY usimcurve21_L12G_HAZ usimcurve21_L12G_RVX usimcurve21_L12G_NFY usimcurve21_L12G_NFZ usimcurve21_L12G_NMX

```

**Appendix K: NASA Neck Sled Simulation Supplementary ISO18571 scores**

Table K-1. NASA Neck Sled Test 600ms ISO18571 scores, **NO Dynamic Relaxation: simcurve1**

<table>
<thead>
<tr>
<th>Case</th>
<th>Head Ax</th>
<th>Head Ay</th>
<th>Head Az</th>
<th>Head Rx</th>
<th>Head Ry</th>
<th>UneckFx</th>
<th>UneckFy</th>
<th>UneckFz</th>
<th>UneckMx</th>
<th>UneckMy</th>
<th>Nij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral 12 G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal 6G</td>
<td>0.779</td>
<td>0.436</td>
<td>0.752</td>
<td>0.750</td>
<td>0.225</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.836</td>
<td>0.630</td>
</tr>
<tr>
<td>Frontal 16G</td>
<td>0.799</td>
<td>0.489</td>
<td>0.792</td>
<td>0.754</td>
<td>0.434</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.816</td>
<td>0.681</td>
</tr>
<tr>
<td>Rearward 6G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.686</td>
</tr>
</tbody>
</table>

Table K-2. NASA Neck Sled Test 600ms ISO18571 scores with **Activated DR: simcurve1**

<table>
<thead>
<tr>
<th>Case</th>
<th>Head Ax</th>
<th>Head Ay</th>
<th>Head Az</th>
<th>Head Rx</th>
<th>Head Ry</th>
<th>UneckFx</th>
<th>UneckFy</th>
<th>UneckFz</th>
<th>UneckMx</th>
<th>UneckMy</th>
<th>Nij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral 12 G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.874</td>
<td>0.615</td>
<td>0.868</td>
<td>0.832</td>
<td>0.532</td>
<td>0.843</td>
</tr>
<tr>
<td>Frontal 6G</td>
<td>0.783</td>
<td>0.510</td>
<td>0.755</td>
<td>0.750</td>
<td>0.310</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.851</td>
</tr>
<tr>
<td>Frontal 16G</td>
<td>0.809</td>
<td>0.523</td>
<td>0.792</td>
<td>0.752</td>
<td>0.497</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.822</td>
</tr>
<tr>
<td>Rearward 6G</td>
<td>0.699</td>
<td>0.534</td>
<td>0.677</td>
<td>0.677</td>
<td>0.551</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.608</td>
</tr>
<tr>
<td>Average</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.686</td>
</tr>
</tbody>
</table>

Further Models have activated dynamic relaxation (DR) phase.

Table K-3. NASA Neck Sled Test 600ms ISO18571 scores: **usimcurve01, CFR calibrated**

<table>
<thead>
<tr>
<th>Case</th>
<th>Head Ax</th>
<th>Head Ay</th>
<th>Head Az</th>
<th>Head Rx</th>
<th>Head Ry</th>
<th>UneckFx</th>
<th>UneckFy</th>
<th>UneckFz</th>
<th>UneckMx</th>
<th>UneckMy</th>
<th>Nij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral 12 G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.837</td>
<td>0.677</td>
<td>0.335</td>
<td>0.810</td>
<td>0.580</td>
<td>0.795</td>
</tr>
<tr>
<td>Frontal 6G</td>
<td>0.727</td>
<td>0.450</td>
<td>0.703</td>
<td>0.750</td>
<td>0.315</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.792</td>
</tr>
<tr>
<td>Frontal 16G</td>
<td>0.715</td>
<td>0.529</td>
<td>0.689</td>
<td>0.761</td>
<td>0.547</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.716</td>
</tr>
<tr>
<td>Rearward 6G</td>
<td>0.587</td>
<td>0.50</td>
<td>0.449</td>
<td>0.608</td>
<td>0.514</td>
<td></td>
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</table>
Table K-4. NASA Neck Sled Test 600ms ISO18571 scores: usimcurve06

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<tr>
<th>Case</th>
<th>Head Ax</th>
<th>Head Ay</th>
<th>Head Az</th>
<th>Head Rx</th>
<th>Head Ry</th>
<th>Unneck Fx</th>
<th>Unneck Fy</th>
<th>Unneck Fz</th>
<th>Unneck Mx</th>
<th>Unneck My</th>
<th>Nij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral 12 G</td>
<td>0.874</td>
<td>0.634</td>
<td>0.833</td>
<td></td>
<td></td>
<td>0.861</td>
<td>0.540</td>
<td>0.856</td>
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<td>0.766</td>
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<tr>
<td>Frontal 6G</td>
<td>0.763</td>
<td>0.458</td>
<td>0.670</td>
<td>0.765</td>
<td></td>
<td>0.346</td>
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<td>0.823</td>
<td>0.637</td>
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<tr>
<td>Frontal 16G</td>
<td>0.824</td>
<td>0.552</td>
<td>0.936</td>
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<td>0.560</td>
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<td></td>
<td>0.853</td>
<td>0.764</td>
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<tr>
<td>Rearward 6G</td>
<td>0.567</td>
<td>0.515</td>
<td>0.517</td>
<td>0.562</td>
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</table>

Further Models have a CORAplus termination time of 300ms.

Table K-5. NASA Neck Sled Test 300ms ISO18571 scores: simcurve1

<table>
<thead>
<tr>
<th>Case</th>
<th>Head Ax</th>
<th>Head Ay</th>
<th>Head Az</th>
<th>Head Rx</th>
<th>Head Ry</th>
<th>Unneck Fx</th>
<th>Unneck Fy</th>
<th>Unneck Fz</th>
<th>Unneck Mx</th>
<th>Unneck My</th>
<th>Nij</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral 12 G</td>
<td>0.885</td>
<td>0.683</td>
<td>0.838</td>
<td></td>
<td></td>
<td>0.829</td>
<td>0.647</td>
<td>0.835</td>
<td></td>
<td></td>
<td>0.786</td>
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Table K-6. NASA Neck Sled Test 300ms ISO18571 scores: usimcurve01, CFR calibrated

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Table K-8. NASA Neck Sled Test 300ms ISO18571 scores: usimcurve08

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Table K-9. NASA Neck Sled Test 300ms ISO18571 scores: usimcurve12, CFR calibrated

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Table K-11. NASA Neck Sled Test 300ms ISO18571 scores: usimcurve16, CFR calibrated

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Table K-14. NASA Neck Sled Test 300ms ISO18571 scores: usimcurve21, CFR calibrated

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Table K-15. NASA Neck Sled Test 350ms ISO18571 scores: simcurve1

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### Table K-16. NASA Neck Sled Test 350ms ISO18571 scores: usimcurve19, CFR calibrated

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### Table K-17. NASA Neck Sled Test 350ms ISO18571 scores: usimcurve21

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### Table K-18. NASA Neck Sled Test 350ms ISO18571 scores: usimcurve27

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### Table K-19. NASA Neck Sled Test 350ms ISO18571 scores: usimcurve21

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### Table K-20. NASA Neck Sled Test 300ms ISO18571 scores: usimcurve30

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Appendix L: Usimcurve19 ISO18571 Frontal 6G CORAplus generated graphs

Figure L-1. Head x-acceleration

Figure L-2. Head z-acceleration

Figure L-3. Head y-Rotational Velocity

Figure L-4. Upper Neck x-Force

Figure L-5. Upper Neck z-Force

Figure L-6. Upper Neck y-Moment
Appendix M: Usimcurve19 ISO18571 Frontal 16G CORAplus generated graphs

Figure M-1. Head x-acceleration

Figure M-2. Head z-acceleration

Figure M-3. Head y-Rotational Velocity

Figure M-4. Upper Neck x-force

Figure M-5. Upper Neck z-force

Figure M-6. Upper Neck y-Moment
Appendix N: Usimcurve19 ISO18571 Lateral 12G CORAplus generated graphs

Figure N-1. Head y-acceleration

Figure N-2. Head z-acceleration

Figure N-3. Head x-Rotational Velocity

Figure N-4. Upper Neck y-Force

Figure N-5. Upper Neck z-Force

Figure N-6. Upper Neck x-Moment
Appendix O: Usimcurve19 ISO18571 Rearward 6G CORAplus generated graphs

Figure O-1. Head x-acceleration

Figure O-2. Head z-acceleration

Figure O-3. Head y-rotational velocity

Figure O-4. Upper Neck x-Force

Figure O-5. Upper Neck z-Force

Figure O-6. Upper Neck y-Moment