NHTSA'S THOR-NT DATABASE

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ABSTRACT

This paper provides a comprehensive overview of the many tests involving the THOR-NT advanced frontal impact dummy that are contained within the NHTSA test database. Since its release in 2005, NHTSA has collected data from over one hundred tests involving the THOR-NT. These include sled tests, vehicle tests, and component tests at different speeds and configurations. This paper serves as a reference for describing the various test series, which include those aimed at assessing biofidelity, evaluating instrumentation, and establishing qualification and injury criteria. This paper also provides analytical examples that demonstrate the utility of the database in studying dummy-related issues. New auxiliary tools, such as data processing software and computer models, are also described. Finally, this paper summarizes some of the lessons learned from this broad test experience, and documents actions that are being taken to enhance dummy performance and acceptance by the international community.

INTRODUCTION

The origins of the THOR-NT advanced frontal impact dummy may be traced to the 7th International ESV conference, when the National Highway Traffic Safety Administration (NHTSA) announced plans to develop an advanced crash test dummy with improved biofidelity under frontal impact conditions and with expanded injury assessment capabilities (Backaitis and Haffner, 1979).

During the ensuing years, the THOR-NT has gone through several stages of development, which are summarized in Figure 1. Significant milestones in this development process are described below.

Anthropometric definition. NHTSA commissioned a study of the anthropometry of human volunteers in a seated posture at the University of Michigan Transportation Research Institute (UMTRI). The resulting three volume report defined the coordinates of the skeletal landmarks for the seated position. Full-sized glass-epoxy reference surface shells (having since been digitally scanned) representing three occupant sizes were developed (Schneider et al, 1983; Schneider et al, 1988).

Concept definition study. Concurrent with the conclusion of the anthropometry study, NHTSA funded a concept definition study for an advanced frontal anthropomorphic test device (ATD). This study laid the foundation for the hardware development efforts to follow (Melvin et al, 1988). This effort encompassed injury assessment priority analysis, an extensive review of available biomechanical impact response and injury data relevant to the automotive environment, and preliminary development of desirable advanced ATD design characteristics and features.

Development of the TAD-50M ATD. The initial advanced ATD was developed by a NHTSA-sponsored consortium of universities and industrial partners working through the SAE Frontal Impact Dummy Enhancement Task Group (Schneider et al, 1992). This new "trauma assessment device" represented a 50th percentile male and was known as the TAD-50M. It consisted of a new torso to which stock Hybrid III arms, legs, head, neck, and a modified pelvis were attached to form a testable unit. Four TAD prototypes were produced.

Concurrent advanced neck and lower extremity development. At the same time as the TAD thorax was being developed, an advanced lower extremity (ALEX) and a new neck were under design. The ALEX eventually gave way to the THOR-Lx, which is capable of mounting to either the THOR-NT or the Hybrid III.

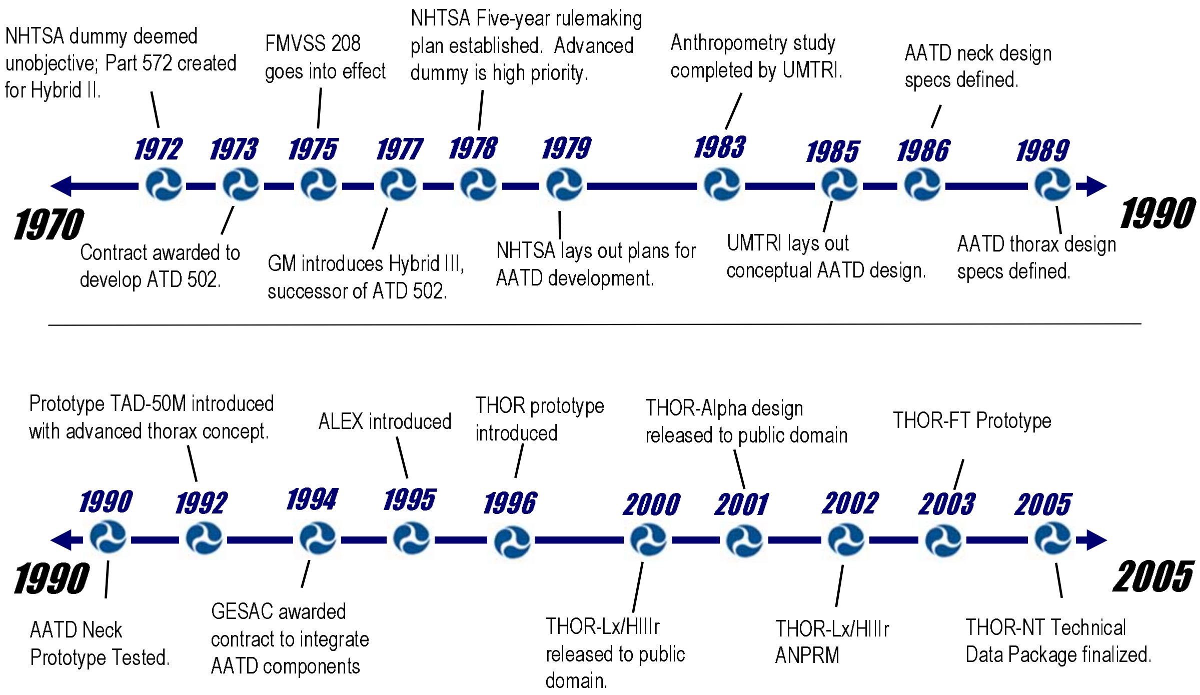

Figure 1. THOR-NT Development Chronology.

<u>THOR prototype: Integration of design concepts.</u> An effort to integrate the various ATD components began in 1994. Two years later, a prototype of the new dummy dubbed "THOR" was introduced. The principal features of the new crash dummy have been described by Rangarajan (1998).

<u>THOR Alpha release.</u> Modifications were incorporated into the design of the prototype THOR which resulted in the introduction of THOR Alpha in 2001. The modifications corrected for poor durability of flexible joints, noise in accelerometers, and problems in handling and storage. A description of the modifications is given by Haffner (2001).

<u>THOR-NT release.</u> An extensive set of modifications were made to the THOR Alpha during the development of the THOR-NT based on user comments and the need for improving the performance of the dummy. These updates are summarized by Shams (2005).

Since the release of the THOR-NT in 2005, NHTSA has tested the dummy in a variety of configurations. Herein is a summary of THOR-NT data that NHTSA has collected. Among the test series are those aimed at evaluating air bags, seat belt pretensioners, and rear seat restraints, one of the original purposes for the dummy.

OBJECTIVE

This paper describes a database encompassing all aspects of THOR-NT tests. The purpose of the database is to provide a configuration management system that will be useful to a broad range of individuals and their special interests.

<u>Biomechanics researchers.</u> The database contains an assembly of THOR-NT data under a variety of test conditions, many of which contain matching tests with post-mortem human subjects (PMHS). This data may be used to assess the biofidelity of the THOR-NT and to suggest injury assessment response values (IARV's).

<u>Vehicle safety researchers.</u> Vehicle crash tests with the THOR-NT provide insights into the measurement capabilities of the THOR-NT. For many test series, matching Hybrid III data provides a comparative benchmark that lends insights into the additional measurement capabilities of the THOR-NT. The database also contains tools such as finite element and multibody models of the dummy to assist in computational analyses of vehicle restraint systems.

<u>Lab Technicians.</u> The database includes information on qualification tests and procedures. The THOR-NT User's Manual describes dummy handling and set-up procedures. Signal processing software is also offered.

<u>ATD Manufacturers</u>. The technical data package contains Level III engineering drawings for the manufacture of the THOR-NT. Also included are maintenance and repair reports which provide insights into future opportunities to improve the durability of the dummy.

This paper describes the elements of the THOR-NT database. Two examples are given to demonstrate its applicability to the aforementioned interest groups.

TEST DATA

The test data may be grouped into three broad categories: sled/crash test data; biofidelity and component data; and qualification data. The data itself is often accompanied by a test report and digital images in the form of still photos (JPG's) and high-speed movies (AVI's) of the test. Each test dataset is described in more detail below, with indications of whether accompanying tests were run with other dummies, volunteers, or human surrogates.

Sled Test/Crash Test Data. These tests are usually performed to evaluate a safety system or a specific test configuration. They often include companion tests with post-mortem human subjects (PMHS) or the Hybrid III and other dummies (including the FT version of THOR developed by the European Union) in order to provide a baseline comparison responses. Table 1 lists the various series of sled/crash tests.

Component Data. Component tests include drop tests and pendulum impacts to body components of the dummy. In some instances, the test protocol requires the dummy to be partially disassembled. These tests are usually performed in order to assess the biofidelity of the dummy. Included among the component tests are abdomen tests, neck pull tests, and femur impact tests. Table 2 lists the various component test series. Multiple tests were run under each series of tests.

Table 1. THOR-NT Full-Dummy Vehicle and Sled Tests

Test Series Focus	Test Description	THOR-NT Tests	Match Tests	Test Lab	Publications
Air bag Evaluation: THOR-NT vs. HIII in OOP scenario	Static air bag deployments for drivers and passengers in OOP positions.	6	HIII	DCX	Kang, 2006
Vehicle Crashworthiness: IIHS full vehicle test	64 km/hr full vehicle IIHS-style test: SUV into an offset deformable barrier, 3-pt belt.	2	HIII	DCX	Ding, 2006
ATD Comparison: THOR-NT and HIII	48 km/hr sled tests; driver/passenger; frontal and frontal-oblique, 3-pt belt, no air bag.	12	HIII	DCX	Ding, 2006
Evaluation of crushable table: study of table-to-abdomen interaction	35 km/hr passenger train collision.	1	HIII	Fed. Railroad Admin	Parent, 2004
ATD Response Comparison: THOR-NT and HIII	40, 48, 56 km/hr frontal sled tests, driver/ passenger, air bag, 3-pt belt and unbelted.	18	HIII	Ford	
Pretensioner configurations	48 km/hr frontal sled tests, 3-pt belt, no air bag, various pretensioner locations.	10	HIII	Hyundai/UVA	Paek, 2006
ATD response comparison: THOR-NT, THOR-FT, HIII	56 km/hr Hyge frontal sled tests, belted driver w/ air bag, passenger without air bag.	5	HIII, THOR-FT	JARI	Onda, 2006
Biofidelity of neck in extension: THOR, HIII, BioRid, Rid-2 vs. Human	8 - 16 km/hr mini-sled, low speed Hyge rear impact tests.	11	HIII, THOR-FT	JARI	
Investigate influence of seating position on ATD response	56 km/hr frontal sled tests, driver, 3-pt belt and air bag.	4	---	JARI	
Air bag Evaluation: OOP behavior with fleet air bags	Static air bag deployments for five modules, OOP-1 position.	10	HIII	L-3/Jaycor	
ATD repeatability in OOP configuration	Repeatable ATS static air bag deployments, OOP-1, -2 positions.	24	HIII	L-3/Jaycor	Chan, 2004
Seats and restraint performance in far side crashes	Far side sled tests, passenger, various seat/restraint configurations.	6	PMHS, WorldSID	MCW	
Evaluation of rear seat restraints	48 km/hr Toyota Corolla frontal sled-mount compliance test, rear seat, 3-pt. belts.	2	HIII	TRC of Ohio	
Race car seat performance	200 km/hr NASCAR-style car impacting a SAFER barrier at 25 degrees.	2	HIII	Univ. of Nebraska	
THOR-NT shoulder design confirmation.	56 km/hr frontal sled testing, FL 3-pt belt, no air bag	8	---	UVa	
Biofidelity/Injury Criteria Development	48 km/hr frontal sled tests, passenger;, FL 3-pt belt, no air bag.	9	PMHS, HIII	UVa	
Thoracic response in low speed frontal crashes	29 km/hr frontal sled tests, passenger;, 3-pt belts.	3	PMHS, HIII	UVa	Forman, 2006

Table 2. THOR-NT Body Component Tests

Test Series Focus	Test Description	Matching Tests	Test Lab	Publications
Neck characterization: human vs. HIII and THOR	Bending and tension, quasi-static tests	HIII	Duke	Dibb, 2006 Stapp
Compare THOR-NT, THOR-FT, HIII	THOR neck, thorax, and abdomen qualification tests	HIII, THOR-FT	JARI	Onda, 2006 SAE
ATD Comparison in neck extension with BioRid, Rid-2	Strap pull (3 config); back impact and inertia	HIII, Volunteer	JARI	
THOR Design Check: Biomechanical Response Req.	Biomechanical response reqs: head, face, neck, thorax, upper and lower abdomen	---	JARI	
THOR-NT lower extremity biofidelity	Pendulum impacts to the femur, lower leg ankle, and foot	---	JARI	
Neck characterization: human vs. HIII and THOR	High-speed extension	PMHS, HIII	MCW	Pintar, 2005 Stapp
Biofidelity of the knee-thigh-hip region	Simulated knee bolster (pendulum) impact to knee.	PMHS, HIII	UMTRI	Rupp, 2003 ESV
ATD thorax coupling and muscle tensing effects.	Cavanaugh-style bench tests, Q-S Indenter	PHMS, HIII	UVA	Shaw, 2005 ESV
Head injuries sustained by football players	Impacts to head/neck - whole body tests	HIII	Va. Tech	

Qualification Data. Prior to each series of tests, the THOR-NT undergoes a complete inspection and a series of qualification tests to assure that it is performing within specifications and meets biofidelity requirements. Qualification follows procedures described in accordance with the THOR Certification Manual. The manual describes 16 qualification tests:

Thorax certification (4 tests): Kroell test of the thorax at two speeds; MCW oblique-type tests of the right and left lower thoracic cage.

Abdomen qualification (2 tests): Upper abdomen impact test; lower abdomen impact test.

Femur qualification (2 tests): Knee impact test on both legs.

Head qualification (2 tests): Head only (head removed from body) 49CFR, Part 572.32 drop test; full dummy head impact test.

Neck qualification (4 tests): Dynamic bending tests (lateral, extension, and flexion) with pendulum; quasi-static O-C joint response.

Face qualification (2 tests): Rigid rod impact; rigid disc impact.

Together with adherence to the engineering drawings, compliance with qualification test requirements serves to assure that the dummy is performing with known, repeatable and biomechanically correct responses. Qualification data is integral in the federalization process. This topic is discussed later in more detail.

OTHER THOR-NT MATERIALS

Aside from the test data itself, the database also contains other information described below.

Journal and Conference Papers. Literature references for the tests described in Tables 1 and 2 are provided. The full-length manuscripts of select papers that are not restricted by copyright concerns are available for download.

Technical Data Package (TDP). The TDP consists of over 500 AutoCAD files of the THOR-NT engineering drawings, and includes drawing specifications and a bill of materials for the dummy. A user's manual and separate manuals for the biofidelity and qualification requirements are also included.

Design reports. These include the full-length reports referenced previously, and more recent reports generated on the development of the THOR-NT.

User Tools. These include computer modeling and data processing software and manuals.

Inspection Reports**.** Each time a THOR-NT unit is returned to NTHSA by a test site, it undergoes a complete inspection. The results of these periodic inspections are documented in reports. These list any maintenance problems discovered during the inspection process and detail any repair procedures found to be necessary.

APPLICATIONS

Aside from the topics discussed within the individual papers that have resulted from a particular series of tests, the database as a whole may be used to investigate many other dummy-related issues.

Two examples are provided below that demonstrate how the THOR-NT database may provide insights into: (1) thorax deflections and (2) ATD neck loads. These examples are only meant to provide a demonstration of the richness of the THOR-NT database by conducting an exploratory analysis of a few dummy-related issues. A much more exhaustive study – one that is beyond the scope of this paper – is needed to fully investigate these two examples.

Example 1. Thorax deflections. An advantage of the THOR-NT dummy is its ability to measure thorax deflections along three (x,y,z) directions at four distinct points on the ribcage: two in the upper thorax (right and left), two in the lower thorax (right and left). The database may be parsed to demonstrate how the deflections vary from location to location depending on the restraint condition and test configuration. This distinction cannot be made with the Hybrid III dummy, which measures chest deflection at a single point (mid-sternum) in the x-direction only.

As examples, four series of tests run under very different conditions were selected for consideration. The first test used for the thorax deflection comparison was from Jaycor's 24-test out-of-position (OOP) repeatability test series referenced in Table 1 and described in Chan, 2004. In this test, the THOR dummy was placed against the air bag in an ISO-1 OOP position as shown in Fig. 2. The air bag used for the test was from a 1992 Honda Accord. With the dummy's head resting on the steering wheel, compressed air was used to rapidly inflate the air bag.

The second test comes from the series of frontal sled tests run by Ford Motor Company to assess dummy behavior under compliance and NCAP test scenarios. For the test selected, the THOR dummy was positioned in the driver's seat. The only restraint was the driver's side air bag (see Fig. 3). The nominal velocity of the test was 40 km/hr.

The third test was a frontal sled test run at the University of Virginia to evaluate biofidelity. Here, the THOR dummy was placed on the passenger side. It was restrained with a three-point belt that had a 4kN force limiter (see Fig. 4). No air bag was present in this case. The sled nominal velocity was 56 km/hr.

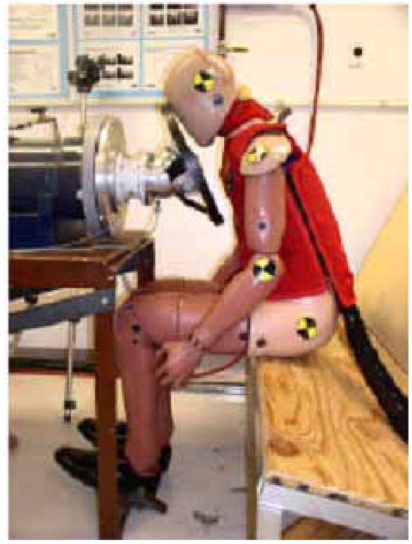

Figure 2. Jaycor OOP repeatability test configuration.

Figure 3. Ford 40 km/hr sled test configuration.

Figure 4. UVA 56 km/hr sled test configuration

Figure 5. Top: THOR-NT positioned in a NASCAR seat with a 6-point harness. Bottom: NASCAR barrier test configuration. Nominal vehicle speed: 200 km/hr.

The fourth test was an oblique impact of a vehicle into a deformable barrier. This test was performed by the University of Nebraska for NASCAR (see Fig. 5). The THOR dummy was restrained by a six-point harness and a HANS head and neck restraint. The nominal velocity was 200 km/hr at a wall impact angle of 25 degrees.

Figure 6 shows overlays of deflections in the (x, y) directions for all four tests. (Note: significant deflections in the z-direction were also evident but are not shown herein). Thorax displacement patterns are seen to vary greatly depending on the test configuration. In the OOP tests, the dummy is placed forward, resting against the air bag. This correlates to most of the displacement (~35 mm) occurring in the – x-direction (inward) of both the upper right and upper left thorax and relatively little in the lower two quadrants.

In the Ford test, the dummy is in a typical seated position, being restrained only with the air bag. Thus, the majority of the displacement is in both the upper right and upper left quadrants. Again, this is a compression in the –x-direction of about 30-35 mm. The difference in this case is that there is also some lateral movement of the upper chest to the right (+y-direction). There is also about ~10mm of compression of the lower right thorax and a slight shift to the right.

The UVA test configuration shows how a shoulder belt affects the deflection pattern. Here, there is moderate deflection in the –x-direction of ~15-20 mm of the upper right and upper left chest. The most deflection for this configuration is seen in the compression of the lower left quadrant (30mm) due to the seat belt. In addition, the lower right quadrant is seen to bulge outward in reaction to the compression of the lower left chest.

Lastly, the NASCAR test configuration shows how the deflection patterns change for an oblique side impact test configuration. In this case, the majority of the deflection is seen in the y-direction, with very little displacement in the x-direction. Here, the lower chest is primarily being compressed laterally, with the upper left and lower left quadrants showing deflections toward the right.

These four tests demonstrate the variation of thorax deflection patterns arising from different crash configurations. The THOR-NT – with its ability to measure (x,y,z) deflections at multiple locations – may be used to study restraint-specific thorax injury potential.

<u>Example 2. ATD neck loads</u>. The European Enhanced Vehicle-Safety Committee (EEVC) has issued a report on recommendations on the future of the THOR (EEVC 2006). The EEVC report includes a remark that the THOR-NT neck loads borne by the cable elements are unreliable due to improper instrumentation and friction problems. The underlying assumption of this remark is that the forces generated by the cable elements are needed to assess injury risk.

Neck tolerance depends upon the loads borne by both the ligamentous spine and the neck muscles (Chancey et al. 2003). In most dummies (including the Hybrid III) the upper head/neck load cell is installed in the head above the OC pin joint and measures all the loads which pass from the neck to the head (i.e., the "cross-sectional" neck loads). The THOR-NT incorporates a construction in which the neck column represents the load path for the osteoligamentous structures and the two cables represent load paths for external musculature. Therefore , only the loads

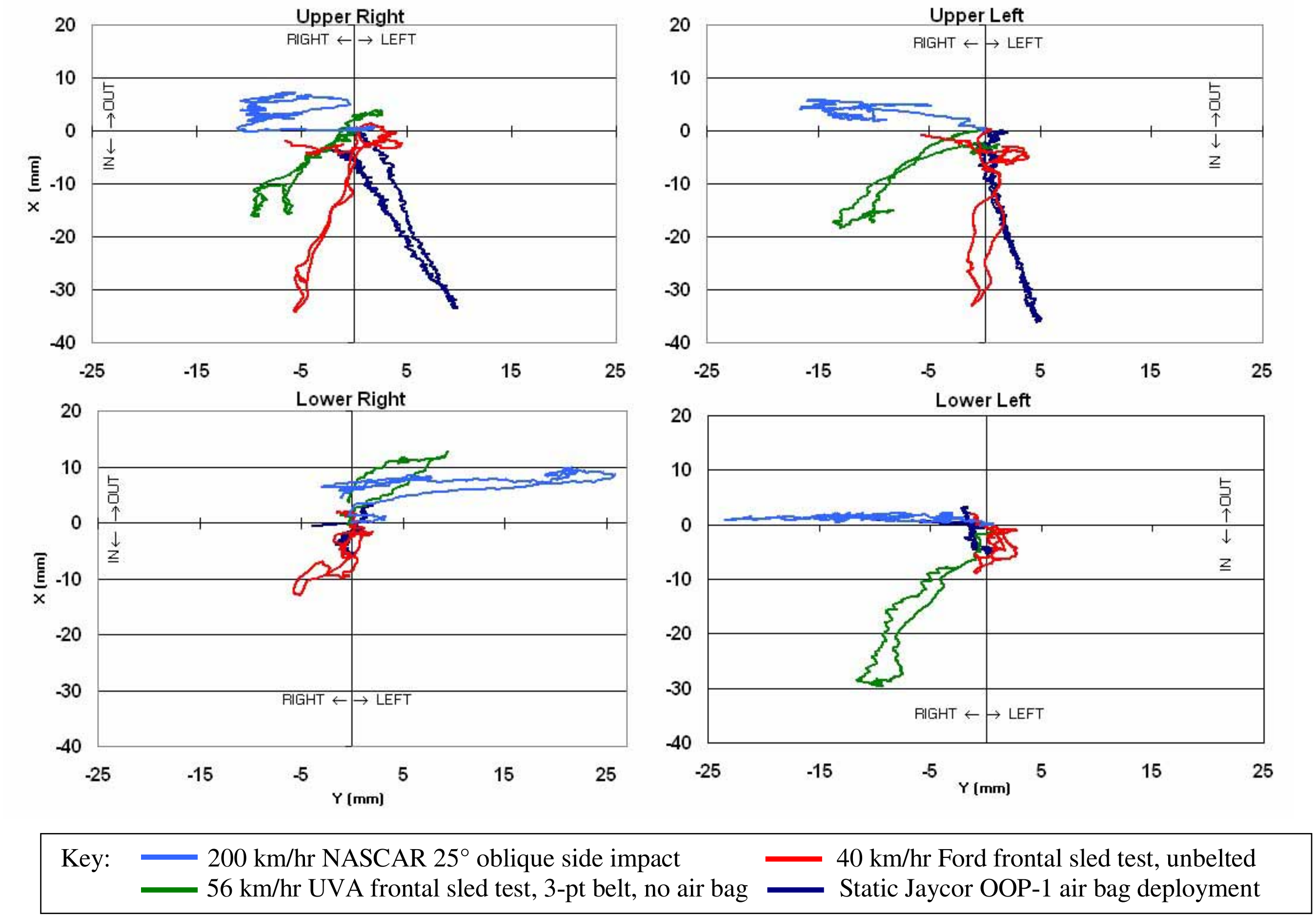

Figure 6. Comparison of (x,y) thorax deflections at the four THOR-NT thorax deflection sites.

measured in the upper neck load cell – which is placed on top of the neck column but below the head – represent injurious loads. The loads borne by the cables are not used to assess injury risk.

Nonetheless, the database may be parsed for evidence of problems related to the THOR-NT neck design. For this, the Jaycor OOP test series may again be examined for dummy neck repeatability. The test series included six repeat tests for both the Hybrid III and the THOR-NT. Figure 7 shows neck tensions measured by the upper neck load cells of both dummies. The THOR-NT shows slightly more variability but it is likely within an acceptable range (i.e., the standard deviation is within 10% of the mean). The source of the variability – whether from seating procedure, the air bag, or the dummy itself – may warrant further investigation.

In Figure 8, the THOR-NT "columnar" neck tension (representing osteoligamentous loads passing through the upper neck load cell only) and the "cross-sectional" neck tension (where the contributions of the cable elements are included) are shown for one of the six tests. The cables are demonstrated to transfer load around the neck column in a fashion analogous to the way muscles transfer load around occipital condyles in a human neck.

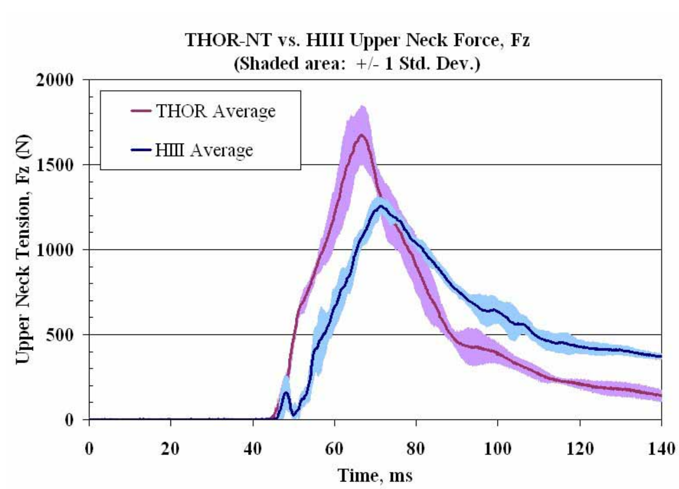

Figure 7. Neck tension repeatability in Jaycor tests

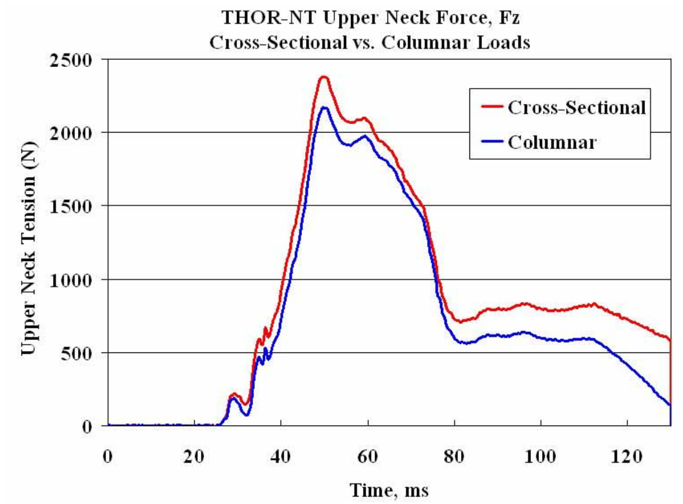

Figure 8. Neck tension: cross-sectional vs. column loads in a Jaycor OOP-1 repeatability test.

DISCUSSION

The two examples given above demonstrate how the THOR-NT database as a whole may be used to investigate safety systems and provide insights into specific dummy-related problems. For instance, the variability seen in the OOP example may lead investigators to employ a more precise THOR-NT positioning procedure than what is currently used for the Hybrid III.

Overall, the test experiences have provided NHTSA with a rich knowledge base of the capabilities and shortcomings of the THOR-NT. The benefits from these lessons learned have evoked a string of efforts to improve usability features in the form of diagnostic equipment, data processing tools, and computer models. Work on these efforts, as well as efforts to federalize the dummy, are summarized below.

Federalization. A candidate anthropometric test device (ATD), or crash test dummy, must undergo a rigorous evaluation and documentation process before it can be considered for incorporation into Part 572 of the Code of Federal Regulations. This process has been developed over many years and includes a thorough dummy and drawing inspection, establishment of dummy qualification criteria, and an evaluation of the dummy's durability, biofidelity, repeatability, and reproducibility (Rhule et al, 2005).

Engineering Drawings. The THOR-NT technical data package includes engineering drawings defining the physical dimensions of the dummy assembly, all subassemblies, and detailed drawings of all of the parts. The weight and center of gravity (CG) of the dummy component segments are also specified in the drawing package.

NHTSA has completed the inspection of the THOR-NT manufactured by GESAC, Inc. Physical dimensions of each part of the disassembled dummy were measured and compared to the drawing package and any discrepancies were noted. Most discrepancies were simple mistakes in a drawing and easily corrected. A few modifications to the physical hardware were required, though none of these modifications significantly affected dummy response or biofidelity. Drawing revisions have been made to account for the discrepancies.

Solid Models. NHTSA has also begun efforts to acquire feature-rich solid models of all THOR-NT parts to include as part of the technical data package. This will aid tremendously in better specifying the design, manufacture, and inspection of the dummy, and could be used to more easily incorporate design modifications as well.

Dummy Qualification. For future federalization purposes, the qualification data may be used to establish upper and lower measurement targets for qualification test corridors. Peak measurements are typically used as a qualification criteria, and historically, NHTSA has used a standard deviation that is less than 10% of the mean (Rhule et al, 2005).

The THOR-NT qualification test corridors that are now used as the basis of acceptability are fairly arbitrary. In the absence of repetitive test data, they have been set to correspond with similar corridors established for the Hybrid III and with human biofidelity corridors. Most qualification tests have been run at a single laboratory (GESAC, Inc.). Over time, the body of qualification results will grow as more dummies are put into use (currently NHTSA has four THOR-NT units) as more labs acquire the capability to run THOR-specific qualification tests. This will allow a re-examination of the corridors to ascertain the proper acceptability range.

Durability. The body of data contains numerous tests from which the durability of the THOR-NT may be inferred. These tests, however, were not generally run to ascertain durability in the context of a federalization process. For example, the NASCAR tests gave NHTSA the opportunity to observe the THOR-NT in a very severe crash in which human kinematics are fairly well known. Additional high-energy component tests and full-body sled tests shall be run by NHTSA to examine the durability of the dummy.

THOR software GUI. One of the challenges associated with the THOR-NT is interpretation of the instrumentation used to determine chest deflection. These instruments, referred to as CRUX's (compact rotary units), are two-bar linkages with three degrees of freedom that measure rotation in degrees. After a test, three rotary CRUX potentiometers are combined in a post-processing routine to compute (x,y,z) deflection measurements in millimeters. In order to compute the deflections, several prescribed steps must be followed. Due to extenuating circumstances, these steps are not always straight-forward, at times making the processing of CRUX data problematic.

To facilitate the processing of CRUX angles into millimeters of deflection, NHTSA is developing a graphical user's interface (GUI) for the CRUX processing software. Aside from aiding in data processing, the more important function of the GUI is to serve as a check to assure that the user has collected the raw data properly and that the correct input information is being used.

Computer Models. NHTSA has completed two LS-Dyna finite element (FE) models of THOR-NT subcomponents: one that represents the thorax and another to represent the lower extremity. NHTSA has also developed a data set that characterizes the THOR-NT and is suitable for use with the Articulated Total Body (ATB) simulation program .

The FE work has generated a realistic geometric and material representation of the dummy with many deformable parts. The ATB work has generated a database of inertial and geometric properties (segment mass, centers of gravity, moments of inertia), joint characteristics (location, type, stiffness) and force-deflection functions for the soft, deformable parts. This data set also serves as a building block for a future MADYMO model of the THOR-NT

CONCLUSIONS

Since the release of the THOR-NT in 2005, NHTSA has collected valuable data from over one hundred tests at various test speeds and configurations, including sled tests, vehicle tests, and THOR component tests. This paper highlights the availability of this data for use in future dummy-related assessments.

Analyses of the THOR-NT data are given that demonstrate its utility in investigating occupant safety systems and dummy-related issues. Two examples are provided herein that demonstrate the utility of the THOR-NT database in exploring dummy-related issues. The examples provide only a cursory look at these topics for the sake of demonstration, not to derive final conclusions on the issues.

Lastly, this paper summarizes lessons learned from this broad test experience, and documents actions that are being taken to enhance dummy performance and acceptance of the THOR-NT by the international community. This represents a significant step forward in demonstrating that the dummy is suitable for use in standardized tests, such as those commissioned by European Union research committees and auto racing sanctioning bodies.

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