Advanced Crash Test Dummy Research
Why Advanced Crash Test Dummies?

• **Field Data**: Significant number of injuries/fatalities still occur despite current regulations/consumer metric programs

• **How to address?**
  1. **Crash Tests**: Evaluate test conditions not currently in regulation/consumer metric programs that are prevalent in the field data
  2. **Dummies**: Develop/document new ATDs that are more human-like and have enhanced instrumentation
  3. **Injury Criteria**: Given 1 and/or 2, develop and apply new injury measures that could be used to design improved safety countermeasures
1. Thor 50th Male – Extended Overview
2. Thor 5th Female
3. LODC 10 year old
4. WorldSID 50th Male
5. WorldSID 5th Female
6. BioRID
THOR-50M

Dan Parent
THOR-50M Overview

• THOR = Test Device for Human Occupant Restraint
  • Anthropomorphic Test Device (ATD)
  • 50th percentile male (“THOR-50M”)
• Provides improvements over the Hybrid III 50th percentile male ATD
  • More biofidelic (human-like)
  • Enhanced instrumentation
  • Increased injury prediction capability
• Used in NHTSA research projects dating back to 1999
  • ~175 tests in Vehicle Database
  • ~1400 tests in Biomechanics Database
• Funded by NHTSA throughout development
# THOR-50M Documentation

<table>
<thead>
<tr>
<th>Title</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawing Package</td>
<td>Engineering drawings describing detailed design, 2D and 3D database</td>
</tr>
<tr>
<td>Qualification</td>
<td>Procedures and response specifications in component and fully body impact tests</td>
</tr>
<tr>
<td>Durability</td>
<td>Elevated-energy qualification tests to ensure sufficient durability in repeated use</td>
</tr>
<tr>
<td>R&amp;R (THOR Qualification)</td>
<td>Repeated qualification tests to evaluate repeatability and reproducibility of results</td>
</tr>
<tr>
<td>R&amp;R (Oblique w/ THOR)</td>
<td>Repeated Oblique crash tests to ensure repeatability and reproducibility of crash test results</td>
</tr>
<tr>
<td>Biofidelity</td>
<td>Quantitative biofidelity assessment and comparison to Hybrid III</td>
</tr>
<tr>
<td>PADI</td>
<td>Procedures for assembly, disassembly, inspection; serves as user’s manual for a dummy</td>
</tr>
<tr>
<td>Seating Procedure</td>
<td>Step-by-step positioning procedure in the driver or right front passenger seat for a crash test</td>
</tr>
<tr>
<td>Injury Criteria</td>
<td>Describes development of injury risk functions and their application to THOR</td>
</tr>
</tbody>
</table>

THOR-50M Drawing Package

• August 2018 version
  • 2D Drawings: PDF, AutoCAD
  • 3D Parametric Database: Autodesk Inventor, STEP
  • Drawing revisions since August 2016 release
  • Parts list

• Updates since August 2016 release
  • External dimensions (per procedure in PADI)
  • Body segment mass & C.G. location
  • Design updates to improve usability, durability, accuracy
  • Drawing updates to improve manufacturability
THOR-50M Qualification Manual

• September 2018 version
  • Step-by-step procedures for qualification testing
  • Performance specifications
    • At least one specification for each measurement used in Injury Criteria
  • Includes comparison to August 2016 specifications

• Updates since August 2016 release
  • Standardized specification corridor width (±10%)
  • Ensure that face response meets biofidelity corridor
  • Reduced total number of specifications
    • Removed redundant measurements in neck tests
    • Use peak resultant deflection in thorax tests
THOR-50M Durability

- Durability in Qualification Procedures
  - 5 tests in each qualification test mode
    1) Baseline level
    2) +10% Energy
    3) +20% Energy
    4) +30% Energy
    5) Baseline level
- NHTSA BioDB (TSTNOs 12085-12159)

- Durability in Crash Tests
  - 150+ vehicle crash tests
  - 300+ sled tests
  - 1000+ component tests
THOR-50M R&R (Qualification)

• Repeatability
  • Similarity of responses from repeated tests on same THOR

• Reproducibility
  • Similarity of responses from different THORs
  • Similarity of responses from the same THOR at different labs

• Quantify results using Coefficient of Variation
  \[ CV = \frac{\sigma}{\mu} \times 100\% \]

• Results used to define qualification specifications

• NHTSA BioDB (TSTNOs 12285-12794)

\[ \text{Tests per ATD} \times \text{ATDs} \times \text{Test Modes} = \text{Qualification Tests} \]

\[ 5 \times 3 \times 24 = 600 \]

\[ 1 \times 5 \times 5 = 25 \]

\[ 5 \times 3 \times 24 = 360 \]

\[ 5 \times 1 \times 2 = 10 \]

\[ 600 \]

\[ 24 \times 5 \times 5 \]
THOR-50M R&R (Oblique w/ THOR)

- **Repeatability**
  - Similarity of responses from repeated tests on same vehicle and same THOR

- **Reproducibility**
  - Similarity of responses from repeated tests on same vehicle and same THOR at different lab

- **Result**
  - R&R metrics same or better than frontal rigid barrier test mode with Hybrid III 50th
  - Recommended improvements to seating procedure

- **Source**
  - Saunders et al., “Repeatability and Reproducibility of Oblique Moving Deformable Barrier Test Procedure,” 2018 SAE World Congress
  - NHTSA VehDB (see paper for TSTNOs)
THOR-50M Biofidelity

- **Biofidelity**
  - Describes the similarity of a surrogate (ATD, human body model) to a human
  - Response corridors are developed from post-mortem human surrogates (PMHS, or cadaver)
  - Surrogate response compared to corridor, quantified using BioRank
  - THOR-50M demonstrates improved biofidelity compared to Hybrid III 50th

- **Source**
  - Data in NHTSA BioDB (see paper for TSTNOs)

<table>
<thead>
<tr>
<th>Body Region</th>
<th>THOR-50M</th>
<th>H3-50M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Excellent</td>
<td>Poor</td>
</tr>
<tr>
<td>Neck</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Thorax</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Marginal</td>
<td>Marginal</td>
</tr>
<tr>
<td>Knee/Thigh/Hip</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Lower Extremity</td>
<td>Good</td>
<td>N/A</td>
</tr>
<tr>
<td>Whole-body</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>
THOR-50M PADI

- Procedures for Assembly, Disassembly, and Inspection
- Also describes
  - Handling and storage
  - H-point tool assembly and use
  - Posture adjustments
  - Instrumentation cable routing and grounding
  - Instrumentation polarity check
  - Thorax/abdomen instrumentation calibration and post-processing
  - External dimension measurement procedure
THOR-50M Seating Procedure

• Describes procedure for positioning THOR-50M in vehicle for crash testing
  • Driver
  • Right Front Passenger

• Changes from previous publication ([NHTSA-2015-0119-0009, NHTSA-2015-0119-0022](https://rosap.ntl.bts.gov/view/dot/40786))
  • Driver heel point accounts for both suspended and floor-mounted accelerator pedals
  • Wider tolerances on H-point target location
  • Additional seat position fore/aft adjustment to avoid leg contact
  • Head angle about the Y-axis set to 0 degrees (± 1 degree), but may deviate after all other steps are conducted

• Published in NTL ([https://rosap.ntl.bts.gov/view/dot/40786](https://rosap.ntl.bts.gov/view/dot/40786))
THOR-50M Injury Criteria

- For each body region:
  - Field and Historical Fleet Data
  - Literature Review
  - Design & Instrumentation
  - Biofidelity
  - Review of Available Data
  - Injury Risk Function Formulation
  - Application of Risk Function to THOR-50M
  - Fleet Test Data
  - Limitations

- Peer-reviewed
  - Reviewer comments and responses to be published
THOR-50M Finite Element Model

• Allows virtual crash tests, parametric analyses
• Developed by NHTSA with support from academic and industry partners
• Recent updates carried out under contract with University of Virginia Center for Applied Biomechanics
  • Updated to meet drawing package, qualification specifications
  • Experimental characterization of neck, thorax
  • Key improvements to torso, pelvis flesh, molded shoes
  • New jacket model to improve robustness
  • Stability checks in increased-energy simulations
  • Decreased simulation times by ~75%

THOR-50M FE Model Version 2.7
THOR-50M Alternate Configurations – Shoulder

• Contract awarded to TRC
  • Design, build, and evaluate two shoulder prototypes
• Evaluate alternate design vs. baseline
  • Quasi-static rotation
  • Fit check in THOR-50M
  • Quasi-static biofidelity (Tornvall et al., 2005)
  • Qualification test (upper thorax)
• Selected one design to move forward
• Next steps
  • Evaluation in sled and/or vehicle testing
  • Complete drawings/specifications
THOR-50M Alternate Configurations – In-dummy DAS

- Contract awarded to DTS
  - Design and install in-dummy data acquisition system (DAS) in THOR-50M
- Evaluate alternate design vs. baseline (umbilical)
  - Compare mass and C.G. locations of body segments
  - Fit check in THOR-50M
  - Compare full set of qualification tests
- Next steps
  - Compare vehicle crash test results
THOR-50M Alternate Configurations – IR-TRACC

• Contract awarded to ATD-LabTech
  • Commercially-available thoracic and abdominal 3D deflection instrumentation
• Evaluate alternate design vs. baseline
  • Calibration
  • Fit check in THOR-50M
  • Qualification tests
  • Sled tests (near-side frontal oblique)
• Next steps
  • Develop framework for evaluating alternate designs
Use in NHTSA Research Projects

8 THOR-50M ATDs owned by NHTSA
164 Vehicle Crash Tests
348 Crash Simulation Sled Tests
1013 Dynamic Component Tests
THOR 50th Questions?
THOR 5\textsuperscript{th} Percentile
Female ATD

Ellen Lee
THOR-05F: 5th Percentile Female ATD

- Incorporates key improvements from THOR-50M
- Human-like characteristics that mimics human seat belt interaction
- Designed to match small female-specific anthropometry and mass properties
- State-of-the-art measurement capabilities, including built-in capacity for on-board DAS
- Improved injury prediction capabilities, e.g. abdominal pressure sensors
Female-specific Design and Data Collection

- Sled tests in multiple configurations using small female specimens, targeting female-specific thoracic injury criterion development
- Abdomen injury data collected on small female specimens
- Pelvis geometry derived from female data
- Existing female cervical spine data considered as part of injury criterion development
- Existing female knee-thigh-hip data considered as part of injury criterion development
- Small female data collected for heel impact, ankle dorsiflexion and ankle inversion/eversion
THOR-05F Biofidelity

• Biofidelity
  • Describes the similarity of a surrogate (ATD, human body model) to a human
  • Response corridors are developed from post-mortem human surrogates (PMHS, or cadaver)
  • Surrogate response compared to corridor, quantified using BioRank

<table>
<thead>
<tr>
<th>Body Region</th>
<th>Biofidelity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Good</td>
</tr>
<tr>
<td>Neck</td>
<td>Marginal</td>
</tr>
<tr>
<td>Shoulder</td>
<td>Excellent</td>
</tr>
<tr>
<td>Thorax</td>
<td>Good</td>
</tr>
<tr>
<td>Abdomen</td>
<td>Marginal</td>
</tr>
<tr>
<td>Knee-Thigh-Hip</td>
<td>Good</td>
</tr>
<tr>
<td>Lower Extremity</td>
<td>Good</td>
</tr>
<tr>
<td>Overall</td>
<td>Good</td>
</tr>
</tbody>
</table>
Current Research

- Evaluating 3 prototype ATDs
  - Repeatability, durability
  - Sled testing in rear and front seat configurations
- Developing Injury Risk Curves
  - Collecting biomechanical data (PMHS) and conducting matched pair ATD tests
- Developing technical reports & documentation:

<table>
<thead>
<tr>
<th>Biofidelity Requirements Manual</th>
<th>R&amp;R and Durability Reports</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofidelity Report</td>
<td>PADI</td>
</tr>
<tr>
<td>Drawing Package</td>
<td>Injury Criteria Report</td>
</tr>
</tbody>
</table>

For more information, see Docket ID NHTSA-2019-0107 NHTSA Crashworthiness Research – THOR-05F Documentation
Large Omnidirectional Child (LODC) ATD

Jason Stammen, Ph.D.
Anthropometry matches actual seated child data
Source: Reed (UMTRI)

Head has inertial/mass properties matching pediatric data
Source: Loyd (Duke)

Shoulders and thorax reflect pediatric anatomy and mimic pediatric response
Sources: Kent/Parent (UVA), Maltese (CHOP), Agnew/Bolte (OSU)

Biofidelic, instrumented abdomen to measure belt-induced loading
Sources: Kent (UVA), Beillas (IFSTTAR), Ramachandra (OSU), Hardy (Wayne State)

Neck can elongate and allows for free Z axis rotation; response matching pediatric data
Sources: Dibb/Luck/Myers (Duke), Thunnissen 1995

Flexible cervicothoracic & thoracic spine for more biofidelic head trajectory and neck loads
Sources: Kang (OSU), Lopez-Valdes/Ash (UVA), Arbogast (CHOP), Pintar/Yoganandan (MCW)
2005 - 2009: Testing of Hybrid III 10YO establishes the need for improvements in biofidelity; pediatric biomechanical studies

Stammen et al. (2012) ABME

FIGURE 11. Applied chin force correlates strongly to the HIC outcome in sled testing (data from Stammen and Sullivan¹⁷).
2005 - 2009: Testing of Hybrid III 10YO establishes the need for improvements in biofidelity; pediatric biomechanical studies

Stammen et al. (2012)

ABME

2010 – 2012: Design and construction of initial LODC prototype thorax; NHTSA decides to leave HIC requirement out of FMVSS 213 due to issues with Hybrid III 10YO chin-chest

Stammen et al. (2014) Advances in Child Injury Prevention
2005 - 2009: Testing of Hybrid III 10YO establishes the need for improvements in biofidelity; pediatric biomechanical studies

2010 – 2012: Design and construction of initial LODC prototype thorax; NHTSA decides to leave HIC requirement out of FMVSS 213 due to Hybrid III 10YO chin-chest issues

2013 - 2014: Initiate internal dummy prototyping effort using lessons learned from Hybrid III 10YO testing; build first in-house prototype for evaluation
2005 - 2009: Testing of Hybrid III 10YO establishes the need for improvements in biofidelity; pediatric biomechanical studies

2010 – 2012: Design and construction of initial LODC prototype thorax; NHTSA decides to leave HIC requirement out of FMVSS 213 due to issues with Hybrid III 10YO chin-

2013 - 2014: Initiate internal dummy prototyping effort using lessons learned from Hybrid III 10YO testing; build first in-house prototype

2015 - 2017: Establish that the LODC has improved biofidelity over HIII-10YO, is durable, and is repeatable tool

<table>
<thead>
<tr>
<th>Body Region</th>
<th>LODC</th>
<th>HIII-10C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>0.79</td>
<td>1.81</td>
</tr>
<tr>
<td>Neck</td>
<td>1.37</td>
<td>2.73</td>
</tr>
<tr>
<td>Thoracic Spine</td>
<td>1.35</td>
<td>1.83</td>
</tr>
<tr>
<td>Thorax</td>
<td>0.79</td>
<td>5.50</td>
</tr>
<tr>
<td>Abdomen</td>
<td>0.78</td>
<td>1.61</td>
</tr>
<tr>
<td>OVERALL ATD</td>
<td>1.02</td>
<td>2.70</td>
</tr>
</tbody>
</table>

Stammen et al. (2016) Stapp
2005 - 2009: Testing of Hybrid III 10YO establishes the need for improvements in biofidelity; pediatric biomechanical studies require improvements.

2010 – 2012: Design and construction of initial LODC prototype thorax; NHTSA decides to leave HIC requirement out of FMVSS 213 due to Hybrid III 10YO chin to chest issues.

2013 - 2014: Initiate internal dummy prototyping effort using lessons learned from Hybrid III 10YO testing.

2015 - 2017: Establish that the LODC has improved biofidelity over H3-10YO, is durable, and repeatable.

2018 – Present: Evaluate upgraded LODC’s both internally and externally.

<table>
<thead>
<tr>
<th>Body Region</th>
<th>LODC</th>
<th>H3-10YO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>0.79</td>
<td>1.81</td>
</tr>
<tr>
<td>Neck</td>
<td>1.37</td>
<td>2.73</td>
</tr>
</tbody>
</table>

From: Seacrist et al. (2019) | Stapp
Suntay et al. (2019) DOT HS
Recent Upgrades
Recent Work

- Usability improvements with slight improvement in biofidelity
- Evaluated R&R
- Shoulder/thorax biofidelity improved by including additional biofidelity test condition

Recent Work

- Feasible to use ATD in non-frontal conditions
- Tested in vehicle rear seat, aircraft seat, lateral, oblique, and rear impact

Recent Work

- Upper arm/shoulder and belt engagement improved; prevent artificial belt folding
Current Activities
Current Activities

- Developing new chest deflection system
- Can be used instead of or in tandem with IR-TRACC
- More details at SAE Government/Industry
Current Activities

• Developing FE model
• Meshing almost complete
• Material property analysis & experimental validation underway
Current Activities

- Initiating a study at Ohio State to evaluate the frontal shoulder range of motion & stiffness in pediatric volunteers
- Trial testing with LODC to refine experimental details
- Volunteer testing starting in 2020
- Real-time biofidelity assessment of LODC
Current Activities

- Leveraging pediatric biomechanical data, developmental transfer functions, CIREN cases, NTDB injury data, and ATD tests to derive injury risk functions
- Initial focus is on abdomen – thorax, head, and spine to follow
Current Activities

- Generating documentation needed for Part 572: drawing package, parts list, user’s manual, and qualification procedures
- Open source ATD: will include material properties, tooling, and other manufacturing details
Summary

- NHTSA initiated work on the LODC to address limitations with Hybrid III 10YO
- Recent pediatric biomechanical research has provided the data needed to make the LODC biofidelic
- Recent work has focused on improving repeatability, usability, and widening its application bandwidth
- Current activities are focused on completing the LODC design, building a computational model, injury risk functions, and Part 572 documentation

For more information, see Docket ID NHTSA-2019-0110 NHTSA Crashworthiness Research – LODC Documentation

https://rosap.ntl.bts.gov/view/dot/41843
WorldSID 50th Percentile Male ATD

Kevin Moorhouse, Ph.D.
WSID-50M: 50\textsuperscript{th} Percentile Male ATD

- Features include: six independent ribs tuned for humanlike response, RibEye measurement system capable of measuring lateral and oblique rib displacements, and on-board DAS
- Anthropometry derived from UMTRI AMVO data set
- Biofidelity quantitatively evaluated using Biofidelity Ranking System (BioRank); demonstrated improvement compared to ES-2re
Current Research

- Developing single-arm qualification test
- Design improvements:
  - Shoulder pad
  - Split thorax pads
  - Sleeveless suit
- Developing technical reports & documentation
  
  Available (see Docket):
  - Biofidelity Evaluation (ESV 2009)

For more information, see Docket ID NHTSA-2019-0108 NHTSA Crashworthiness Research – WorldSID-50M Documentation
Current Research

• Developing single-arm qualification test

• Design improvements:
  • Shoulder pad
  • Split thorax pads
  • Sleeveless suit

• Developing technical reports & documentation

Future Reports:
• RibEye Implementation/Evaluation Report
• R&R, Durability Report
• PADI, Qualification Procedures
• Injury Criteria, Drawing Package

For more information, see Docket ID NHTSA-2019-0108 NHTSA Crashworthiness Research – WorldSID-50M Documentation
WorldSID 5\textsuperscript{th} Percentile
Female ATD

Kevin Moorhouse, Ph.D.
WSID-05F: 5\textsuperscript{th} Percentile Female ATD

- Represents small-size adult female and adolescent
- Features include: six independent ribs tuned for humanlike response, RibEye measurement system capable of measuring lateral and oblique rib displacements, and on-board DAS
- Anthropometry derived from UMTRI AMVO data set
Current Research

• Evaluating Biofidelity
  • Dummy tests complete
  • Developing new response targets
  • Refining BioRank system
  • Comparing to SID-IIs

• Measuring Mass Properties

• Developing Seating Procedure

• Future Work
  • Dummy Upgrades
    • Pelvis, shoulder, and neck bracket
  • RibEye Implementation/Evaluation
  • R&R Evaluation
  • Injury Risk Curve Development

• Durability Evaluation

• Qualification Procedures Development

• PADI

• Drawing Package

For more information, see Docket ID NHTSA-2019-0109 NHTSA Crashworthiness Research – WorldSID-05F Documentation
BioRID-II 50th Percentile Male ATD

Kevin Moorhouse, Ph.D.
BioRID-II: 50th Percentile Male ATD

- Offers human-like characteristics, such as a fully articulated spine that contains elastomeric elements that represents muscles and discs.
- The unique design of the BioRID-II allows it to move like a human while promoting realistic seat back interaction.
- Includes state-of-the-art measurement capabilities that can detect whiplash injuries.
Current Research

• Developing Extension-Based Injury Criteria
  • Collecting biomechanical data (PMHS) and conducting matched pair ATD tests
• Installation of qualification sled
• Evaluation of qualification tests
• Developing technical reports & documentation

Available (see Docket):
• Biofidelity Evaluation (Stapp 2012)
• Various other Stapp/IRCOBI/ESV/TIP publications

Future work:
• R&R, Durability, Drawing Package, PADI
• Qualification Procedures, Seating Procedure
• Injury Criteria, Injury Risk Curves

For more information, see Docket ID NHTSA-2019-0111 NHTSA Crashworthiness Research – BioRID-II Documentation
## Summary of NHTSA ATD Research Dockets

<table>
<thead>
<tr>
<th>ATD</th>
<th>Docket Number - Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>THOR-05F</td>
<td><strong>NHTSA-2019-0107</strong> - NHTSA Crashworthiness Research – THOR-05F Documentation</td>
</tr>
</tbody>
</table>
Clarification or Questions?