NHTSA Female Crash Safety Research Plan

Introduction

Safety is the top priority for the U.S. Department of Transportation (DOT) and the National Highway Traffic Safety Administration (NHTSA). As equity is also a priority, NHTSA is working to address sex inequalities in crash safety outcomes. Although more male motor vehicle occupants are killed in motor vehicle crashes than females,[1] recent studies suggest that female occupants have higher injury and fatality risk in comparable motor vehicle crashes.

NHTSA recently updated the results of a 2013 study[2] that compared relative fatality risk for females versus males. The update includes the most recent fatal crash data and found that the relative risk of fatality between females and males has been reduced, especially when considering newer vehicles.[3] The increase in fatality risk for females relative to males for model year 2010-2020 vehicles was found to be 6.3 ± 5.4% and is significantly less than for model year 1960-2009 vehicles (18.3 ± 1.2%). For model year 2015-2020 vehicles, the estimated difference in fatality risk between females and males appears further reduced to 2.9 ± 9.8% percent for the average of drivers and right-front passengers; however, due to data scarcity, this statistic will need further observation. In addition to comparing model year ranges, the study also assessed relative fatality risk for different generations of occupant protection systems. For the latest generation of systems (dual airbags, seat belt pretensioners and load limiters), the estimated female fatality risk relative to males was 5.8 ± 3.8%, which is statistically significantly lower than for belted occupants in vehicles without those occupant protections (21.0 ± 3.5%). A 2015 NHTSA study[4] demonstrated that three-point belts and airbags were equally effective in reducing fatalities for both males and females.

With respect to injuries, a study[5] by the Insurance Institute for Highway Safety (IIHS) demonstrated that vehicle countermeasures benefit both sexes, and accounting for crash severity reduces the difference in injury risk between males and females. However, a study by Forman et al.[6] demonstrated that when limited to frontal crashes with belted occupants and controlling for select crash and occupant factors, females were at a greater risk of injury compared to males, though the study also demonstrated that injury risk for both sexes was reduced in newer model year vehicles. This study also showed that the largest differences in injury risk between female and male belted occupants occurred in the lower extremities.

[1] National Center for Statistics and Analysis, (2021). Traffic safety facts 2019: A compilation of motor vehicle crash data (Report No. DOT HS 813 141). National Highway Traffic Safety Administration.
[2] Kahane, C. J., (2013). Injury vulnerability and effectiveness of occupant protection technologies for older occupants and women. (Report No. DOT HS 811 766). Washington, DC: National Highway Traffic Safety Administration.
[3] Noh, E. Y., Atwood, J. R. E., Lee, E., Craig, M. J., (2022) Female crash fatality risk relative to rales for similar physical impacts (Report No. DOT HS 813 358). Washington, DC: National Highway Traffic Safety Administration.
[4] Kahane, C. J., (2015). Lives saved by vehicle safety technologies and associated Federal Motor Vehicle Safety Standards, 1960 to 2012 – Passenger cars and LTVs – With reviews of 26 FMVSS and the effectiveness of their associated safety technologies in reducing fatalities, injuries, and crashes. (Report No. DOT HS 812 069). Washington, DC: National Highway Traffic Safety Administration.
[5] Brumbelow, M.L., Jermakian, J.S., (2021). Injury risks and crashworthiness benefits for females and males: Which differences are physiological? Traffic Injury Prevention, 23:1, 11-16, DOI: 10.1080/15389588.2021.2004312
[6] Forman, J., Poplin, G.S., Shaw, C.G., McMurry, T.L., Schmidt, K., Ash, J., Sunnevang, C., (2019). Automobile injury trends in the contemporary fleet: Belted occupants in frontal collisions. Traffic Injury Prevention, 20:6, 607-612, DOI: 10.1080/15389588.2019.1630825

Given these findings and their associated limitations, NHTSA seeks to better understand the possible sex inequalities in crash safety outcomes, particularly those not addressed in vehicles with modern crashworthiness countermeasures. Further, NHTSA is interested in evaluating the potential benefits of improved female anthropomorphic test devices (ATDs), more commonly known as crash test dummies, as well as finite element (FE) human body models (HBM), to provide the tools necessary to develop effective safety countermeasures. To do so, a comprehensive research plan has been developed and is described herein. The primary objective of this research plan is to generate information to support overall knowledge on sex equity in crashworthiness and to support future agency decisions.

The key research questions NHTSA aims to address are:

1. What is the current state of knowledge on fatality and injury risk for females involved in motor vehicle crashes?
2. What are the causes of elevated motor vehicle crash related risk for females?
3. What can be done to better protect females involved in motor vehicle crashes? An extension of this question is: Would the development of new ATDs (e.g., a 50^{th} percentile female) benefit female crash safety in a way that cannot be achieved with the tools NHTSA currently has under development (i.e., 5^{th} percentile female and 50^{th} percentile male advanced crash test dummies; human body models of various sizes including 50^{th} percentile female)?

This Female Crash Safety Research Plan outlines NHTSA's research in the four core areas below, which serve as the organizational structure of the plan:

Field Data Analysis

Using sources that include the Fatality Analysis Reporting System (FARS), the National Automotive Sampling System - Crashworthiness Data System (NASS-CDS), the Crash Investigation Sampling System (CISS), and the Crash Injury Research and Engineering Network (CIREN) databases, NHTSA conducts analysis to investigate motor vehicle crash-based injury and fatality incidence and risk. Previous NHTSA work has studied injury and fatality risks for males and females, including the recently published study comparing relative fatality risks as described in the introduction. To address research questions #1 and #2, NHTSA is analyzing NASS-CDS, CISS, and CIREN data to document differences in injury risk, causation, and mechanisms for females versus males. These studies also aim to describe other vehicle and crash scenario factors that may contribute to differences between females and males.

Key milestones:

- Series of reports documenting current state of knowledge on relative fatality and injury risk for females versus males

Advanced Anthropomorphic Test Devices (ATDs) and Experimental Biomechanics

Experimental biomechanics and anthropometric studies provide a deeper understanding of how women are physically different from men and how these differences may yield unique injury patterns, tolerance, and mechanisms. These data collection efforts can be used to further knowledge related to female-specific response and injury tolerance/risk associated with motor vehicle crashes. Such research results will not only help address research question #2, but they will support further improvements of ATD biofidelity assessments and injury risk curve development.

To address research question #3, NHTSA has focused on developing advanced ATDs that are more biofidelic (i.e., are more human-like in how they respond to crash forces) than current dummies and have improved instrumentation and sensing capabilities. NHTSA's advanced female ATDs make use of all available female-specific data for design (including size and shape), response, and injury risk. The current female ATDs under development are 5th percentile in size; the THOR-05F frontal impact ATD and WorldSID-05F side impact ATD.

Key milestones:

- THOR-05F documentation ready for release to public
- WorldSID-05F documentation ready for release to public

Human Body Modeling

NHTSA supports the Global Human Body Models Consortium's (GHBMC) development of finite element (FE) human body models (HBMs) and their use to study motor vehicle crash induced injuries. The HBMs that are historically most used are the 50th percentile male and 5th percentile female (corresponding to current regulated ATD sizes), although a range of other sizes and shapes exist. In addressing research question #2, NHTSA is utilizing male and female HBMs to investigate possible causes of injury risk differences between females and males. To address research question #3, NHTSA is also using HBMs to assess possible benefits of developing new physical crash test dummies. As part of this effort, NHTSA is supporting the development, evaluation, and demonstrated application of a 50th female HBM.

Key milestones:

- NHTSA evaluation of a 50th percentile female FE HBM
- Decision point – Determine the potential need to initiate development of 50th percentile female ATD(s)

Fleet Testing and Countermeasure Studies

NHTSA conducts crash tests to assess the crashworthiness performance of vehicle structures and occupant restraint systems. After development and refinement of advanced dummies and human body models, NHTSA will conduct both virtual and physical fleet testing to assess how the various HBMs, THOR-05F and WorldSID-05F interact with vehicle systems, respectively. To addresses research question #3, research efforts will be aimed at conducting restraint countermeasure studies to understand how restraints can be optimized for female safety.

Key milestones:

- Countermeasure study evaluating restraint optimization for frontal impact ATDs and HBMs
- Countermeasure study evaluating restraint optimization for side impact ATDs and HBMs

Specific Research Tasks

This section presents a detailed list of NHTSA's ongoing and planned research in each of the four core areas.

Field Data Analysis

Key research areas:

1. *Injury Risk*: NHTSA is developing detailed multi-variable models using National Automotive Sampling System - Crashworthiness Data System (NASS-CDS) and Crash Injury Sampling System (CISS) data to describe injury odds ratios for females versus males given a comprehensive set of covariates across a wide range of motor vehicle crash types.

2. *Fatality Risk:* NHTSA recently published a study[7] evaluating relative fatality risk between females and males utilizing Fatality Analysis Reporting System (FARS) data. The above NASS-CDS and CISS studies will also evaluate fatality as a dependent outcome to estimate the relative odds of fatality for females versus males.

3. *Case Studies:* NHTSA is utilizing available real-world motor vehicle crash injury and fatality datasets to complete the following case studies
    a. *Injury Case Studies:* NHTSA is using in-depth case studies of the Crash Injury Research and Engineering Network (CIREN) database to examine risk factors and understand the causes of apparent female/male differences in crash-related injury outcomes.
    b. *Fatalities Despite Modern Occupant Protection Systems:* NHTSA is planning to update a previous report on fatal crashes despite modern restraints (airbags, seatbelts, etc.). The case study will include documentation of factors that may contribute to differences in outcomes for females versus males.

Advanced ATDs and Experimental Biomechanics

Key Research Areas:

THOR-05F – 5th Percentile Female Frontal ATD

1. *Injury Risk Curve Development and Biofidelity Assessment*: This research primarily involves collecting female post-mortem human subject (PMHS) data and conducting matched pair tests with the THOR-05F in support of both injury risk curve development and biofidelity assessments. Where possible, the development of injury risk curves will consider other covariates such as age. Below is a detailed list of research tasks in this area.

[7] Noh, E. Y., Atwood, J. R. E., Lee, E., Craig, M. J., (2022) Female crash fatality risk relative to rales for similar physical impacts (Report No. DOT HS 813 358). Washington, DC: National Highway Traffic Safety Administration.

a. *In-vehicle Expanded Biofidelity Assessment:* This task is collecting both PMHS and ATD data necessary to comprehensively document THOR-05F biofidelity in conditions representing various real-world motor vehicle occupant restraint conditions. In addition, this research task will compare the biofidelity of THOR-05F to the Hybrid III 5th female ATD (HIII-05F).
b. *Neck:* This task is collecting female PMHS data to facilitate an improved assessment of the biofidelity of the THOR-05F neck. Additional experimental and modeling work may also be required to complete development of injury criteria and human-ATD transfer functions based on previously conducted THOR-05F tests in tension, compression, flexion, and extension.
c. *Thorax:* This task is using PMHS injury data and ATD matched-pair testing collected in the *In-Vehicle Expanded Biofidelity Assessment* task together with previously collected female-specific data to develop an improved thoracic injury criterion.
d. *Abdomen:* This task is collecting female PMHS data to support injury risk curve development as well as biofidelity assessment of the THOR-05F. Additionally, differences in both response and injury risk between male and female PMHS data from already-conducted abdomen tests will be analyzed.
e. *Knee-Thigh-Hip:* This task is collecting female PMHS and ATD data to develop injury criteria for the THOR-05F.
f. *Tibia:* This task will collect female PMHS and ATD data for developing a tibia bending injury criterion for THOR-05F.
g. *Ankle:* This task will collect female PMHS and THOR-05F data to assess and improve THOR-05F ankle biofidelity and to develop ankle injury criteria.

2. *Design Improvements for Durability*: Initial testing with the THOR-05F has identified durability issues that need to be remedied. Work is currently underway to document all durability concerns and possible design changes needed. THOR-05F design improvements are planned to address durability concerns.

3. *Finalize ATD Documentation:* This involves producing final documentation (biofidelity; durability; repeatability and reproducibility; qualification procedures; procedures for assembly, disassembly, and inspection; 3-D drawings; injury criteria; seating procedures) that would be required to support ATD federalization and/or corresponding use in testing programs [i.e., Federal Motor Vehicle Safety Standards (FMVSS) and/or U.S. New Car Assessment Program (NCAP)]. Some preliminary documentation is already available to the public (https://www.regulations.gov/docket/NHTSA-2019-0107). As documentation is updated and/or finalized, it will be made available to the public at the same location.

4. *Development of a THOR-05F FE Model*: A FE model of the THOR-05F is currently being developed and will aid in establishing a biofidelic and durable design. The model is also planned to be used for future parametric studies involving small female ATD responses. Efforts also include planned enhancements to the model.

WorldSID-05F – 5th Percentile Female Side ATD

1. *Injury Risk Curve Development and Biofidelity Assessment:* This research primarily involves collecting small female PMHS data, developing small female biomechanical response corridors, assessing biofidelity of matched pair test data with the WorldSID-05F, and developing injury risk curves. Where possible, the development of injury risk curves will consider other covariates such as age. Experimental PMHS tests are planned, mostly focusing on the thorax. Assessment of methods typically used for scaling 50th percentile male data to that of 5th percentile females is also planned.
    a. *Adult Thorax:* This task is collecting adult female (with healthy bone quality) PMHS data to develop small female biomechanical response corridors and assess biofidelity of matched pair test data with the WorldSID-05F and SID-IIs. In addition, analyzing differences in both response and injury risk between male and female PMHS data is planned.
    b. *Elderly Thorax:* This task is collecting elderly adult female (with poor bone quality) PMHS data in a side impact condition with seat belt and airbag to aid in generating an elderly small female thoracic injury risk curve and assess the biofidelity of the WorldSID-05F relative to elderly small female biomechanical response corridors.

2. *Design Improvements for Biofidelity:* Initial testing with the WorldSID-05F has identified some areas of insufficient biofidelity relative to scaled 50th percentile male PMHS biomechanical response corridors. The findings have been presented to the WorldSID-05F Technical Evaluation Group as well as at the 2022 SAE Government/Industry Meeting. Design improvements to address these biofidelity concerns are planned.

3. *Finalize ATD Design and Documentation:* This involves producing final documentation (biofidelity; durability; repeatability and reproducibility; qualification procedures; procedures for assembly, disassembly, and inspection; 3-D drawings; injury criteria; seating procedures) that would be required to support ATD federalization and/or corresponding use in testing programs [i.e., Federal Motor Vehicle Safety Standards (FMVSS) and/or U.S. New Car Assessment Program (NCAP)]. As documentation is finalized, it will be made available to the public at https://www.regulations.gov/docket/NHTSA-2019-0109.

Experimental Biomechanics

1. *Female Seated Anthropometry and Seating Preference Studies:* This effort will include posture/seating assessments of females versus males, studies of driver foot placement, studies of thoracic geometry and a new/expanded seated anthropometry study for 5th, 50th, and 95th percentile females and males. The results will be applied in part to support seating procedure development and seated assessments of ATDs and HBMs.

2. *High-speed, Forward-facing, Reclined Seating:* This research includes sled tests with female PMHS in similar test configurations as male PMHS to identify differences in kinematics and injury risk in high-speed, forward-facing impacts with reclined seating.

3. *High-speed, Rear-facing, Reclined Seating:* This research includes sled tests with female PMHS in similar test configurations as male PMHS to identify differences in kinematics and injury risk in high-speed, rear-facing impacts with standard and reclined seating.

4. *50th Percentile Female Biofidelity/Response Data Collection:* This research will focus on data collection to support 50th female-specific biofidelity corridors for use in validating 50th percentile female HBM(s) and/or 50th percentile female ATD(s). This data collection and assessment would in part support analysis related to the potential need for 50th percentile female ATD(s).

5. *Whiplash:* A 50th percentile female rear impact ATD FE model (named EvaRID) and an initial prototype 50th percentile female rear impact ATD (BioRID-P50F) has been developed to assess the performance of automotive seats and head restraints. Future work will include further assessment and development of the tools needed to predict whiplash injuries in females.

6. *Rib Cage/Fracture Risk:* Multiple studies are underway related to female rib response and fracture risk: (1) identify rib and thorax biomechanical response corridors for female occupants so that human body models can be improved for better accuracy in identifying injury potential, (2) develop analytical methods to derive material property parameters required to improve the biofidelity of human body model ribs, and (3) identify contributions of various thoracic structures (ribs, viscera, superficial tissue) to overall thoracic response for various demographics including female, pediatric, and older occupants.

Human Body Modeling

Key research areas:

1. *50th Percentile Female HBM:* NHTSA is supporting the development and evaluation of a 50th percentile female human body model by the Global Human Body Models Consortium (GHBMC), which will be used in parametric analyses to examine female injury risk, as well as assess possible benefits of developing 50th percentile female ATDs.
    a. *Preliminary Studies:* A 50th percentile female human body model was scaled from the GHBMC 5th percentile female model to match height and weight targets (NHTSA internal study). This model is being used in preliminary studies to determine whether restraints optimized for a 50th percentile female would be different from restraints optimized for current ATD sizes.
    b. *Model Development and Evaluation:* GHBMC developed a new 50th percentile female human body model. This new model was morphed from the 5th percentile female model to match detailed 50th percentile female human medical imaging data. NHTSA is currently evaluating the model.
    c. *Validation and Application*: NHTSA plans to complete research supporting extended validation and demonstrated application of the new 50th percentile female HBM.
    d. *Countermeasure Studies:* The new 50th percentile female HBM will be used in countermeasure studies to assess its utility in studying injury risk in various crash types. These studies will be done in coordination with item #4 in the *Fleet Testing and Countermeasures Studies* section of this research plan. Results from this study will be used

to support a decision on the potential need for the development of 50th percentile female ATDs.

2. *Parametric Modeling Studies:* To investigate causes of increased risk for females, NHTSA is conducting internal parametric studies using HBMs.
    a. *Ankle Injury Risk:* In this study, factors such as foot placement will be parametrically varied to discern possible female/male response differences.
    b. *Thorax Injury Risk:* This parametric study is investigating factors such as airbag properties, seat belt load limiting, and knee bolster location on female/male differences in rib deflection and injury. Preliminary findings suggested that geometry differences between the 5th percentile female and 50th percentile male human body models may be contributing to injury risk differences found in simulations. Item #3a below aims to better establish how sensitive predicted thoracic injury risks are to changes in thoracic geometry/shape.

3. *HBM Geometry/Shape:* The research efforts described below aim to explore the needs for and development of statistically average representations of the respective HBMs for body regions whose predicted injury risks are sensitive to changes in shape, geometry and/or related mechanical properties.
    a. *Thorax:* This project aims to use a large sample of radiological scans (e.g., computed tomography scans) of females and males to evaluate shape differences (e.g., rib angles, depth/breadth) between females and males. Findings to be used both in establishing average thorax geometry in HBM model development and for establishing parameter ranges to be evaluated in HBM studies.
    b. *Other Body Regions:* Pending results of rib cage depth/shape-based studies, other body regions will be investigated in efforts to establish different percentile and sex HBMs with statistically average representations of key body regions (e.g., spine, abdomen, knee-thigh-hip, ankle).

Fleet Testing and Countermeasure Studies

Key research areas:

1. *Existing Fleet Data Analysis:* This research involves analysis of existing enforcement information request response (IRR) data for frontal testing, comparing paired data of Hybrid III 50th percentile male (HIII-50M) and 5th percentile female (HIII-05F) in the same FMVSS No. 208 conditions.

2. *Fleet Testing – THOR-05F:* This research involves the planned execution of passenger vehicle crash tests utilizing the THOR-05F in FMVSS No. 208, oblique, and/or rear seat conditions. Results to be contrasted with those of current ATDs (HIII-05F, HIII-50M, THOR 50th male).
    a. Baseline frontal and oblique testing using THOR-05F in front and rear seating positions
    b. Full-scale fleet evaluation testing using THOR-05F

3. *Fleet Testing – WorldSID-05F:* This research involves the planned execution of passenger vehicle crash tests utilizing the WorldSID-05F in FMVSS No. 214 oblique pole and MDB conditions. Results to be contrasted with those of current ATDs (SID-IIs 5th female, ES-2re 50th male, WorldSID 50th male).

a. Baseline pole and MDB testing using WorldSID-05F in front and rear seating positions
b. Full-scale fleet evaluation testing using WorldSID-05F

4. *Countermeasure Studies:* Parameter studies are planned that will explore optimized restraint system designs that provide equivalent injury risk mitigation for females as compared to males. The study will evaluate current system design performance and consider changes in design parameters targeting 5^{th} and/or 50^{th} percentile females.
    a. Countermeasure study evaluating restraint optimization for HIII-05F, THOR-05F, and 5^{th} and 50^{th} percentile female HBMs
    b. Countermeasure study evaluating restraint optimization for SID-IIs, WorldSID-05F, and 5^{th} and 50^{th} percentile female HBMs