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HBM Virtual Testing Framework Development and Demonstration

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16. Abstract The study's two objectives were (1) to propose a virtual testing framework for evaluating vehicle occupant protection using human body models (HBMs), and (2) to perform an initial demonstration of that framework. The framework is intended for the broader safety research community to facilitate occupant protection assessment. Development focused on high-level steps, including HBM validation, vehicle model development and validation, crash simulation setup (HBM positioning, settling, and belt fitting), and injury assessment with potential weighting factors. The initial demonstration compared the performance of a detailed vehicle and a parametric vehicle model and evaluated the framework's feasibility and robustness. The demonstration used 11 HBMs in seven sizes and shapes and four crash conditions, producing 28 crash simulations with the detailed vehicle model by GM and 35 simulations with the parametric vehicle model by UMTRI. Results showed generally consistent predictions for occupant kinematics and injury risks between the two vehicle-model approaches, with discrepancies in a few isolated cases. Despite differences in HBM geometry, settling method, and belt fitting approach, the two vehicle models produced similar overall weighted average injury risks (Pjoint of 44.1%±11.5% vs. 42.5%±11.3%). This study highlights the potential of the HBM virtual testing framework for occupant protection assessment while identifying limitations and areas for future improvement.					
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Table of Contents

Background	1
Objectives.....	3
Task 1: HBM Virtual Testing Framework Development	5
Framework Overview.....	5
HBM Validation.....	6
Vehicle Model Development and Validation.....	7
Simulation Setup	9
HBM and Seat Positioning	10
HBM Settling.....	11
HBM Belt Fitting.....	13
Crash Condition Definition	14
Sampling Weight.....	14
Injury Assessment	15
Task 2: HBM Virtual Testing Initial Demonstration	17
GHBMC HBMs.....	17
Vehicle Models	18
Model Validations Against Crash Tests.....	20
Simulation Matrix	21
HBMs and Setup.....	21
Vehicle Models and Crash Conditions	22
Injury Assessment.....	22
Simulation Results.....	22
Occupant Kinematics.....	22
Occupant Injury Measures and Injury Risks	27
Time Frame	30
Discussion.....	31
General Trends	31
Robustness and Reproducibility.....	31
Limitations and Future Work	32
Conclusions	35
References.....	37
Appendix A. GM and UMTRI Model-Predicted Head and Hip Excursions Different Conditions	A-1

List of Figures

Figure 1. Overview of HBM virtual testing framework. Presented are the five main components of the framework: (1) HBM Validation; (2) Vehicle Model Development and Validation; (3) Simulation Setup; (4) Sampling Weight; (5) Injury Assessment.....	6
Figure 2. Method for developing parametric vehicle and restraint models (Boyle et al., 2024). Shown are the four main components of creating and demonstrating the parametric vehicle compartment model (Generic Vehicle Model; Upgraded Vehicle Model; Parametric Vehicle Model; Model Demonstration).....	8
Figure 3. An example of the method for defining lateral intrusion in the vehicle model. A similar approach is applied for intrusions associated with frontal crashes.	9
Figure 4. Integration of vehicle, restraint, and occupant models using the morphed GHBM C simplified models (Hu et al., 2019). The figure presents the five stages of model set-up: (1) Position Hip and Eye; (2) Adjust Seat Location; (3) Adjust HBM Limbs; (4) Occupant – Seat Interface; (5) Re-fit Seatbelt.	10
Figure 5. HBM settling illustration by pre-simulation method based on GHBM C M50-OS v2.3.....	12
Figure 6. Demonstration of a proper routing of the seat belt on the M50-OS model.....	13
Figure 7. Demonstration of an automated belt fitting procedure based on volunteer belt fit data.....	14
Figure 8. Stock GHBM C models used in this study.....	17
Figure 9. Stock and morphed GHBM C models used in this study.....	18
Figure 10. Two driver compartment models used in this demonstration	19
Figure 11. Geometric comparison between the detailed and parametric vehicle models.....	20
Figure 12. Model validation results against belted HIII ATD in a 35 mph frontal crash.....	20
Figure 13. Model validation results against unbelted HIII ATD in a 20 mph frontal crash.....	21
Figure 14. Occupant injury risks for different body regions across all HBMs and crash conditions.....	29
Figure 15. Pjoint comparison between the two vehicle models, grouped by crash conditions P-values are based on the ANOVA and student T-test.	29
Figure 16. Pjoint value comparison between the two vehicle models, grouped by HBMs P-values are based on the student T-test.	30

List of Tables

Table 1. Driving posture model recommended for the HBM virtual testing (Reed et al., 2002) .	11
Table 2. Injury risk curves and scaling method	16
Table 3. Summary of GM and UMTRI simulation conditions	22
Table 4. Occupant kinematics at 100 ms in the 35 mph pure frontal crash	24
Table 5. Occupant kinematics at 100 ms in the 20 mph pure frontal crash	25
Table 6. Occupant kinematics at 100 ms in the 30 mph oblique frontal crash	26
Table 7. Occupant injury measures predicted by the HBMs	27

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Background

In vehicle crash safety, virtual testing with human body models (HBMs) offers several advantages over physical testing with anthropomorphic test devices (ATDs). First, HBMs provide greater biofidelity with more accurate anatomy of the human body. Second, HBMs support postures beyond ATD capabilities (e.g., highly reclined). Third, HBMs can be morphed to represent a range of body sizes and shapes not available in physical ATDs. Finally, HBMs enable injury risk evaluation across many load cases that are impractical in physical testing due to cost or the absence of an appropriate ATD.

Combining virtual tests with HBMs and physical tests with ATDs can help provide a safety rating for a vehicle that is more comprehensive. However, virtual HBM testing introduces technical challenges not typically encountered in physical testing, including these.

- *Model development and validation:* Original equipment manufacturers (OEMs) may be unwilling to share computational vehicle models; consequently, an efficient, reproducible process is needed to develop accurate vehicle models for virtual testing. HBMs also need to be properly developed, validated, and specified.
- *Model bias and correction:* Even with rigorous validation, discrepancies between simulations and physical tests persist. Errors can arise from the vehicle, restraint system, and ATD models. The framework should identify and, where appropriate, correct these biases.
- *Simulation setup:* Setup choices (occupant position/posture, belt fit, HBM settling, boundary conditions, physical test parameters/control factors) can materially affect results. A standard procedure is needed to minimize unwanted variability.
- *Model robustness and replicability:* Finite element (FE) simulations may terminate early due to model errors. Results can also vary by solver, version, and computing environment. Robustness and reproducibility should be evaluated and documented.
- *Sampling and weighting:* With HBMs across varied crash conditions, a principled method is needed to combine results to estimate real-world consequences (e.g., field data informed weighting).

Euro NCAP includes pedestrian human modeling to predict head impact time (HIT) and has proposed expanding virtual testing to additional impact configurations and active safety scenarios (e.g., farside occupant protection and AEB pre-impact braking). Euro NCAP's Vision 2030 (2022) identifies prospective virtual testing scenarios including farside impact, protection equity, whiplash protection parity, lower extremity injury risk, variations in impact angle, reclined seating, and occupant size and sex. Euro NCAP also plans to introduce "virtual testing with spot testing" to reduce test burden. The Insurance Institute for Highway Safety plans to add virtual testing to its rear impact whiplash injury rating procedure (currently limited to ATDs). To our knowledge, a complete virtual testing framework focused on occupant protection using HBMs is not yet available.

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Objectives

The study had two objectives: (1) to propose a virtual testing framework for evaluating vehicle occupant protection using HBMs; and (2) to conduct an initial demonstration of that framework. For the second objective, the demonstration was conducted both by an OEM with proprietary detailed vehicle models and a non-OEM using only publicly available information (e.g., simplified parametric occupant compartment model). Differences in these parallel demonstrations of the framework (including models, set-up, and results) are presented and discussed.

The following specific tasks were conducted.

- Task 1: HBM Virtual Testing Framework Development
- Task 2: HBM Virtual Testing Initial Demonstration

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Task 1: HBM Virtual Testing Framework Development

This report focuses on the development of a high-level framework. The goal was to identify important steps with rationale, rather than specific details for each step. The virtual testing framework addressed the following:

- **HBM Validation:** Describe how HBM results should be validated to ensure they are reliable.
- **Vehicle Model Development and Validation:** Outline the process that will be used for developing the vehicle models and validating the simulation results.
- **Simulation Setup and Robustness:** Detail how the robustness of simulations could be achieved by automating the setup processes.
- **Sampling Weight:** Describe the basis of weighting the simulation results with a large set of HBMs and simulation conditions.
- **Injury Assessment:** Explain how virtual testing occupant injury predictions will be evaluated to provide a comprehensive safety assessment covering a wide range of occupants and crash conditions.

Framework Overview

Figure 1 shows an overview of the proposed HBM virtual testing framework. The framework has five principal components.

1. HBM Validation
2. Vehicle Model Development and Validation
3. Simulation Setup
4. Sampling Weight
5. Injury Assessment

First, selected HBMs are validated against post-mortem human subjects (PMHS) or similar biomechanical tests, either by applying response corridors or subject-specific impact responses. Second, the vehicle model is validated against physical vehicle crash tests with ATDs, preferably in several conditions. Here, “vehicle model” refers to an occupant compartment model that includes key interior elements and restraint systems. The model may be a detailed vehicle or occupant compartment model provided by an OEM (potentially encrypted). If an OEM is unavailable, a simplified parametric vehicle model will be used that can be morphed to match vehicle geometry and tuned to match the test results. The parametric model is a computational representation of the occupant compartment defined by adjustable parameters enabling rapid customization of geometry, structural properties, and restraint system characteristics. The validated parametric model and diverse HBMs are integrated via an automated simulation setup procedure across crash conditions sampled from field data. Simulated injury outcomes are then combined body region injury risk curves and field data informed sampling weights to produce the final virtual testing scores. Details and challenges are described in the following sections.

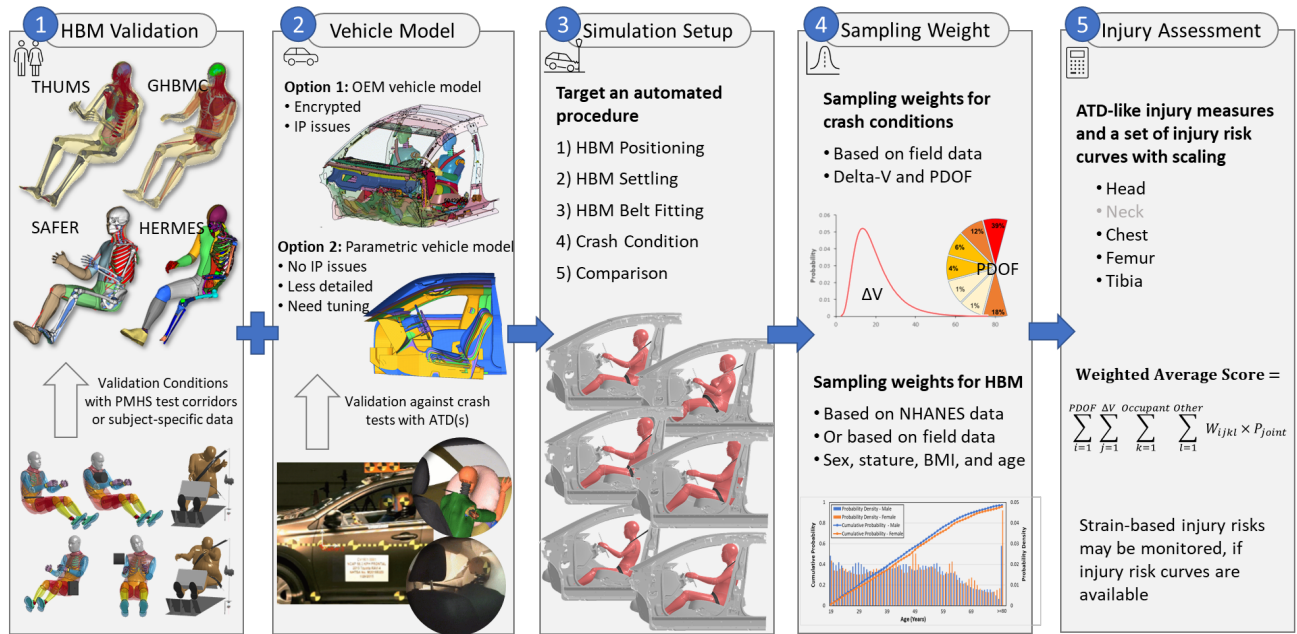


Figure 1. Overview of HBM virtual testing framework. Presented are the five main components of the framework: (1) HBM Validation; (2) Vehicle Model Development and Validation; (3) Simulation Setup; (4) Sampling Weight; (5) Injury Assessment

HBM Validation

HBMs used in the virtual testing framework should be rigorously validated against available biomechanical data included from PMHS tests. State-of-the-art whole-body HBMs such as those developed by the Global Human Body Models Consortium¹ (GHBM) or the Total Human Model for Safety (THUMS²) have been validated against similar biomechanical datasets at both body-region and full-body levels; see model documentation for details (GHBM, 2022; THUMS User Community, n.d.). The framework should specify recommended impact conditions, PMHS-based or related biofidelity corridor references, and explicit validation criteria. Additionally, the framework should specify specific vehicle crash conditions (e.g., crash pulse and restraint

1 Editor's Note: Created in April 2006 the Global Human Body Models Consortium (GHBM) currently includes General Motors Holdings LLC, Honda R&D Co., Hyundai Motor Co., Nissan Motor Corp. Ltd., Renault S.A., and Stellantis N.V. NHTSA is a sponsor and Autoliv Inc., Ford Motor Co., and Faurecia SE are participants contributing to the technical development. The objective of GHBM is to consolidate world-wide research and development work in human body modeling into a single global effort to advance crash safety technology. GHBM's mission is to develop and maintain high fidelity FE human body models for automotive crash simulations. GHBM has developed a family of "virtual humans" including male and female seated occupants of various sizes and pedestrians including a 6-year-old child.

2 Editor's Note: Toyota Motor Corporation in cooperation with Toyota Central R&D Labs, Inc., founded the THUMS project in 1997 to develop the THUMS (Total Human Model for Safety). Over time it, too, developed into a consortium, the THUMS User Community (TUC), now a project of the Ludwig-Maximilians-Universitaet Muenchen in cooperation with the AUDI, Autoliv Development, BMW, Mazda, Mercedes-Benz, Porsche, Toyota, Volkswagen, and ZF Automotive Germany GmbH. Toyota participates also as THUMS base-model provider in the TUC project. Together with the Associated Partners BAST and Universidad Pontificia Comillas and the Development Partners DYNAmore and ESI, the TUC project works on various topics regarding the THUMS and to set up a framework and requirements for the implementation of HBMs in vehicle and traffic safety applications.

conditions similar to or slightly more severe than targeted crash conditions) for model stability and robustness verification.

Mesh quality is fundamental to achieving high-fidelity, robust simulation results. Regardless of certification status, HBM mesh quality should be reported as a best practice. For solid and shell elements, report: warp, age, aspect ratio, skew angle, Jacobian, and minimum/maximum element angle.

Because we target additional virtual frontal impact load cases across HBM sizes, we propose a set of PMHS-based certification conditions. To ensure omni-directional applicability, both frontal impact and side impact certification conditions are proposed. At a minimum:

- Thorax Hub Impact (6.7 m/s) - (Lebarbé and Petit, 2012)
- Abdominal Bar Impact (6.0 m/s) - (Hardy et al., 2001)
- Oblique abdominal hub impact (6.7 m/s) – (Viano, 1989)
- Lateral Sled Impact (6.7 m/s) - (Cavanaugh et al., 1990)
- Lateral shoulder impact (4.5 m/s) – (Koh et al., 2005)
- Block impact to pelvis (10 m/s) – (Bouquet et al., 1998)
- Frontal Sled Impact (11m/s) - (Shaw et al., 2009)

Boundary conditions and specific kinematic response corridors for executing above certification conditions are being developed separately. HBM developers and/or those applying the framework would submit certification results for their models.

Simulation quality will also be documented as part of the framework. Recommended measures include energy balance, timestep changes throughout the simulation, mass increase at the beginning and at the end of simulation, and animation with section cut. As with mesh quality, no single pass/fail limit is prescribed; reporting is a best practice to support transparency and reproducibility.

Specifications for post-processing simulation results (e.g., nodal acceleration, sectional forces, deflections, filtering class) will be made available for users.

Vehicle Model Development and Validation

The framework supports two vehicle model options: (1) a detailed occupant compartment model provided by an OEM, including vehicle interior, seat, seat belt, air bags, and other components; (2) a publicly available parametric vehicle model (described below). OEM models may be unavailable due to intellectual property constraints or may be shared with encryption, complicating handling.

When an OEM occupant compartment model with restraint systems is unavailable, the current virtual testing framework proposes the use of a parametric model of the vehicle interior and restraints that is rapidly tunable to target geometry and crash testing results. Figure 2 summarizes the development and validation process from a prior study that is applied in the current framework (Boyle et al., 2024). The process used a generic vehicle driver compartment model based on interior geometries of 14 vehicles (Iraeus & Lindquist, 2016). The model includes a generic seat, seat belt, steering wheel rim and column, roof side rail, and outboard seat air bags.

The model was updated to include front passenger interior and restraint systems as well as driver and right front passenger curtain and knee air bags. The process demonstrated by Boyle et al. enables morphing of the generic vehicle model to other vehicle geometries based on well-defined vehicle dimensions and measures. Modeled restraint system components are parameterized so that factors affecting occupant performance (e.g., belt load limit characteristics, air bag size, air bag mass flow rate, air bag venting, steering column stroke force and distance, knee bolster stiffness, seat cushion stiffness) can be varied to match physical testing data. Demonstrated validation of a set of morphed vehicle models against frontal and side US-NCAP crash tests was documented by Boyle's group.

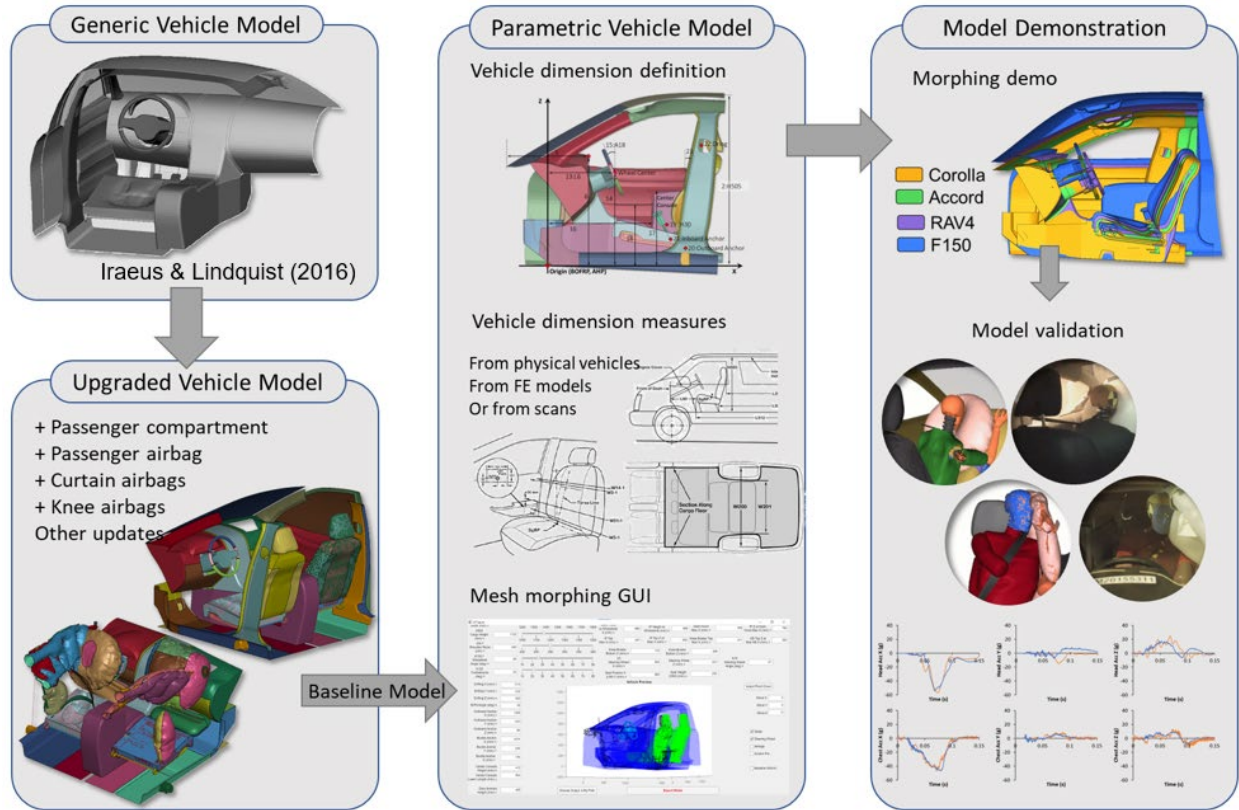


Figure 2. Method for developing parametric vehicle and restraint models (Boyle et al., 2024). Shown are the four main components of creating and demonstrating the parametric vehicle compartment model (Generic Vehicle Model; Upgraded Vehicle Model; Parametric Vehicle Model; Model Demonstration)

The parametric vehicle model described by Boyle et al. (2024) also enables user-specified intrusion profiles for the instrument panel (left/center/right upper and lower), steering wheel, and toe pan to support morphed vehicle model validation. Lateral door intrusion can be specified by defining a maximum intrusion and applying horizontal and vertical scaling factors to a span of the door panel (see Figure 3 for an example execution involving a side NCAP moving deformable barrier test of a 2015 Toyota RAV4).

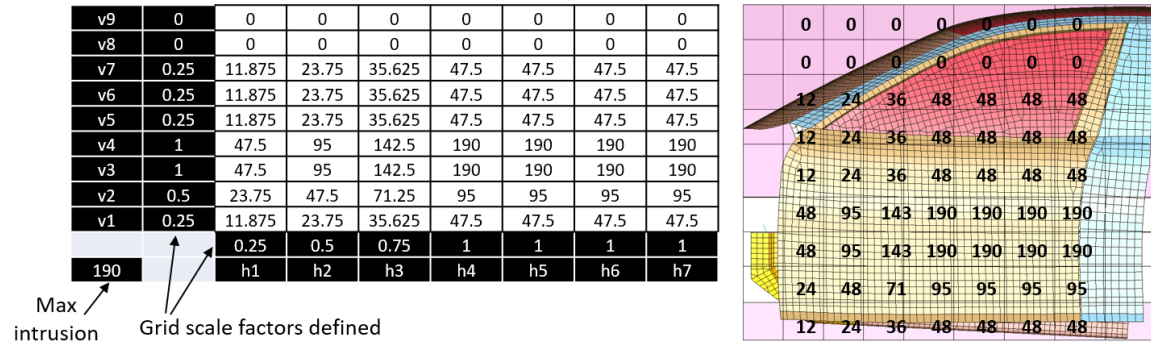


Figure 3. An example of the method for defining lateral intrusion in the vehicle model. A similar approach is applied for intrusions associated with frontal crashes.

Where possible, the virtual testing framework described herein should apply data from applicable crash test conditions for model validation and tuning, to ensure comprehensive validation. The number of tests will depend on similarity between virtual testing load cases and available physical tests. Evaluation criteria for quantifying model validity should be used (e.g., CORA, BioRank, ISO 18571-2022) across relevant ATD responses (e.g., head excursion and acceleration, chest acceleration and deflection, pelvis acceleration, femur and tibia forces, and lap and shoulder belt forces). Criteria may vary by response and must be objective in nature and repeatable and reproducible. The framework should allow OEMs to review and confirm the tuned parametric model's fidelity to the subject vehicle. Components such as the knee bolster, seat cushion, air bag, etc., may be replaced with OEM-certified sub-models.

Simulation Setup

The virtual testing framework requires a well-defined simulation setup procedure to ensure repeatable and reproducible results. For example, prior work by (Hu et al., 2019) established an automated method to integrate HBMs of varied sizes with the restraint system and vehicle models for crash simulations. Hu et al.'s methods, as shown in Figure 4, include the following workflow:

1. applying a volunteer-based occupant seating posture model to position the HBM head and hip locations and the seat H-point location given occupant and vehicle packaging parameters;
2. adjusting seat location together with HBM positioning to achieve desired hip and eye positions;
3. calculating and automatically adjusting upper and lower limbs so hands are on the steering wheel and the feet are on the pedal or footrest;
4. settling the HBM on the seat (methods described below); and
5. applying an automated belt-fitting tool to fit the seat belt on the occupant model.

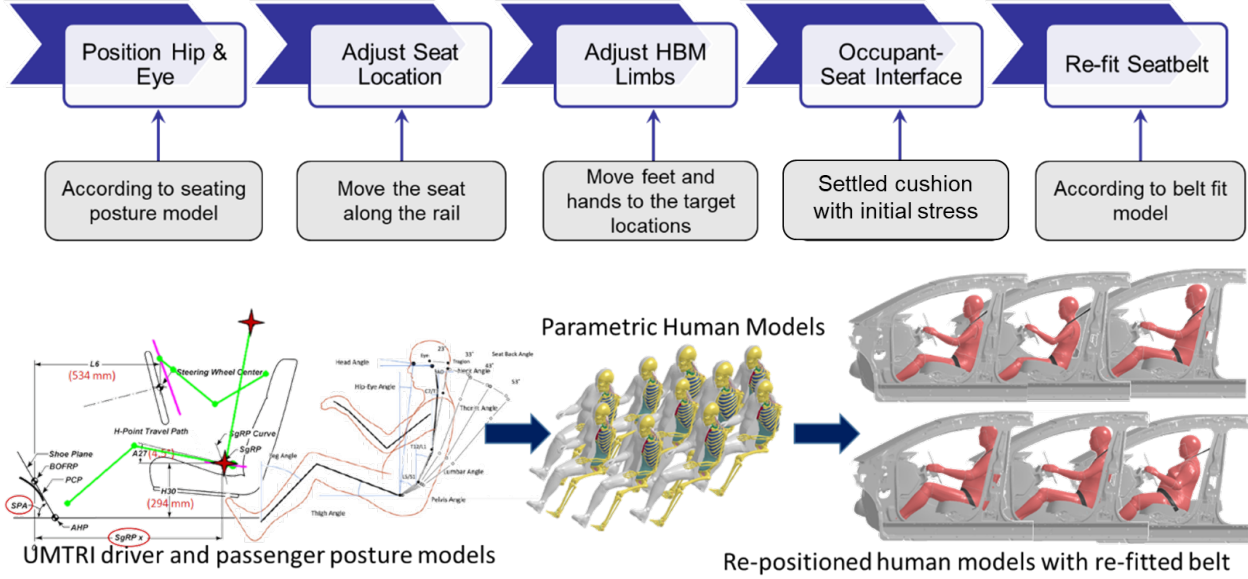


Figure 4. Integration of vehicle, restraint, and occupant models using the morphed GHBM simplified models (Hu et al., 2019). The figure presents the five stages of model set-up: (1) Position Hip and Eye; (2) Adjust Seat Location; (3) Adjust HBM Limbs; (4) Occupant – Seat Interface; (5) Re-fit Seatbelt.

The simulation setup procedure aims to be as automated as possible to reduce potential variability from manual steps and to improve reproducibility and replicability. Therefore, the following steps are specifically emphasized.

HBM and Seat Positioning

HBM position and posture, along with seat position, should be based on statistical driver seating posture models (e.g., Reed et al., 2002, or Park et al., 2016). As shown in Table 1, the Reed et al., model predicts posture and position as functions of occupant characteristics (i.e. stature, body mass index [BMI], and sitting height to stature ratio [SHS]) and vehicle packaging factors. Vehicle packaging factors, which include seat height (H30), steering wheel X (L6), and seat track angle (A27), should be based on vehicle design for predicting driving postures (SAE International, 2008). Based on the regression model shown in Table 1, the model-predicted driver hip and eye locations (only in the X direction) are used to position the HBMs, and the predicted driver-selected seat H-point location is used to position the seat before each simulation. For each simulation, the driver's hands should be positioned on the steering wheel by adjusting the shoulder and elbow angles, and the right and left feet/shoes should be positioned onto the gas pedal and the footrest, respectively, by adjusting the hip, knee, and ankle angles. It should be noted that, for right front passengers, the seat location is not directly correlated with occupant size, thus the seat location could be considered as a variable when setting up the simulations.

Since the seating positions for the 5th percentile female (F05), and 50th percentile male (M50), and 95th percentile male (M95) ATDs are well defined, HBMs corresponding to the same sex, height and weight of the ATDs could be positioned at the same corresponding seating positions. This alternative option enables the reuse of standardized seat positions in current practice for HBMs, thereby reducing the variables in seat positions from ATDs.

Table 1. Driving posture model recommended for the HBM virtual testing (Reed et al., 2002)

Dependent Variable	Regression Model*	Note
H_Point_X	$H_Point_X = 16.8 + 0.433 * Stature - 0.24 * H30 - 2.19 * CA + 0.41 * L6$	Seat H-point for seat model positioning
H_Point_Z	$H_Point_Z = SgRP_Z + (SgRP_X - H_Point_X) * \sin(STA)$	
Hip_X	$Hip_X = 12.2 - 3.5 * BMI + 3 * CA + H_Point_X$	Human model hip point
Hip_Z	$Hip_Z = -97.1 + 1.2 * BMI + 0.1068 * L6 + 1.1 * CA + H_Point_Z$	
Hip2Eye_Angle	$Hip2Eye_Angle = -56.2 + 100.2 * SHS + 0.0147 * L6 + 0.1 * CA + 0.136 * BMI$	Hip-to-eye angle and eye location
Hip2Eye_Distance	$Hip2Eye_Distance = -418.5 + 0.348 * Stature + 859.6 * SHS$	
Eye_X	$Eye_X = Hip_X + Hip2Eye_Distance * \sin(Hip2Eye_Angle)$	

* CA: cushion angle, STA: seat track angle, H30: seat height, L6: Steering wheel X, SHS: sitting height/stature ratio

HBM Settling

There are different HBM settling methods that are commonly used, including but not limited to, pre-simulation, seat squash, pusher block, and simple morphing. Among them, pre-simulation, seat squash, and pusher block methods keep the stress in the seat cushion, while simple morphing does not consider cushion stress.

We have found through prior experience that including seat cushion deformation and stress induced by gravity acting on the ATD is important for accurately predicting restraint system interactions in frontal crashes. This prior experience and associated recommendation for using pre-simulation for HBM settling has not been documented elsewhere and as such is described below.

To use pre-simulation to settle the HBM onto a seat, the HBM needs to be brought into the sled model above the seat with minimum gaps and distances between the HBM, seat cushion, and seat back, as shown in Figure 5. The HBM will then settle onto the seat due to gravity. During the settling process, the head or neck must be constrained so that the eyes of the HBM maintain a forward position. When using LS-DYNA in the settling process, for example, the solid hexahedral elements of the HBM should use element formulation -1 and tetrahedral elements should use element formulation 13. This ensures that HBM deformation aligns with the target location relative to the seat and allows for realistic pelvis/thigh flesh compression on the seat cushion. A small mass damping should be applied to the entire HBM to reduce the simulation duration, allowing the HBM and the seat to reach equilibrium faster within one or two seconds of simulation duration. This speed-up in simulation may slightly affect the settling depth of the HBM into the seat, but it is generally acceptable.

During the settling of the HBM, boundary conditions should be applied to the palms and shoes. When simulating a driver, for example, this enables the palms to be properly placed on the steering wheel and the feet to be placed on their target pedal and footrest positions. The settling of the HBM in the seat and repositioning of the limbs is done in a single pre-simulation. The

position of the Hybrid III 50th percentile ATD, based on the measurements from the test report, is compared with the GHBMCM50-OS v2.3 model after the settling simulation, as shown in Figure 5.

After completing the settling pre-simulation, the deformations of the seat cushion and seat back will be used to calculate the initial stress exerted by the HBM using simple LS-DYNA function. The new coordinates of the settled HBM can then be extracted to form a repositioned HBM, ready for subsequent crash simulations to evaluate its safety performance.

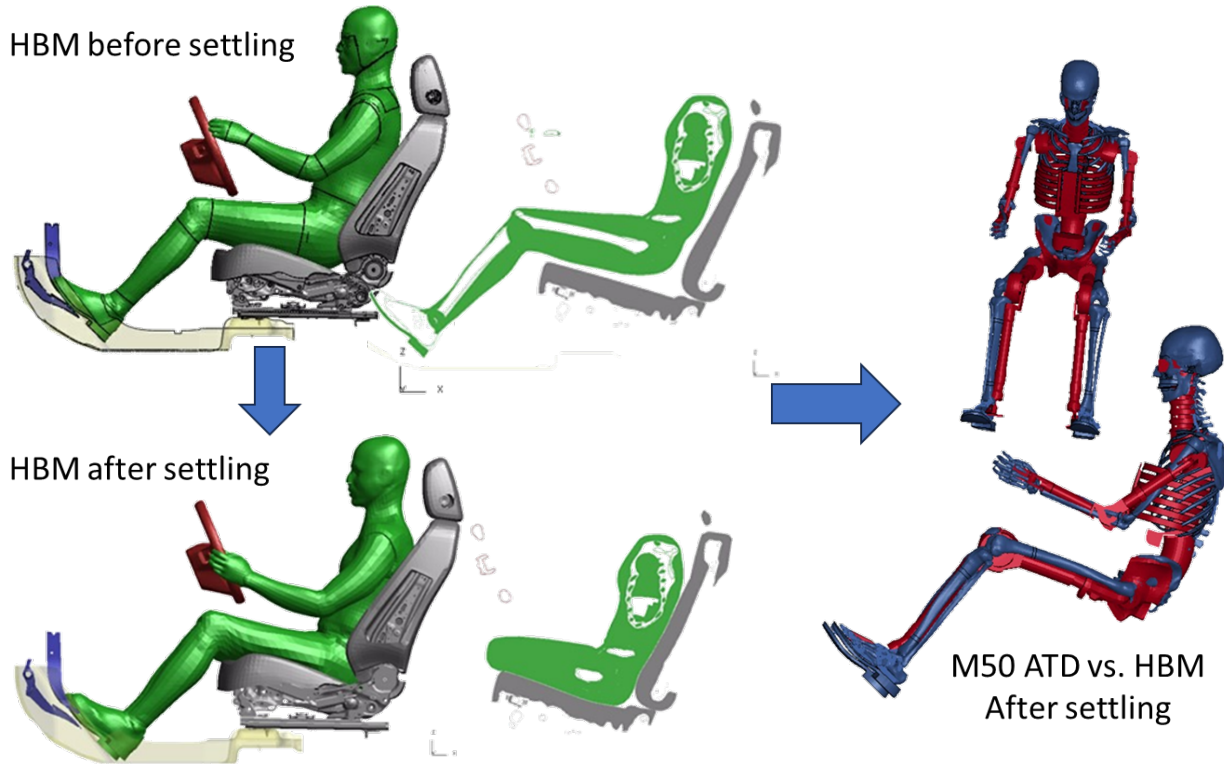


Figure 5. HBM settling illustration by pre-simulation method based on GHBMCM50-OS v2.3

Because pre-simulations depend on the material properties of the HBM and seat cushion, the pre-simulation-predicted HBM hip location may not always match the target hip location predicted by the statistical sitting posture models based on volunteer tests. To achieve an acceptable match between the HBM and the occupant hip location predicted by the sitting posture model, the seat squash and pusher block methods can be used. Both seat squash and pusher block methods can force the HBM into the targeted hip location, deform the seat cushion by the HBM geometry, and save the deformed cushion nodal locations along with the stress for crash simulations. However, depending on the seat design, the deformation and stress in the cushion may not perfectly balance the occupant's weight.

While the above provides a general overview of recommended steps to place the HBM in a vehicle seat, more detailed methods with specific steps and tolerances would need to be described to enable repeatability and reproducibility.

HBM Belt Fitting

There is no well-accepted standard method to fit a seat belt onto an HBM. However, if the HBM is in the same size and shape of an ATD, the general principles to fit the seat belt onto the ATD can be applied to the HBM. An example of a properly routed seat belt on the HBM is shown in Figure 6.



Figure 6. Demonstration of a proper routing of the seat belt on the M50-OS model

However, as representative HBMs vary across a wide range of sizes and shapes, the above belt fitting method could result in different belt locations, especially for obese HBMs where a clear and direct seat belt path is not obvious. To solve this problem, prior work described an automated belt-fitting procedure that enables rapid development of realistically positioned belts for all occupants according to belt fit models based on volunteer data (Reed et al., 2012, 2013, 2019). Figure 7 illustrates the steps in the belt fitting procedure. The algorithm uses the positions of the shoulder belt defined with respect to the clavicle and sternum and the position of the lap belt with respect to the anterior superior iliac spine (ASIS) predicted by the model using occupant characteristics and seat belt D-ring and anchorage locations as inputs.

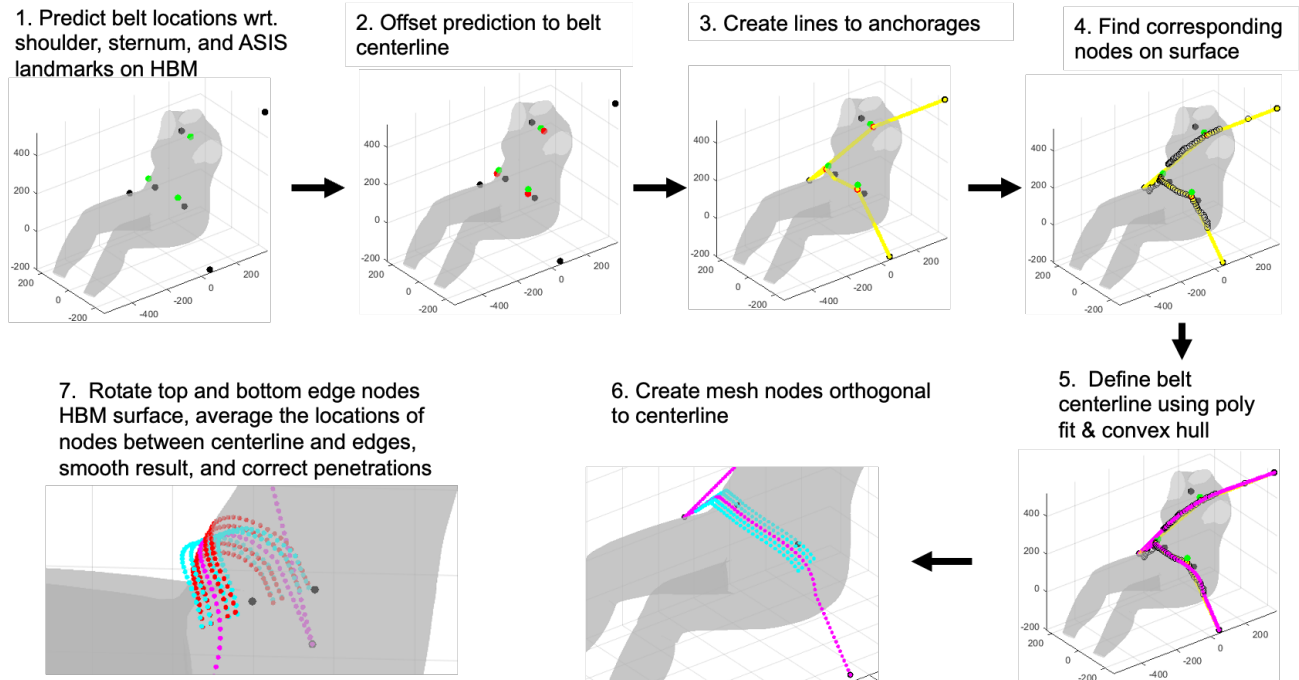


Figure 7. Demonstration of an automated belt fitting procedure based on volunteer belt fit data

Crash Condition Definition

Full vehicle kinematics from vehicle crash tests or computer simulations, as determined by instrumentation affixed to the undeformed vehicle compartment, should be extracted first. The full vehicle kinematics data will be used to define the boundary conditions of the occupant compartment model for virtual testing with HBMs. We recommend accelerometer sensors at the front and rear left/right rockers to be used to prescribe the vehicle kinematics onto the occupant compartment model.

Sampling Weight

The HBM virtual testing procedure should cover a broad set of HBMs that are not limited to the adult ATD sizes. To do so, the HBM sampling should cover populations that may not be represented by current ATDs, such as obese occupants. The number of HBMs and the associated occupant characteristics that can properly represent the entire population have been investigated in previous studies (Larsson et al., 2024, Sun et al., 2024). We also recommend combining simulation results with different HBMs based on a weighting factor of each HBM. If a limited number of HBMs are used, the weighting factor for each HBM could be simply assigned as 1. However, if a large set of HBMs are used in the virtual testing, different weighting factors will be ideal. The weighting factors should be estimated based on the number of HBMs to be used and a population probability density computed from data in the most recent U.S. National Health and Nutrition Examination Survey release (Fryar et al., 2021). Prior studies provided some examples (Zhang et al., 2017, Hu et al., 2019).

Injury Assessment

As a starting point, a virtual testing framework utilizing HBMs can apply injury measures that correspond to those available for use with ATDs. In the current framework and associated demonstration, Hybrid III ATD-based injury measures were identified for use in the HBMs. These injury measures include those for the head, neck, chest, femur, and tibia, while other body regions or non-standardized injury measures can also be monitored.

When using HBMs with sizes and shapes that differ from standard ATDs, injury risk curve scaling should be applied (e.g., as applied by Hu et al., 2019). Table 2 shows the injury risk curves and the associated scaling methods used in the demonstration of the virtual testing framework presented herein. For each simulation, injury measures for the head (HIC and BrIC), neck (force and N_{ij}), chest (deflection), femur (force), and tibia (force) are considered. The neck forces (tension and compression) and the intercepts for calculating the N_{ij} are normalized based on the size of the C1 vertebra. The chest deflection is normalized by the chest depth, which is measured from the spinal process of T8 vertebra to the mid-sternum at the fourth intercostal space. The femur and tibia forces are normalized based on the cross-sectional area of the femur and tibia as measured at the subject load cell locations.

The list of HBM injury measures applied in virtual testing can evolve (e.g., application of a new criterion) and vary based on the virtual testing condition (e.g., frontal impacts versus side or rear impacts). For example, strain-based thoracic injury risk functions developed for THUMS and detailed GHBM models are available (Kulkarni, 2022), however such injury risk curves are not readily available for all body regions and body sizes of interest, and they are currently model-specific.

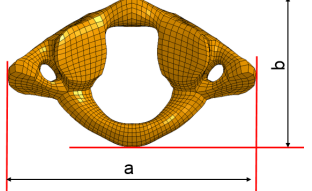
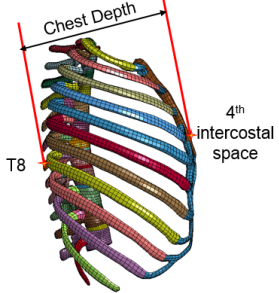
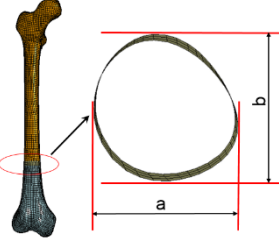
A model correction or penalty term could be potentially included to correct the HBM predictions. For example, if the model consistently overestimates the ATD chest injury risks compared to the physical tests, a ratio of chest deflections between the simulations and tests may be applied to scale the final virtual testing score. This step will potentially be useful if future field data or physical test data are available to estimate model correction terms. Alternatively, if the model error is not a systematic error, a model penalty term could be used for HBM injury measures with low correlations to the physical tests.

To use the sampling weight to combine the injury predictions from simulations, we propose to use a weighted average score as defined in Eq. 1.

$$\text{Weighted Average Score} = \sum_{i=1}^{PDOF} \sum_{j=1}^{\Delta V} \sum_{k=1}^{Occupant} \sum_{l=1}^{Other} W_{ijkl} \times P_{joint}, \quad (\text{Eq.1})$$

in which W_{ijkl} is the weighting factor for each simulation based on the PDOF, ΔV , occupant covariates, and other conditions (e.g., posture) and P_{joint} is the combined injury probability of different body regions of a HBM similar to that used in the current US-NCAP crashworthiness rating protocol. The weighting factors could be determined based on field data analysis along with computational simulations, if the virtual testing sample is large enough. If the virtual testing sample is small, equal weighting should be used for all simulations. Accordingly, equal weighting was used in the Task 2 demonstration described on the next pages.

Table 2. Injury risk curves and scaling method

Body Region	Injury Risk Curve	Scaling
Head (HIC15 and BrIC)	$\begin{cases} P_{HIC}(AIS3+) = \Phi\left(\frac{\ln(HIC15) - 7.45231}{0.73998}\right) \\ \text{where } \Phi = \text{cumulative normal distribution} \\ P_{BrIC}(AIS3+) = 1 - e^{-\left(\frac{BrIC}{0.987}\right)^{2.84}} \end{cases}$	Same injury risk curves were used for all human models
Neck (Nij, T/C in kN)	$\begin{cases} P_{Nij}(AIS3+) = \frac{1}{1 + e^{3.227 - 1.969Nij}} \\ P_T(AIS3+) = \frac{1}{1 + e^{10.9745 - 2.375T}} \\ P_C(AIS3+) = \frac{1}{1 + e^{10.9745 - 2.375C}} \\ P_{neck} = \text{Max}(P_{Nij}, P_T, P_C) \end{cases}$	 $F = F_{subject} \times \frac{a_{midsize} \times b_{midsize}}{a_{subject} \times b_{subject}}$
Chest (D in mm)	$\begin{aligned} P_{chest}(AIS3+) &= \frac{1}{1 + e^{10.5456 - 1.568 * D^{0.4612}}} \\ P_{chest/age}(AIS3+) &= \frac{1}{1 + e^{12.597 - 0.0586 * \text{Age} - 1.568 * D^{0.4612}}} \end{aligned}$	 $D = D_{subject} \times \frac{\text{Depth}_{midsize}}{\text{Depth}_{subject}}$
Femur and Lower Tibia (F in kN)	$\begin{aligned} P_{femur}(AIS2+) &= \frac{1}{1 + e^{5.795 - 0.5196F}} \\ P_{lower_tibia}(AIS2+) &= \frac{1}{1 + e^{5.795 - 0.5196F}} \end{aligned}$	 $F = F_{subject} \times \frac{a_{midsize} \times b_{midsize}}{a_{subject} \times b_{subject}}$
$P_{joint} = 1 - (1 - P_{head}) \times (1 - P_{neck}) \times (1 - P_{chest}) \times (1 - P_{femur}) \times (1 - P_{lower_tibia})$		

Task 2: HBM Virtual Testing Initial Demonstration

The goal of this task is to conduct an initial demonstration of the virtual testing using currently available tools. Both stock and morphed GHBM simplified HBMs were used for all simulations. A detailed occupant compartment model and the parametric vehicle model tuned to match the detailed vehicle geometry were used for the demonstration. For comparison purposes, GM used the detailed occupant compartment model and University of Michigan Transportation Research Institute (UMTRI) used the parametric vehicle model independently. Therefore, the HBM settling and belt fit methods between GM and UMTRI are slightly different as noted in the following sections.

GHBM HBMs

In this demonstration, we used 11 HBMs for all the crash simulations, including four stock GHBM simplified models (i.e., GHBM-F05-OS, GHBM-F50-OS, GHBM-M50-OS, and GHBM-M95-OS), and seven HBMs morphed from GHBM-M50-OS representing the same size of the four stock GHBM models as well as three obese models with BMI of 40 and stature corresponding to the midsize female, midsize male, and large male (F50-BMI40, M50-BMI40, and M95-BMI40).

Figure 8 shows the four stock GHBM simplified models, a mesh quality demonstration, and validation dataset (Elemance, n.d.).

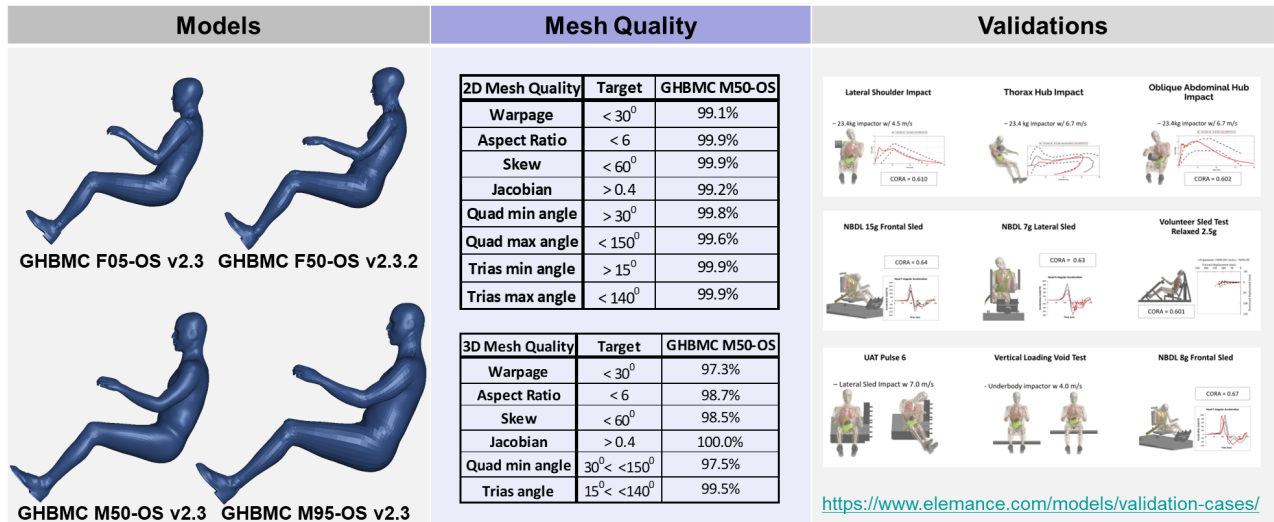


Figure 8. Stock GHBM models used in this study

Figure 9 shows the seven morphed GHBM models along with the four stock GHBM models. The detailed method for morphing the GHBM model into any given age, sex, stature, and BMI has been presented by Zhang et al. (2017) and Hu et al. (2017). For the sake of completeness, the whole-body mesh morphing method is presented briefly here. The process begins with statistical models of skeletal components, including the ribcage, pelvis, femur, and tibia, along with external body shape models of human geometry that describe morphological variations within the population as functions of age, sex, stature, and BMI. Mesh morphing methods were then used to morph a baseline human model into target geometries while maintaining high geometric accuracy and good mesh quality. Given a target sex, age, stature, and BMI, the statistical human

geometry models developed previously predict thousands of points that define the body posture (Reed et al., 2000, 2002; Park et al., 2016), the size and shape of the external body surface (Reed & Parkinson, 2008), and ribcage (Shi et al., 2014; Wang et al., 2016) and lower extremity bone geometries (Klein, 2015; Klein et al., 2015; Brynskog et al., 2021). The skeleton and external body shape geometries were integrated together based on the landmarks and joint locations shared in both skeleton and external body shape models. The integrated skeleton and body shape geometry can be found in Hu et al. (2022).³ Once the target geometries were developed, the baseline model was morphed to match the target geometries using a landmark-based 3D non-linear interpolation technique based on radial basis functions. The entire morphing process is automated and requires less than 5 minutes per model using a typical desktop computer.

As shown in Figure 9, the geometries of the stock and morphed GHBM models are slightly different despite having the same stature and BMI values. This is because the morphed GHBM models are based on the geometries predicted by the statistical human geometry model, whereas the stock GHBM models are based on individual-specific data. For example, the morphed F05 GHBM model has a slightly longer torso and shorter legs compared to the stock F05 GHBM model, while the morphed M50 GHBM model has a slightly shorter torso than the stock M50 GHBM model. Such geometric differences are referred to as residual errors associated with human population with the same covariates and will likely affect their impact responses in crash simulations.

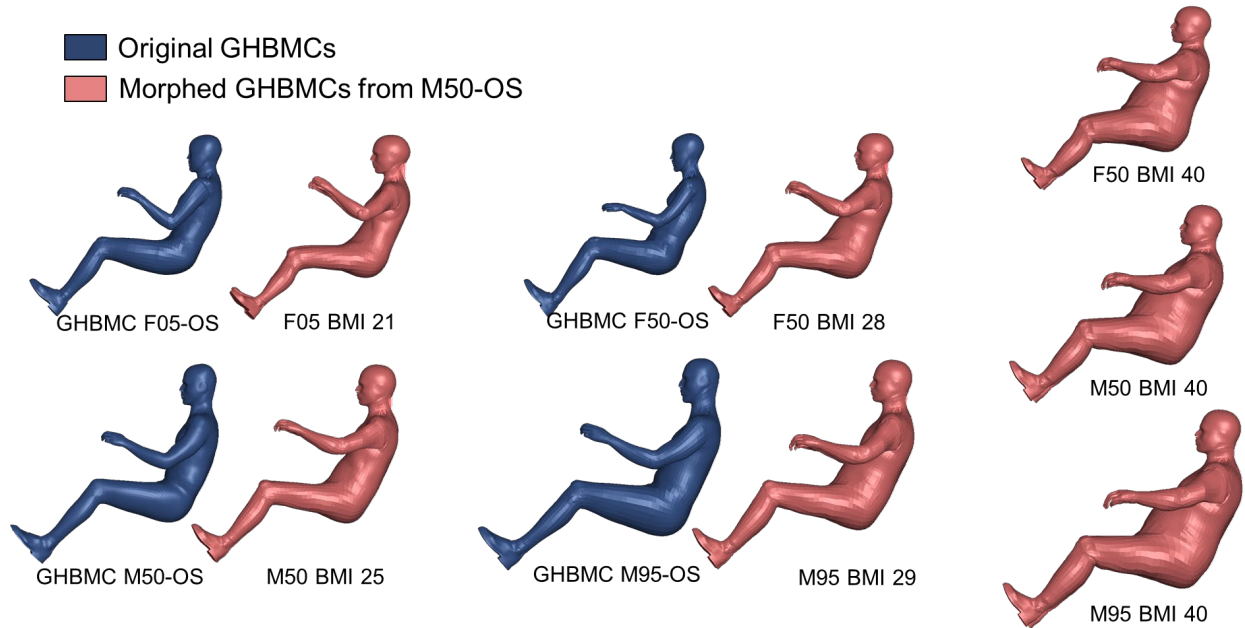


Figure 9. Stock and morphed GHBM models used in this study

Vehicle Models

In this demonstration, we used two vehicle models for comparison purposes. The first is a detailed vehicle driver compartment model as shown in Figure 10a, and the second is a

³ Working at UMTRI, Hu and colleagues (2022) developed the Human Element-based Model for Enhanced Safety trademarked as HERMES. They describe HERMES in the IRCOB paper as "the first HBM developed specifically to be morphed to a wide range of body sizes and shapes, enabling efficient population-based simulations."

parametric vehicle driver compartment model that was morphed per Boyle et al. (2024) to match the detailed vehicle geometry, as shown in Figure 10b.

The following summarizes the steps to produce the parametric vehicle driver compartment model. First, a generic vehicle driver compartment model developed by (Iraeus & Lindquist, 2016) was upgraded by including additional curtain and knee air bags. The resulting vehicle model was used as the baseline model in the morphing process. Second, a total of 23 geometric measures or locations were defined for the parametric vehicle model (documented in Boyle et al., 2024), so that the baseline model can be morphed into the target geometry. A parametric framework was developed to morph the baseline vehicle model into vehicle geometries based on the set of vehicle dimensions and measures. In this study, once the vehicle parameters were collected, they were transformed into landmarks by selecting a set of nodes related to each measurement. Then several steps of mesh morphing were conducted sequentially, so that only a small set of vehicle parts were involved in each morphing step. This allowed much of the original shape of the baseline vehicle geometry to be maintained, while meeting the target vehicle geometric measurements. Note that the seat, steering wheel and column, seat belt, and air bag geometries were kept intact in this morphing process; however, the air bag size and shape can be varied by the restraint design parameters.

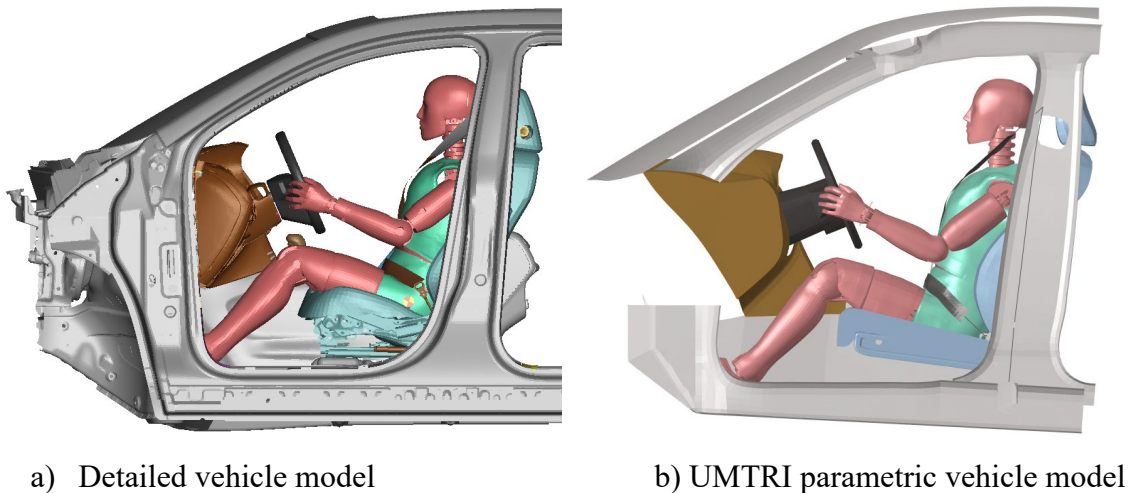


Figure 10. Two driver compartment models used in this demonstration

Figure 11 shows the morphing user interface and the geometric comparison between the detailed vehicle and the parametric vehicle models. Overall, the vehicle interior geometries look very similar.

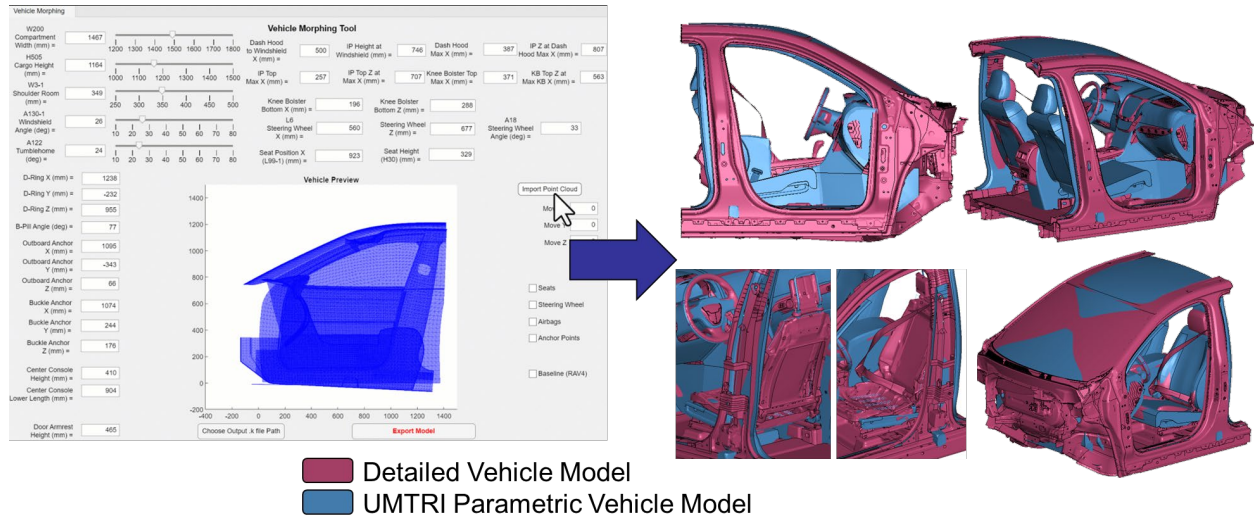


Figure 11. Geometric comparison between the detailed and parametric vehicle models

Model Validations Against Crash Tests

As shown in Figure 12 and Figure 13, the two vehicle models were validated against the HIII ATD responses in two vehicle crash tests, including a 35 mph US NCAP frontal crash test and a 20 mph frontal crash test with an unbelted HIII ATD. The detailed vehicle model was constructed based on the vehicle parameters, while the model variables of the parametric vehicle model were tuned to match the testing results. The model variables include air bag and pretension deployment times, seat belt load limit, steering column force, driver air bag diameter, inflation, vent size, and tether length, seat cushion stiffness, as well as knee bolster characteristics.

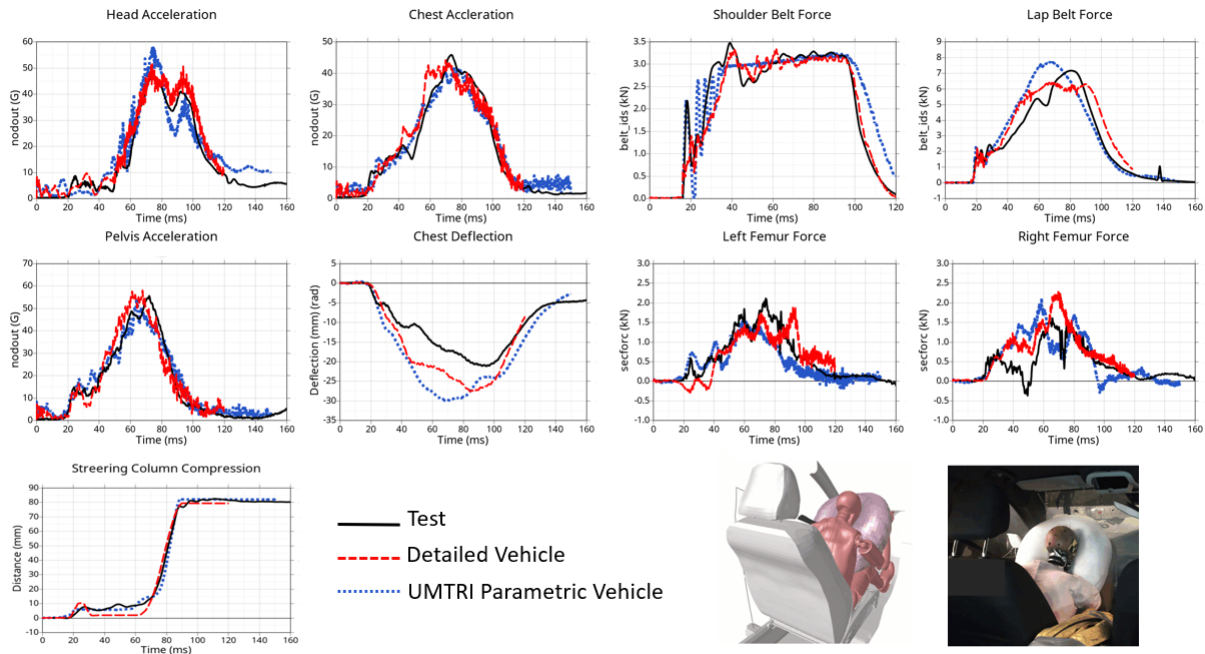


Figure 12. Model validation results against belted HIII ATD in a 35 mph frontal crash

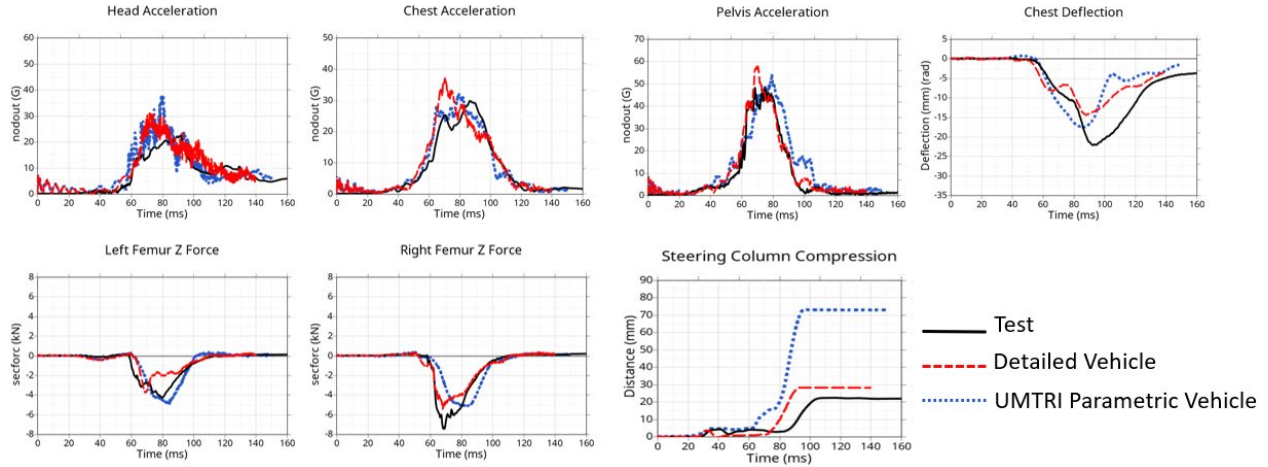


Figure 13. Model validation results against unbelted HIII ATD in a 20 mph frontal crash

Generally speaking, both the detailed vehicle model and the parametric vehicle model correlated well with the testing data. However, both models overestimated the chest deflection in the belted testing condition and underestimated the chest deflection in the unbelted testing condition. Based on our experiences, this is due to a limitation of the HIII ATD model. Furthermore, the parametric vehicle model significantly overestimated the steering column compression in the unbelted test, however this difference did not cause ATD kinematic differences between the test and the simulation. Therefore, we considered both vehicle models acceptable for the current demonstration of the virtual testing framework.

Simulation Matrix

HBMs and Setup

In this demonstration, a total of 11 HBMs were used, including four stock GHBM simplified models and seven morphed GHBM models to represent a diverse population as described previously. GM used the four stock GHBM models and three morphed obese models for all the simulations, while UMTRI used the seven morphed GHBM models for all the simulations. This setup allows us to compare the performance of the stock and morphed GHBM models with the same stature and weight across the four standard anthropometries.

In terms of the seating locations of the HBMs, both GM and UMTRI followed the UMTRI driving posture model to predict the HBM hip and eye locations. However, for the M50, F05, and M95 HBMs, GM positioned the HBMs based on the HIII ATD seating locations.

GM used the traditional pre-simulation method for HBM settling, while UMTRI used the seat squash method for HBM settling. Both methods kept the gravity-induced strain/stress in the seat, which is necessary for an accurate crash simulation. However, the pre-simulation may deform the soft tissues in the pelvis and abdomen areas, while the seat squash does not, which may result in slightly different hip locations between GM and UMTRI. To check whether such hip location difference affects occupant impact responses, UMTRI conducted additional simulations with the HBMs matching the GM HBM hip locations for comparison purposes.

Vehicle Models and Crash Conditions

GM used the detailed vehicle model for all the simulations, while UMTRI used the parametric vehicle model for all the simulations. For each vehicle model, we conducted simulations with seven HBMs under four impact conditions, including 20 mph pure frontal, 35 mph pure frontal, and 30 mph $\pm 30^\circ$ oblique impacts. This resulted in a total of 56 HBM simulations: 28 with the detailed vehicle model and 28 with the UMTRI parametric vehicle model. For comparison purposes, UMTRI conducted seven additional simulations under 35 mph pure frontal condition with the HBMs' hip locations matching the GM locations. Table 3 summarizes the similarities and differences between the GM and UMTRI simulation conditions.

Table 3. Summary of GM and UMTRI simulation conditions

	GM	UMTRI
HBM (Figure 9)	4 stock GHBM models and 3 morphed obese GHBM models	7 morphed GHBM models
Vehicle (Figure 10)	Detailed vehicle model	Parametric vehicle model
Seating location and settling	F05, M50, and M95 based on ATD locations, others HBMs based on UMTRI location with gravity settling	UMTRI seating locations with seat squash settling 7 additional simulations at 35 mph to match GM HBM hip locations
Belt fit	Conventional belt fit	UMTRI volunteer data
Crash pulse	35mph frontal, 20mph frontal, 30mph near-side and far-side oblique 30°	

Injury Assessment

In this demonstration, HBM injury assessment followed Eq.1 proposed in the virtual testing framework. However, BrIC was not considered in this demonstration to keep Pjoint more consistent to the current US-NCAP. Nij was not used for neck injury assessment because the injury risk is not zero at zero Nij and the neck/cervical spine has the lowest risk of injury in field crashes compared to other body regions. No injury risk correction was used due to the lack of proper correction terms, and equal weighting was used for all simulations due to the small sample size.

Simulation Results

Occupant Kinematics

Model-predicted occupant kinematics are demonstrated in Table 4 to Table 6, in which HBM motions at the 100 ms are shown. The head and hip excursions are provided in the Appendix. It should be noted that the detailed vehicle model run by GM used four stock GHBM models and three morphed obese models, while the UMTRI parametric vehicle model used seven morphed GHBM models. Therefore, the geometries of the four non-obese HBMs (F05, F50, M50, and M95) are also different between the detailed and parametric vehicle models. The HBM settling methods are different between the GM and UMTRI simulations as well, which led to slightly different HBM hip locations. At the 35 mph pure frontal crash condition, three simulations are shown for each HBM in Table 4, representing the detailed vehicle model (left), UMTRI parametric vehicle model with HBM matching the GM hip location (middle), and UMTRI

parametric vehicle model (right). At other crash conditions, only two simulations are shown in Table 5 and Table 6 for each HBM, representing the detailed vehicle model (left) and UMTRI parametric vehicle model (right).

At 35 mph, different HBMs show significantly different kinematics and hazardous contacts; however, kinematics for the same size of HBMs are generally consistent between the detailed and parametric vehicle models, regardless of the HBM hip location. For example, the M95 and M95-obese models show signs of striking-through the air bag due to the higher head excursions, and the three obese HBMs show significant knee-to-bolster contacts, which may increase the lower extremity injury risks. The largest kinematic difference between the detailed and parametric vehicle models is in the F50-obese model, where the F50-obese model submarined in the detailed vehicle model but not in the parametric vehicle model. After a detailed review of the case, we found that different HBM settling methods resulted in slight changes in abdomen geometry, and the lap belt location in the detailed vehicle model is higher than that in the parametric vehicle model. Consequently, the F50-obese model in the detailed vehicle model is subject to a higher submarining risk than in the parametric vehicle model. The F05 model in the detailed vehicle model shows more lower extremity excursions than in the parametric vehicle model, which is related to the slightly higher lap belt position and the greater downward motion of the HBM in the detailed vehicle model.

At 20 mph the kinematics of different HBMs show similar trends as compared to the 35-mph condition, such as higher head excursions in tall HBMs and higher lower extremity excursions in obese HBMs. The kinematics for the same HBM between the detailed vehicle model and the UMTRI parametric vehicle models are consistent without any obvious difference, except that the F50-obese model submarined due to a poor lap belt fit.

In the 30 mph oblique crash conditions, the HBM kinematics are similar to those in the pure frontal crashes with slight lateral motion of the torso and sometimes a head rotation. The M95 model stroked through the air bag in the detailed vehicle model, but not in the UMTRI parametric vehicle model. The F50-obese model submarined in both the near-side and far-side oblique crashes similar to what occurred in the 35 mph pure frontal crash condition. In the near-side oblique crashes, the HBM head sometimes rotated to the left in the parametric vehicle model due to the interaction with the curtain air bag, while it did not occur in the detailed vehicle model.

Table 4. Occupant kinematics at 100 ms in the 35 mph pure frontal crash

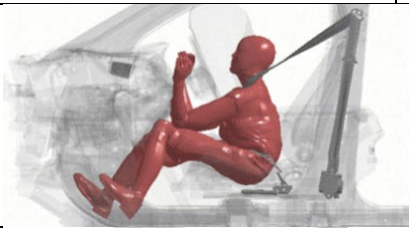
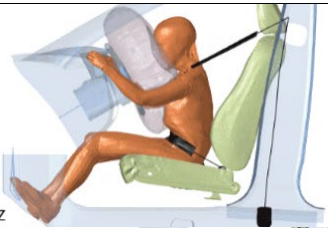
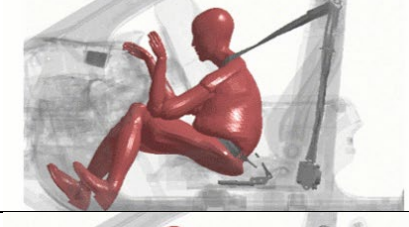
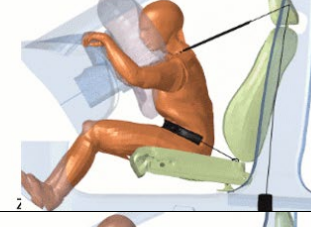
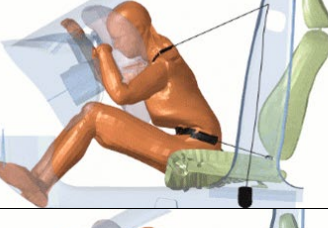
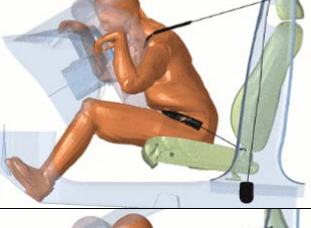
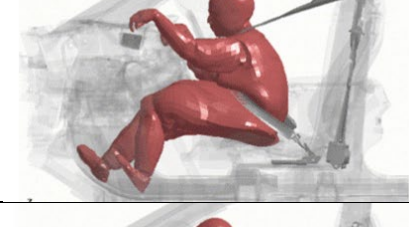
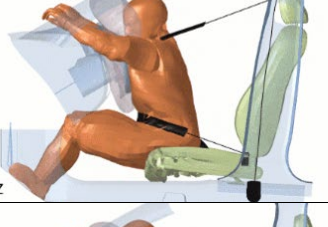
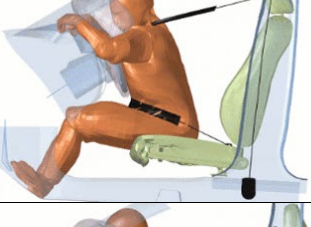
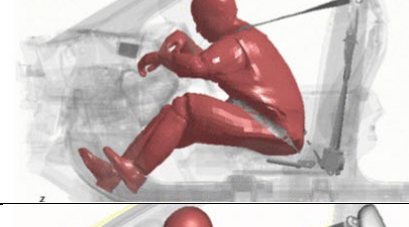
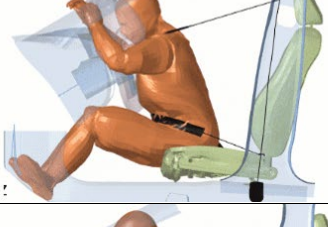
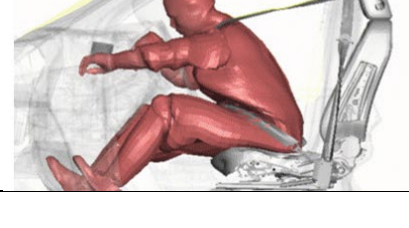
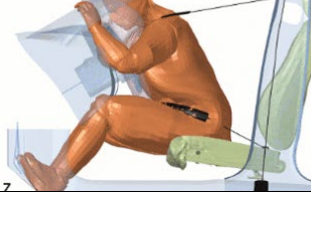
	GM Detailed Vehicle Model	UMTRI Parametric Vehicle Matching GM Hip Location	UMTRI Parametric Vehicle
F05			
F50			
M50			
M95			
F50-Obese			
M50-Obese			
M95-Obese			

Table 5. Occupant kinematics at 100 ms in the 20 mph pure frontal crash

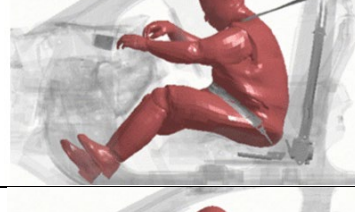
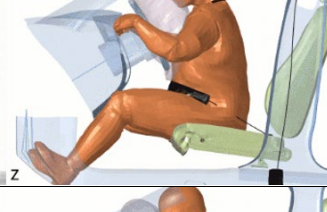
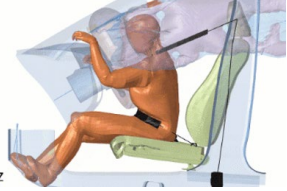
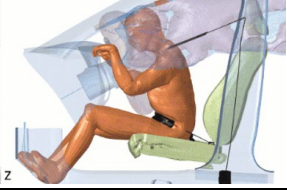
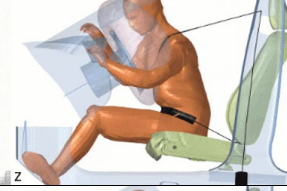
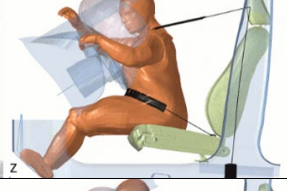
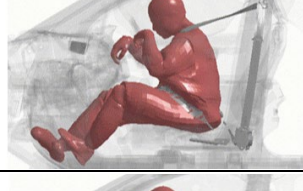
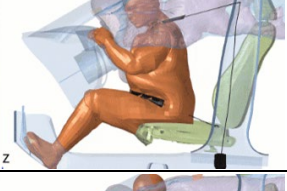
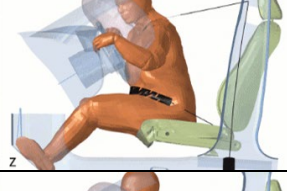
	GM Detailed Vehicle Model	UMTRI Parametric Vehicle
F05		
F50		
M50		
M95		
F50-Obese		
M50-Obese		
M95-Obese		

Table 6. Occupant kinematics at 100 ms in the 30 mph oblique frontal crash

	Near-Side Oblique 30°		Far-Side Oblique 30°	
	GM Detailed Vehicle Model	UMTRI Parametric Vehicle	GM Detailed Vehicle Model	UMTRI Parametric Vehicle
F05				
F50				
M50				
M95				
F50-Obese				
M50-Obese				
M95-Obese				

Occupant Injury Measures and Injury Risks

The model-predicted occupant injury measures in all HBM and crash conditions are shown in Table 7, where high HIC values due to air bag strike-through and high femur forces due to submarining are highlighted.

Table 7. Occupant injury measures predicted by the HBMs

		GM Detailed Vehicle Model							UMTRI Parametric Vehicle Model						
35 mph Frontal		F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob	F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob
	HIC15	338	329	211	924	185	212	283	365	289	263	1127	286	348	1889
	Sternum Def.	51.5	52.7	48.7	55.1	52.6	58.4	59.4	53.4	54.0	55.2	57.2	48.6	56.3	60.4
	Femur Force	2.32	1.97	3.84	2.85	7.38	7.24	7.59	1.21	2.80	2.85	5.20	4.44	6.24	8.57
	Lower Tibia Force	3.72	3.73	3.77	3.22	4.65	3.4	4.6	1.53	3.06	2.77	3.71	3.55	3.23	5.46
20 mph Frontal		F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob	F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob
	HIC15	326	211	87	96	112	73	79	435	272	246	215	228	215	243
	Sternum Def.	53.7	55.4	45.8	44.1	47.8	50.2	50.2	56.1	54.1	54.2	52.1	50.6	58.6	57.5
	Femur Force	2.46	1.9	3.05	0.7	5.48	6.8	7.15	1.36	3.11	3.19	5.42	4.22	4.18	5.96
	Lower Tibia Force	3.29	3.89	3.99	3.48	3.8	2.87	4	1.04	3.75	3.26	3.08	3.14	2.18	3.67
30 mph Near-side Oblique		F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob	F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob
	HIC15	400	305	184	1306	300	286	222	322	249	238	247	254	265	254
	Sternum Def.	52.8	53.6	46.6	40.9	52.7	46	47.1	54.7	53.2	54.1	50.8	42.8	49.0	53.1
	Femur Force	2.07	1.38	3.52	3.11	7.72	9.1	10.2	0.98	2.38	2.85	5.19	4.33	5.26	6.24
	Lower Tibia Force	1.63	3.07	2.74	4.15	2.37	3.07	4.16	0.75	1.42	1.95	2.55	1.47	3.16	3.82
30 mph Far-side Oblique		F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob	F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob
	HIC15	348	516	224	470	218	158	146	345	281	252	369	219	390	519
	Sternum Def.	52.7	58.7	49.2	45.5	54.1	60.1	56.4	56.4	54.3	54.2	55.5	53.3	60.7	61.5
	Femur Force	2.65	2.86	2.96	1.89	6.32	5.95	6.59	1.45	2.36	2.61	3.94	3.15	2.83	4.07
	Lower Tibia Force	3.49	2.99	3.58	3.32	4.8	6.46	7.32	2.27	3.20	2.15	2.52	2.77	1.87	2.67
		Detailed Vehicle Model							UMTRI Parametric Vehicle Model						
35 mph Frontal		F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob	F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob
	HIC15	338	329	211	924	185	212	283	365	289	263	1127	286	348	1889
	Sternum Def.	51.5	52.7	48.7	55.1	52.6	58.4	59.4	53.4	54.0	55.2	57.2	48.6	56.3	60.4
	Femur Force	2.32	1.97	3.84	2.85	7.38	7.24	7.59	1.21	2.80	2.85	5.20	4.44	6.24	8.57
	Lower Tibia Force	3.72	3.73	3.77	3.22	4.65	3.4	4.6	1.53	3.06	2.77	3.71	3.55	3.23	5.46
20 mph Frontal		F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob	F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob
	HIC15	326	211	87	96	112	73	79	435	272	246	215	228	215	243
	Sternum Def.	53.7	55.4	45.8	44.1	47.8	50.2	50.2	56.1	54.1	54.2	52.1	50.6	58.6	57.5
	Femur Force	2.46	1.9	3.05	0.7	5.48	6.8	7.15	1.36	3.11	3.19	5.42	4.22	4.18	5.96
	Lower Tibia Force	3.29	3.89	3.99	3.48	3.8	2.87	4	1.04	3.75	3.26	3.08	3.14	2.18	3.67
30 mph Near-side Oblique		F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob	F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob
	HIC15	400	305	184	1306	300	286	222	322	249	238	247	254	265	254
	Sternum Def.	52.8	53.6	46.6	40.9	52.7	46	47.1	54.7	53.2	54.1	50.8	42.8	49.0	53.1
	Femur Force	2.07	1.38	3.52	3.11	7.72	9.1	10.2	0.98	2.38	2.85	5.19	4.33	5.26	6.24
	Lower Tibia Force	1.63	3.07	2.74	4.15	2.37	3.07	4.16	0.75	1.42	1.95	2.55	1.47	3.16	3.82
30 mph Far-side Oblique		F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob	F05	F50	M50	M95	F50-Ob	M50-Ob	M95-Ob
	HIC15	348	516	224	470	218	158	146	345	281	252	369	219	390	519
	Sternum Def.	52.7	58.7	49.2	45.5	54.1	60.1	56.4	56.4	54.3	54.2	55.5	53.3	60.7	61.5
	Femur Force	2.65	2.86	2.96	1.89	6.32	5.95	6.59	1.45	2.36	2.61	3.94	3.15	2.83	4.07
	Lower Tibia Force	3.49	2.99	3.58	3.32	4.8	6.46	7.32	2.27	3.20	2.15	2.52	2.77	1.87	2.67

Note: The **red bold** font highlights higher HIC values due to air bag bottoming out and higher femur forces due to submarining. For the femur and lower tibia forces, only the max values are shown.

Figure 14 shows the injury risk comparison of different body regions for all HBMs between the detailed vehicle model and the UMTRI parametric vehicle model in all four crash conditions. The detailed vehicle model and the UMTRI parametric vehicle model show consistent pattern in injury risks with respect to the body region. In particular, the head injury risks are low across different HBMs and crash conditions, except for the air bag bottoming out cases (2 in detailed vehicle model and 2 in UMTRI parametric vehicle model) described previously. The chest injury risk is the highest among all body regions for the majority of HBM and crash conditions, and F05 and F50 models have higher chest injury risks compared to other HBMs regardless of the vehicle model and crash condition. The primary contributor to chest deflection is the seat belt load, which is not a variable of crash severity. The three obese models sustained higher femur injury risks than those in non-obese HBMs in both vehicle models and all crash conditions. The lower tibia injury risks show the least consistent results between the two vehicle models, especially in the 30 mph far-side oblique crash condition. However, both vehicle models suggested that female and/or obese occupants tend to have higher lower tibia injury risks.

Figure 15 and Figure 16 compare the Pjoint values between the two vehicle models by crash condition and by HBM, respectively. The two vehicle models show similar Pjoint values between the two vehicles in each crash condition without statistically significant differences. However, if the comparison is based on HBMs, the M50 and F50-obese models show statistically significant differences in the predicted Pjoint values. The M50 model used by UMTRI is the morphed model and predicted slightly higher chest deflection in all crash conditions than the stock GHBM M50 model used by GM. Because chest injury risk dominated the Pjoint for M50, the Pjoint of the UMTRI parametric vehicle model is higher than that of the detailed vehicle model. Regarding the F50-obese model, the detailed vehicle model is associated with submarining in all crash conditions due to the poor belt fit. Consequently, the F50-obese model in the detailed vehicle model is associated with a higher Pjoint than that in the parametric vehicle model.

By combining all the HBMs and crash conditions together, the Pjoint for the detailed vehicle model is $44.1\% \pm 11.5\%$, while the Pjoint for the UMTRI parametric vehicle model is $42.5\% \pm 11.3\%$. These results suggest that the two vehicle models provide consistent overall injury risk predictions when all cases are combined.

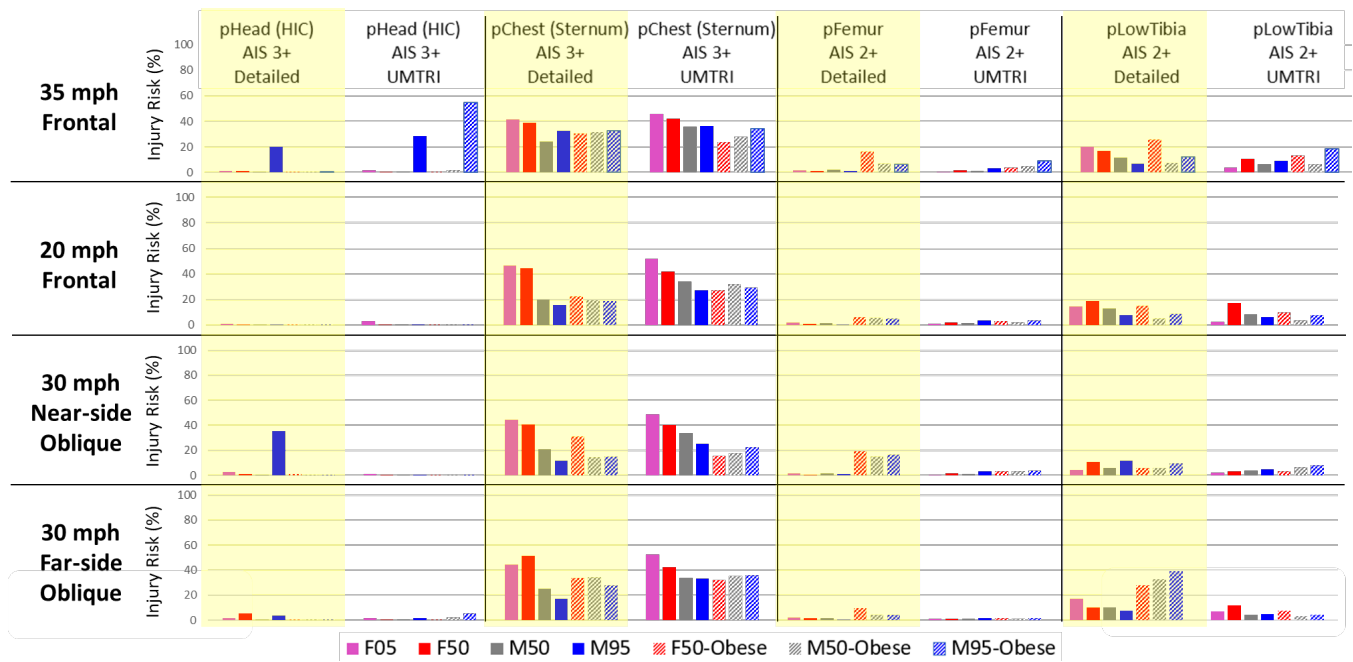


Figure 14. Occupant injury risks for different body regions across all HBMs and crash conditions

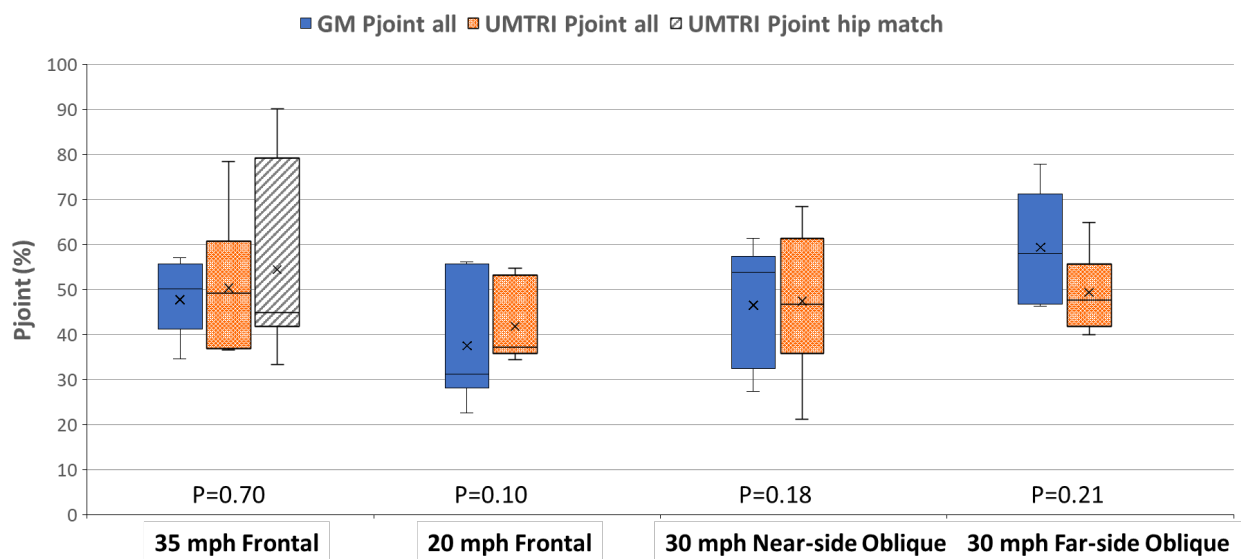


Figure 15. Pjoint comparison between the two vehicle models, grouped by crash conditions
P-values are based on the ANOVA and student T-test.

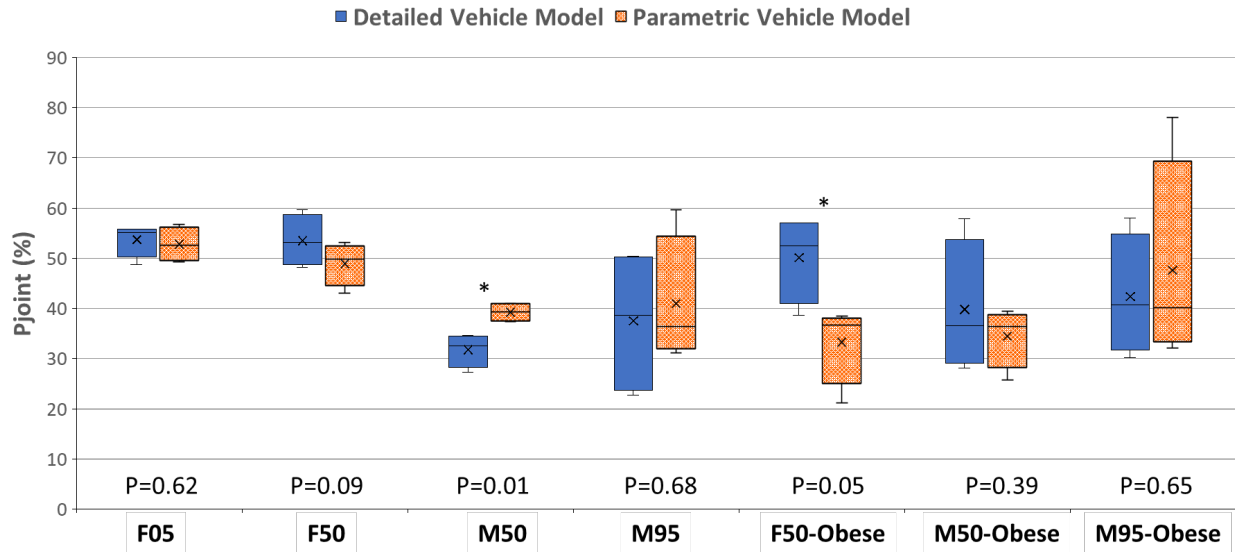


Figure 16. *Pjoint* value comparison between the two vehicle models, grouped by HBMs
P-values are based on the student *T*-test.

Time Frame

Through the initial demonstration process, we gained a solid understanding of the time it took to evaluate a single vehicle using the proposed virtual testing framework. The time required is dependent on the number of HBMs and crash conditions, so the time reported below is based on a total of seven HBMs across four different crash conditions using the detailed vehicle model at GM and using the parametric vehicle model at UMTRI.

At GM, with an experienced engineer, it takes approximately half a day to extract needed components - seat, steering wheel, gas pedal, and footrest - from the sled model for HBM settling simulation. Each HBM requires a few hours to set up for both the settling and crash simulations, followed by one day for running the simulations and result extraction. At this stage, the estimated virtual testing time frame is within weeks for experienced engineers.

At UMTRI, the process to morph the parametric vehicle model into the target geometry is automated, so the time required is for the geometry measures and visual inspection of the geometry match, which is approximately a couple of hours. The HBM positioning, settling and belt fitting processes are fully automated, thus it should be done in minutes. The simulation time depends on the simulation numbers and the number of cores used, but result extraction is also automated. Considering all the steps, the estimated virtual testing time frame is within a few days at UMTRI.

Discussion

General Trends

In this study, we developed a HBM virtual testing framework and used two vehicle models along with 11 HBMs to demonstrate the effectiveness of the framework. For comparison purposes, the simulations conducted by GM utilized the detailed vehicle model, four stock GHBMC simplified adult models and three morphed obese models, pre-simulation HBM settling, and manual belt fitting; while the simulations conducted by UMTRI are with the parametric vehicle model, seven morphed GHBMC models, seat squash HBM settling, and automated belt fitting.

Considering all the differences between the GM and UMTRI simulations, we found that the occupant kinematics are largely consistent between the GM and UMTRI simulations with the only exception being the F50-obese case. For the F50-obese case, GM positioned the lap belt at a higher location than that in the UMTRI parametric vehicle model. As a result, the occupant submarined in all simulated cases. This finding indicates that the seat belt location needs to be controlled more accurately in the virtual testing framework to achieve consistent simulation results, especially for obese occupants. It should be noted that among the three obese HBMs, only the F50-obese HBM showed significant differences between the GM and UMTRI simulations.

We also found that the general trends in the injury risk predictions among different HBMs and across various body regions are consistent between the GM and UMTRI simulations with the exception being the M50 and F50-obese cases. The injury risk difference in the F50-obese model is due to the lap belt location and submarining kinematics, which has been explained previously. The injury risk difference in the M50 model is mainly due to the model geometric differences that induced higher chest injury risks in the UMTRI model. Specifically, GM used the stock GHBMC M50 model, while UMTRI used a morphed GHBMC model based on the statistical geometry predictions for the M50. In other words, the GM model represents a specific person with the M50 stature and weight, while the UMTRI model represents a population average at M50. This result indicates that HBMs with the same stature, weight, and material properties could sustain geometric differences as residual errors in the statistical geometry model.

Despite all the differences mentioned above, the weighted average P_{joint} for the detailed vehicle model ($44.1\% \pm 11.5\%$) and the UMTRI parametric vehicle model ($42.5\% \pm 11.3\%$) are very similar.

Robustness and Reproducibility

Among all the simulations, neither GM nor UMTRI experienced any error termination after minor adjustments to the shoe null shell thickness, demonstrating that both the detailed vehicle model and the parametric vehicle model along with the stock and morphed GHBMC models are robust in the selected crash conditions. However, the robustness in other crash conditions needs further investigation. Model reproducibility was evaluated by comparing the same HBM model results calculated by UMTRI and GM. The calculated weighted average virtual testing scores are similar, while the P_{joint} for each simulation varied by HBM and body regions. The reproducibility can be improved by using the automated belt fitting algorithm, which can effectively eliminate the belt location variations on the same HBM.

Limitations and Future Work

One of the main goals of this study is to determine whether a parametric vehicle model can be used for future vehicle virtual testing safety evaluation. The simulation results are encouraging, because the parametric vehicle model and the detailed vehicle model showed consistent occupant kinematics and injury risk predictions for the majority of the simulated cases. However, we identified a few limitations in the current parametric vehicle models. First, the steering column sometimes behaves differently compared to the detailed vehicle model in terms of the stroke, as shown in the unbelted ATD validation case, although it did not seem to significantly affect the occupant injury risks. Second, the knee bolster in the parametric vehicle model is a simple surface with contact characteristics, which can be improved. Since the belted ATD does not contact the knee bolster in the majority of vehicles in US-NCAP frontal crash tests, the knee bolster will not be properly validated by the belted ATD crash test alone. In this study, an unbelted ATD crash test was used to further validate the knee bolster model. We believe that this is necessary, because all the HBM simulations resulted in occupant knee-to-bolster contacts. Third, the vehicle seat model in the parametric vehicle model is not parametric (lack of cushion springs, anti-submarining bar, etc.), which should be improved in the future, although the seat effect on occupant injury risks is not significant based on the current simulations. Last, the curtain air bag used in the oblique impacts is not validated against any physical testing, which can be improved in the future. Future studies should explore a variety of vehicle models to validate the robustness of the parametric vehicle modeling framework and to assess the sensitivity of HBMs to variations across different vehicle designs.

The model validation processes for both the detailed and parametric vehicle models are based on expert opinions rather than true parameter optimizations using quantitative metrics. While this approach provides an efficient means of validating vehicle models, future work should investigate the feasibility of semi-automated validation through optimization techniques driven by objective functions, such as CORA, BioRank, ISO 18571-2022. Achieving this will require consensus on the selection of appropriate objective functions as well as on methods for aggregating scores across different test measurements.

In this study, for comparison purposes, we used the four stock GHBM models in the detailed vehicle model and four morphed GHBM models with the same statures and weights in the UMTRI parametric vehicle model. Although the Pjoint values are generally consistent between the two sets of HBMs, it is evident that even with the same stature and body weight the HBMs exhibit differences in geometries, particularly in sitting height and fat percentage. Therefore, we recommend that future HBMs better define occupant characteristics by at least including sitting height. In addition, the morphed HBMs may be further improved with subject-specific model validation when more PMHS tests become available.

In this study we only used seven occupant sizes/shapes and four crash conditions. As a result, the same weighting factor was applied to all simulations. To properly represent the entire population, previous studies have suggested that seven to 10 occupants of each sex should be used (Larsson et al., 2024; Sun et al., 2024). Therefore, a larger sample size of HBMs and crash conditions may be considered in the future to properly represent the whole population.

This study only used GHBMC simplified models for the demonstration purposes. It is not clear how other HBMs, such as THUMS and SAFER would perform under similar conditions. The results presented here are solely based on GHBMC models and cannot be generalized for other HBMs.

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Conclusions

In this study we developed a virtual testing framework for vehicle occupant protection evaluation using HBMs and performed an initial demonstration of the proposed virtual testing framework. The proposed virtual testing framework is intended for the broader safety research community to facilitate occupant protection assessment. Our main goals were to compare the performance of the detailed vehicle and parametric vehicle model, and to evaluate the feasibility and robustness of the virtual testing framework. We used 11 HBMs in seven sizes/shapes and four crash conditions, resulting in 28 crash simulations using the detailed vehicle model and 35 simulations using the parametric vehicle model for the demonstration. Based on the simulation results, we found that the detailed vehicle model and the parametric vehicle model provided consistent predictions for occupant kinematics and injury risks with some discrepancies in a few isolated cases. Despite the differences in the HBMs' geometries, settling methods, and belt fitting methods between the detailed vehicle model and the parametric vehicle model, the two vehicle models showed similar overall weighted average injury risks (Pjoint of $44.1\% \pm 11.5\%$ vs. $42.5\% \pm 11.3\%$). This study highlights the potential of the HBM virtual testing framework for occupant protection assessment while identifying limitations and areas for future improvement.

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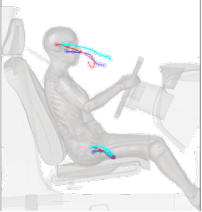
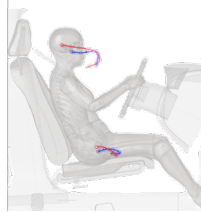
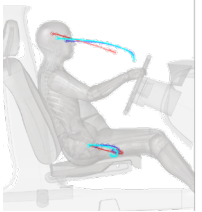
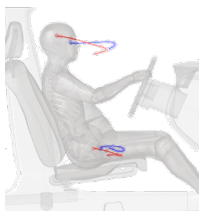
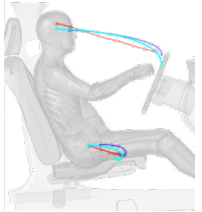
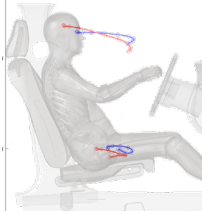
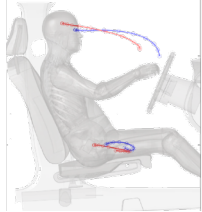
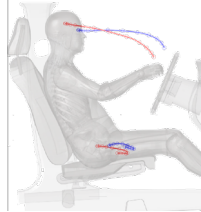
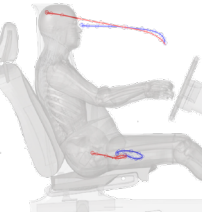
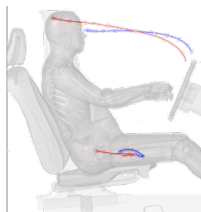
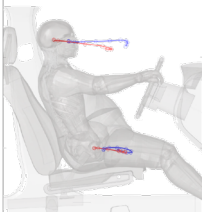
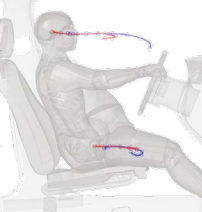
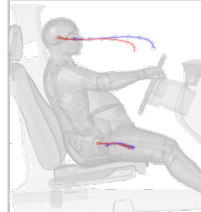
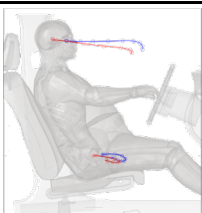
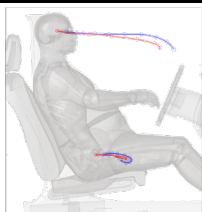
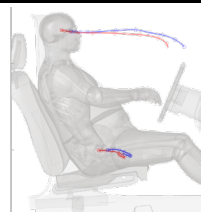
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**Appendix A. GM and UMTRI Model-Predicted Head and Hip Excursions
in Different Conditions**

	35mph	20mph	Near-Side Oblique 30°	Far-Side Oblique 30°
F05				
F50				
M50				
M95				
F50-Obese				
M50-Obese				
M95-Obese				

----- GM, ----- UMTRI, ----- UMTRI Hip Match

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