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Task Implementation Plan

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1. Background

The current design process for vehicle safety systems relies heavily on impact conditions defined by the Federal Motor Vehicle Safety Standards (FMVSS), Insurance Institute for Highway Safety (IIHS), and US New Car Assessment Program (US-NCAP). The majority of these crash conditions use anthropomorphic test devices (ATDs) that are in a standard driving position, i.e., seated nominally with a seat back angle ~25 degrees from vertical. In contrast, highly- and fully-automated vehicle concepts have included adaptable seat configurations with seats that recline by 60 degrees or more. It is therefore expected that occupants in highly- and fully-automated vehicles will be more frequently seated in a reclined posture in severe crashes.

Reclined passengers exhibit different biomechanical and injury responses in motor vehicle crashes (MVC) than nominally-seated, forward-facing passengers. Studies of crash data suggest that reclined occupants have greater mortality in MVC than normally seated occupants (Dissanaike et al., 2008), and that they can be severely injured even in low-speed crashes (Richards et al., 2006). Although reclined posture may contribute to the kinematic phenomenon known as submarining, in which the occupant slides underneath the lap belt and the lap belt deforms the abdomen (Tang and Liu, 2012), most laboratory studies examining submarining have positioned the subject in a posture that is similar to the standard driving posture (Luet et al., 2012) or used boundary conditions not representative of frontal crashes (Kim et al., 2015; Uriot et al., 2006; Steffan et al., 2002). Given that current restraint systems are validated and tested with an occupant surrogate forward-facing in a normal seated posture, improved restraint systems may be needed to provide equivalent protection to passengers in nonstandard postures. Studies on the kinematic, biomechanical, and injury response of passengers seated in alternative postures under consideration for automated vehicles are therefore critically needed to develop appropriate injury assessment tools and safety systems. The new data will also apply to passenger seating positions in non-automated vehicles that include reclining or rear-facing capability.

2. Research Objectives

The objective of the study is to collect kinematic response and injury data for occupants in non-traditional seating configurations that may be present in automated vehicles, with a focus on highly reclined occupants. We will gather data for men close to 50^{th}-percentile targets for stature and weight. We will use the collected data to develop biofidelity corridors and, in an optional task, injury criteria applicable to midsize-male surrogates (i.e., 50^{th}-percentile male THOR ATD). In optional tasks, the biofidelity of the THOR ATD and GHBMC finite element (FE) human body model (HBM) in the relevant situations will be assessed against the PMHS-derived biofidelity corridors using matched testing and simulation. This work will be conducted in collaboration with the Medical College of Wisconsin (MCW), who was awarded Phase II of the project. The primary outcome of this research will be a cohesive dataset that can be 1) used for future validation of ATDs and human body models (HBMs), and 2) easily replicated for future PMHS tests.

The following major tasks will be performed:

- Conduct PMHS sled tests to determine kinematic response and injury of mid-size male occupants in reclined postures exposed to frontal (zero-degree) crash pulses.
- Construct biofidelity corridors derived from the PMHS data to assess ATD and HBM biofidelity, including biomechanically appropriate metrics, such as multi-point chest deflection, belt loads, head kinematics, spine kinematics, and/or others.
- Optional: Perform matched-pair tests using the THOR 50^{th}-percentile-male ATD, and assess the biofidelity of the ATD against the PMHS corridors.
- Optional: Carry out matched simulations using the GHBMC 50^{th}-percentile-male FE model and assess the biofidelity of the model against the PMHS corridors.

- Optional: Develop injury criteria (head, neck, spine, thorax, abdomen, and/or others) relevant to the THOR ATD using the matched data from the PMHS and THOR ATD tests.
- Optional: Conduct PMHS sled tests to determine kinematic and injury responses of midsize male occupants in reclined postures exposed to alternative principal direction of force (PDOF) crash pulses.

3. Research Plan

3.1 Task 1: Project Management

Dr. Matt Reed serves as project PI and will contribute to all phases of the research effort. Dr. Lauren Zaseck is the technical contact for the Task Order, and will oversee the PMHS testing. Dr. Jingwen Hu will oversee the human body modeling efforts for the project. Dr. Jonathan Rupp will serve as a consulting Project Manager to support experimental design, analysis of data, and dissemination of research results. Communication between Drs Reed, Zaseck, and Hu will be frequent in-person contact as needed. Communication with Dr. Rupp will consist of weekly conference calls, and additional discussions over e-mail or telephone as needed.

A kick-off WebEx meeting was held with NHTSA on October 10, 2018. At this meeting, UMTRI presented initial plans for conducting the tests. Collaboration with the Medical College of Wisconsin (MCW), who was awarded Phase II of the project, was discussed along with the timeline for project deliverables and milestones.

A public workshop to discuss the research plans was held at UMTRI on November 27, 2018. In attendance was the project COR (TO) and other NHTSA personnel; the project's Phase II Principal Investigator and key technical personnel from MCW; and representatives from government, industry, and other academic institutions. Approximately 55 people were in attendance and approximately 40 additional people participated via WebEx. Initial test plans for Phase I and Phase II of the project were presented by UMTRI and MCW, respectively, with subsequent discussion with meeting attendees. Attendees provided input on numerous aspects of the project, including design of the test buck, specimen selection and instrumentation, and test matrix. Comments were also invited via e-mail. Select comments from the workshop, in addition to comments received via email, are included in this Test Plan as an attachment. In general, attendees supported the idea of MCW and UMTRI collaborating throughout the project. Attendees also agreed that sled buck design, restraints, and instrumentation should be as reproducible and well-characterized as possible so that the test series can be repeated or used in validation of ATDs and human body models. Attendees also commented that although a knee bolster would likely not be a feature in final automated vehicle designs, not including a bolster in the test series may lead to excessive specimen translation and unwanted damage to both the specimen and instrumentation. It was also agreed that oblique tests should be reserved for a later Phase of the project. A range of comments were received regarding the range of occupant postures and restraint system configuration that should be used, and thus no consensus was made regarding those aspects of the test plan during the workshop. Attendees suggested that instrumentation be sufficient to identify specimen submarining, and that submarining be well-characterized and defined. Comments received during the workshop have been incorporated throughout this Task Implementation Plan.

UMTRI will arrange future meetings with the Contracting Officer (CO), Contracting Officer Representative (COR), and supporting NHTSA technical staff, which will include the following:

- Monthly web conference using an internet conferencing tool (i.e., Webex) to discuss the progress of the project.

- Mid-term review (by April 1st, 2020 at UMTRI) to review progress, and discuss the conduct of the sled tests, with UMTRI providing briefing materials in advance and giving a presentation at the meeting.
- Final review (by October 1st, 2021 at NHTSA HQ) to review the ATD and PMHS test results, HBM simulations, and developed injury criteria.

3.2 Task 2: Implementation Plan

The COR (TO) will review this draft Task Implementation Plan within ten days and UMTRI will make any requested modifications within ten days. Any subsequent edits to the Plan will be submitted to the COR (TO) via email for review. We anticipate that the plans outlined in this document will be reviewed with NHTSA as data become available from simulations and physical testing.

3.3 Task 3: Sled Buck Fabrication

A custom sled buck assembly will be constructed for the PMHS and ATD tests (Figure 3.1). The sled buck was designed using input from NHTSA and comments received from attendees at the public workshop. The sled buck assembly consists of a single spring-controlled seat, open seat back, 3-point restraint, and knee bolster. The test rig can be rotated to achieve input pulses with any principal direction of force (PDOF).

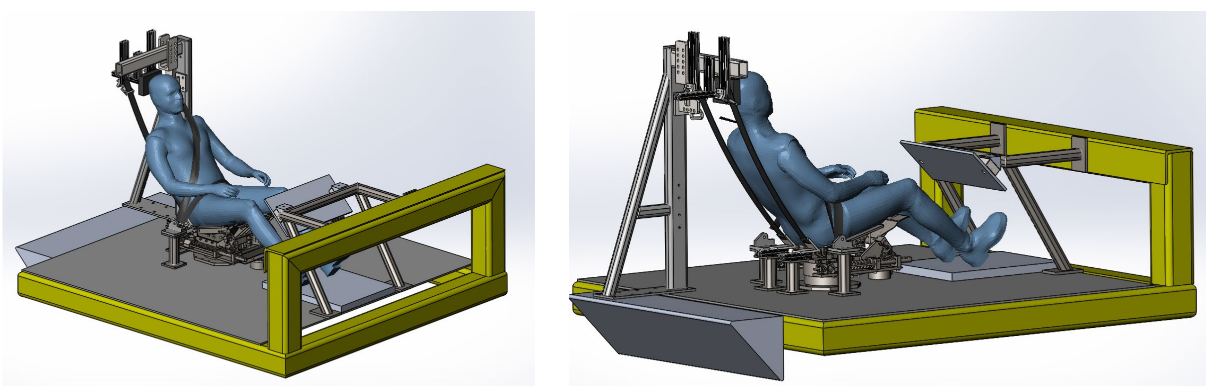


Figure 3.1. Oblique front (left) and oblique rear (right) views of the testing sled buck assembly to be used for the PMHS and ATD testing.

The test seat (Figure 3.2) was selected based on input from NHTSA, comments received during the public workshop, and a literature review of previous studies examining PMHS submarining. To aid in achieving the primary outcome of this research, the test seat must be well characterized, constructed of materials that will be available for future studies, and have geometry and material characteristics that are easily modeled. The seat selected for the present work is a spring-controlled seat based on a design developed at The Laboratory of Accidentology and Biomechanics (LAB) in France (Uriot et al., 2015). The seat was originally developed for studies of submarining and restraint performance. The goal of the design was to create a seat that performed like a production seat but was reproducible and repeatable.

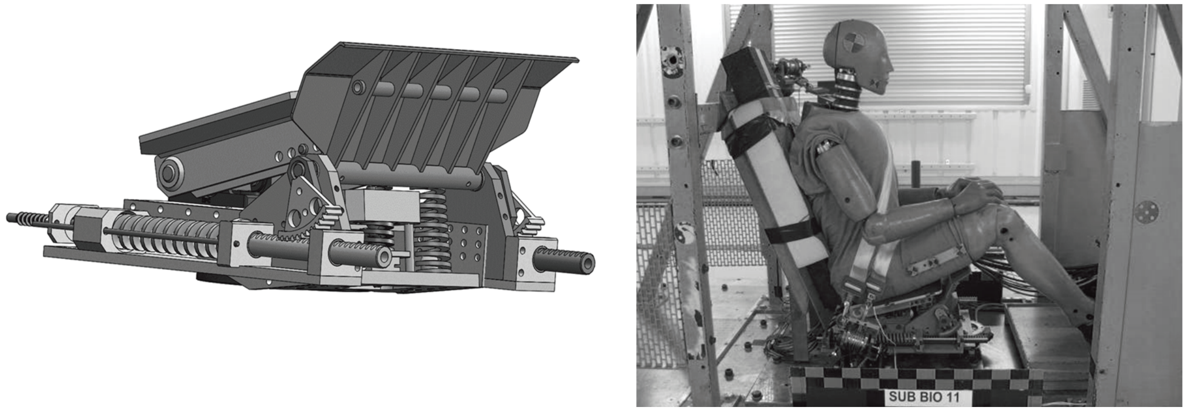


Figure 3.2. Semi-rigid seat developed at LAB to be used in the present research. CAD rendering (left), and test set up showing a HIII ATD positioned on the seat (Uriot et al., 2015).

The LAB seat consists of a rigid aluminum plate with two sets of springs fixed under the front portion of the plate. An aluminum anti-submarining ramp is positioned in front of the seat, with two springs to dictate the stiffness of the ramp. The angles of the seat pan and anti-submarining ramp are adjustable. We are currently evaluating the performance of this design using human body model simulations. Ramp angles and spring stiffnesses in the modeling are equal to those used in the Uriot study, and we are communicating with the LAB research staff to understand their design. We currently anticipate using spring stiffnesses and ramp angles similar to those used in the “front seat configuration” tests conducted by the LAB team in previous studies, but we will first, in conjunction with MCW, assess whether the performance is suitably similar to that of production seats over a relevant range of conditions and make modifications if necessary. We anticipate that we will use a single seat stiffness and ramp angle for the test series. Thus, the final design of the seat will therefore likely be a simplified version of the original LAB seat, with simplifications being mutually agreed upon between MCW and UMTRI.

We have received CAD drawings of the seat from LAB staff, and the seat will be constructed in-house by UMTRI technicians. MCW and UMTRI will use the same seat design for their respective test series. Given the importance of the seat pan on occupant kinematics, both seat pans will be constructed at one institution. The remaining components of the seat will be identical between MCW and UMTRI, with similar parts ordered from the same vendor. The seat does not include any proprietary parts, and we do not currently anticipate any excessive lead times on any components of the seat.

The test rig has an open seat back consisting of two support straps secured to metal support plates behind each of the PMHS’ posterior superior iliac spine and head support. The positioning of the seat back supports is adjustable to position the subject in the proper reclining posture for a given test. The open seatback allows for the installation of spinal instrumentation and triad markers so that spine kinematics can be determined throughout the loading event. The open seatback also improves access of spinal and pelvis landmarks, leading to more complete and standardized subject positioning.

In response to comments received at the public workshop, the test rig also includes a padded knee bolster that can be adjusted relative to the seat. The current plan is to place the bolster such that PMHS submarining can occur if the belt does not engage the pelvis, but will subsequently arrest the lower extremity motion. The PMHS will initially be allowed to translate freely but the bolster will arrest movement immediately prior to the point at which the seatbelt contacts the ribcage or installed instrumentation. Simulations will be used to determine the appropriate location of the bolster relative to the lower extremities, and the results will be scaled to each PMHS' anatomy to determine the position of the bolster for each test. This setup will allow for the relevant submarining data to be collected while minimizing the risk of damage to instrumentation and catastrophic injury to the specimen. Foot translation will also be arrested after the point of submarining to prevent the lower legs from translating upwards and hyperextending the knees.

The test rig will include a seat belt with a load limiter, and sliding latchplate with a locking tongue. The seatbelts will be provided by ZF (parent company of TRW and a leading automotive restraint supplier), who will also supply UMTRI with the FE model of the belt to incorporate into our HBM simulations. The seat belt will be configured with the shoulder belt passing over the left shoulder, and the D-ring and retractor assemblies will be attached to the seat back, simulating a seat-integrated restraint. The D-ring location will be adjusted to provide accurate belt fit based on our measurements on volunteers. For each test, the belt will be manually pretensioned by manually retracting the shoulder belt 10 cm, utilizing the method of Pintar et al. (2010). The seatbelt characteristics will be documented in the final PMHS test report.

Recent modeling efforts at UMTRI have demonstrated that in high-speed, frontal impacts using a production seatbelt with load limiter but without an airbag, the occupant may experience extreme head excursions with head contact on the knee (Figure 3.3). This is due to production seatbelts in front seats typically being designed to be used in conjunction with airbag(s) in high-speed frontal crashes. If a knee-bolster is present, the occupant tends to experience higher head excursion and the head is likely to contact the structures in front of the occupant. Such kinematics may lead to a high head injury risk, and will complicate the development of biofidelity corridors in the present research. Thus, the present test series will use a 10-mm-diameter load limiter to limit PMHS head excursions, which results in a load limit of approximately 3.5-4.0 kN depending on PMHS anthropometry and test set up.

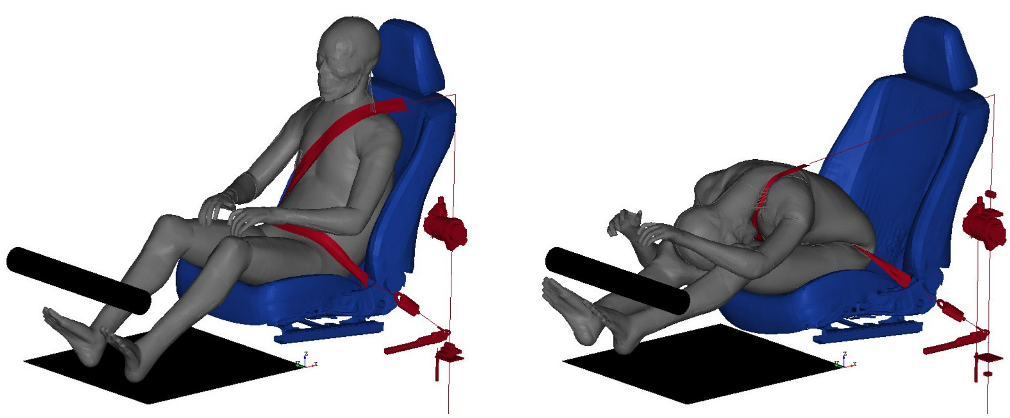


Figure 3.3. Screenshots showing HBM kinematics in high-speed (35 mph), frontal impact at time zero (left) and time of maximum head excursion (right). In the simulation, the model's head exhibits extreme excursions and contacts the knee.

The test buck will be rigidly fixed to UMTRI's horizontal impact sled. Figure 3.4 shows the sled with a child seat test buck installed. The UMTRI impact sled is a 450-kilogram, 2x2-meter-square platform that travels on an 18-meter track into a pneumatic, rebound-type decelerator to simulate crash velocities and decelerations. The sled is accelerated by a pneumatically-powered ram on one end of the track. The impact takes place at the opposite end, where a pneumatic spring controls the duration and magnitude of the impact. Up to ten offboard digital high-speed video cameras record the kinematics of vehicle components and ATDs. Cameras will be installed onboard if necessary to record spinal kinematics.

Figure 3.4. UMTRI's horizontal impact sled, shown with a child seat test buck attached.

Data collected from the sled buck will include sled acceleration, knee bolster forces, seat belt forces, and seat belt webbing payout. Test rig characterization will be done using UMTRI-owned ATDs. Prior to starting the PMHS tests, matched ATD tests will be conducted at UMTRI and MCW using our respective test rigs to ensure that the rigs perform similarly.

3.4 Task 4: Frontal Impact Sled Tests (Biofidelity) – PMHS, 50th

3.4.1 Overview of Research Approach

In this task, the biomechanical response of occupants in various reclined postures to zero-degree (i.e., frontal) medium- and high-speed impact will be determined using PMHS selected to target 50th-percentile-male anthropometry. Loads applied to the seatbelt and knee bolster will be measured, along with accelerations and angular rotations of the head, spine, pelvis, and lower extremities. Timing of bone fractures will be determined by strain gages on the ribs, clavicle, and sternum. 3D kinematics of the PMHS will be determined using high-speed video from four cameras to track the positions of 3D markers rigidly attached to various locations on the PMHS and test fixture. Test results will be analyzed to develop biofidelity corridors and, in an optional task, injury criteria specific to the 50th-percentile male will be developed. The biofidelity corridors will also be used evaluate the performance of the THOR 50th-percentile ATD and the GHBMC 50th-percentile-male HBM in optional tasks.

3.4.2 Test Matrix

The primary factors that can be explored in the test matrix are recline angle, impact speed, and restraint configuration. Discussions with NHTSA, MCW, and industry partners at the public workshop have demonstrated large knowledge gaps regarding how altering the seat recline angle and various components of restraint system (belt anchorage locations, pretensioner force, load limits, and knee bolster location and characteristics) influence PMHS response. The initial test matrix (Table 3.1) therefore consists of 12 tests meant to establish the PMHS response in both low- and high-speed conditions in both a baseline upright condition, and a moderately-reclined condition. The baseline upright condition represents the standard automotive posture of ~25° recline. The 45° recline tests represents a moderately-reclined posture condition.

The remainder of the test matrix will be established after completion of the initial 12 tests. During that time, additional FE modeling will be conducted at UMTRI and MCW to further explore the influence of more severe seat recline angles (>45°) and various configurations of restraints on occupant response. Once the initial 12 tests are completed, UMTRI, MCW, and the COR (TO) will examine the data in conjunction with the modeling work to finalize the test matrix. UMTRI, MCW, and the COR (TO) will jointly make the decision on the specific factors to explore in the test matrix, which will be based on maximizing the relevance and utility of the test data for both academic study and applicability for industry. The final full test matrix will have significant overlap with the series run at MCW. A minimum of 24 tests will be conducted, with three tests run in each configuration. The test design allows the potential for more than 24 total tests to be conducted, as described in Section 3.4.3.

Table 3.1 PMHS test matrix.

Number of Tests	Delta V (kph)	Seat Back Angle	Restraint Configuration	Knee Bolster
3	32	25°	Baseline	Out of contact
3	56	25°	Baseline	Out of contact
3	32	45°	Baseline	Out of contact
3	56	45°	Baseline	Out of contact
3	TBD	TBD	TBD	TBD
3	TBD	TBD	TBD	TBD
3	TBD	TBD	TBD	TBD
3	TBD	TBD	TBD	TBD

3.4.3 Running Multiple Tests on a PMHS

When possible, two tests will be conducted on each PMHS in the low speed condition, with the recline angle being the only variable altered, allowing for within-subject assessment of the effects of recline. After the first test, each PMHS will undergo a CT scan to check for injuries and specimen structural integrity will be assessed, including the decay level of the specimen. The CT scan will be conducted the night of the test date. A PMHS will only undergo a second test if no significant injuries were sustained in the first test, and no extensive decay or soft tissue damage is found on the specimen. Decay level will be determined by UMTRI staff and our Emory subcontractor, who has two decades of experience working with PMHS. The timeline for conducting two tests on a PMHS is as follows:

Day 1: Run first PMHS test during daytime, CT scan at night
Day 2: Evaluate CT scan for injuries and PMHS for decay, finalize decision on running second test
Day 3: Run second PMHS test during daytime, CT scan at night, store PMHS in freezer or refrigerator until autopsy

The PMHS will be stored in the refrigerator in between tests, and will only be removed to room temperature during instrumentation, testing, and CT scanning. We anticipate that each PMHS will be in a room temperature environment for approximately seven hours for each test, and three hours for each CT scan.

Exclusionary injuries include, but are not limited to, fractures of the pelvis or lower spine, serious (AIS3+) internal soft tissue injuries, or marked deterioration or damage to the tissue in the belt-loaded areas. A small number of rib fractures sustained during the first test will not automatically exclude a PMHS from a second test, as outlined in Section 3.4.5.2. The final decision on whether to test a PMHS a second time will be confirmed with NHTSA.

The initial 12 test matrix, as outlined in Table 3.1, will therefore consist of 12 tests using 9-12 individual PMHS. The 32 kph tests will use 3-6 individual PMHS, with the final number used dependent on our ability to test a PMHS twice. Six PMHS will be used for the six 56 kph tests. Given the cost and time savings anticipated with testing a single PMHS twice versus testing two PMHS once, this plan potentially allows for more than 24 total tests to be conducted over the course of the test series while remaining within the allotted project budget and timeline. The total number of tests conducted will be at least 24, with the final count dependent on the number of PMHS tested twice.

3.4.4 Crash Pulses

The crash pulses used in the present study will include low-speed and high-speed pulses of ΔV = 32 kph and ΔV = 56 kph. Example 32 kph and 56 kph pulses achieved with UMTRI's sled are shown in Figure 3.5. Although the presented curves will be used to guide the final pulses of the present test series, the actual pulses may vary depending on the final mass of the test rig. Once the test rigs at UMTRI and MCW have been fabricated, the test pulses will be tuned and matched as much as possible between the two institutions to produce similar duration and time to peak acceleration.

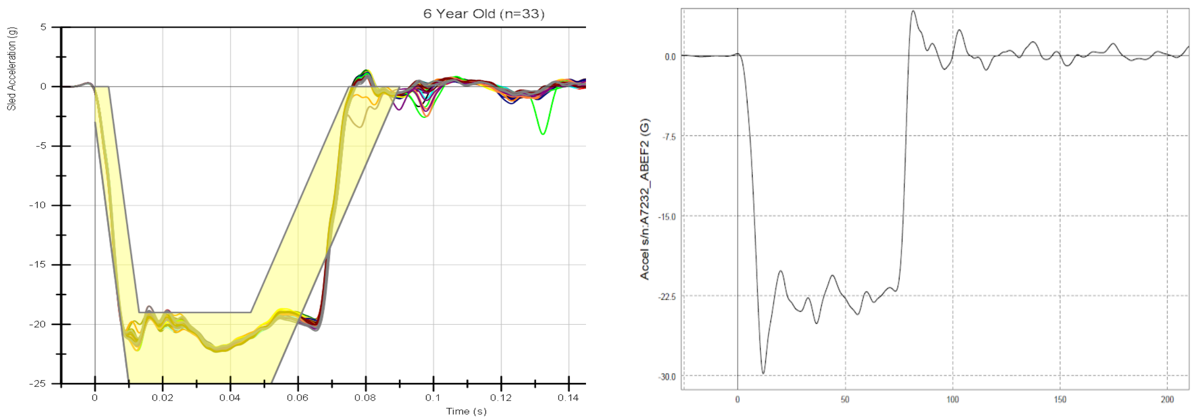


Figure 3.5. Example 32 kph (left) and 56 kph (right) pulses achieved with UMTRI's sled.

3.4.5 PMHS Selection and Screening

3.4.5.1 PMHS Procurement and Storage

Whole-body PMHS will be procured from the University of Michigan's Anatomical Donation Program, from which UMTRI has obtained PMHS for previously conducted NHTSA-funded projects. All PMHS will be fresh frozen and unembalmed.

UMTRI's cadaver laboratory space includes freezer storage for eight whole-body PMHS and chest freezer space for PMHS components. We also have refrigerator storage for two whole-body PMHS for use during the PMHS instrumentation and testing process.

3.4.5.2 PMHS Inclusion/Exclusion Criteria

In most previous PMHS test series in the crash safety domain, the objective of the testing has been to generate response and tolerance data intended to be used with an existing physical ATD. Given that test outcomes are often hypothesized to vary with body size, researchers usually attempt to restrict their specimens to be similar to the target ATD with respect to some overall body dimensions (e.g., stature and body weight). In practice, however, a narrow range is difficult to achieve and hence the actual range use varies fairly widely (even if it's still characterized as "50^{th}-percentile male", for example).

Data from a recent large-scale test series conducted at multiple institutions for the Warrior Injury Assessment Manikin program illustrates this clearly. Figure 3.6 shows the distribution of stature achieved across three Universities for whole-body tests aimed at the development of a "50^{th}-percentile male" ATD. The figure shows that only about 70% of the specimens were within the central 50% of the US population with respect to stature. In other words, even sampling within the middle half of the distribution of stature can be challenging. A similar range of subject characteristics is also seen in many other PMHS impact studies targeting the midsize male (e.g. Lessley et al., 2010; Maltese et al., 2002; Miller et al., 2013; Shaw et al., 2006 and 2009; Yoganandan et al., 2014).

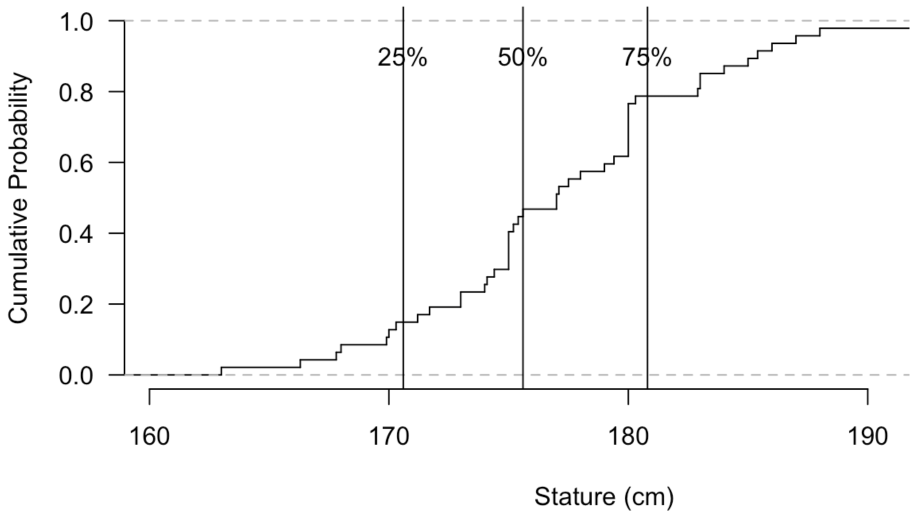


Fig 3.6. Cumulative distribution of male body stature of PMHS obtained across three Universities for a recent U.S. Army study. For comparison, population 25%, 50% and 75% quantiles from the National Health and Nutrition Examination Survey (NHANES) for U.S. men are shown.

It is important to emphasize that the previous focus on restricting specimen size (usually with limited success) is based on the assumption (or hypothesis) that body size will influence test outcomes. For example, the length of the torso may be positively related to the maximum forward head excursion in a frontal impact, and whole-body mass may be positively related to belt loads. The traditional response to these (usually implicit) hypotheses has been to attempt to restrict the range of PMHS characteristics. However, as noted above, due to the reality of specimen availability, "50th-percentile" specimens usually span at least the middle 50% of the population range on the sampling variables (typically stature and body weight).

Restricting the population excessively is actually counterproductive and reduces the value of the dataset. The key observation is that a diverse sample provides more information about the population of people to be protected in crashes. **If the hypothesized anthropometric effects are real and important**, they can be estimated statistically from the data. If they are unimportant relative to other sources of variance, this finding also provides critical information. Importantly, no value is lost by using a wider range of specimens, and much can potentially be gained.

Statistical modeling of anthropometric effects is rare in injury biomechanics studies. Instead, researchers use two approaches in an attempt to address anthropometric variability:

> *Normalization* – choosing dependent measures that are expressed as fractions of relevant physical dimensions. Expression of chest deflection as a percentage of chest depth or breadth is the most common example.
>
> *Scaling* – Adjusting values, such as peak force or peak deflection, by reference to simplified mechanical models. Common methods include equal-stress/equal-velocity scaling and impulse-momentum scaling. These methods make strong assumptions about the consistency of shape and material properties across specimens.

(We note that the terms normalization and scaling have not been used consistently in the literature.) These methods are applied to both scalar outcomes (e.g., peak force) and corridor development. Human modeling studies using morphed finite-element models demonstrate that these scaling methods do not accurate model the differences in response that result from differences in human body size and shape at the level of body regions or the whole body, due to the complex effects of body shape and heterogeneous anatomical structures.

Hence, the best way to address the inevitable anthropometric effects is through statistical modeling. That is, we carefully design and conduct the study to allow the effects of anthropometric variability to be quantified if they turn out to be important. This includes sampling subjects from a wide range on the variables of interest to ensure sufficient statistical power even with small samples.

One important consideration in the design of the experiment is to avoid unintentional correlations in the test matrix. A basic tenet of experiment design is to avoid correlating factors that are separately of interest. For example, in the test matrix for this project, we will independently vary restraint characteristics and seat back angle, so that we can differentiate their effects. (But we will deliberately correlate some variables that effectively become a single variable: we will move the upper belt anchorage with the seat back in the manner of a seat-integrated restraint.)

With respect to anthropometry, we want to ensure the major variables we expect to influence outcomes (torso length and body weight) are uncorrelated with our test variables. So, we want to ensure that, for example, we do not test only heavy specimens at large seat back angles and only lighter specimens at more upright seat back angles, because then we would be unable to differentiate the effects of body mass and seat back angle.

With small numbers of specimens in each test condition (typically three, with the current preliminary matrix), a more homogeneous subject pool makes it easier to ensure similar means and variances in these sampling variables across test condition bins. On the other hand, a more homogeneous sample reduces the ability to assess body size effects.

Importantly, a more diverse subject pool also greatly increases the value of the dataset for modeling purposes. With the development of fast, accurate finite-element morphing methods, detailed computational models can now be used to do subject-specific modeling of whole-body tests. Obtaining PMHS response data suitable for subject-specific modeling studies is a major benefit of the current study. The benefit will be directly proportional to the diversity of the subject pool.

In this research, we expect that the belt interaction with the pelvis will be an important determinant of kinematics. In previous research, we have shown that the variability in lower abdomen shape associated with body mass index (BMI) is associated with the initial (pre-crash) position of the belt with the respect to the pelvis. Hence, BMI may be more important to control within test conditions than body weight. Given the variability in specimens, it will be difficult to balance the mean stature, body weight, and BMI within each test cell. Therefore, our proposed approach to specimen inclusion criteria is as follows:

1. Define test condition bins by seat back angle, restraint condition, and impact delta-V (preliminary matrix is in Table 3.1).
2. Define anthropometric acceptance criteria for specimens from 25th to 75th%ile stature for US men (170 cm to 181 cm) and BMI from 18.5 to 30 kg/m^2. Body mass will be constrained by the stature and BMI ranges.
3. Within each cell of the test matrix, we will attempt to have the mean of the three specimens as close as possible to the median-male targets based on ATD reference anthropometry, i.e., 1750 mm

stature and BMI of 25 kg/m^2. To achieve this, we will choose test conditions from the matrix based on the available specimen characteristics.

We will analyze the data using standard regression methods to quantify the effects on outcome measures of interest of the experiment design variables (seat back angle, delta-V, and restraint configuration) along with anthropometric variables. We will consider possible interactions between anthropometric variables and experiment variables (for example, are the effects of BMI on torso kinematics different across seat back angles?). Note that we are readily able to consider nonlinear effects. It will be straightforward to apply traditional scaling methods to these data, but we also expect to be able to demonstrate the inadequacy of those methods using the statistical analysis as well as subject-specific modeling. We will also use functional analysis methods to develop time-series targets for midsize-male ATDs as well as arbitrary male occupant sizes. These methods are capable of providing mean predictions as a function of test conditions and anthropometric variables. These methods therefore quantitatively evaluate the factors that influence the response, and have been previously used in the literature to analyze impact kinematics data (e.g., Samuels et al., 2016).

The criteria for BMI is limited to include the designations of "normal" and "overweight" PMHS as defined by the US Centers for Disease Control and Prevention. This range encompasses the median U.S. male adult BMI of 27.7 kg/m^2 (NHANES). The BMI range is also limited so that there is no significant overlap in PMHS BMI between the UMTRI test series and the MCW test series, which will focus on small female and obese male. The T-score criteria excludes osteoporotic subjects that would likely be at a disproportionately elevated risk of bone fracture. Finally, the criteria for age range reflects that the majority of potential PMHS are elderly.

The inclusion criteria are as follows:

- $18 \leq$ Age ≤ 80 years
- $170 \leq$ Height ≤ 181 cm (25^{th} to 75^{th} percentiles for US men)
- $18.5 \leq$ BMI ≤ 30 kg/m^2
- $-2.5 \leq$ T-score ≤ 2.5

Specimens that fall slightly outside of the outlined inclusion criteria in any category will be considered on an individual basis, and the final acceptance decisions for the specimen will be made following discussion with NHTSA.

PMHS will be excluded for the following:

- HIV, hepatitis B, and hepatitis C
- Cancer with bone metastases
- Knee or hip replacements
- Pre-existing fractures to the spine, pelvis, or femur
- Spinal fusion
- Artificial discs
- Greater than five pre-existing rib fractures

Recent modeling work at UMTRI (Zaseck et al., 2017; Zaseck et al., 2018) has suggested that occupant kinematics and torso response in impacts are unaffected by the presence of up to three pre-existing rib fractures, and minimally affected by six pre-existing rib fractures, which are findings supported by observations from PMHS impact studies (Duma et al., 2006; Kindig et al., 2010; Shaw et al. 2007; Yoganandan, Pintar, and Gennarelli, 2004). Therefore, PMHS with five or fewer pre-existing rib fractures will not be automatically excluded from the project.

3.4.5.3 PMHS Screening

Prior to accepting a cadaver for this study, the cadaver will be CT scanned and the results of the CT scan will be reviewed to identify any preexisting skeletal fractures, degenerative conditions, or other skeletal abnormalities. DXA will also be performed to characterize bone density prior to acceptance of the body. Medical records containing no identifying information will be reviewed for each PMHS.

3.4.5.4 Cadaver Anonymity

The anonymity of PMHS will be maintained at all times. No personally identifiable information will be recorded or accessible by UMTRI personnel. Each PMHS will be referenced using a unique PMHS ID number. Information unique to each PMHS will be limited to sex, anthropometry, cause and date of death, and date of birth. In the case where details of the PMHS's medical history are required, a request will be made to U-M Anatomical Donations, and they will release only those details relevant to the study.

3.4.5.5 Laboratory Safety Considerations

All laboratory personal, research staff, and visitors will comply with the University of Michigan's Occupational Safety & Environmental Health hazard guidelines "Exposure Control Plan - Bloodborne Pathogens" and the "UMTRI Biosciences Division Cadaver Testing Lab Standard Operating Procedures."

3.4.6 PMHS Preparation

For each subject tested, anthropometric measurements will be recorded prior to installation of the instrumentation (Table 3.2). Immediately prior to testing, the PMHS will be dressed in a tight-fitting full body leotard.

Table 3.2. PMHS anthropometric measurements to be recorded (measurements in kg and cm)

Weight	Chest Breadth	Foot Length	Calf Circumference
Stature	Waist Breadth	Left Foot Length	Ankle Circumference
Shoulder Height	Hip Breadth	Right Foot Length	Neck Circumference
Vertex To Symphysis	Trochanter Breadth	Avg Foot Length	Scye To Shoulder Circ.
Waist Height	Left Foot Breadth	Waist Back Length	Chest Circumference
Crotch Height	Right Foot Breadth	Bicep Circumference	Waist Circumference
Tibial Height	Avg Foot Breadth	Elbow Circumference	Butttock Circumference
Head To Trochanter	Head Length	Forearm Circumference	Chest Depth
Vertex To Mentum	Menton-Sellion Length	Wrist Circumference	Waist Depth
Head Breadth	Shoulder To Elbow	Thigh Circumference	Buttock Depth
Bizygomatic Breadth	Forearm Hand Length	Lower Thigh Circumference	Waist Back Length
Biacromial Breadth	Ankle Height	Knee Circumference	

3.4.7 PMHS Instrumentation

PMHS instrumentation for the tests of Task 4 is shown in Figure 3.7. The PMHS will be instrumented in locations as close as reasonably possible to instrumentation locations of the THOR 50^{th}-percentile ATD. Additional instrumentation will be installed to sufficiently determine the biomechanical and kinematic response of the subjects under the loading conditions examined, and to provide a comprehensive dataset for HBM validation. Since comments received during the public workshop indicated that instrumentation on the pelvis would aid in determining the extent of submarining, 6DOF sensors and uniaxial strain gages will be installed onto the posterior aspect of the PMHS iliac wings. A 6DOF sensor will be installed as low on the spine as possible without interfering with the test seat in the case of submarining (likely L4/L5).

PMHS instrumentation will include:

- 6DOF sensors (Ax, Ay, Az, ARx, ARy, ARz) rigidly attached to the head, spine (T1, T8, T12, L4/L5), iliac wings, femurs (left and right), and tibiae (left and right).
- Uniaxial strain gages on the left clavicle, sternum, ribs 4-7, and left and right ASIS
- 3D triad targets on the faces of 6DOF sensors, and rigidly attached to the skeleton (acromion, ulnar styloid, humeral epicondyles, femoral epicondyle, and lateral malleolus)
- Bilateral 3D triad targets rigidly attached to the anterior ribs at the mid and lower thorax
- Metal dowels fixed to the pubic symphysis or iliac wings to serve as markers for subject positioning

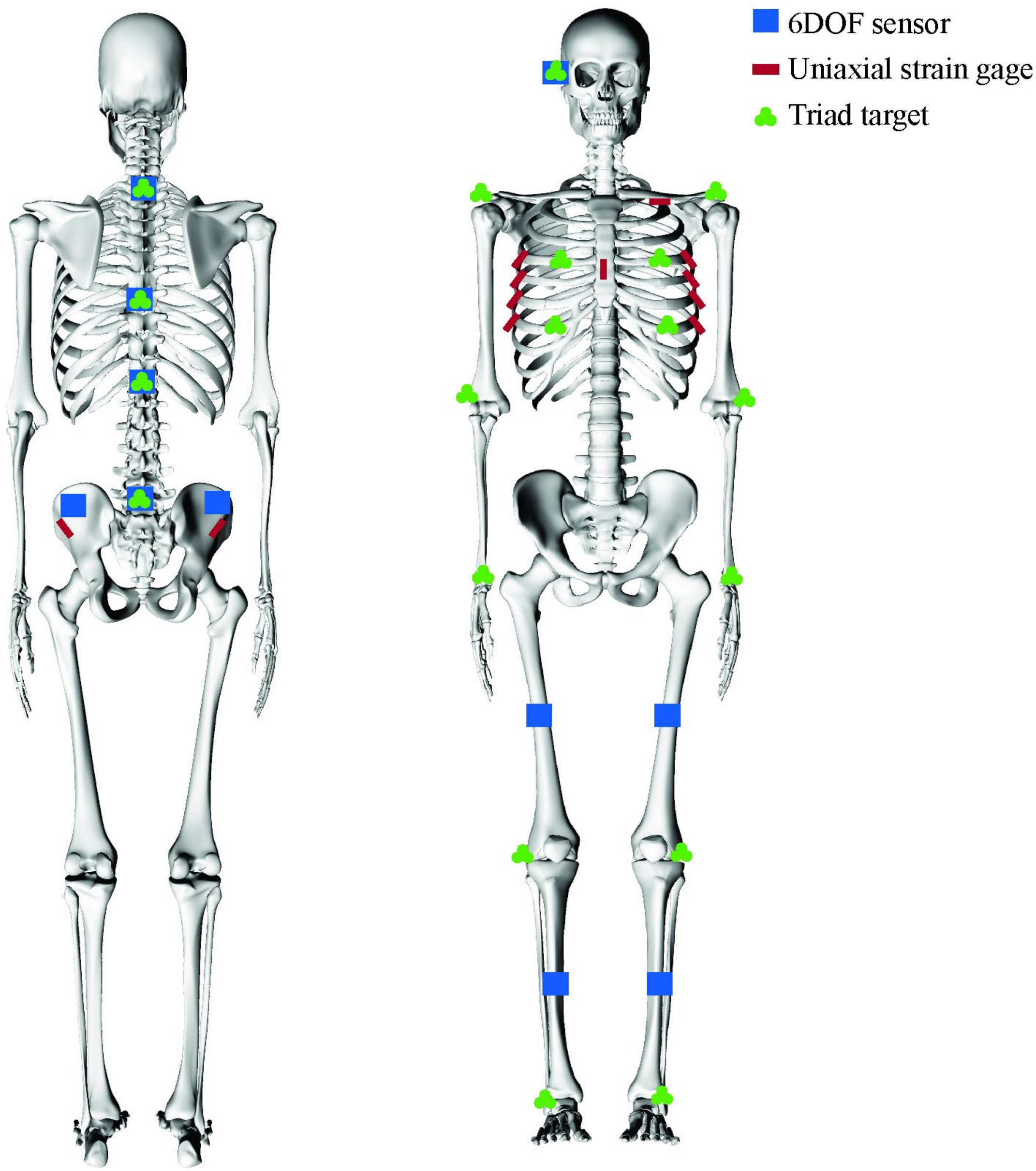


Figure 3.7. Instrumentation for 50th percentile male PMHS zero-degree tests (Task 4).

Chest deflection will be determined using 3D targets rigidly installed to the anterior mid- and lower-thoracic ribs. The methods used will be similar to those used in UVA's Gold Standard tests (Figure 3.8; Shaw et al., 2009). In short, flesh will be excised down to the rib surface, and a metal mount will be rigidly fixed to the bone surface. A 3D reflective marker will be screwed into the mount so that 3D rib translation can be tracked with high-speed camera images. The actual hardware design may slightly differ from the Shaw et al. study to best align with the present project's goals and test conditions. 3D targets will also be installed onto the seat belt.

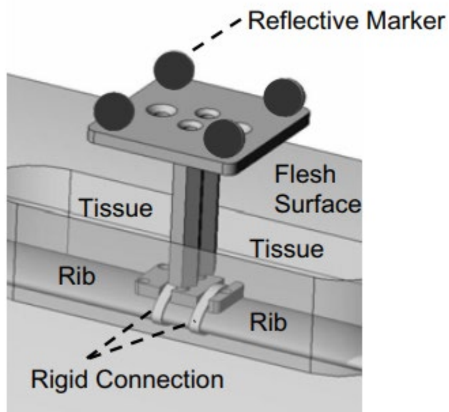


Figure 3.8. 3D motion tracking marker installed rigidly onto the rib. From UVA's Gold Standard tests (Shaw et al., 2009).

This method offers distinct advantages over using a chestband to measure deflection. Chestbands are installed on the surface of the skin and therefore measure external chest deflection, which differs from skeletal deflection, especially in subjects with thick adipose tissue. Chestbands are also rigidly fixed to the subject at one point, usually the spine, which may result in measurement artifacts as that single point is constrained. By tracking markers rigidly fixed to the ribs, we will be able to obtain accurate time histories of the 3D movement of the ribs (Shaw et al., 2009), which will be used in conjunction with our 3D spine kinematic data to determine chest deflection. The rigid markers are also smaller and less obtrusive than chestbands, and will therefore interfere less with the seatbelt and other instrumentation.

Instrumentation will be installed using standard procedures UMTRI has employed in previous studies for NHTSA and others. Positioning of the strain gages on the thorax will initially coincide with locations of fracture patterns typically seen in zero-degree 3-point seat belt loading, and may be adjusted as injury data are obtained throughout the test series. Once instrumented, digital photos of instrumentation will be taken, and a pre-test CT scan of the PMHS will be obtained to record sensor locations with respect to the skeleton.

3.4.8 PMHS and Belt Positioning

The PMHS will be positioned into the test fixture using positioning targets developed from human volunteer data recently collected at UMTRI. In the study, UMTRI measured the three-dimensional locations of skeletal landmarks and belt routing targets of volunteers seated in fixed seat back angles (SAE A40) ranging from a standard automotive recline to a severely-reclined angle. The tested angles were 23, 33, 43, and 53 degrees with and without a foam head support. The volunteers included a diverse sample of 24 men and women with a wide range of age and body size (Figure 3.9). Bony landmark data were used to estimate joint center locations and a statistical analysis was conducted to develop a posture-prediction model suitable for use in positioning physical and computational passenger surrogates for crash simulation. Figure 3.10 shows examples of skeletal posture prediction for one body size across three seat back angles representing "baseline upright" (25°), "moderately-reclined" (45°), and "severely-reclined" (60°) postures. The result is a statistical model that takes the subject's stature, body weight, and sitting height, along with the nominal seat back angle, and calculates positioning targets for the subject. We will use the "head unsupported" posture targets for the baseline tests and "head supported" postures for more-reclined conditions. The targets include the critical three-dimensional locations of head and torso landmarks, torso joint center locations, and pelvis angle. The model also produces targets for lower extremity landmarks. Each PMHS will therefore be positioned in a posture relevant to real-life seated posture based on a person with similar anthropometry. The PMHS will be positioned using the following sequence and priority: (1) Pelvis position and angle, (2) T1 fore-aft position relative to the hips, (3) head angle and fore-aft position relative to T1, and (4) upper and lower extremity positioning. This positioning sequence was developed for the WIAMan program (using a different posture dataset) and was found to be practicable. Note that additional analysis of the data will be performed to create the appropriate equations for calculating these targets. The PMHS hands will be positioned onto the thighs, and the arms and legs will be allowed to move freely during the loading event.

Figure 3.9. Examples of posture and belt fit at 53-deg recline with (top) and without head support (bottom) in UMTRI study of reclined passengers.

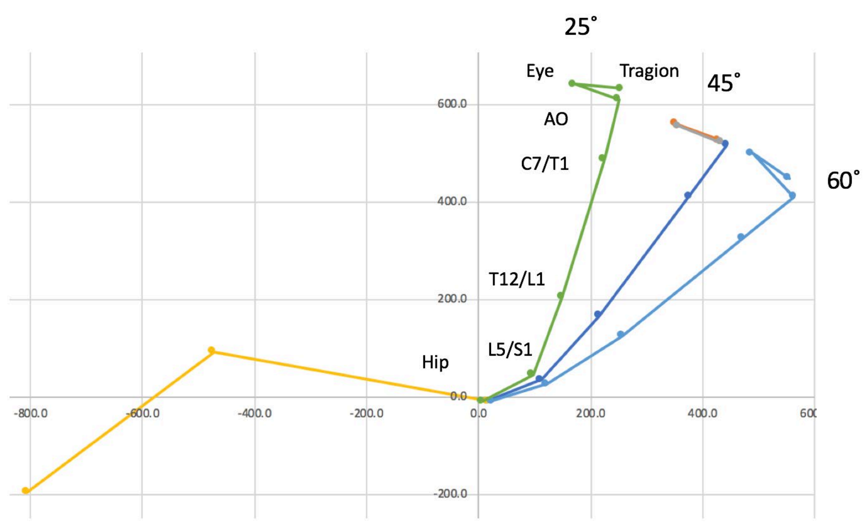


Figure 3.10. Example of skeletal posture prediction for one body size across three seat back angles. Additional landmarks (ASIS, pelvis front plane angle, and T1 surface) will be added to facilitate PMHS positioning.

Body region positioning in three dimensions will be determined using a FARO arm coordinate measurement machine. Immediately prior to testing, final subject positioning of the landmarks outlined in Table 3.3 will be recorded, providing references for HBM positioning and additional PMHS tests. We will also perform a 3D, whole-body surface scan of the PMHS in pre-test position using a 3D Sense handheld optical scanner. These data will be valuable for ensuring accurate representation of the PMHS posture and position, along with belt fit, in subsequent modeling studies.

Table 3.3. Posture landmarks for 50th-percentile-male PMHS zero-degree tests (Task 4)

PMHS/Instrumentation Landmarks	**Fixture and Seatbelt Landmarks**
Pubic symphysis metal dowel	Fixture Origin (TBD)
C7	Shoulder belt anchorage
Femoral condyle, lateral, left and right	Lapbelt anchorage
Malleolus, lateral, left and right	Seat back surface, four corners
Patella	Seat surface, four corners
Tragion, left and right	Seat foam surface, four corners
Infraorbitale, left and right	Knee bolster top, left and right
Acromion, left and right	Knee bolster bottom, left and right
Humeral epicondyle, left and right	Point streams on seat belt routing over torso and lap
Minimum of 3 points on all accessible 6DOF sensors	

Prior to each test, the belt system will be conditioned by drawing the belt fully from the retractor and allowing it to return five times, helping to standardize the retractor performance. The belt will be routed relative to the subject using targets derived from the volunteer belt-routing data obtained by UMTRI, described above. Specifically, we will aim to achieve a target lap belt vertical position relative to the pelvis ASIS landmarks calculated from the volunteer data. Prior to each test, the lap belt will also be manually pretensioned, and the force required to pretension the belt will be recorded. The lateral position of the shoulder portion of the belt at the clavicle will also be based on the volunteer data.

The pre-test posture and body shape of the PMHS will be recorded using a hand-held 3D scanner (e.g., Sense from 3D Systems). These data will be aligned with the pre-test landmark data obtained with the FARO Arm.

3.4.9 Three-Dimensional Motion Tracking

PMHS kinematics will be determined by tracking the position of marker triads rigidly attached to the PMHS skeleton and 6DOF sensors and reflective markers attached to numerous locations on the sled buck. The X, Y, and Z coordinates of the markers, along with yaw, pitch, and roll orientations of the mounting blocks, will be tracked in both the global and sled coordinate systems from high-speed video images at 1000 Hz using TEMA software. The use of redundant camera angles to obtain high-speed video will allow multiple viewpoints of each marker, increasing the confidence and accuracy of our tracking.

3.4.10 Post-Test Documentation

Immediately following the experiment, post-test images of the PMHS will be recorded and the PMHS will be palpated to determine the existence of any obvious fractures and/or injuries. Following examination, the PMHS will be carefully removed from the test fixture and a CT scan will be conducted. After the first test conducted on each specimen, the CT images will be reviewed for any skeletal or soft tissue injuries. As suggested by a workshop attendee, CT images of the brain will also be examined for putrefaction or pneumocephalus. If no injuries are detected, and the specimen is deemed in suitable shape for a second test, as outlined in Section 3.4.3, a second impact test will be conducted on the specimen as soon as possible.

After the second test conducted on a specimen, or after the first test if injuries are noted prior to the test, an autopsy will be conducted to identify any bone fractures, ligamentous tears or ruptures, cartilage damage, vessel damage, or skin abrasions. When possible, injuries will be classified according to the Abbreviated Injury Scale 2008 update. Injuries will be documented and photographed and a summary of the results including descriptions, illustrations, photographs, and CT images of all injuries will be provided, along with raw DICOM images. All pre- and post-test documentation will be included in a test summary report following NHTSA's requirements.

3.5 Task 5: Biofidelity Corridor Creation

Once the data are processed and normalized, biofidelity corridors (BC) will be constructed using a method developed in part by the current study team (Gayzik et al., 2015), which is based on Nusholtz (2013). This method involves aligning the loading portion of a signal by shifting each signal in time such that the cross-correlation coefficient between the loading portion of all signals is maximized. BC are then developed using the final mean and standard deviation of the aligned signals at each time point. BC will be developed for biomechanically significant metrics, which may include multi-point chest deflection, belt loads, head kinematics, spine kinematics, or others. The developed BC will be defined so that they can be objectively compared using Correlation and Analysis (CORA) and/or Biofidelity Ranking System (BioRank) methods. UMTRI has extensive experience developing BC from PMHS impact data (e.g., Miller et al., 2013; Wood et al., 2014). The proposed method has the advantage of maintaining the shape of each curve while minimizing the differences between the curves. By aligning the signals using only the loading portion, the aspects that are experimentally controlled influence the time shifting, and factors that are not controlled, such as interactions with the test fixture and internal dynamics, are not considered. For force, moment, and displacement data, the loading portion is defined as the time between the initiation of the test and the time at which the metric reaches the greatest local maximum. For acceleration data, the end of the loading is considered the time at which the integrated signal (i.e., velocity) reaches the greatest local maximum.

Signals will be excluded from the BC if the signal is determined to be biomechanically invalid, arising due to sensor malfunction or any unintended negative influence on the signal. Responses that are statistical outliers will only be excluded if the data are biomechanically invalid. UMTRI will compile a report including sufficient data for the corridors to be independently reproduced, including justification for any subject data exclusions, any sensor data manipulation, a description of the methodology used to construct the corridors, and any manipulation of future surrogate data required for comparison to the corridors.

4. Optional Tasks

4.1 Award Priority for Optional Tasks

The following is our recommendation for the priority of award of the Optional Tasks outlined in the project Request for Proposals, and our rationale for the recommendation:

1. Optional Task 6 – Dummy Matched Pair Tests
    - Current ATDs have not yet been validated in highly-reclined scenarios, and conducting matched pair tests with the THOR ATD would provide invaluable information on the ATD performance in the impact conditions tested. For a minimal cost commitment, such tests will clarify if THOR is appropriate to use in highly-reclined scenarios, or, conversely, will reveal which improvements to the ATD are needed such that it may be used in the tested impact conditions.
2. Optional Task 8 – Frontal Impact Sled Tests – Injury Criteria
    - There is currently a lack of published injury criteria relevant for 50th percentile male ATDs tested in highly reclined postures. Given that the cost to develop injury criteria is

minimal, such criteria will be critical as existing ATDs are assessed in highly reclined environments, and will aid in driving the design of safety systems in such alternative seating configurations.

3. Optional Task 7 – Human Body Model Evaluation/Improvement, 50th Male
    - Current human body models (HBM) have not been validated in highly reclined postures, and therefore cannot presently be used to assess occupant response in such conditions. For a moderate cost, the GHBMC HBM could be validated against the PMHS data collected in Task 4, giving insights into the performance of the model in the relevant impact conditions. Once validated, the GHBMC model can then be quickly and cheaply used to make educated initial decisions regarding seating environment or restraint configurations for highly reclined occupants before running time-consuming and costly PMHS tests.
4. Optional Task 9 – Additional Sled Tests (Biofidelity) – PMHS, 50th
    - The main test series of Task 4 cannot examine all important factors relevant to occupants seated in highly reclined postures. The completion of an additional test series will allow further data to be gathered that will fill in knowledge gaps from the main series, or explore important questions that the data from the main test series brought to light. For example, the tests of Task 9 might include optimization of the restraints to best protect the occupant, or the exploration of additional recline angles to determine the onset of submarining behavior in the PMHS.

4.2 Optional Task 6: Dummy Matched Pair Tests

4.2.1 Test Matrix

Three THOR ATD tests will be conducted for each test condition from Task 4 (Table 1.3), for a total of 24 ATD tests.

4.2.2 ATD Instrumentation

Instrumentation for the tests of optional Task 6 will include instrumentation standard to the THOR 50th-percentile-male ATD. Additional 6DOF blocks and triad markers will be installed onto the ATD torso, pelvis, and extremities in locations corresponding to PMHS instrumentation (Section 3.4.8) to ensure equivalent kinematic tracking between the ATD and PMHS tests.

4.2.3 ATD Positioning

The posture and belt routing targets for the ATD tests of optional Task 6 will be determined by averaging the positioning of the PMHS tests of Task 4. The ATD will be positioned using the following sequence and priority: (1) pelvis position and angle, (2) T1 fore-aft position relative to the hips, and (3) head angle and fore-aft position relative to T1. In the likely event that the ATD lacks sufficient adjustability to match these targets exactly, priority will be given to placing the pelvis and the top of the thorax in the target locations.

A FARO arm will be used to digitize all landmark positions, and final positioning for all landmarks will be recorded. For each test, the seat belt will be preconditioned as described in Section 3.4.9. We will also perform a 3D, whole-body surface scan of the ATD in pre-test position using a 3D Sense handheld optical scanner. These data will be valuable for ensuring accurate representation of the ATD posture, position, and belt fit in subsequent modeling studies. In particular, we will be able to overlay the 3D shape of the PMHS and ATD to demonstrate similarities and differences in postures and pre-test belt interactions.

4.2.4 Global and Local Coordinate Systems

The test fixture global coordinate system will follow the recommendations of SAE J1733 (1994), with the positive z-axis directed downward, positive x-axis directed forward relative to the seat, and positive y-axis directed away from the seat's left to its right. ATD instrumentation coordinate systems will follow the recommendations of SAE J211 (1995).

4.2.5 Post-Test Documentation

Immediately following the experiment, post-test images of the ATD will be recorded and the ATD will be visually examined for any obvious structural damage. Post-test photographs will be taken to document final ATD positioning in the test rig. Following examination, the ATD will be carefully removed from the test fixture and further examined for structural damage. Any damage will be photographed, and a summary of the results will be provided. Raw DICOM images will be provided. All pre- and post-test documentation will be included in a test summary report, and will follow NHTSA's formatting requirements.

4.3 Optional Task 7: Human Body Model Evaluation/Improvement, 50th Male

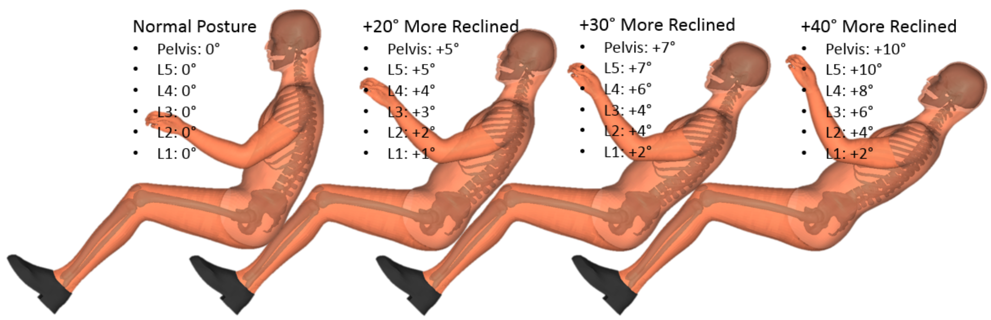
We plan to use the detailed GHBMC 50th percentile male model (GHMBC-M50-O) to simulate the occupant impact responses in each of the eight frontal impact sled test conditions specified in Table 1.1. We propose to use the detailed model instead of the simplified GHBMC model (GHMBC-M50-OS) for the following reasons. (1) The GHBMC detailed model was developed as a research tool to study occupant impact response and injury mechanism in complex loading conditions, while the GHBMC simplified model was developed mainly as a fast tool to study occupant kinematics and design optimization. Therefore, we believe that the detailed model is more suitable than the simplified model to be used in this study, which aims at quantifying the whole-body kinematic and injury responses in various reclined postures. (2) In the highly reclined conditions, submarining may become the major focus for human modeling. Since the detailed model sustains more detailed anatomical representations of the hard and soft tissues in the abdomen, lumbar, and pelvis regions than the simplified model, it will better capture the loading path and stiffness associated with the submarining kinematics. (3) The detailed model is expected to better simulate the potential injuries (e.g. bone fractures) associated with the loading conditions in this proposed study than the simplified model.

We understand that there is no published work on GHBMC model responses in highly reclined conditions, and NHTSA may have done some preliminary studies on GHBMC responses in reclined postures. Therefore, we are open for further discussion on which GHMBC model to use. Due the complexity of the GHBMC detailed model, it might not be stable in highly reclined postures and it runs much longer than the simplified model. We propose to use the detailed model in the current proposal, but if the GHBMC simplified model is used, the associated budget for this task will be reduced.

To simulate the sled conditions, an FE model of the sled buck assembly will be developed based on the geometry of the physical parts. This will include the sled base, spring-controlled seat assembly, and the restraint system. The material properties of the seat rig and restraint system will be modeled based on the material used in the tests, while other supporting structures will be modeled as rigid. We've developed the spring-controlled seat model for some preliminary simulations, and the seat model worked well in various crash conditions.

A set of parametric FE models representing the seatbelt systems used in the sled tests will be provided by ZF, which will include seatbelt retractor with pre-tensioner and load limiter, seatbelt webbing, latch plate with locking tongue, and anchor/buckle pre-tensioner. The parameters (load limit, loading rate, etc.) of the pre-tensioner(s), load limiter, and locking tongue have been optimized to represent the ZF seat belt systems based on the component testing.

To properly position the GHBMC-M50-O model, a mesh morphing method will be used to position the GHBMC model based on PMHS testing and the seating posture model described in Section 3.4.8. This will require adjustment of the pelvis angle, multiple spine angles (especially on the lumbar and cervical levels), and limb positions. We proposed to use our mesh morphing method instead of the traditional pre-simulation method for GHBMC positioning for two reasons. First, the mesh morphing method (<30 mins) is much faster than the pre-simulation (24 hours to several days). Second, the mesh morphing method can rigorously control any joint angle with smooth soft tissue transitions and high mesh quality, while pre-simulations require multiple prescribed motions which may not always result in desired mesh qualities with a short simulation duration. Figure 4.1 shows some preliminary results of using the UMTRI mesh morphing method to position the GHBMC-M50-O model into more reclined postures by changing the pelvis angle and lumbar spine curvature. The morphed models have essentially the same weight and mesh quality (Figure 4.1) of the original GHBMC model based on the minimal Jacobian values. More details on the UMTRI mesh morphing method can be found in our previous publications (Hwang et al., 2016; Zhang et al., 2017a; Hu et al., 2018).



Mesh Quality	Original GHBMC	+20° More Reclined	+30° More Reclined	+40° More Reclined
Min Jacobian (2D)	0.33	0.33	0.33	0.33
Jacobian<0.7 (2D)	17,400 (1%)	17,406 (1%)	17,415 (1%)	17,436 (1%)
Min Jacobian (3D)	0.30	0.30	0.30	0.30
Jacobian<0.5 (3D)	92,481 (2%)	92,486 (2%)	92,486 (2%)	92,486 (2%)

Figure 4.1: Illustration of mesh morphing method for GHBMC pelvis and lumbar posture adjustment.

For each simulation, the seatbelt anchorage locations will be defined based on the corresponding sled test and seatbelt fitting will be conducted in a semi-automatic manner using LS-PrePost, ensuring that the belt location with respect to the pelvis and shoulder match the mean values obtained in PMHS testing. The crash pulse from the corresponding sled test will be defined as the prescribed motion. To properly simulate the interaction between the GHBMC and the seat, a controlled drop simulation with gravity will be conducted to check the seat deformation due to GHBMC weight alone without changing the GHBMC posture. The resultant seat-spring and GHBMC pelvis flesh deformations as well as the associated stresses will be carried for the crash simulations by using the *INTERFACE function.

The PMHS impact response measurements (i.e., biofidelity corridors), kinematics plots, seat reaction loads, and knee bolster loads will be collected for evaluating each simulation. To quantitatively compare the impact responses between the simulations and the PMHS tests, errors in the peak values of the excursions and CORrelation and Analysis (CORA) ratings will be calculated. The CORA score will be calculated using the combination of cross-correlation rating and corridor rating, which calculates the deviation of two curves by means of corridor fitting, and measures the extent of linear relationship between the time histories of test and simulation signals based on ratings of phase, size, and shape. UMTRI has routinely used CORA for model evaluations (Zhang et al., 2017b; Hu et al., 2017a).

4.4 Optional Task 8: Frontal Impact Sled Tests - Injury Criteria

In optional Task 8, UMTRI will construct injury assessment reference curves (IARCs) and injury criteria relevant to the THOR ATD. UMTRI will use the method of matched pair testing with equivalence metrics (MPEM). Recently, UMTRI has led efforts to develop the MPEM method for the WIAMan project. The method assumes that ATD and PMHS responses differ since ATDs do not fail and cannot perfectly reproduce human responses. The development of IARCs thus requires biomechanical data from PMHS and ATDs in matched-pair tests so the fidelity of the ATD response can be assessed and transformation functions can be developed to relate ATD measurements to PMHS injury. The test methodologies outlined in Phase I, Tasks 4 and 6 are designed as PMHS and ATD matched-pair tests, employing similar structural matches between the surrogates (accomplished via data normalization), test initial conditions, boundary conditions, and input loading.

By design, our PMHS instrumentation is installed close to locations of similar sensors on the THOR ATD so that the PMHS response can be mapped to the ATD response at the same measurement location level of a chosen equivalence metric. The chosen equivalence metric aims to best describe the limit of human tolerance to a specific injury, and can include impulse, input force, compression or time (among others), and is derived from measurement locations external to the surrogate. The data will then be mapped from the external measurement location to the injury prediction measurement location (i.e., applied seat belt force to the ATD clavicle mapped to the ATD clavicle load cell force).

The matched-pair method will be used in place of the MPEM method if (1) biomechanical parameters measured on the PMHS differ from the location where corresponding instrumentation is installed on the ATD, (2) insufficient data exist to develop a reliable translation between PMHS and ATD measurement locations, or (3) equivalence metrics cannot be obtained due to a lack of data needed for the calculations. The method choice will be assessed on an individual basis, with the MPEM method used whenever possible.

Once the PMHS data are mapped to the ATD data, statistical methods such as survival analysis will be used to construct IARCs relevant for the THOR ATD (Kent and Funk, 2004). PMHS injury will be treated as uncensored when injury timing is known from strain gage data. Weibull, log-normal, normal, and log-logistic distributions will be considered in the analysis (Kuppa et al., 2003; McKay and Bir, 2009; Pintar et al., 1997; Yoganandan et al., 2013), and the best fit from these probability distributions will be determined based on statistical outcomes, such as the corrected Akaike information criterion. Injury criteria will be taken from the IARCs, assuming an acceptable level of risk of 5% (Mertz, Prasad, and Irwin, 1997).

When injuries occur, UMTRI will develop THOR ATD-relevant IARCs and injury criteria for areas including, but not limited to, the head, neck, spine, thorax, and/or abdomen. The choice of the most appropriate biomechanical metric for the IARCs will be assessed for each body region using statistical methods such as Receiver Operating Characteristic curves, Hosmer-Lemeshow statistic, maximum log-likelihood, or others (Baker, Hsu, and Gayzik, 2018). Goodness of fit assessments will be reported for all considered metrics. IARCs and their statistical analysis will be completed using statistical software (e.g., SAS or R). UMTRI's final IARC report will include sufficient detail for independent result reproduction.

4.5 Optional Task 9: Additional Sled Tests (Biofidelity) – PMHS, 50th

4.5.1 Test Matrix

The test matrix for Task 9 will be developed upon discussion with UMTRI, MCW, and the COR (TO) following completion of the test series of Task 4. The test matrix will be constructed to either fill in the gaps in data seen following Task 4, or examine an additional factor(s) not explored in Task 4 (e.g., alternative PDOFs). The same test matrix will be used in the test series conducted at UMTRI as well as the series conducted at MCW.

The test matrix for Task 9 will include twelve whole-body tests, with each PMHS being tested twice, if possible. Three tests will be conducted in each condition.

4.5.2 PMHS Preparation

PMHS preparation for Task 9 will follow the procedures outlined in Section 3.4.6.

4.5.3 PMHS Instrumentation

PMHS instrumentation for Task 9 will be identical to that of the zero-degree PMHS tests of Task 4, outlined in Section 3.4.7.

4.5.4 PMHS Positioning

PMHS positioning for Task 9 will be identical to that of the zero-degree PMHS tests of Task 4, outlined in Section 3.4.8.

4.5.5 Three-Dimensional Motion Tracking

PMHS kinematics for Task 9 will be determined by tracking the position of reflective markers rigidly attached to the PMHS skeleton as described in Section 3.4.9.

4.5.6 Post-Test Documentation

Post-test documentation, examination, and injury cataloging for Task 9 will follow the protocols outlined for Task 4 in Section 3.4.10.

5. Request for Government Furnished Property (GFP)

UMTRI will use in-house ATDs for test rig characterization. Once the test rig has been built and characterized, UMTRI requests an instrumented, calibrated THOR 50th percentile ATD, or HIII 50th percentile ATD if the THOR is unavailable, for pulse verification in Tasks 4, 6, and 9. Each set of pulse verifications will occur over a ten-day period immediately prior to starting the PMHS or ATD test series. UMTRI also requests an instrumented, calibrated THOR 50th percentile ATD for the testing of Task 6. GFP will be returned per project requirements.

6. Timeline and Deliverables

Table 6.1 lists milestones and deliverables for the project. Monthly progress reports will be submitted no later than the 15th day of each month in the form of email, written or presentation-based progress reports. Monthly briefings will be held as needed by UMTRI through U-M's BlueJeans web meeting system or another system specified by NHTSA (i.e., WebEx).

Table 6.1. Milestones and Deliverables Schedule for Phase I.

Item #	Task	Milestones (M) and Deliverables (D)	Due Date
1	1	Participate in Kickoff Meeting (M)	October 10th, 2018
2	1	Participate in Public Research Presentation (M)	November 27th, 2018
3	2	Submit Draft Implementation Plan (D)	December 14th, 2018
4	2	COR (TO) comments on or approves Draft Implementation Plan (M)	Within 10 days of receipt of Item #3
5	2	Submit Final Implementation Plan (D)	Within 10 days of Item #4
6	2	Submit proposed changes to Final Implementation Plan (D)	As needed
7	2	COR (TO) provides approval, disapproval, or comments on Final Implementation Plan (M)	Within 1 week of Item #6
8	3	Fabricate ADS Sled Buck Assembly (M)	Before start of Task C.4.4
9	4	Submit Technical Data Packages for PMHS tests (D)	Within 30 days of test execution
10	1	Participate in Mid-Term Review (M)	April 1st, 2020
11	4	Submit Draft Report on PMHS tests (D)	September 1st, 2020
12	4	COR (TO) comments on or approves Draft Report on PMHS tests (M)	Within 10 days of receipt of Item #11
13	4	Submit Final Report on PMHS tests (D)	October 1st, 2020
14	5	Submit Draft Report on biofidelity corridors (D)	Within 11 months of completion of Task C.4.4
15	5	COR (TO) comments on or approves Draft Report on biofidelity corridors (M)	Within 10 days of receipt of Item #14
16	5	Submit Draft Report on biofidelity corridors (D)	Within 12 months of completion of Task C.4.4
17	2	Participate in Final Review (M)	October 1st, 2021
18	2	Participate in Meetings – Monthly Web Conference (M)	Monthly
19	1	Submit Monthly Progress Reports (D)	15th of each month, following the month being reported
20	2	Submit Lessons Learned Memorandum (D)	October 1st, 2021
OPTIONAL TASK 6			
21	6	Submit Technical Data Packages for matched pair sled tests (D)	Within 30 days of test execution
22	6	Submit Draft Report on matched pair tests (D)	Within 5 months of execution
23	6	COR (TO) comments on or approves Draft Report on matched pair tests (M)	Within 10 days of receipt of Item #22
24	6	Submit Final Report on matched pair tests (D)	Within 6 months of execution
OPTIONAL TASK 7			
25	7	Submit Draft Report on HBM simulations (D)	Within 5 months of execution
26	7	COR (TO) comments on or approves Draft Report on HBM simulations (M)	Within 10 days of receipt of Item #25
27	7	Submit Final Report on HBM simulations (D)	Within 6 months of execution
OPTIONAL TASK 8			
28	8	Submit Draft Injury Criteria Report (D)	Within 5 months of execution
29	8	COR (TO) comments on or approves Draft Injury Criteria Report (M)	Within 10 days of receipt of Item #28
30	8	Submit Final Injury Criteria Report (D)	Within 6 months of execution
OPTIONAL TASK 9			
31	9	Submit Technical Data Packages for PMHS tests (D)	Within 30 days of test execution
32	9	Submit Draft Report on PMHS tests (D)	Within 11 months of execution

33	9	COR (TO) comments on or approves Draft Report on PMHS tests (M)	Within 10 days of receipt of Item #32
34	9	Submit Final Report on PMHS tests (D)	Within 12 months of execution

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8. Attachment – Comments Received at Public Research Presentation and Via E-Mail

Included as a separate pdf file.