Occupant Safety in Automated Vehicles
- Effect of Seatback Recline on Occupant Restraint -

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ABSTRACT: The introduction of highly automated vehicles will influence occupant seating behavior and seat design, including broader adoption of reclined seating postures. The goal of this study was to perform a preliminary assessment of the usability of two occupant FE models (NHTSA THOR FE, and GHBMC Simplified Occupant) to examine restraint interactions, occupant kinematics, and occupant protection challenges for reclined occupants in frontal collisions. During frontal crash simulations, the GHBMC simplified model tended to exhibit a greater propensity for submarining and greater forward flexion of the lumbar spine compared to the THOR model. These findings will help define needs for occupant protection research for reclined occupants in automated vehicles.

KEY WORDS: safety, restraint, automated vehicle, seat, occupant, injury, simulation [C1]

1. Introduction

The adoption of highly automated vehicles (HAVs) brings the possibility of a new variety in seating postures uncommon in the traditional driving environment. By removing the necessity to interact with vehicle controls, we remove some of the only existing factors that constrain the posture choice of the driver. Instead, the occupant (formerly the driver) may be allowed to choose from among a much greater variety of postures. Thus, vehicle safety systems may be challenged to protect the occupants over a much wider range of potential postures and seating choices.

To adequately assess occupant safety in highly automated vehicles requires tools (human body models, dummies) capable of predicting restraint interactions and injury risk in the wide variety of postures and seating choices made newly possible. As they were designed for use in more traditional seating environments, the biofidelity, usability, and injury prediction capability of the available tools is currently unknown for novel HAV-type seating postures.

One of the novel seating postures that will be possible with automated vehicles will be for all occupants to be capable of traveling in a reclined position. Reclining presents a potential challenge for restraint system performance. With a standard, b-pillar-mounted D-ring, reclining the seat has the potential to move the torso backwards and out-of-contact with the shoulder belt. Reclining also increases the initial distance between the head and the airbag, potentially affecting the degree and timing of interaction between the head and airbag. Reclining also has the potential to rotate the lumbar spine and pelvis backwards. This may affect the manner in which the pelvis engages with the lap belt and the seat structure.

The goal of this study was to perform an initial evaluation of the usability, stability, and potential injury prediction capabilities for the GHBMC simplified 50th percentile male occupant model (GHBMC-M50-OS) and the NHTSA THOR finite element (FE) model in frontal collisions with various degrees of seat recline.

2. Methods

Simulations were performed with the publicly-available NCAC Camry 2012 FE vehicle model(1). Stability of the vehicle model was verified by performing preliminary simulations of a NCAP-style 56 km/h, full-width rigid barrier impact. As this was an initial scoping and usability study, it was desired to decrease the severity of the collision for the evaluation of the effect of recline angle. Thus, for the main portion of this study the simulation consisted of a 56 km/h impact from the Research Moving Deformable Barrier model available from NHTSA, impacting with a PDOF of zero degrees and centered on the front of the Camry model.

To remove potential confounding effects of the steering wheel, all simulations were performed with the occupant model seated in the right front passenger position. The seat was the stock seat available with the NCAC model. The restraint system in the NCAC model was replaced with restraint component models provided by a restraint manufacturer. These consisted of a retractor-petensioned, force-limiting three-point belt; a right-front-passenger frontal airbag; a side-curtain airbag; and a outboard side torso airbag (Fig. 1).

Fig. 1 The NCAC Camry model used in this study (left), with integrated airbags (right).
Simulations were performed with the D-ring mounted in the standard B-pillar location, and also with the D-ring integrated into the seat back. For the integrated D-ring case – the D-ring was moved to a point in space approximately 9 cm above and 10 cm behind the outboard shoulder, and was defined to be rigidly connected to the upper portion of the seat back structure (such that its location moved with the seat back when the seat was reclined). The seat was then reinforced with beam elements overlaid on the initial structural elements of the seat back and seat pedestal. These were strengthened until the entire assembly maintained structural integrity with limited deformation during a simulation of a FMVSS 210-type belt pull test (Fig. 2).

![Fig. 2 Seat-integrated D-ring with reinforced seat. The D-ring was placed in the position shown, rigidly connected to the seat back. Beam elements were added to the seat structure (left) to ensure integrity of the seat during an FMVSS 210-type belt pull test (right).](image1)

The target seatback recline angles for this study were 25° (upright), 45° (semi-reclined), and 60° (reclined). These were defined based on a line drawn between the seat back rotation center and a point near the top edge of the back surface of the seatback (Fig. 3).

![Fig. 3 The three seatback angles investigated in this study.](image2)

The THOR model used for this study was the publicly-available NHTSA THOR FE model, version 2.1. It was positioned using the positioning tree defined in the model, and was settled into the seat using the seat deformer tool available in LS-Prepost. The positioning was performed with a goal of maintaining contact between the back of the dummy and the seat back, maintaining contact between the thighs and the seat cushion for at least 2/3 of the length of the seat cushion, and having the feet placed on the floorpan.

The human body model used for this study was the simplified version of the GHBMC 50th percentile male occupant model (GHBMC-M50-OS, version 1.8.3). This model was positioned through a series of simulation steps, including both gravity settling and forced motion. First, the model was gravity-settled into the seat. Then the torso and head were forced backwards into contact with the seat back and head rest using simulations with a prescribed displacement. Once a satisfactory position was achieved with the head and upper body, the arms were positioned via the model positioning tree.

For this paper, the primary outcomes of interest are the general kinematics and restraint interactions, along with observations on the usability of the models. For more in-depth analyses, however, the THOR and GHBMC models were instrumented with measurement outputs relevant for injury risk prediction. For the THOR model, this included all of the stock THOR instrumentation, as described in the 2015 NCAP Request for Comments published by NHTSA. For the GHBMC simplified model, the instrumentation included measurements designed to be analogous to the THOR instrumentation, where possible based on the model construction.

3. Results and Discussion

3.1. Positioning and Usability

The NHTSA THOR FE model was not capable of being positioned in the semi-reclined and reclined positions via the positioning tree without losing contact between the feet and the floor. The maximum recline angle that could be achieved with the THOR model was 40°. As a result, all semi-reclined simulations with the THOR model were performed at this angle. Because of this positioning limitation, fully-reclined simulations were not performed for the THOR model. It is currently unknown if this limitation in recline angle is an artifact of the THOR FE model, or if it is true also for the physical dummy. Future work should include evaluating the physical THOR in reclined postures.

When positioned in the 40° semi-reclined position, the NHTSA THOR FE model exhibited a gap between the torso jacket and the upper portion of the abdomen insert. This type of gap would not be present in the physical dummy, as the jacket extends down and is secure by a lower strap. Thus, in the model this gap was filled by adding a strip of shell elements to preserve continuity between the torso jacket and the abdomen insert covering.

The NHTSA THOR model exhibited stability in each of the simulations included in this study, and all were completed with normal termination.

The GHBMC-M50-OS was able to achieve the desired positions in both the semi-reclined and fully-reclined positions. As noted above, this was accomplished through a combination of gravity settling, forcing, and adjustment with the positioning tree. It is worth noting that gravity settling alone is not sufficient to lay the model back into the seat. Under gravity alone, the model remains seated semi-upright, supporting its own weight (Fig. 4). The head and torso will not lay back into the semi-reclined and reclined positions unless forced to do so. This is likely due to a combination of the stiffness of the spine, and the stiffness of the superficial tissues. Future work should include examining advanced positioning and morphing tools, such as PIPER, to evaluate their potential utility in positioning in reclined postures.

In initial simulations a stability issue was observed with the GHBMC-M50-OS model, with negative volume errors occurring in the abdomen resulting from loading by the lap belt. This was addressed by adding null shell elements around each hexahedral element within the abdominal block. These were placed around each surface of each element, resulting in an internal 3D mesh of shell elements. A contact definition was then applied to these shells, preventing self penetration. This prevented inversion of the
underlying hexahedral elements, thus eliminating negative volume errors. After making this modification all of the GHBMC-M50-OS simulations performed in this study terminated normally.

3.2. Kinematics and Restraint Interactions

Fig. 5 shows a comparison of the kinematics at peak forward excursion of the GHBMC-M50-OS and the NHTSA THOR FE model in the upright and the semi-reclined positions (both with a standard B-pillar-mounted D-ring). The GHBMC model exhibited greater forward motion of the pelvis, with the pelvis rotating backwards and the lap belt penetrating into the abdomen. This was affected at least partially by the interaction between the flesh and the skeleton of the GHBMC simplified model. In the GHBMC-M50-OS, the superficial tissue layer is not connected to the underlying skeleton. Instead of maintaining continuity, the flesh layer is allowed to slide over the pelvis when subjected to shearing forces. As a result, the pelvis is allowed to slide forward underneath the lap belt, and over the seat cushion, even though there is some engagement with the flesh. This lack of continuity between the flesh and the pelvis is likely not biofidelic, but the proper degree of coupling is currently unknown.

With the THOR, the underside of the pelvis appeared to engage with the anti-submarining structure of the seat pan to a greater degree than the GHBMC model. As a result, instead of rotating backwards, the pelvis of the THOR model rotated forwards into the lap belt. This resulted in greater restraint by the lap belt and the seat pan, less forward excursion of the pelvis, less flexion of the lumbar spine, and less engagement of the knees with the knee bolster. The THOR model also exhibited greater forward flexion of the neck compared to the GHBMC model, due to less forward rotation of the torso and limited engagement with the airbag. Again, it is unknown to what degree the THOR model responses reflect the responses of the physical dummy, as the model has not been evaluated for fidelity in this particular loading scenario. Future work should include tests with the physical THOR dummy in a reclined posture to compare to the model responses.

Fig. 6 shows the kinematics of the GHBMC-M50-OS in the semi-reclined and fully reclined positions, comparing the standard B-pillar-mounted D-ring to the results with the D-ring integrated into the seat back. By integrating the D-ring with the seatback, the D-ring location followed the seatback as it was reclined backwards. As a result, while there was an initial separation between the shoulder belt and the torso with the standard D-ring, the seat-integrated D-ring maintained initial contact between the
shoulder belt and the chest in both the semi-reclined and reclined positions. By maintaining this initial contact, the seat-integrated D-ring allowed the shoulder belt to engage the occupant earlier in the collision, resulting in less forward excursion of the head and less head acceleration and angular velocity. While they had similar forward pelvis motions, however, the seat-integrated D-ring tended to show a greater flexion angle and resultant force in the lumbar spine compared to the standard D-ring. This is likely the result of decreased forward rotation of the upper body, affected by a combination of the earlier belt engagement and the more horizontal shoulder belt angle.

Thus, although a seat-integrated D-ring may help address some restraint challenges posed by reclined occupants (e.g., initial belt contact and earlier engagement), submarining-related issues may remain a concern. Some supplemental restraint design consideration may still be needed to help control forward pelvis motion and reduce the risk of submarining. It is currently unknown to what degree the change in kinematics and lumbar spine loading observed with the seat-integrated D-ring may affect lumbar spine injury risk. Future work should include evaluating the biofidelity of the GHBMC-M50-OS lumbar spine under this type of loading (combining shear, compression, and bending), and assessing its fidelity in predicting injury risk in that region.

4. Conclusions

This study performed a series of full-vehicle frontal impact simulations with the GHBMC-M50 simplified occupant model, and the NHTSA THOR FE model, as a preliminary assessment of their usability for studying restraint interactions and injury risk in reclined seating postures. The NHTSA THOR FE model was limited in its ability to recline, achieving a maximum recline angle of 40°. The GHBMC-M50-OS model was able to achieve all desired recline angles, using a combination of gravity settling and forced positioning. Stability issues were observed in the GHBMC-M50-OS when the abdomen was loaded by the lap belt. This was solved by superposing a mesh of null shell elements within the abdomen to eliminate internal penetrations.

In the semi-reclined position, the GHBMC-M50-OS tended to exhibit more forward motion of the pelvis, more backwards rotation of the pelvis, more penetration of the lap belt into the abdomen, and more flexion in the lumbar and thoracic spines compared to the THOR model. In the semi-reclined and reclined positions with the GHBMC-M50-OS, a seat-integrated D-ring tended to result in earlier engagement of the torso, less forward head motion, less head acceleration, and less head angular velocity compared to a standard B-pillar mounted D-ring. The seat-integrated D-ring did, however, result in greater resultant force and flexion angle in the lumbar spine. These results represent a preliminary assessment. Future work should include evaluating the fidelity of the GHBMC-M50-OS and NHTSA THOR FE models in reclined seating environments, and evaluating their accuracy in assessing tradeoffs among various restraint configurations.

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