Chest Response to Steering Wheel Lower Rim Impact: Comparative Analysis of THOR-50M and GHBMC Models

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Abstract This study investigates the chest deflection sensitivity of the THOR-50M and the GHBMC model under unbelted impact conditions against the lower rim of a steering wheel. IR-TRACC responses were recorded at four distinct locations on the THOR-50M. Various vertical impact points were evaluated to quantify response variations. Results indicate significant variations in chest deflection between upper and lower impact locations, potentially due to differential rib cage stiffness. Finite element models predicted similar trends. The GHBMC model exhibited lower chest deflection compared to the THOR-50M, attributed to its detailed anatomical features. Notably, the GHBMC model showed significantly lower variation in peak chest deflection between upper and lower impact points (1.3 mm delta) compared to the THOR-50M model (15.6 mm). These findings provide insights into the differential response characteristics of the THOR-50M thorax relative to the human body model under the loading condition studied.

Keywords Chest deflection, finite element analysis (FEA), GHBMC, THOR-50M, NHTSA.

I. INTRODUCTION

In 2023 the National Highway Traffic Safety Administration (NHTSA) published a Notice of Proposed Rulemaking (NPRM) to amend its regulations to include the Test Device for Human Occupant Restraint (THOR) 50th percentile adult male (THOR-50M) into Part 572 of the Federal Motor Vehicle Safety Standards (FMVSS). The agency has also indicated its intention to initiate rulemaking to allow use of the THOR-50M as a compliance option in FMVSS No. 208. This advanced crash test dummy is intended to capture accurate and biofidelic responses in frontal crash tests. The NHTSA's intention to incorporate the THOR-50M into FMVSS No. 208 highlights the agency's desire to improve occupant protection and vehicle safety standards [1].

Previous research presented at the 2022 STAPP Conference highlighted significant differences between the THOR-50M and the Hybrid III 50th percentile male (HIII AM50) dummies in FMVSS 208 tests. The study, conducted jointly by Ford and Nissan, demonstrated that the THOR-50M tended to predict elevated injury risk compared to the Hybrid III ATD, particularly in unbelted crash scenarios. Compared to 2017–2020 CISS injury rates, the THOR-50M overpredicts injury risk for chest and brain injuries. It also overpredicts injury risk for neck AIS3+ injuries, while the HIII-AM50 is closer to CISS data. Additionally, the increased Nij (neck injury) predicted by the THOR-50M is not evident in the injury rates observed in the field (CISS). For an Anthropomorphic Test Device (ATD) to be effective in regulatory and compliance testing, it is essential that it consistently delivers repeatable and reproducible results that can accurately predict the injury risk in the field [2].

Further studies have evaluated the THOR-50M's performance in various crash scenarios. Dix *et al.* [3] conducted an evaluation of the THOR-50M's in-dummy data acquisition system, comparing it with an external data acquisition system (DAS). Their findings indicated that the DAS system does not influence results, however they did note elevated variation, not related to the in dummy DAS. Additionally, Global Human Body Models Consortium (GHBMC) has developed high-fidelity finite element (FE) human body models (HBMs) for crash simulations, accurately replicating human body dynamics and validated against various impact scenarios [4].

The current study investigates the chest deflection sensitivity of the THOR-50M dummy when seated in the driver position in the unbelted test condition. Observing variations in the chest response of the THOR-50M, the authors included the GHBMC model to evaluate whether the HBM exhibits similar tendencies. The research specifically focuses on the biomechanical responses of these models when impacted by the lower rim of a steering wheel, simulating an unbelted impact scenario. Finite element modeling and analyses were employed to assess

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these responses and to validate the effectiveness of the THOR-50M in replicating human body dynamics.

II. METHODS

SLED Test: Evaluation of THOR-50M at 25 mph (40 kmph) Under Unbelted Conditions

A variation study was conducted to evaluate the performance of the THOR-50M dummy in the FMVSS No. 208 25 mph unbelted flat frontal test. The study involved four driver-side sled tests for the 25 mph (40 kmph) unbelted flat frontal test dictated in FMVSS No. 208. A typical mid-sized sedan was used as the surrogate for this study. The THOR-50M was positioned in the driver position in all four tests, with the seating being matched for all tests. Consistent dummy kinematics were observed across all tests, as depicted in Fig. 1. The driver restraint system was unbelted, comprising a driver front airbag and knee airbag. The primary objective was to assess the repeatability and reproducibility of the THOR-50M dummy's responses under these controlled conditions.

Fig. 1. Driver THOR-50M dummy kinematics showing consistency among all four tests.

Table I represents the various injury responses of the dummies, and the results indicate excessive variation (highlighted in red) in neck and chest responses. Specifically, neck variation resulted from header/windshield contact due to the THOR-50M's taller stature. Chest deflection showed the highest variation, ranging from 30 mm to 59 mm with a coefficient of variation (CV) of 31% (25% normalized CV), indicating moderate variability and a standardized measure of dispersion. This necessitated a more detailed study to understand the chest deflection sensitivity responses of the THOR-50M dummy.

TABLE I INJURY RESPONSES OF THOR-50M DUMMY IN THE FMVSS NO. 208 25 MPH UNBELTED FLAT FRONTAL TESTS

Injury parameter	NHTSA Normalising factor	Test 1	Test 2	Test 3	Test 4	Average	Standard deviation	CV (%)	Normalised CV
		ATD1	ATD2	ATD3	ATD3				
HIC15	1724	175	157	280	279	223	66	30	4
BRIC	0.96	0.52	0.56	0.67	0.6	0.59	0.06	11	7
Neck Tension	4662	1189	1082	1318	1232	1205	98	8	2
Neck compression	5017	3257	2660	4261	2986	3291	691	21	14
Nij (2020 constants)	1.11	1.1	0.88	1.34	1.01	1.08	0.19	18	17
Chest deflection (max)	51.4	58.9	30.3	44.3	32.9	41.6	13.0	31	25
Abdomen deflection		35	27.7	24.3	23	27.5	5.4	20	
Left Femur	10577	2678	2306	2395	2490	2467	159	6	2
Right Femur	10577	2748	2727	2683	2557	2679	86	3	1

Coefficient of variation (CV)= standard deviation/average:
acceptable (CV<10) marginal (CV:10-20) extreme (CV>20)
Normalized CV calculated using NHTSA normalizing factor in place of sample mean

Experimental setup: unbelted chest response of THOR-50M

To investigate the chest deflection sensitivity of the THOR-50M dummy, a laboratory-level setup was established. Various impact locations on the THOR-50M were identified for impact by the lower rim of the steering wheel under the unbelted condition. The seating layout and steering-wheel distance were consistent with those of the surrogate vehicle utilized in sled tests. The steering wheel was inclined at 28 degrees relative to the vertical axis, and prior to impact the center of the lower rim was aligned with the designated impact point on the dummy. The lower rim of the steering wheel impacted the chest region of the THOR-50M dummy at nine specific chest datum points, as illustrated in Fig. 2(a).

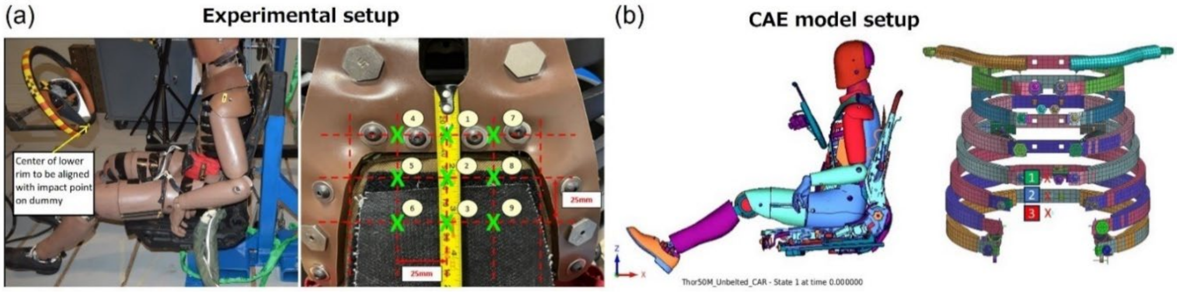

Fig. 2. Steering-wheel impact testing on THOR-50M: (a) experimental setup, and (b) corresponding CAE.

To ensure symmetric loading on the left and right IR-TRACC devices, this study specifically focuses on the mid-row impact points, designated as Impact Points 1, 2, and 3, as depicted in Fig. 2(a). These points represent typical positions where the lower rim of the steering wheel may impact the chest. Each impact location is spaced 25 mm apart along the vertical (Z) axis. The steering wheel, weighing approximately 2.4 kg, was used to impact the chest at an average velocity of 12 m/s at specified locations. These parameters were set to match the maximum deflection observed during sled testing.

Computational Model: THOR-50M and GHBMC based on Experimental Testing

The THOR-50M dummy was positioned in the CAE model according to the test coordinate measurement data, as depicted in Fig. 2(b). A CAE sensitivity analysis was subsequently conducted, focusing on the dummy's positioning (pelvis angle) and the coefficient of friction (CoF) between the dummy and the steering wheel. An optimized pelvis angle of 20 degrees and a CoF of 0.4 were determined based on correlation with experimental results. The analysis were performed using the PAM-CRASH explicit solver, version 2019. The contact between the dummy and the steering wheel was modeled using SYMMETRIC NODE-TO-SEGMENT WITH EDGE TREATMENT (TYPE 33) to accurately simulate the interaction. The chest impact location was replicated as per the test setup, as shown in Fig. 2(b).

The GHBMC model was positioned with reference to the hip point of the THOR dummy, ensuring that the overall stature was accurately attained, as shown in Fig. 3(a). From Fig. 3(b), it can be observed that the rib configurations of the GHBMC and THOR-50M models are well aligned. Additionally, Fig. 3(c) illustrates the four identified nodes on the GHBMC ribs (marked as UR, UL, LR, and LL) corresponding to the IR-TRACC positions in the THOR-50M dummy. From these identified nodes on the front rib to the corresponding nodes aligned straight to the back of the rib, the initial and final distances were recorded to measure chest compression, replicating the THOR-50M IR-TRACC measurement method. This practice ensures consistency in chest deflection data recording, facilitating accurate comparisons between the two models.

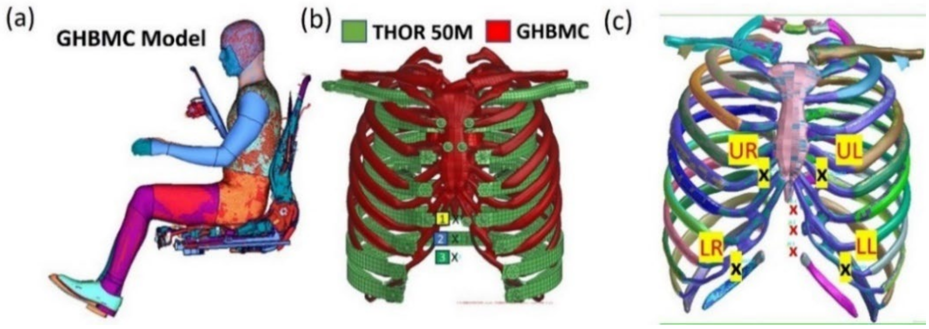

Fig. 3. (a) Positioning of the GHBMC model, (b) rib configuration comparison between THOR-50M and GHBMC, (c) deflection record of GHBMC at the same point as THOR-50M.

III. RESULTS

Influence of impact point on chest response of THOR-50M

Table II presents the IR-TRACC responses at four locations for three impact points. For impact point 1, chest deflection was more pronounced in the upper region, while at impact point 3, it was more significant in the lower region. Above impact point 2 (i.e. impact point 1), ribs are tied together so when the steering wheel contacts this impact point, load is transmitted directly to the IR-TRACCs, resulting in large deflections (46 mm). Below impact point 2 (i.e. impact point 3), untied ribs and a larger rib cage opening lead to lower deflections (37 mm). Hikida *et al.* reported a similar tendency and attributed it to the differential stiffness of the rib cage, with the upper chest being stiffer, due to sternum and rib attachments, and the lower chest being more flexible [5]. Three tests per condition ensured repeatability, with standard deviations under 1%.

TABLE II THOR-50M CHEST RESPONSES AT DIFFERENT IMPACT LOCATIONS

Impact point	Upper Left (mm)	Upper Right (mm)	Lower Left (mm)	Lower Right (mm)
1	45.5±0.7	41.4±0.3	17.1±0.2	18.8±0.0
2	39.6±0.1	37.7±0.3	24±0.4	28.1±0.7
3	25.6±0.2	21.6±0.6	33.4±0.9	37.2±0.6

THOR-50M Chest Responses: test vs predicted

The predicted chest responses for all cases are recorded and tabulated in Table III for comparison with the test results. It was observed that the CAE overpredicted chest deflection at all locations for impact point 1, whereas for impact point 3 the CAE underpredicted the chest response. Notably, for both impact locations the CAE predictions for the highest chest deflection were within a relative error of 10%. At impact point 2, the FE model overpredicted the chest deflection in the upper region and underpredicted the chest deflection in the lower region, with a relative error within 15%. Consequently, the highest chest deflection at each impact point was considered for comparison with the GHBMC chest response.

TABLE III EXPERIMENTAL AND CAE THOR-50M CHEST IMPACT RESPONSES COMPARISON

Impact Point 1	Upper Left	Upper Right	Lower Left	Lower Right
Test, mm	45.5	41.4	17.1	18.8
CAE, mm	50.5	47.7	20	21.4
Error (%)	**-10**	-15	-15	-13
Impact Point 2	**Upper Left**	**Upper Right**	**Lower Left**	**Lower Right**
Test, mm	39.6	37.7	24	28.1
CAE, mm	34.3	32.2	27.1	31.7
Error (%)	**13**	15	-13	-13
Impact Point 3	**Upper Left**	**Upper Right**	**Lower Left**	**Lower Right**
Test, mm	25.6	21.6	33.4	37.2
CAE, mm	24.9	21.9	28.6	34.9
Error (%)	3	-1	14	**6**

GHBMC Chest Response Evaluation

The simulation results at the same impact points (1, 2, and 3) on the GHBMC model are consolidated in Table IV. The GHBMC exhibited lower chest deflection in each region compared to the THOR-50M. This lower chest deflection in GHBMC may be attributed to the presence of ribs, muscles, soft tissues, and internal organs, which possess different mechanical properties compared to ATDs. These detailed anatomical features in HBMs enhance the absorption and distribution of impact forces more effectively than the simplified structures in ATDs, resulting in lower chest deflections in HBMs under similar impact conditions [6].

TABLE IV CHEST IMPACT RESPONSES FOR GHBMC

Impact Point	Upper Left	Upper Right	Lower Left	Lower Right
1	34.7	33.7	13.3	12.4
2	27.8	26.2	23.2	21.1
3	18.6	17.7	33.4	30.4

Comparative Analysis of Thoracic Responses in THOR-50M and GHBMC Models

Table V summarizes the chest impact responses for both the THOR-50M and GHBMC models at three different impact points. The data indicate the highest chest deflection values recorded for each model at three impact locations. The variation in peak chest deflection between impact points 1 and 3 is lower for GHBMC (1.3 mm) than for THOR-50M (15.6 mm). While GHBMC shows consistent peak deflections at different locations (34.7 mm at point 1, and 33.4 mm at point 3), THOR-50M shows a significant difference (50.5 mm at point 1, and 34.9 mm at point 3). Thus, GHBMC maintains similar peak deflections with varying impact locations, whereas THOR-50M exhibits notable changes in deflection sensitivity at lower impact locations. Additionally, specific reductions in chest deflection, ranging from 6% to 31%, were noted at each impact point, indicating variations between the two models under identical impact conditions.

TABLE V CHEST IMPACT RESPONSES FOR THOR-50M AND GHBMC

Impact Point	THOR-50M	GHBMC	Deflection reduction in GHBMC
1	50.5	34.7	31%
2	34.3	27.8	20%
3	34.9	33.4	6%

IV. DISCUSSION

The primary focus of this study is to highlight the variation in peak chest deflection between impact points 1 and 3, which is significantly lower for the GHBMC model (1.3 mm) compared to the THOR-50M model (15.6 mm). The GHBMC model demonstrates consistent peak deflections across different locations (34.7 mm at point 1, and 33.4 mm at point 3), whereas the THOR-50M model exhibits substantial differences (50.5 mm at point 1, and 34.9 mm at point 3). This indicates that the GHBMC model maintains similar peak deflections with varying impact locations, while the THOR-50M model shows notable changes in deflection sensitivity. Additionally, the results reveal variations in chest deflection across different impact points, with the THOR-50M model's peak deflection ranging from 6% to 31% higher than that of the GHBMC model (Table V), depending on the impact and measurement locations. The strengths of this study include the comprehensive methodology, which combines experimental and computational approaches, and the controlled impact conditions, which ensure the reliability of the results. However, limitations include the specific unbelted conditions, which may not fully represent all real-world scenarios. Future research should explore additional impact scenarios, including belted conditions and different vehicle types, to provide a more comprehensive understanding of chest deflection sensitivity.

V. CONCLUSION

This study provides valuable insights into the chest deflection sensitivity of the THOR-50M and the GHBMC model, employing component test conditions that replicate an impact by the lower rim of the steering wheel at different chest points in an unbelted condition. The results show that the THOR-50M exhibits greater sensitivity in chest deflections, as well as higher peak deflection among impact points, compared to the GHBMC model. These findings highlight the differential response characteristics of the THOR-50M thorax to steering-wheel rim impacts when compared to the HBM.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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