DEPARTMENT OF TRANSPORTATION
National Highway Traffic Safety Administration
THOR-50M Notice of Proposed Rulemaking
Docket No. NHTSA-2023-0031
RIN 2127-AM20

Technical Appendices to Preamble

Table of Contents

Appendix A – Analysis of NHTSA Upper Thorax Qualification Test Data

As was discussed in the preamble, some members of ISO/TC 22/SC 36 Working Groups 5 and 6 have suggested design changes to THOR-50M – specifically a shorter rib guide – in order to meet the Euro NCAP upper thorax qualification specifications. NHTSA, in considering whether to implement these design changes, analyzed its own qualification testing data. As we explain below, the preliminary analysis suggests that the difficulty meeting the Euro NCAP specification might stem not from the dummy design, but from the qualification specifications themselves.

The original publication of Euro NCAP TB026[1] specified individual X- and Z-axis deflection requirements, which were similar to the NHTSA August 2016 Qualification Procedures specifications ("NHTSA 2016" for short), but with a narrower corridor width. The NHTSA 2016 specifications used individual X- and Z-axis deflection requirements of –46.4 to –38.0 mm (10% width) and 25.6 to 31.2 mm (10% width) respectively, where these specifications were determined from testing of NHTSA-owned THOR-50M ATDs. Euro NCAP TB026[2] specified similar but narrower requirements for individual X- and Z-axis deflection of –45.0 to –39.1 mm (7% width) and 27.0 to 31.1 mm (7% width) respectively. The basis for these specifications is not clear, though a presentation to the ISO WG5 stated that "At the request of the Euro NCAP Frontal Impact WG, Humanetics proposed narrow certification corridors for THOR 50M dummies."[3]

In the September 2018 version of the THOR-50M Qualification Procedures ("NHTSA 2018" for short), the individual X- and Z-axis deflection requirements were replaced with resultant deflection requirements, primarily to ensure that the metric used to calculate injury criteria, peak resultant deflection, was assessed by at least one of the qualification test modes. Similarly, in Version 1.1 and newer of Euro NCAP TB026, the individual X- and Z-axis deflection requirements were replaced with a resultant deflection along with a ratio of Z-axis to X-axis deflection. While individual X- and Z-axis deflection requirements are no longer assessed as part of the proposed qualification specifications, these measurements can still be determined from the data collected in the upper thorax qualification test.

Figure A.1 shows the upper left and upper right peak resultant deflections from the 25 upper thorax qualification tests conducted as part of the THOR-50M R&R study. This figure also includes the NHTSA's proposed qualification specifications for peak resultant deflection, as well as those from Euro NCAP TB026 Version 1.2 (black dashed lines). While all of the tests would meet the proposed peak resultant deflection specifications, 10 of the tests had higher peak resultant deflections than the narrower Euro NCAP TB026 specifications, 7 of which were above the upper limit for both the upper left and the upper right thorax.

[1] European New Car Assessment Programme (2020). THOR Specification and Certification, Version 1.0, *available at:* https://www.euroncap.com/en/for-engineers/supporting-information/technical-bulletins/
[2] European New Car Assessment Programme (2020). THOR Specification and Certification, Version 1.0, *available at:* https://www.euroncap.com/en/for-engineers/supporting-information/technical-bulletins/
[3] ISO-TC22-SC36-WG5_N1228_THOR_Corridor_Review_08JUN20.pdf.

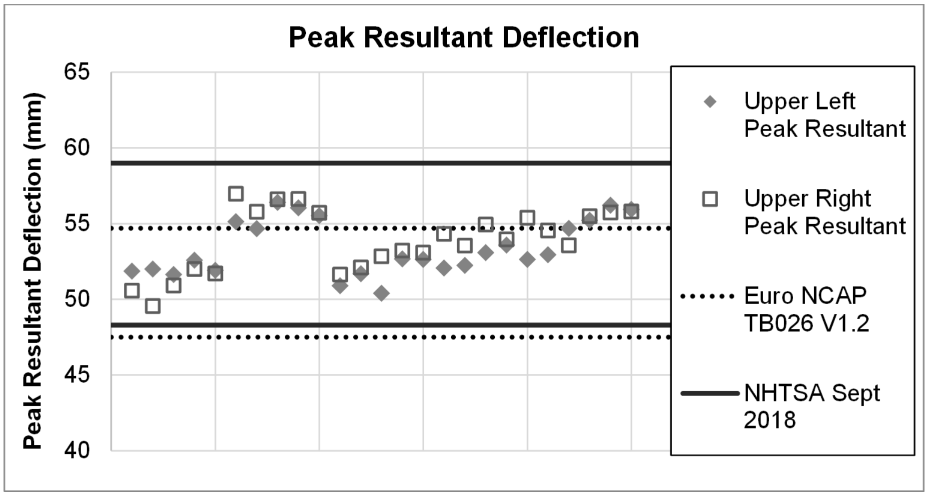

Figure A.1. Upper thorax qualification test peak resultant deflections from 25 THOR-50M tests.

For the same tests, the individual X- and Z-axis deflections were calculated and compared to both the NHTSA 2016 specifications and those of Version 1.0 of the Euro NCAP TB026. As a majority of the related comments made to ISO WG5 implicated the Z-axis deflection as a measure of particular difficulty, it was expected that there would be a divergence between the NHTSA THOR-50M test results and the Euro NCAP specification. However, there is only one observation that would meet the NHTSA specification but not the Euro NCAP specification (see first data points on Figure A.2). Otherwise, six of the tests would fall outside both the NHTSA 2016 and Euro NCAP Z-axis deflection specifications, with three showing upper left Z-axis deflections below the lower limit (all with S/N DL9207) and three showing upper left Z-axis deflections above the upper limit (all with S/N DO9798). All other tests would fall within both the NHTSA and Euro NCAP specifications.

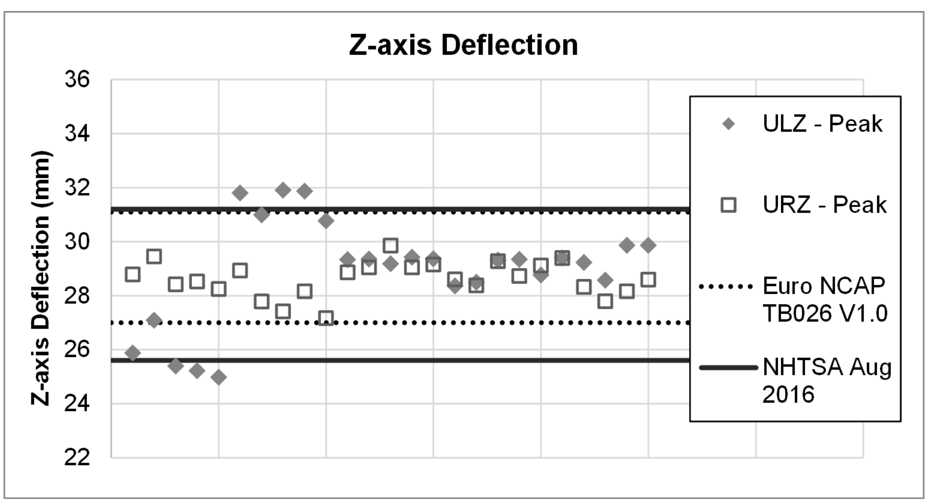

Figure A.2. Upper thorax qualification test peak Z-axis deflections for 25 THOR-50M tests.

In contrast, just over half of the observations (14 of the 25 tests) would fall within the NHTSA 2016 X-axis deflection specifications, with the tests falling outside of the specifications all showing a larger magnitude (more negative) X-axis deflection: the upper right in tests 6 through 10 (all with S/N DO9798); the upper right in tests 16, 18, and 20 (all with S/N DO9799 at laboratory #2), and both the upper left and upper right in tests 23 through 25 (all with S/N DO9799 at laboratory #3). Only 7 of the 25 observations would meet Version 1.0 of the Euro NCAP TB026 X-axis deflection specification, with all other tests showing a larger magnitude of X-axis deflection than the specification.

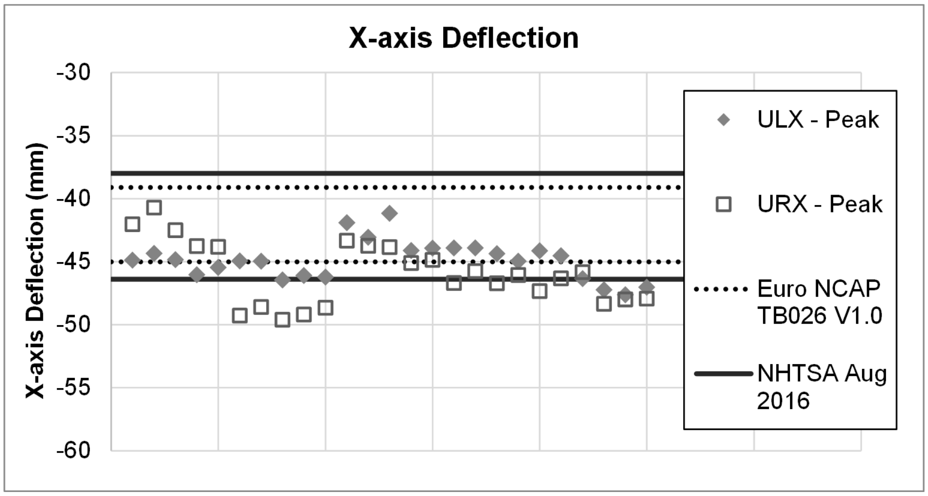

Figure A.3. Upper thorax qualification test peak X-axis deflections for the 25 THOR-50M tests used to develop the NHTSA 2018 specifications.

There are two possible explanations for this discrepancy. One is that in Repeatability and Reproducibility testing conducted in 2015-2016, one of the THOR-50M ATDs tested (S/N DO9799) displayed notably lower deflections than the others (Figure A.4). Since this was the ATD that was subsequently tested at two different test facilities, the results from S/N DO9799 were overrepresented in the calculation of the specifications (15 tests from DO9799 vs. 5 tests from each of two other THOR-50M ATDs). As evident in Figure A.4, there is a distinctly bi-modal characteristic, where the first 10 tests (S/Ns DL9207 and DO9798) have an average X-axis deflection of -45.9 mm and the last 15 tests (S/N DO9799) have an average X-axis deflection of -39.9 mm. As the NHTSA 2016 specification was based on the average of all 50 data points (25 left and 25 right), this resulted in two clusters of results, each close to limits of the specification. While it is not clear what caused the difference in results been DO9799 and the other two THOR-50Ms, this separation was not seen in the 25 tests used to develop the NHTSA 2018 specifications (Figure A.1 or Figure A.3).

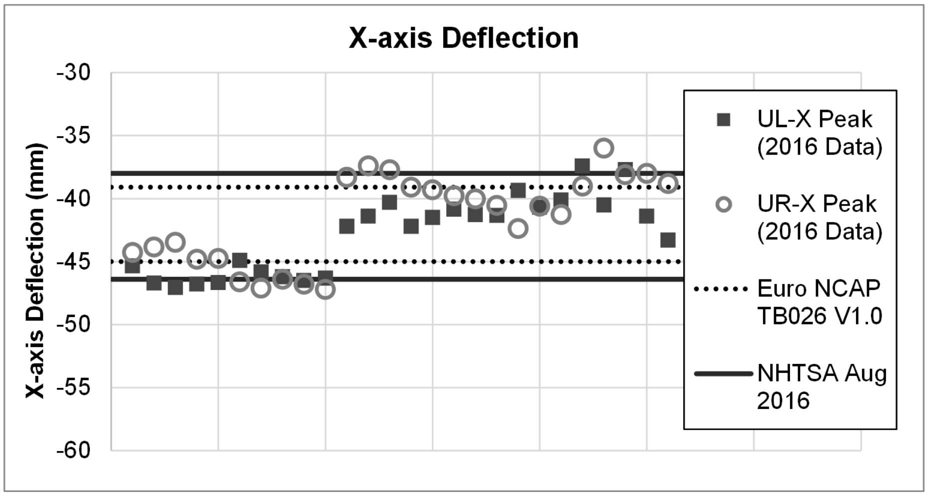

Figure A.4. Upper thorax qualification test peak X-axis deflection for 25 THOR-50M tests conducted in 2016.

Another possible reason that only a subset of the NHTSA 2018 tests would fall within the NHTSA 2016 X-axis deflection specifications is that between the two testing regimes, there was a design change to the sternum. Initial testing showed similar responses on the same THOR-50M ATD before and after the strapped sternum was installed, with X-axis and Z-axis deflections the same or slightly larger in magnitude when the strapped sternum mass was installed. In theory, the slightly larger deflection would result in improved biofidelity, though a comparison between the responses showed that the qualitative biofidelity was effectively unchanged (Figure A.5), and BioRank scores were comparable (No Strap: 1.042; Strap: 1.035). Thus, since the strapped sternum mass provided improved durability without negative influence on biofidelity, it was incorporated into the drawing package and all NHTSA-owned THOR-50M ATDs were updated accordingly. The repeatability and reproducibility study was then repeated for the upper thorax qualification test mode, and used to develop the proposed specifications.

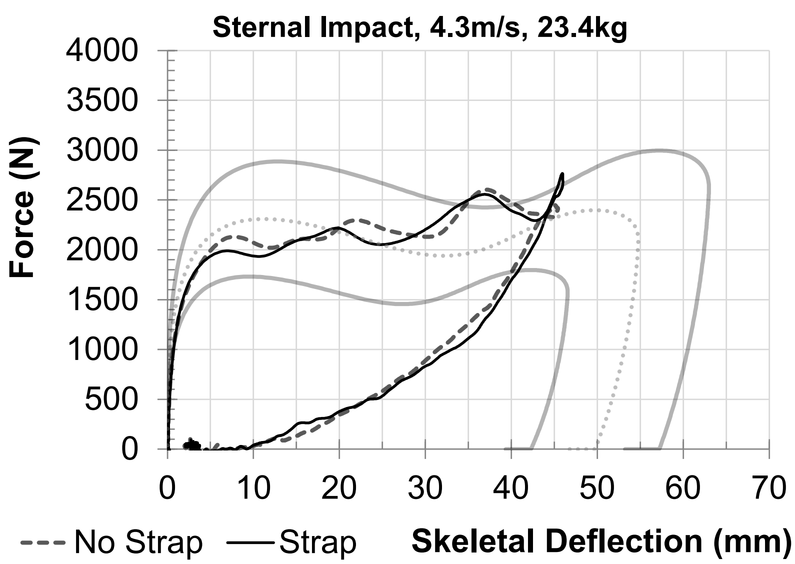

Figure A.5. Skeletal deflection in the blunt thoracic impact biofidelity test condition, comparing the response with and without the strapped sternum installed.

For the sake of comparison, if the tests with the strapped sternum mass installed were used to develop individual X-axis and Z-axis specifications, the resulting limits would be different than the NHTSA 2016 specifications. The largest change would be in the X-axis specification, where the corridor mean would be just over 3 mm higher in magnitude (more negative) than the NHTSA 2016 specification (Figure A.6), and all but one of the observations would fall within the corridor. Meanwhile, the Z-axis specification would be effectively unchanged (Figure A.7).

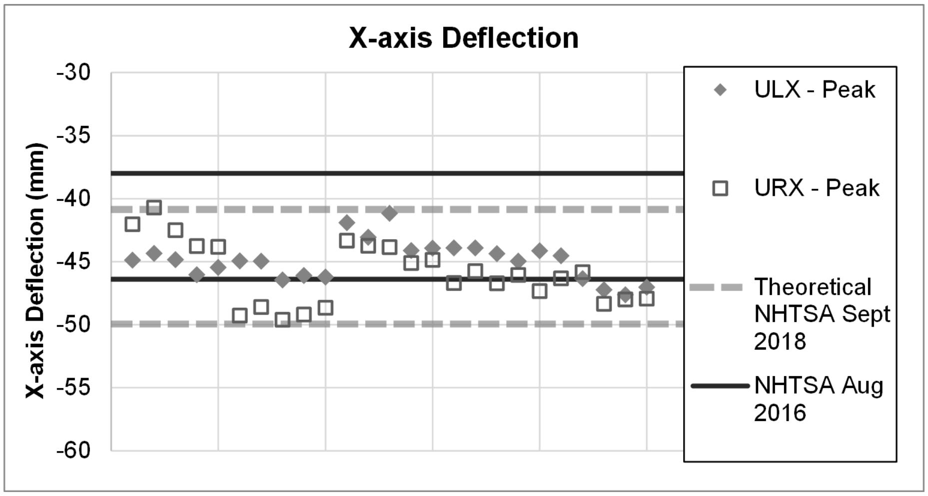

Figure A.6. Theoretical X-axis deflection specification calculated from 25 THOR-50M tests used to develop the NHTSA 2018 specifications.

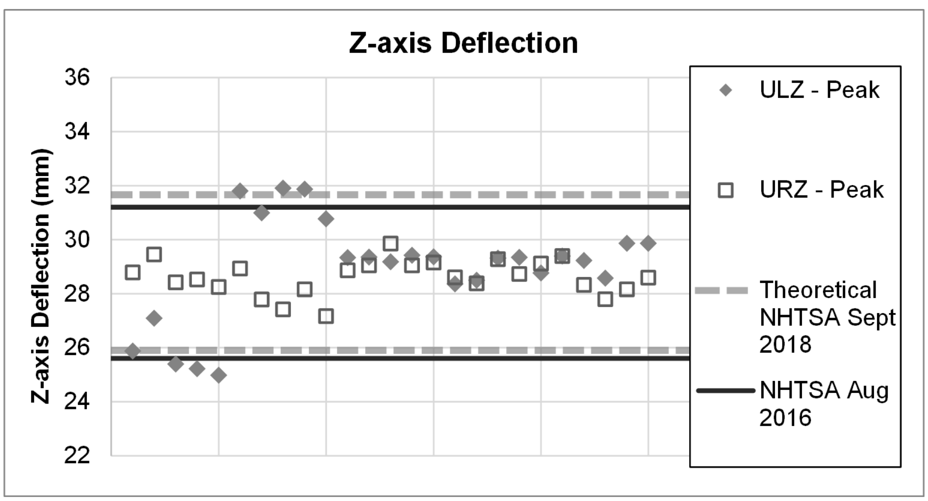

Figure A.7. Theoretical Z-axis deflection specification calculated from 25 THOR-50M tests used to develop the NHTSA 2018 specifications.

This may explain the perceived difficulty in meeting the Euro NCAP specifications. If the Version 1.0 specifications were based on the NHTSA 2016 specifications, or similarly based on testing without the strapped sternum mass, the specifications would not be representative of the expected response of the THOR-50M ATDs with the strapped sternum mass are installed, and would thus be difficult to meet. While Euro NCAP did change the specifications in Version 1.1, the basis for formation of the specifications is still unclear, so it is possible that the initial specifications were translated into peak resultant deflection, but could still reflect a design without the strapped sternum mass installed.

Appendix B – NHTSA modelling of Spine flex joint

As noted in the preamble, members of Working Group 5 have apparently observed variations in the ATD responses in the upper thorax qualification tests that have led to difficulties in meeting the Euro NCAP qualification specifications. NHTSA's understanding is that some WG5 members have suggested that this variation in response is due to variation in the lumbar spine flex joint (specifically, the vertical displacement (Z-axis) of the ribs is too high). One potential cause that has been identified is that that the material comprising the lumbar spine flex joint was softer than specified in the 2023 drawing package. The lumbar spine flex joint assembly drawing (472-3740) specifies molding using material specification of Butyl Rubber, Shore A 75±2. A 2019 presentation from Porsche presented results of several lumbar spine flex joints from different manufacturers tested both for hardness and for dynamic response.[4] Porsche found that lumbar spines fabricated by two different manufacturers measured lower hardness than this specification, as low as 58 Shore A. When tested dynamically in a neck pendulum configuration, the softer lumbar spines showed larger magnitudes of Y-axis rotation, lower shear (X-axis) force, and higher axial (Z-axis) force.

These findings highlight the importance of ensuring that rubber parts such as the lumbar spine flex joint meet the material specifications on the associated drawing.[5] Nevertheless, to further investigate this potential issue, NHTSA conducted a modeling exercise using Version 2.7 of the THOR-50M finite element (FE) model. A limitation of this analysis is that the THOR-50M FE model Version 2.7 has not been specifically validated in the Gold Standard sled test conditions. The thorax of the model is generally softer than that of the physical THOR-50M in the Gold Standard 1 and 2 conditions, with the model showing peak resultant deflections around 35% higher than the physical THOR-50M. As such, findings from the lumbar spine stiffness variation study are likely to be directionally correct, but different in magnitude. Interestingly, the model and the physical THOR-50M show similar peak resultant deflections in the Gold Standard 3 condition (38 mm vs 36 mm, respectively).

In this study, three possible material stiffness variations of the thoracic spine flex joint (472-3646) and lumbar spine flex joint (472-3746) were investigated: decreased 50%, baseline, or increased 50%. These properties were applied independently to each flex joint, resulting in a full-factorial array of nine (9) configurations. For each configuration, simulations were conducted in the upper thorax qualification test condition as well as three sled test conditions described earlier as the Gold Standard 1, 2, and 3 conditions.

In the upper thorax qualification test condition, the largest change in peak resultant thorax deflection was 1.14 mm (2.5%), which occurred when both the thoracic spine and lumbar spine flex joint stiffnesses were increased by 50%. As this was a smaller change than expected, two additional simulations were run, where the stiffness of both joints were either increased 90% or decreased by 90%. When the stiffnesses were increased by 90%, the results were similar to the 50% increase condition, as the peak resultant deflection increased by 1.2 mm (2.6%). When both joints were decreased in stiffness by 90%, the peak resultant deflection decreased by 2.36

[4] ISO-TC22-SC36-WG5_N1212_THOR_Lumbar_Spine_and_Pelvis_Flesh.pdf.

[5] The Partnership for Dummy Technology and Biomechanics, of which Porsche is a member, also suggested that the higher Z-axis deflection could be caused by differences in the material properties of the abdominal inserts, which Mercedes-Benz found to vary greatly in density. For the abdominal inserts (upper abdomen: 472-4621, 472-4622, 472-4623; lower abdomen: 472-4764, 472-4765), drawing specifications include the material type as well as performance specifications, such as stiffness at defined compression levels. It is not clear whether Mercedes-Benz confirmed these material specifications as well, and if they were not met, what actions were taken.

mm (5.1%). This suggests that a decrease in stiffness of the spine flex joints can influence the upper thorax qualification response, but by a much smaller magnitude than the width of the qualification specifications.

Considering the X-axis and Z-axis deflections independently, the changes in X-axis deflection were similar but slightly smaller than the changes in resultant deflection, while the changes had a larger effect on Z-axis deflection. Of the original nine simulations, the largest change in Z-axis deflection occurred when both flex joints were decreased in stiffness by 50%, or when the thoracic spine stiffness was decreased by 50% while the lumbar spine stiffness was increased by 50%. In these conditions, the Z-axis deflection decreased by 6.7% and 7.1%, respectively. When the stiffness of both joints was decreased by 90%, the Z-axis deflection decreased by 14.4%. This finding conflicts with the suggestion by the Partnership for Dummy Technology and Biomechanics (PDB) that decreases in lumbar spine flex joint stiffness would cause increases in Z-axis deflection in the upper thorax qualification test. Either way, the magnitude of variation investigated in this simulation study (90% decrease in stiffness) is likely much larger in magnitude than would be expected between a 75 Shore A and a 58 Shore A material. Conversely, this suggests that the upper thorax qualification test alone would not be sufficient to identify whether the lumbar spine flex joint meets the material specification.

In the Gold Standard 1, 2, and 3 sled test conditions, varying the flex joint stiffness by 50% in either direction resulted in more noticeable changes in the thoracic response than in the qualification test condition. Overall peak resultant deflection, which is the measure used to predict the risk of thoracic injury in the THOR-50M,[6] occurred in the upper left quadrant of the thorax in all three conditions. In all cases, increasing or decreasing the thoracic and lumbar flex joint stiffnesses by 50% resulted in a less than 10% change in peak resultant deflection (Table B.1). The largest change in response occurred in the Gold Standard 2 test condition when the thoracic and lumbar stiffness was increased by 50% (3.3 mm, or 8.2% decrease). Peak resultant deflection also decreased in the Gold Standard 3 condition when thoracic and lumbar stiffness was decreased by 50% (2.8 mm, or 7.3% decrease).

[6] Craig, M., Parent, D., Lee, E., Rudd, R., Takhounts, E., Hasija, V. (2020). Injury Criteria for the THOR 50th Male ATD. Docket ID NHTSA-2019-0106-0008.

Table B.1. Peak resultant, X-axis, and Z-axis deflections, in mm, predicted by THOR-50M FE model in Gold Standard sled test conditions when varying thoracic and lumbar spine flex joint stiffness. To prevent amplification of low-magnitude measurements, percent changes are normalized by the respective resultant measurement.

Resultant	Decrease 50%	Baseline	Increase 50%
Gold Standard 1	76.23 (1.2%)	75.31	75.53 (0.3%)
Gold Standard 2	40.66 (1.0%)	40.26	36.95 (-8.2%)
Gold Standard 3	35.18 (-7.3%)	37.95	38.96 (2.7%)
X-axis Deflection	**Decrease 50%**	**Baseline**	**Increase 50%**
Gold Standard 1	-75.49 (-1.3%)	-74.50	-74.64 (-0.2%)
Gold Standard 2	-40.54 (-1.3%)	-40.03	-36.52 (8.7%)
Gold Standard 3	-30.54 (3.6%)	-31.91	-30.12 (4.7%)
Z-axis Deflection	**Decrease 50%**	**Baseline**	**Increase 50%**
Gold Standard 1	10.70 (0.1%)	10.62	10.09 (-0.7%)
Gold Standard 2	8.87 (-0.7%)	9.14	10.52 (3.4%)
Gold Standard 3	14.26 (-5.8%)	16.47	17.31 (2.2%)

Individual X-axis and Z-axis deflections were reviewed as well to determine if the change in resultant masked any changes in the individual components of deflection, and results were mixed (Table B.1). In the Gold Standard 1 condition, decreasing the flex joint stiffness slightly (1 mm or 1.3%) increased X-axis deflection and had no effect on Z-axis deflection. In the Gold Standard 2 condition, increasing the flex joint stiffness decreased the X-axis deflection (3.5 mm or 8.7%), but increased the Z-axis deflection (1.4 mm or 3.4%). In the Gold Standard 3 condition, decreasing the flex joint stiffness decreased both the X-axis (1.4 mm or 3.6%) and Z-axis (2.2 mm or 5.8%) deflections. Overall, there did not appear to be a consistent trend on the influence of thoracic and lumbar spine flex joint stiffness on thoracic response among the Gold Standard test conditions.

In summary, computational analysis using the THOR-50M FE model demonstrated that while variation in the lumbar and thoracic spine flex joints does influence the thoracic response in both qualification and sled test conditions, this variation is smaller than the expected test-to-test and ATD-to-ATD variation.

Appendix C – List of serialized parts in NHTSA's THOR-50M ATDs.

Part Description	Part Number	Part Description	Part Number
Lower Abdomen Erect Posture Foam	472-0011	Lower Abdomen Bag Assembly	472-4763
Lower Abdomen Neutral Posture Foam	472-0012	Lower Abdomen Front Foam Layer	472-4764
Skull Cap Skin	472-1310	Lower Abdomen Rear Foam Layer	472-4765
Head Skin Assembly	472-1320	Femur Plunger Assembly	472-5420
Confor Foam, Face	472-1401	Upper Leg Compression Element	472-5206
Neck Mechanical Assembly	472-2000	Knee Flesh Insert - Molded	472-5301
Neck Occipital Condyle Cam	472-2019	Assembly, Inboard/Outboard Slider	472-5310
Neck Molded Assembly	472-2120	Knee Flesh Left/Right	472-5502
Front Spring Assembly	472-2220	Thigh Flesh - Left	472-5503-1
OC Stop Assembly	472-2230	Thigh Skin - Right	472-5503-2
Rear Spring Assembly	472-2240	Shoulder Spring	472-6827
Left Shoulder Pad Assembly	472-3110-1	Left Lower Leg Assembly	472-7000-1
Right Shoulder Pad Assembly	472-3110-2	Right Lower Leg Assembly	472-7000-2
Thorax Elliptical Rib #1 - Assembly	472-3310	Tibia Compliant Bushing Assembly	472-7315
Thorax Elliptical Rib #2 - Assembly	472-3320	Stop Assembly, Plantar	472-7527
Thorax Elliptical Rib #3 - Assembly	472-3330	Stop Assembly - Dorsi	472-7530
Thorax Elliptical Rib #4 - Assembly	472-3340	Stop Assembly - Eversion	472-7533
Thorax Elliptical Rib #5 - Assembly	472-3350	Stop Assembly - Inversion	472-7534
Thorax Elliptical Rib #6 - Assembly	472-3360	Left Molded Shoe Assembly	472-7800-1
Thorax Elliptical Rib #7 - Assembly	472-3370	Right Molded Shoe Assembly	472-7800-2
Thorax Bib Assembly	472-3400	H-Point Tool	472-8500
Upper Thorax Spinebox Weldment	472-3620	Rib Set	472-RS
Neck Pitch Change Mechanism Assembly	472-3630	Left Shoulder Cover	472-3895-1
Upper Thoracic Spine Flex Joint Assembly	472-3646	Right Shoulder Cover	472-3895-2
Lumbar Spine Pitch Change Assembly	472-3670	Left Lower Leg Flesh Assembly	472-7370-1
Lumbar Spine Flex Joint Assembly	472-3746	Right Lower Leg Flesh Assembly	472-7370-2
Pelvis/Lumbar Mounting Block Assembly	472-3760		
Jacket Assembly	472-3900		
Pelvis Assembly	472-4000		
Molded Pelvis Flesh	472-4100		
Left Iliac Assembly	472-4380-1		
Right Iliac Assembly	472-4380-2		
Upper Abdomen Assembly	472-4600		
Upper Abdomen Internal Foam Rear Layer	472-4621		
Upper Abdomen Internal Foam Middle Layer	472-4622		
Upper Abdomen Internal Foam Front Layer	472-4623		

Appendix D – Low-Speed Belted Sled Test Series – Additional Information

One source of data NHTSA looked at to assess repeatability is a sled test series conducted to assess the performance of THOR-50M in low-speed belted conditions. These tests were based on the rigid barrier, perpendicular impact belted crash test specified in FMVSS No. 208 for the HIII-50M. The test matrix is provided in Table D.1.

Table D.1. Low-speed belted sled test matrix

Target Speed (km/h)	Delta-V (km/h)	THOR-50M in Driver Seat		THOR-50M in Front Outboard Passenger Seat	
		TSTNO	TSTREF	TSTNO	TSTREF
24	28.1	v10302	S170809-1	v10306	S170814-1
24	28.1	v10303	S170809-2	v10307	S170815-1
24	28.1	v10304	S170810-1	v10308	S170815-2
32	37.4	v10289	S170724-1	v10292	S170726-1
32	37.4	v10290	S170725-1	v10293	S170727-1
32	37.4	v10291	S170725-2	v10294	S170727-2
40	45.6	v10298	S170802-2	v10295	S170731-1
40	45.6	v10299	S170803-1	v10296	S170801-1
40	45.6	v10300	S170803-2	v10297	S170802-1

Notes: These tests have been published in the NHTSA Vehicle Database, as identified by Test Number.

The test buck was created from the body of a vehicle that was crash tested in a frontal rigid barrier configuration with an impact velocity of 32 km/h. The original vehicle interior equipment was retained, but several modifications were made to improve the repeatability of the test configuration: the seat bottom was rigidized, and the seat cushion was replaced with a new original equipment manufacturer seat cushion after every two tests; the passenger air bag deployment door was removed, and the passenger side of the windshield was replaced with a steel plate; the knee air bag reaction surface trim was removed and replaced with a 6 mm steel plate and 55 mm IMPAXX 500 foam recessed approximately 60 mm. Restraint system components were triggered manually at the same time that they deployed in the crash test conducted at 32 km/h: driver and passenger frontal air bag primary and secondary deployments occurred at 21.75 ms and 26.75 ms after impact, respectively; knee bolster air bags deployed at 21.8 ms after impact; and the retractor and anchor pretensioners deployed at 19.8 ms and 24.75 ms, respectively. In the 24 km/h test condition, the pretensioners triggered, but no air bags were deployed.

Appendix E – Low-Speed Unbelted Sled Test Series – Additional Information

Table E.1 displays the test matrix for the sled test series used to evaluate the repeatability of the THOR-50M.

Table E.1. Low-speed unbelted sled test matrix

Target Speed (km/h)	THOR-50M in Driver Seat		THOR-50M in Front Outboard Passenger Seat	
	TSTNO	TSTREF	TSTNO	TSTREF
32	11083	S190410-1	11086	S190423-1
32	11084	S190412-1	11087	S190424-1
32	11085	S190416-1	11088	S190425-1
40	11089	S190711-1	11092	S190719-1
40	11090	S190715-1	11093	S190722-1
40	11091	S190716-1	11094	S190724-1

Note: These tests have been published in the NHTSA Vehicle Database, as identified by Test Number.

As noted in the preamble, of the four CVs over 10% in this test series, only one was over 10% when normalized (BrIC in the driver 40 km/h condition, 14%).

To investigate this, NHTSA reviewed the head CG X-, Y-, and Z-axis angular rates (Figure E.1), as these three components form the basis for the BrIC injury metric. The primary axis of rotation of the head is about the Y-axis, while the X- and Z-axis angular rates are in the noise. The head initially rotates forward (negative Y) at a very similar rate across the three tests in this condition, with peak rates occurring at a similar time (~70 ms) of -32.3 rad/s, -32.9 rad/s, and -31.3 rad/s in tests v11089, v11090, and v11091 respectively (average = -32.1 rad/s, standard deviation = 0.67 rad/s, CV = 2.1%). The head angular rate then decreases and changes direction, eventually reaching a rearward peak at between 85 and 90 ms of 53.0 rad/s, 45.6 rad/s, 34.0 rad/s (average = 44.2 rad/s, standard deviation = 7.8 rad/s, CV = 17.7%). The similarity of the peak forward rotation rates contrasted with the differences in the peak rearward rotation rates suggests that the interaction of the head with the restraint system is not consistent across the three tests, primarily after 70 ms after T-zero. Differences in head resultant acceleration (Figure E.1, bottom right), are more subtle, but the peak head acceleration is lowest in test v11091, for which the peak Y-axis angular rate was also the lowest of the three tests. Reviewing the high-speed video for these three tests indicates that the head interacts with the sun visor starting around 65 milliseconds, which pushes the sun visor up into contact with the headliner. This begins to arrest the forward and upward motion of the head, while at the same time the interaction of the top of the head and forehead area causes the head to rotate backwards. Though the difference is barely perceptible, it appears that there is more contact between the head and the front edge of the sun visor where it attaches to the roof in test v11090, followed by v11089 and then v11091. This is confirmed by the head resultant acceleration (Figure E.1, bottom right), where the peak acceleration is highest in test v11090 and lowest in v11091. Similarly, the peak neck compression force (Figure E.2) is of the lowest magnitude in v11091, while tests v11089 and v11090 have more similar peak neck compression forces.

Therefore, this variation in BrIC appears to result in a difference in head interaction with the sun visor and underlying roof structure, brought about by small differences in the timing and/or position of the head at the time of contact that could be brought on by initial position differences, differences in interaction of the pelvis and thighs with the seat cushion during initial forward translation, or differences in knee interaction with the knee bolster and/or knee bolster air bag.

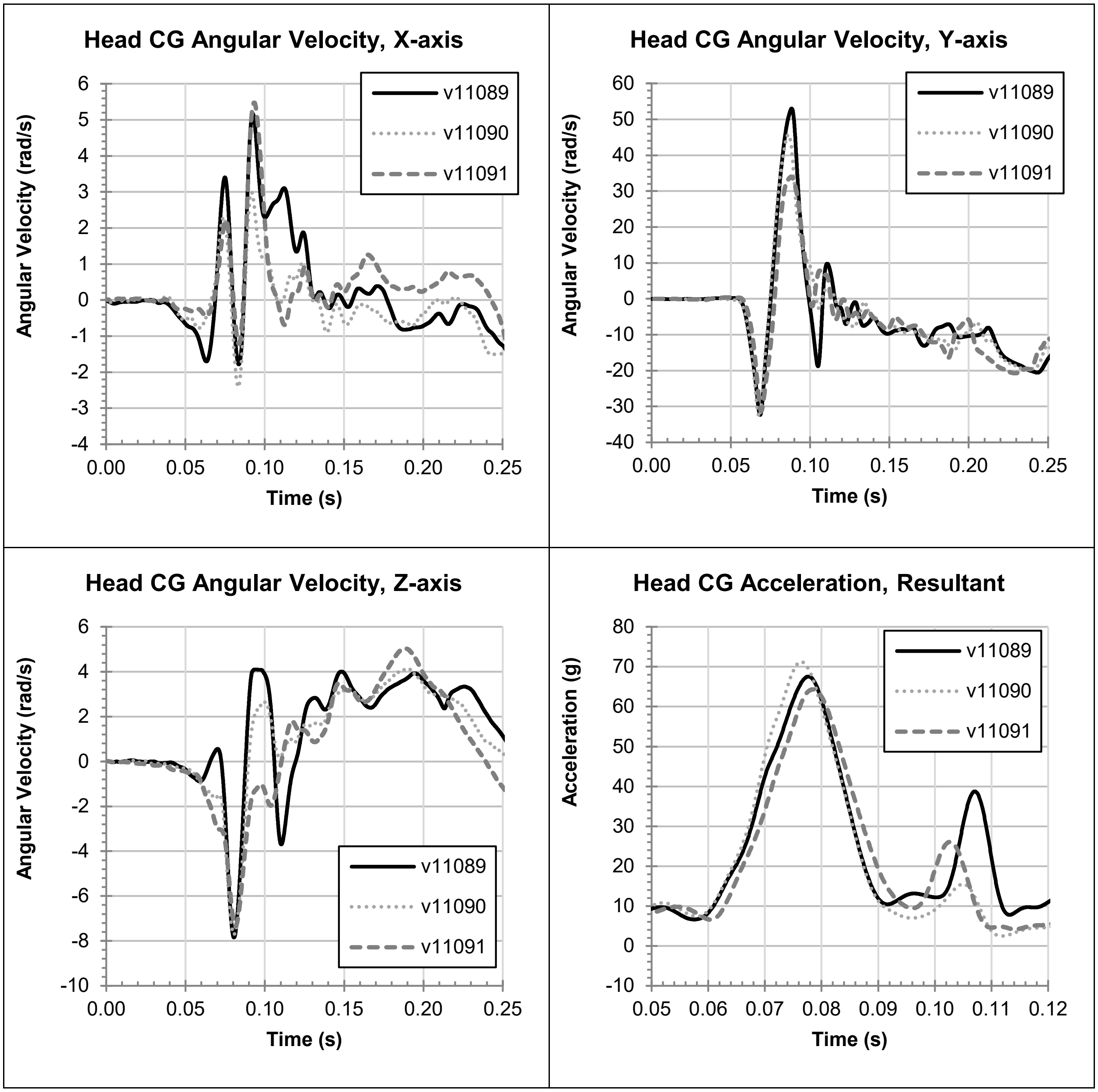

Figure E.1. Head CG angular rate about the X (top left), Y (top right), and Z (bottom left) axes; head CG resultant acceleration (bottom right; note that time axis range has been changed for clarity) in the driver 40 km/h unbelted condition.

We also note that there was one measurement with a relatively low CV, but an associated normalized CV above 10%. This occurred for the Nij measurement in the Driver 40 km/h condition, where the CV was 4.7% and the normalized CV was 10.7%. Because this CV was over 10%, NHTSA investigated further.

Because we normalized by the value of Nij associated with a 50% injury risk, this indicates that the average value of Nij from the three tests in the driver 40 km/h condition were above an Nij associated with 50% risk of injury. The upper neck load cell Z-axis force (Figure E.2) and Y-axis moment (Figure E.3, bottom left) were inspected further, as these are the two measurements used in the calculation of Nij. The Y-axis moment exhibits several peaks that cannot be explained by the interaction of the dummy with the restraint system and vehicle interior, including but not limited to an early peak at around 40 milliseconds of 45 to 75 Nm, which is well before any appreciable interaction with the frontal air bag. Compare this to the Y-axis moment in the previous tests (Figure E.3), which suggests damage to the Y-axis moment measurement of the upper neck load cell or possibly the associated cabling between tests v11088 and v11089. As such, the upper neck load cell Y-axis moment measurements should be considered questionable for tests v11089 through v11094, and further investigation of the load cell in question (Humanetics 10380JI4 DP1349) should be carried out.

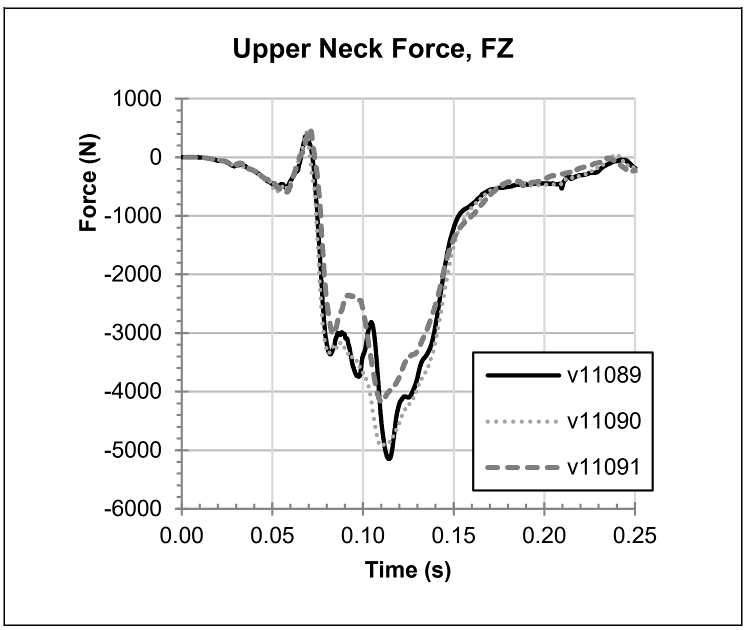

Figure E.2. Neck Z-axis force in the Driver 40 km/h unbelted sled test condition.

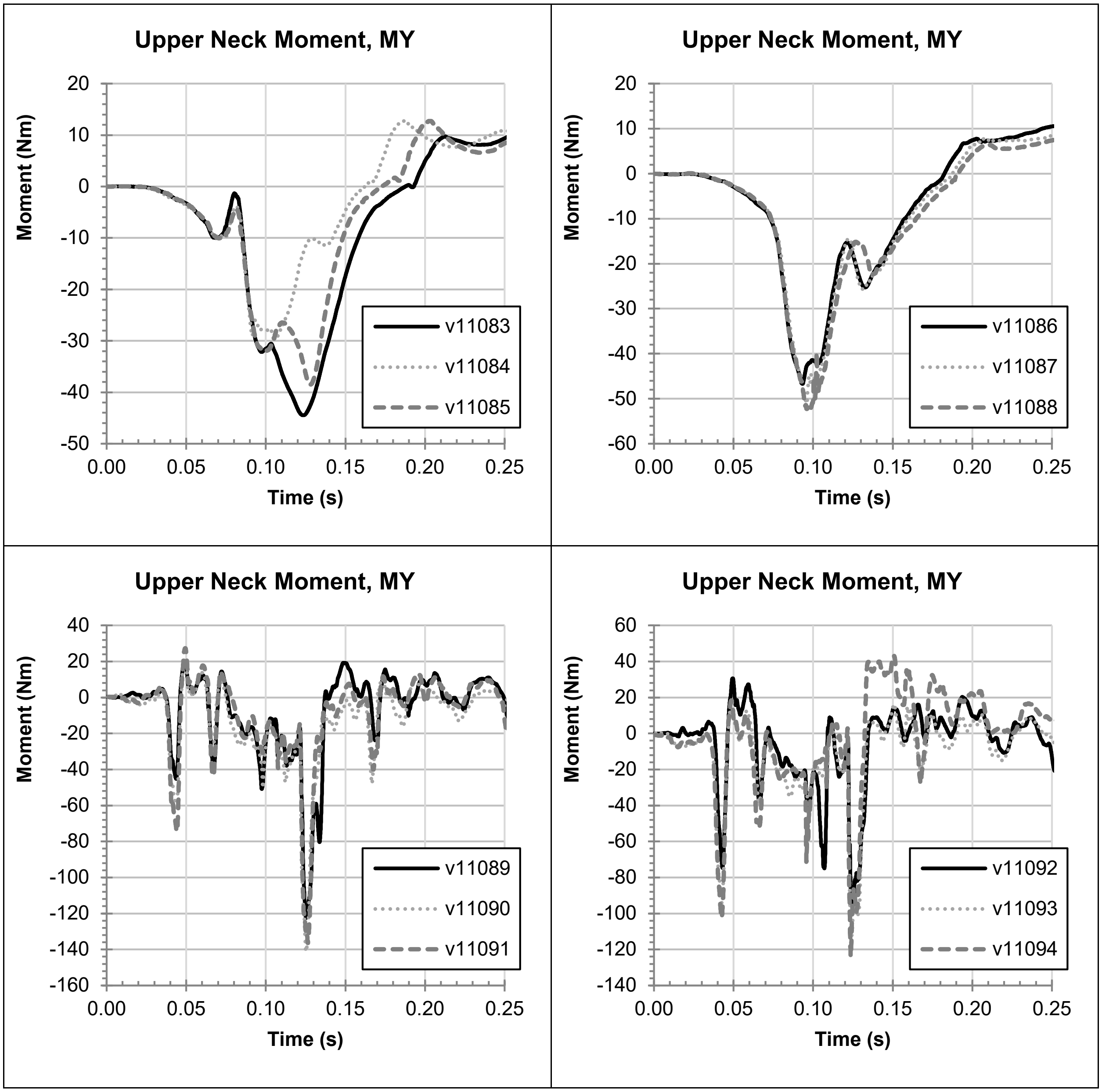

Figure E.3. Neck Y-axis moment in the four unbelted sled test conditions: Driver 32 km/h (top left), Driver 40 km/h (bottom left), right front passenger 32 km/h (top right), and right front passenger 40 km/h (bottom right) conditions.

Appendix F – OMDB Vehicle Crash Testing – Additional Information

As noted in the preamble, in developing THOR-50M, NHTSA ran a series of full-vehicle oblique tests with a moving deformable test barrier (OMDB). While there were no signs of damage beyond normal wear and tear and no part replacements were necessary, NHTSA did observe some sensor anomalies or failures to sensors. These are listed in Table F.1 and Table F.2.

Table F.1. Sensor anomalies observed in THOR-50M S/N D09798 (driver) during the Oblique R&R test series

Sensor	Anomaly	Cause	Test Number(s)
Lower Neck Load Cell (all axes)	Questionable spikes throughout	Undetermined	v09499
Front Neck Spring Tower Load Cell	Questionable spikes between 100ms and 150ms	Incorrect neck zeroing procedure	v09499
Lower Left Chest X-axis Displacement (IR-TRACC)	Questionable data throughout	Undetermined	v09499, v09500, v09501
Abdomen Left X-axis Displacement (IR-TRACC)	Questionable spike at 20-24ms; dropouts throughout	Undetermined; possibly loose retaining ring	v09499, v09500, v09501, v09699, v09725, v09726
Abdomen Right X-axis Displacement (IR-TRACC)	Questionable spike at 20-24ms; dropouts throughout	Undetermined; possibly loose retaining ring	v09725, v09726
Femur Left Y-axis Moment	Channel Failed	Could not reproduce	v09725
Mid Tibia Right Y-axis Acceleration	Channel failed at 55ms	Undetermined	v09806
Foot Left Z-axis Acceleration	Channel not installed	Known issue	v09699, v09725, v09726
Foot Right X-axis Acceleration	Questionable data after ~45ms	Broken wires	v09802

Note: The underlying test data is available in the NHTSA crash test database.

Table F.2. Sensor anomalies observed in THOR-50M S/N DL9207 (right front passenger) during the Oblique R&R test series

Sensor	Anomaly	Cause	Test Number(s)
Head CG Y-axis Acceleration	Questionable data 82.9ms to 105ms	Loose Amphenol connector pins	v09499
Rear Neck Spring Tower Load Cell	Channel failed	Undetermined	v09806, v09807
T1 X-axis Acceleration	Questionable data after ~50ms	Undetermined	v09802
T1 Z-axis Acceleration	Questionable data after ~50ms	Undetermined	v09802
Upper Left Chest X-axis Displacement (IR-TRACC)	Questionable data after approximately 80.0 ms	Undetermined; characteristic of loose retaining ring	v09807
Upper Right Chest X-axis Displacement (IR-TRACC)	Questionable spike at 34.3ms	Undetermined; characteristic of blips	v09499, v09500, v09501
Abdomen Right X-axis Displacement (IR-TRACC)	Questionable spike at 126 ms	Undetermined; minor blip late in event	v09500, v09501
Femur Right X-axis Force	Questionable spikes throughout	Could not reproduce	v09699, v09725
Femur Right Y-axis Force	Channel failed, no data	Could not reproduce	v09699, v09725
Femur Right Y-axis Moment	Questionable spikes throughout	Could not reproduce	v09725, v09726
Mid Tibia Left X-axis Acceleration	Channel failed, no data	Undetermined	v09806, v09807
Mid Tibia Right X-axis Acceleration	Questionable data after ~30ms	Undetermined	v09806
Lower Tibia Left Y-axis Moment	Channel failed, no data	Could not reproduce	v09725, v09726
Lower Tibia Left Z-axis Force	No valid data after ~70ms	Undetermined	v09802, v09807
Lower Tibia Right Y-axis Force	Channel failed at 62.1ms	Loose Amphenol connector pins	v09726
Lower Tibia Right Z-axis Force	Channel failed, no data	Could not reproduce	v09726
Foot Right X-axis Acceleration	Channel failed at 57.2ms	Loose Amphenol connector pins	v09725, v09726, v09802

Note: The underlying test data is available in the NHTSA crash test database.

As noted in Section VII.B.2, the only sensor anomalies that occurred in channels used in the calculation of injury criteria were the chest and abdomen IR-TRACC sensors. An example of these anomalies can be seen in the right front passenger (DL9207) of tests v09499, v09500, and v09501 (Figure F.1). Throughout the time-history, there are several instances where the voltage drops abruptly over a less than 0.1 millisecond period then returns to its previous state. These voltage drops are characteristic of the "blips" described in Section IV.F.2. Once linearized, scaled, filtered, and converted to three-dimensional resultant deflection local spine coordinate system, these “blips” are no longer evident (Figure F.2), thus would not influence the calculation of injury risk for this occupant.

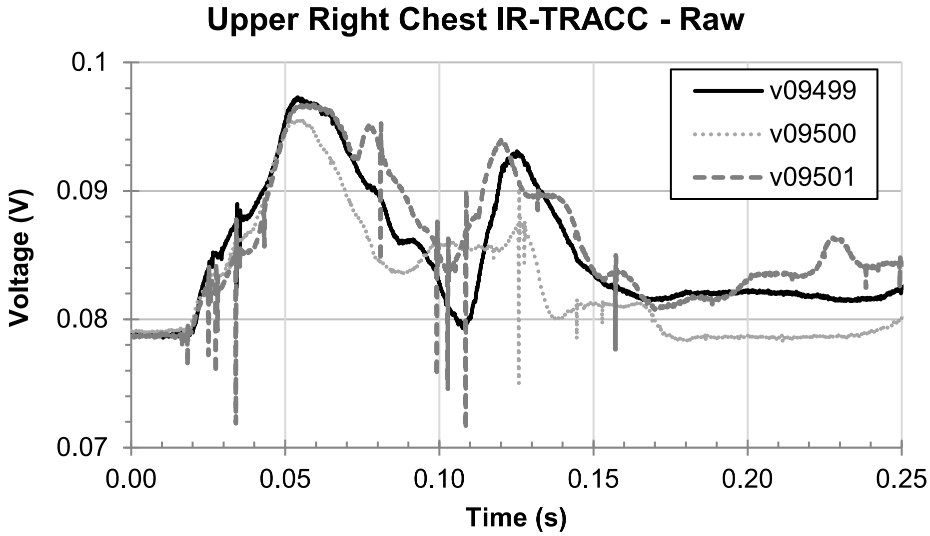

Figure F.1. Upper right chest IR-TRACC raw voltage for DL9207 (right front passenger) in the OMDB R&R test series.

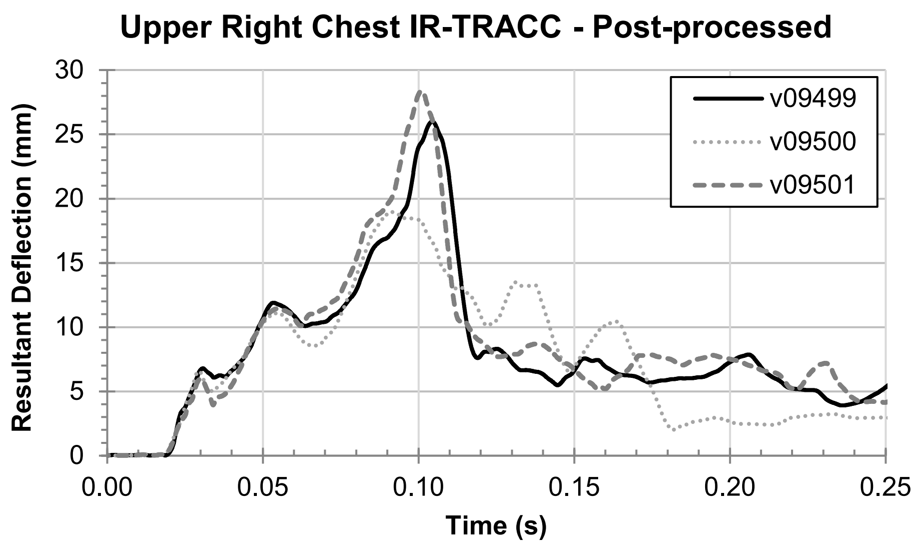

Figure F.2. Upper right chest IR-TRACC post-processed resultant deflection for DL9207 (right front passenger) in the OMDB R&R test series.

The list of sensor anomalies is often generated by the test laboratory itself, which introduces subjectivity in the determination of a sensor anomaly. There is currently not an objective methodology for identifying questionable channels. An example of this is the neck spring cable load cells; since the load cells only measure in compression, and there is not a physical connection between the neck springs and the load cell, are often several points during a test where the neck spring loses then regains contact with the load cell, resulting in impact-driven spikes in the response (Figure F.3). While these spikes are technically physical in nature, unfamiliar laboratory technicians would be likely to mark the neck spring cables as anomalous or questionable data. This test series was conducted before an issue with the length of the neck spring cables was identified, where the neck cables were too short to allow proper zeroing of the head-neck platform, thus a pre-load was being applied to some neck cables. This can be seen in the anterior neck cable of the driver in test v09499, as once the neck flexes forward after 75 milliseconds after impact, the neck cable force drops below 0 to roughly -100 N, which indicates that a 100 N preload was applied to the front neck cable. Similarly, a roughly 75 N preload was applied to the posterior neck cable, as evident when the cable force drops below zero after 200 milliseconds. In a later test of the same make/model vehicle with the proper length neck cables, this preloading does not appear, and the subsequent mechanical noise is not present (Figure F.4).

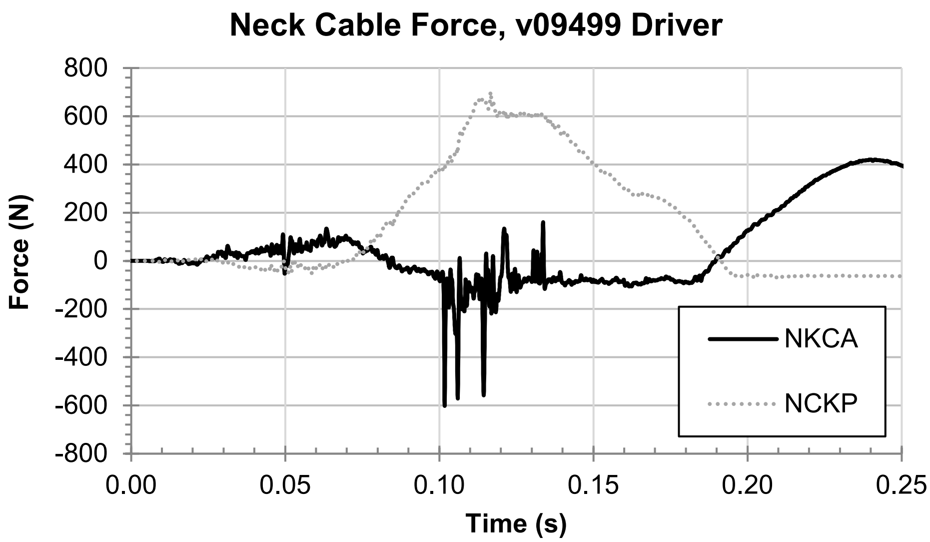

Figure F.3. Front (NKCA) and rear (NCKP) neck cable forces for the driver (DO9798) in test v09499.

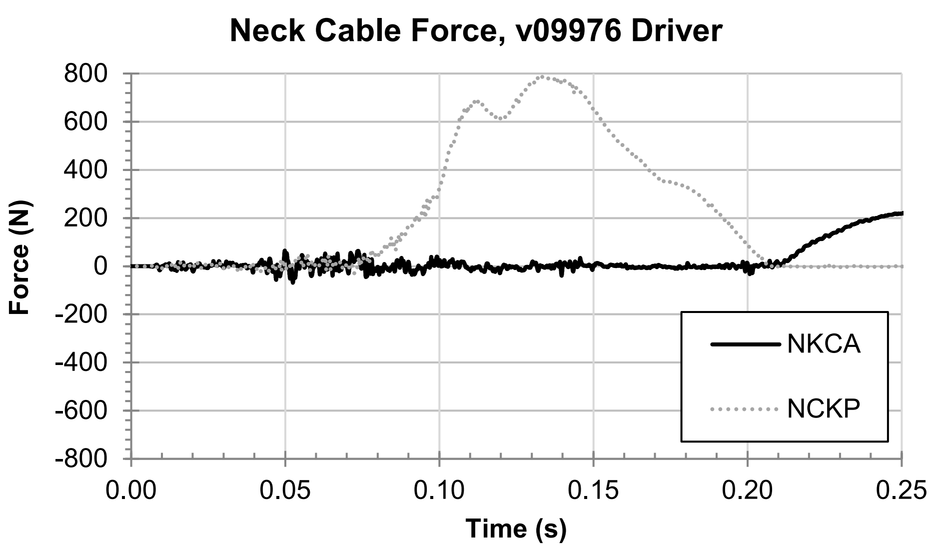

Figure F.4. Front (NKCA) and rear (NCKP) neck cable forces for the driver (DO9798) in test v09976.

Appendix G – Comparison of Proposed and TB026 Qualification Test Parameters and Acceptance Intervals

Table G.1. Head Impact Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification (TB026, Version 1.3)		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05		1.95	2.05	
Peak Probe Force	N	5022	6138	10%	4890	5976	10%
Peak Head CG Resultant Acceleration	g	105.3	128.7	10%	104.9	120.7	7%

Table G.2. Face Rigid Disk Impact Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	6.68	6.78		Inspection (every 3 tests), replace if multiple large cracks		
Peak Probe Force	N	6378	7796	10%			
Peak Head CG Resultant Acceleration	g	124	152	10%			

Table G.3. Neck Torsion Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Pendulum velocity at 10 ms after T0	m/s	1.71	2.09	10%	1.71	2.09	10%
Pendulum velocity at 15 ms after T0	m/s	2.57	3.14	10%	2.57	3.14	10%
Pendulum velocity at 20 ms after T0	m/s	3.46	4.23	10%	3.46	4.23	10%
Pendulum velocity at 25 ms after T0	m/s	4.27	5.22	10%	4.27	5.22	10%
Impact Velocity	m/s	4.95	5.05		4.95	5.05	
Peak Upper Neck	N-m	37.3	45.6	10%	37.9	43.6	7%
Peak Neck Fixture Rotation	deg	43.1	52.7	10%	43.0	49.5	7%
First Peak Upper Neck Angular Velocity	deg/s	1251	1529	10%	1358	1536	7%

Table G.4. Neck Flexion Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Pendulum velocity at 8 ms after T0	m/s	1.57	1.92	10%	1.57	1.92	10%

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Pendulum velocity at 16 ms after T0	**m/s**	3.13	3.82	10%	3.13	3.82	10%
Pendulum velocity at 24 ms after T0	**m/s**	4.42	5.41	10%	4.42	5.41	10%
Impact Velocity	**m/s**	4.95	5.05		4.95	5.05	
Peak Upper Neck	**N-m**	27.9	34.1	10%	27.3	31.5	7%
Upper Neck F_z most positive value prior to 40 ms	**N**	774	946	10%	835	961	7%
Peak Head Angular Velocity (relative to earth)	**deg/s**	-2172	-1777	10%	-1993	-1732	7%
Peak Head Rotation (relative to pendulum)	**deg**	-71.0	-58.1	10%	-65.3	-56.7	7%

Table G.5. Neck Extension Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ± %	Min.	Max.	Corridor Width ±%
Pendulum velocity at 10 ms after T0	**m/s**	1.74	2.12	10%	1.74	2.12	10%
Pendulum velocity at 20 ms after T0	**m/s**	3.30	4.04	10%	3.30	4.04	10%
Pendulum velocity at 30 ms after T0	**m/s**	4.53	5.54	10%	4.53	5.54	10%
Impact Velocity	**m/s**	4.95	5.05		4.95	5.05	
Peak Upper Neck	**N-m**	-25.3	-20.7	10%	-24.9	-20.4	10%
Peak Upper Neck	**N**	-3210	-2626	10%	-3103	-2539	10%
Peak Head Angular Velocity (relative to earth)	**deg/s**	1855	2267	10%	1855	2267	10%
Peak Head Rotation (relative to pendulum)	**deg**	58.5	71.5	10%	57.1	69.8	10%

Table G.6. Neck Lateral Flexion Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Pendulum velocity at 4 ms after T0	**m/s**	1.06	1.30	10%	1.06	1.30	10%
Pendulum velocity at 8 ms after T0	**m/s**	2.09	2.55	10%	2.09	2.55	10%
Pendulum velocity at 12 ms after T0	**m/s**	3.16	3.86	10%	3.16	3.86	10%
Impact Velocity	**m/s**	3.35	3.45		3.35	3.45	
Upper Neck first peak after 40.0 ms	**N-m**	44.8	54.7	10%	44.8	51.5	7%
First Peak Head Angular Velocity (relative to earth)	**deg/s**	1226	1498	10%	1256	1445	7%
Peak Head Rotation (relative to pendulum)	**deg**	37.6	45.9	10%	38.0	43.8	7%

Table G.7. Upper Thorax Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	4.25	4.35		4.25	4.35	
Peak Probe Force	N		3039	10%	2642	3039	7%
Peak Upper Left Resultant Deflection	mm	48.3	59.0	10%	47.5	54.7	7%
Peak Upper Right Resultant Deflection	mm						
Difference Between Peak Left & Right Resultant Deflections	mm	N/A	< 5				
Force at Left & Right Peak Resultant Deflection	N	2409	2944	10%			
Ratio of Left Z- and X-axis Deflection at Time of Peak Resultant Deflection					0.62	0.75	4%
Ratio of Right Z- and X-axis Deflection at Time of Peak Resultant Deflection							

Table G.8. Lower Thorax Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	4.25	4.35		4.25	4.35	
Peak Probe Force	N	3136	3832	10%	3372	3880	7%
Left or Right Resultant Deflection at Peak Force	mm	45.8	56.0	10%			
Peak left and right lower X-axis rib deflection	mm				-52.4	-45.6	7%

Table G.9. Lower Abdomen Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	3.25	3.35		3.25	3.35	
Peak Force	N	2626	3210	10%	2572	3143	10%
Lower left abdomen X-axis deflection at time of Peak Force	mm	-91.3	-74.7	10%	-83.8	-72.8	7%
Lower right abdomen X-axis deflection at time of Peak Force							
Difference Between Peak Left & Right X-axis Deflections	mm	_	< 8		_	< 8	

Table G.10. Upper Leg Qualification Response Requirements

Parameter	Units	SEPT. 2018 Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	2.55	2.65		2.55	2.65	
Peak Probe Force	N	4221	5158	10%	4221	5158	10%
Peak Femur Force,	N	-3314	-2712	10%	-2712	-3314	10%
Peak Resultant Acetabulum Force	N	1478	1806	10%	1478	1806	10%

Table G.11. Revised Upper Leg Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	3.25	3.35		Not currently specified		
Peak Probe Force	N	7500	9166	10%			
Peak Femur Force,	N	-5412	-4428	10%			
Peak Resultant Acetabulum Force	N	2464	3012	10%			

Table G.12. Knee Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	2.15	2.25		SAE J2876 every 3 tests SAE J2856 every 9 tests		
Peak Femur Z-axis Force	N	-7156	-5855	10%			
Knee Deflection at Peak Femur Force	mm	-22.2	-18.2	10%			

Table G.13. Left Ankle Inversion Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05		N/A		
Peak Lower Tibia	N	-555	-454	10%			
Peak Ankle Resistive Moment	Nm	-43.0	-35.2	10%			
Peak Ankle X-axis Rotation	deg	-37.9	-31.0	10%			

Table G.14. Right Ankle Inversion Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05		N/A		
Peak Lower Tibia	N	-555	-454	10%			
Peak Ankle Resistive Moment	Nm	35.2	43.0	10%			
Peak Ankle X-axis Rotation	deg	31.0	37.9	10%			

Table G.15. Left Ankle Eversion Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05		N/A		
Peak Lower Tibia	N	-629	-514	10%			
Peak Ankle Resistive Moment	Nm	38.7	47.3	10%			
Peak Ankle X-axis Rotation	deg	26.6	32.5	10%			

Table G.16. Right Ankle Eversion Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	1.95	2.05		N/A		
Peak Lower Tibia	N	-629	-514	10%			
Peak Ankle Resistive Moment	Nm	-47.3	-38.7	10%			
Peak Ankle X-axis Rotation	deg	-32.5	-26.6	10%			

Table G.17. Ball of Foot Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width ±%	Min.	Max.	Corridor Width ±%
Impact Velocity	m/s	4.95	5.05		N/A		
Peak Lower Tibia	N	-3487	-2853	10%			
Peak Ankle Resistive Moment	Nm	49.8	60.8	10%			
Peak Ankle Y-axis Rotation (in dorsiflexion)	deg	30.4	37.2	10%			

Table G.18. Heel Qualification Response Requirements

Parameter	Units	Proposed Specification			Euro NCAP Specification		
		Min.	Max.	Corridor Width %	Min.	Max.	Corridor Width %
Impact Velocity	**m/s**	3.95	4.05		N/A		
Peak Lower Tibia	**N**	-3478	-2846	10%			