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Optimizing Seat Belt and Airbag Designs for Rear Seat Occupant Protection in Frontal Crashes

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ABSTRACT – Recent field data have shown that the occupant protection in vehicle rear seats failed to keep pace with advances in the front seats likely due to the lack of advanced safety technologies. The objective of this study was to optimize advanced restraint systems for protecting rear seat occupants with a range of body sizes under different frontal crash pulses. Three series of sled tests (baseline tests, advanced restraint trial tests, and final tests), MADYMO model validations against a subset of the sled tests, and design optimizations using the validated models were conducted to investigate rear seat occupant protection with 4 Anthropomorphic Test Devices (ATDs) and 2 crash pulses. The sled tests and computer simulations were conducted with a variety of restraint systems including the baseline rear-seat 3-point belt, 3-point belts with a pre-tensioner, load limiter, dynamic locking tongue, 4-point belts, inflatable belts, Bag in Roof (BiR) concept, and Self Conforming Rear seat Air Bag (SCaRAB) concept. The results of the first two sled series demonstrated that the baseline 3-point belt system are associated with many injury measures exceeding injury assessment reference values (IARVs); showed the significance of crash pulse and occupant size in predicting injury risks; and verified the potential need of advanced restraint features for better protecting the rear-seat occupants. Good correlations between the tests and simulations were achieved through a combination of optimization and manual fine-tuning, as determined by a correlation method. Parametric simulations showed that optimized belt-only designs (3-point belt with pre-tensioner and load limiter) met all of the IARVs under the soft crash pulse but not the severe crash pulse, while the optimized belt and SCaRAB design met all the IARVs under both the soft and severe crash pulses. Two physical prototype restraint systems, namely an "advanced-belt only" design and an "advanced-belt and SCaRAB" design, were then tested in the final sled series. With the soft crash pulse, both advanced restraint systems were able to reduce all the injury measures below the IARVs for all four ATDs. Both advanced restraint systems also effectively reduced almost all the injury measures for all ATDs under the severe crash pulse, except for the THOR. The design with the advanced-belt and SCaRAB generally provided lower injury measures than those using the advanced belt-only design. This study highlighted the potential benefit of using advanced seatbelt and airbag systems for rear-seat occupant protection in frontal crashes.

KEYWORDS – Rear seat, Occupant protection, Frontal crash test, Crash simulation, Restraint optimization, Seat belt, Airbag

INTRODUCTION

The current design process for vehicle safety systems relies heavily on crash tests to ensure vehicle crashworthiness and occupant protection. In the U.S., crash test programs include those defined in Federal Motor Vehicle Safety Standards (FMVSS), the U.S. New Car Assessment Program (US-NCAP), and the safety rating system designed by Insurance Institute for Highway Safety (IIHS). In Europe, China, Japan, and many other countries, similar crash test programs are available. Most regulation and consumer crash tests have focused on the protection for front seat occupants due to their high occupancy. Even for crash test programs that include rear seat occupants, such as Euro-NCAP and China-NCAP, their safety criteria are not as comprehensive as those used for front seat occupants. As a result, advanced safety

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technologies that are widely used in front seating positions are less frequently available in the vehicle rear seat environment.

A direct consequence of the lack of technologies is that the safety advantage of sitting in the rear seats over the front seats in frontal crashes has diminished significantly for newer vehicle models in the recent years, due to the significant improvement of occupant protection in front seats. Many studies have even shown that front seats are safer than the rear seats in frontal crashes with newer vehicles, especially for older occupants. For example, Kuppa et al. (2005) conducted a double-paired comparison study using data from the Fatality Analysis Reporting system (FARS), and found that occupants younger than 50 years old benefit from sitting in rear seats, while the front seats can provide statistically significantly better protection to belted occupants 50 years and older in frontal crashes. Smith and Cummings (2006) confirmed the findings from Kuppa's study, and also suggested "when front passenger airbags are present and occupants are belted, putting adults in front and children in back will enhance child safety without sacrificing adult safety". Kent et al. (2007) extended Kuppa's study and found that the relative effectiveness of rear seats for belted adult occupants in newer vehicle models is lower than that in older vehicle models in frontal crashes. Similarly, Sahraei et al. (2009) found that vehicle model year has a significant effect on the protective effect from the rear seat relative to the right front seat based on the FARS data. Based on a matched-cohort analysis of the NASS-CDS data, Bilston et al. (2010) concluded that "the safety for front seat occupants has improved over the last decade, to the point where, for occupants over 15 years of age, the front seat is safer than the rear seat."

The safety design of vehicle rear seat occupants is challenging because of the wide range of occupant sizes and ages that must be considered and protected. Unlike the front seat, which is occupied almost entirely by adults, the rear seat environment must accommodate younger children in child restraint systems with a 5-point harness restraint and older children using belt-positioning booster seats and vehicle belts alone. In addition, the rear seats may be more likely to be used by older population who are not able or willing to drive. This diverse population in rear seats has posed different challenges for safety designs, which may conflict with each other. For instance, the injury patterns for the rear-seated older children and adult populations are different in frontal crashes. For belted children, the most frequently injured body region is the head, while for adults, especially older occupants, the most frequently injury body region is the chest (Kuppa et al., 2005). The main source of head injuries for rear seated children is the back of the front seat, while the major source of chest injuries for rear seated adults is the seat belt (Kuppa et al., 2005). These results suggest that the restraint system types and characteristics that provide optimal protection for children may be different from those that provide optimal protection for adults in frontal crashes. An advanced restraint system capable of adapting to a range of occupant sizes and conditions and addressing different injury priorities and causations is necessary for systematically improving the rear seat occupant protection.

Fewer studies have focused on restraint system designs for rear seat occupants than for front seat occupants in frontal impacts. Using MADYMO simulations, Zellmer et al. (1998) explored the protective effects of seat belt load limiters and pre-tensioners on rear seat occupants in frontal crashes. They found that chest loading was significantly reduced with pre-tensioners and load limiters, but the optimal load limiter level depends on occupant size and the space available for ride-down. Using similar computational simulations, Kent et al. (2007) found that even though there is a tradeoff between chest deflection and head excursion for rear seat occupants, they can be reduced at the same time with seat belt load limiters and pre-tensioners even in the absence of an airbag and knee bolster for load sharing. Forman et al. (2008) performed frontal sled tests with different sizes of ATDs in rear seats, and found that load limiters and pre-tensioners can effectively reduce the chest deflections for all the ATDs without increasing their head excursions. Tests using post-mortem-human-subjects (PMHS) have also been conducted by the same group (Forman et al., 2009), and the results suggested that 3-point seat belts with progressive load-limiters and pre-tensioners can improve the kinematics (increase forward torso rotation) of rear seat occupants with reduced belt load and chest acceleration. Hu et al. (2012b; 2013a; 2013b) conducted several series of frontal sled tests and computational simulations focusing on optimizing the rear seat and belt geometries for 6-12 year-old (YO) children, mid-size adults, and infants in rear-facing child restraints. It was found that the optimal belt anchorage locations and seat cushion length and stiffness were significantly different for occupants with different sizes, suggesting that adaptive/adjustable restraint systems may be necessary to simultaneously improve the rear seat occupant field performance for all age groups. However, in these studies, advanced restraint features were not investigated.

More recently, Hu et al. (2015) conducted a more comprehensive study using frontal and oblique sled tests to quantify the effects of crash pulse, impact angle, occupant size, front seat location, and restraint system on rear seat occupant impact responses. The results demonstrated the importance of considering the effects of occupant size and crash pulse on rear-seat occupant protection, and also showed that advanced restraint features, such as a pre-tensioner, load limiter, 4-point belt, inflatable belt and different types of airbags, have the potential to help provide additional protection for rear seat occupants with diverse occupant sizes. However, this study only reported results with advanced restraints for 6 YO and 5th percentile female ATDs, and the advanced restraints tested were conceptual designs without optimization.

The objective of this study was to optimize advanced restraint systems for protecting rear seat occupants with a range of body sizes and different frontal crash pulses. This study extended sled tests from Hu et al. (2015) by conducting computational design optimizations with different advanced restraint systems and more sled tests with a wider range of ATD sizes.

METHODS

Method Overview

As shown in Figure 1, this study included three series of sled tests and two series of computational simulations focusing on model validation and design optimization. It started with a set of baseline tests to establish the baseline performance of a typical, non-advanced restraint system in a variety of frontal crash scenarios with a variety of occupant sizes. The results of the baseline tests have been reported previously (Hu et al. 2015). The baseline test results were used to validate a set of computational models, including the sled system, restraints, and different sizes of ATDs. Then, advanced restraints, including both advanced belt technologies and airbag designs, were selected for the second series of sled tests, whose results were used for further model validation. With the help of computational design optimizations, a final series of sled tests with a set of final optimal designs were conducted, and their results were compared with those from the baseline tests.

Testing Setup and Conditions

A sled buck was built to represent a current compact vehicle. Four ATDs, including THOR-NT 50th male with the SD3 shoulder, Hybrid-III (HIII) 5th female, HIII 95th male and HIII 6 YO were used. In all the sled tests, the lap belt anchorage locations and the D-ring location were based on those in the selected compact vehicle, which met the FMVSS 210 and Economic Commission for Europe (ECE) R14 anchorage zone. The floor pan of the vehicle under the rear seat was removed and replaced with a simple sheet metal box section, reinforced with foam board inside. This allowed for easy replacement if it was deformed during testing, and helped ensure a more repeatable series. It should be noted that only the larger occupants (50th and 95th) deformed the sheet metal replacement.

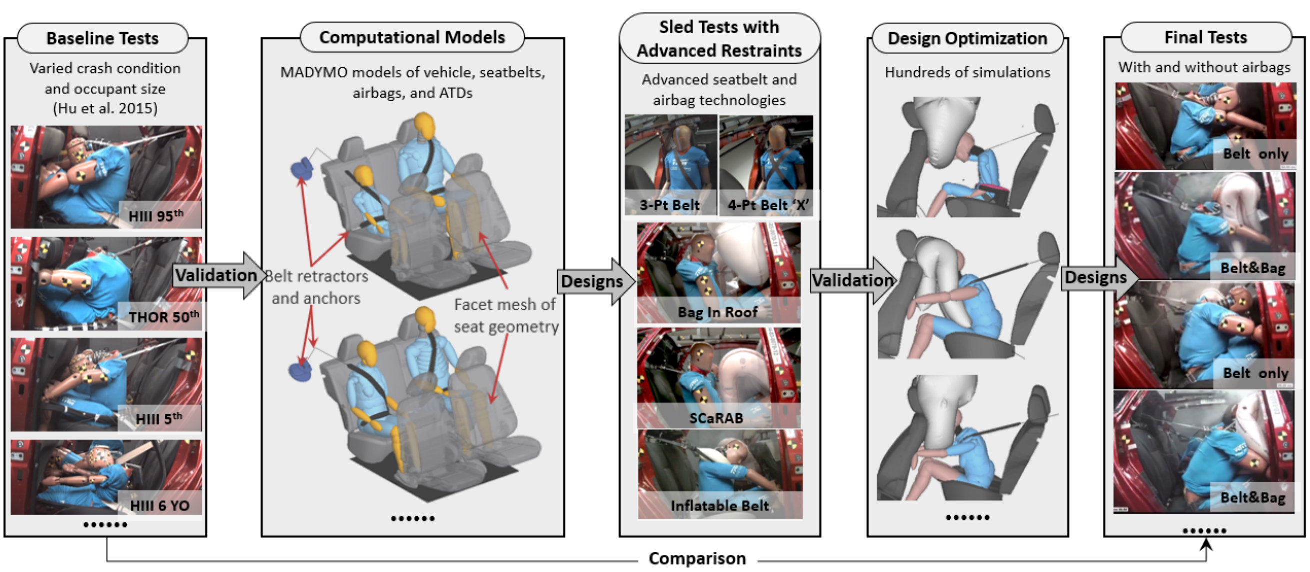

Figure 1. Method overview

Booster seats were not used for the 6 YO ATD in the baseline tests, but were used in all the sled tests with advanced restraint systems. Additional baseline conditions with the 6 YO ATD using booster seats were also conducted in the final sled series to quantify the effects from booster seat on the occupant injury measures. All the other sizes of the ATDs were positioned based on the IIHS seating procedure for rear seat occupants (Insurance Institute for Highway Safety, 2012). For THOR 50th, the neck pitch mechanism was set to "Neutral" position, while the lower thoracic pitch mechanism was in the "Slouched" position in all the tests. All the ATDs were certified prior to testing. A 3-D coordinate measurement laser device was used to measure the initial ATD position/posture and restraint system configuration in each test to improve test repeatability and document initial conditions.

For the front seat position, the driver's seat was positioned in the mid-track location for all the tests, except for those with the 95th ATD because 95th ATD needed larger space to be accommodated. For the 95th ATD, the driver's seat was positioned such that a 20-mm space was set between the knee and front seat prior to the test. For all the ATDs at the passenger's side, the front seat track position was set to match the driver's side for the 5th ATD, and the seat back angle was changed to 3 degrees measured at the head rest post, which is 9 deg more forward than the driver side. This resulted in a 150-mm distance from the knee to the back of the front seat. Then, this offset distance (150 mm) was kept the same for all of the occupants by adjusting the front seat location relative to the knees for each occupant size evaluated. Table 1 shows the front seat location for each ATD and each side of the test buck.

Two crash pulses (soft vs. severe) used in this study are shown in Figure 2. The soft pulse was the "fleet soft" and the severe pulse was the "fleet severe" based on US NCAP frontal barrier tests. These two pulses were selected by comparing the 2011-2012 B-Segment NCAP crash pulses from 25 small cars. The pulse severity ranking is shown in Figure 2, in which OLC++ (Occupant Load Criterion) is the metric used to rank the pulse severity (Kübler et al., 2008). The one with smallest dynamic crush was used as the "fleet severe" and the one with an average crush was the "fleet soft".

Table 1. Front seat locations in the tests

ATD size	Left		Right	
	Seat Back Angle*	**Seat Position (Knee/Seat Offset)**	**Seat Back Angle***	**Knee/Seat Offset**
6 YO	12 deg	Mid	3 deg	150 mm
5th	12 deg	Mid (110 mm)	3 deg	150 mm (Mid seat track)
THOR 50th	12 deg	Mid (70 mm)	3 deg	150 mm
95th	12 deg	2 notches fwd of Mid (20 mm)	3 deg	150 mm (Approx full fwd)

*The seat back angle was measured at the head rest post, in which 12 deg is corresponded to a normal seat back angle.

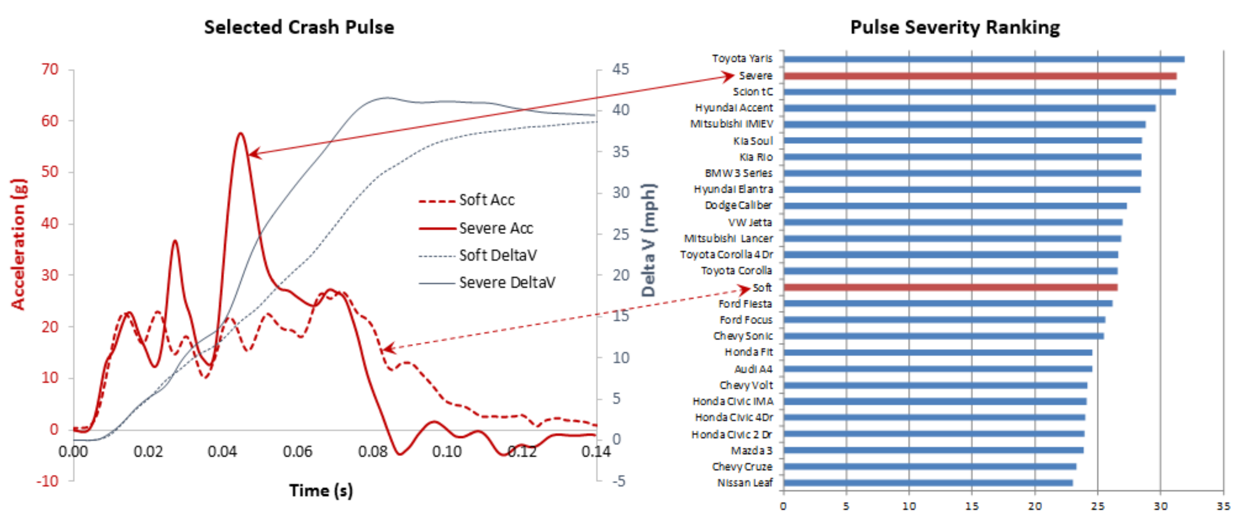

Figure 2. Soft and severe crash pulses based on US-NCAP tests from 25 small cars

The ATD instrumentation used in each test on the THOR 50th, H-III 5th, 95th and 6 YO ATDs are shown in Appendix A. All the data were filtered based on SAE J211. Measurements on the knee and lower legs in the THOR 50th were not used. In addition, maximal head excursions were quantified for all the tests based on high-speed video data (1,000 frames/s).

In all the tests, the injury measures and their associated Injury Assessment Reference Values (IARVs) are shown in Table 2 (Mertz et al., 2003; Takhounts et al., 2013). All the results are reported as the percentage of the IARVs. However, it should be mentioned that Head Injury Criterion (HIC) values in a non-contact event may not be directly associated with the head injury risks, and Nij tends to over predict neck injury risks (Digges et al., 2013). Brain Injury Criterion (BrIC) was developed by Takhounts et al. (2013) based on simulation results from a computational human brain model. It was calculated using the following equation:

$$BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xc}}\right)^2 + \left(\frac{\omega_y}{\omega_{yc}}\right)^2 + \left(\frac{\omega_z}{\omega_{zc}}\right)^2}$$

where ω_x, ω_y, and ω_z are the head angular velocity, and ω_{xc}, ω_{yc}, and ω_{zc} are the critical maximum angular velocities in each direction. In this study, 66.25, 56.45, and 42.87 Rad/s were used for ω_{xc}, ω_{yc}, and ω_{zc}, and BrIC of 0.87 corresponded to 50% of AIS 3+ brain injury risk (Takhounts et al., 2013).

Advanced Rear Seat Restraint Technologies

To investigate the effects of advanced restraints, 3-point seat belts with pre-tensioner(s), constant load limiter (CLL), progressive load limiter (PLL), or switchable load limiter (SLL), dynamic locking tongue (DLT), 4-point belt, inflatable belt, Bag-in-Roof (BiR) concept, and Self Conforming Rear seat Air Bag (SCaRAB) concept (Figure 3) were used in the sled tests. The FMVSS No. 209 type 2 seat belt assembly elongation requirement was not considered.

Table 2. Target IARVs for different sizes of the ATDs

Occupant	HIC15	BrIC	Neck T (N)	Neck C (N)	Nij	Chest G (g)	Chest D (mm)
6 YO	700	0.87*	1490	1820	1.0	60	40
5th	700	0.87	2620	2520	1.0	60	52
THOR 50th**	700	0.87	4170	4000	1.0	60	63
95th	700	0.87	5440	5440	1.0	55	70

* BrIC was developed based on adult head/brain models and adult ATD data. Scaling would likely be necessary to arrive at a unique BrIC value that represents 50% risk for a 6 YO.
** The IARVs for THOR 50th was based on those on HIII 50th ATD, but the chest injury risks calculated in the following sections were based on the newly-developed chest injury risk curves for THOR 50th.
Neck T: Neck Tension, Neck C: Neck Compression, Chest G: Chest Acceleration, and Chest D: Chest Deflection.

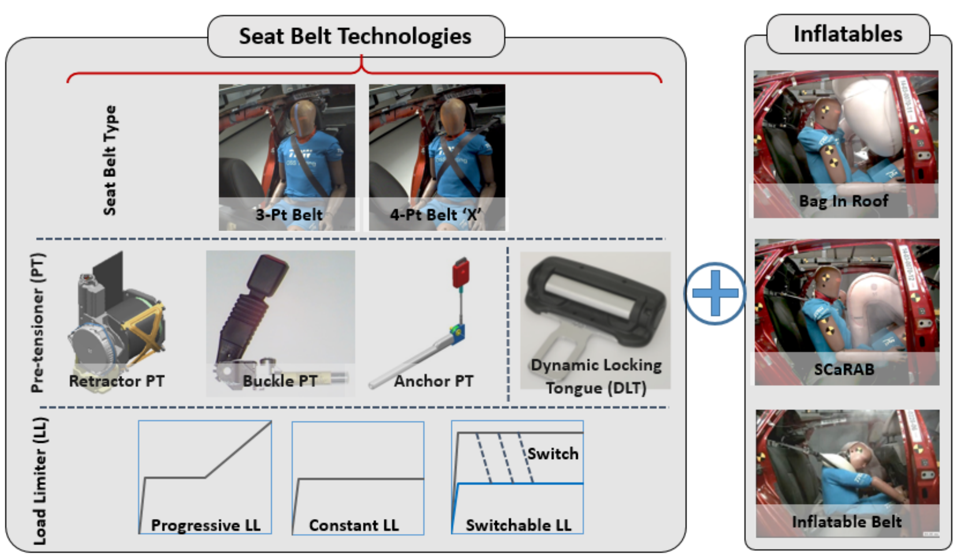

Figure 3. Different advanced restraint systems evaluated in this study

The restraint components investigated for this study were intended to engage the occupant early in the event and allow the restraint systems to help absorb the energy with a lower load without allowing contact to the front seat. Pre-tensioners were used to engage the occupant early by moving the onset of belt force earlier in a crash. A retractor pre-tensioner, the most common form of pre-tensioner, helped to reduce the slack in the shoulder portion of the belt system. An anchor pre-tensioner reduced slack in the lap portion, and a buckle pre-tensioner added pretension to both the lap and shoulder segments of the belt system. All of these pre-tensioner configurations were evaluated in this study.

In general once a pre-tensioner fires, the load limiter in the retractor manages belt force to reduce loads on the occupant, potentially allowing the occupant to travel further while absorbing energy. A CLL provides a constant belt force as the webbing is pulled out of the retractor regardless of the occupant size or crash pulse. In general, a larger occupant or more severe crash pulse will produce larger excursions. In contrast, a PLL increases the belt force as the webbing is pulled out. As a result, the increased belt force may limit the higher excursions that can be seen with larger occupants.

The DLT is a design consisting of a seat belt tongue (the plate which fastens into the buckle) with a rotating cam and a concealed spring. The DLT allows webbing to pass freely through the tongue when buckling. However, in the event of hard braking or a crash resulting in greater than about 45 N of force on the belt, the DLT clamps the webbing and prevents the webbing transferring from the shoulder belt portion to the lap belt portion. It works with other seat belt technologies helping to reduce loads on the occupant's chest.

A further option with a belt only system was the 4-point belt. Two retractor pre-tensioners with CLLs positioned the belt over both shoulders, and two tongues anchored the lap portion. Since this system engaged both shoulders, the load was more evenly distributed over the occupant with more symmetrical loading to the left and right sides of the body than with a three-point belt.

There are limitations in the belt system when trying to balance low belt loads and excursion. One option to mitigate the excursion and allow low belt loads is to incorporate an airbag. Two airbag concepts were investigated in the study. The BiR deploys from the roof of the vehicle between the rear seat occupant and front seat back. The SCaRAB deploys from the front seat back, conforming to the space between the occupant and front seat back. In this study, the BiR inflator output, bag volume, and construction is similar to a passenger airbag for the front seat. In comparison, the SCaRAB inflator output and bag volume are relatively small, similar to a driver airbag and less than half the size of the BiR.

An inflatable belt has a tubular inflatable bladder contained within an outer cover, generally on the shoulder belt only. During a crash, the bladder inflates with gas to increase the contact area between the occupant and restraint and also tighten the belt, both of which can potentially reduce the chest injury risk.

Sled Test Matrix

Detailed descriptions of the baseline testing conditions and a portion of the sled tests in the second sled series have been reported by Hu et al. (2015). Therefore, in this study, we only focused on the second and final series of the sled tests shown in Figure 1, both of which used advanced restraint designs.

The test matrices for the second series and the final series with advanced restraint technologies are shown in Tables 3 and 4. The second series focused on testing various combinations of advanced restraints for computer models to validate against, while the final series focused on the optimal restraints with and without an airbag. For tests with the 6 YO ATD, a Graco® Backless TurboBooster® was used to reduce the potential for submarining. Based on the results from the baseline tests, the sled tests in the second series were conducted with the severe crash pulse, while the final sled tests included both the soft and severe crash pulses. More design specifications are shown in Appendix B.

Table 3. Sled test matrix for the second series with advanced restraints

No.	Pulse	Side	ATD	Belt	Airbag
0070-22	Severe	Left	6 YO	3pt belt/ 9.5mm PLL/ retractor-PT/ buckle-PT	None
0228-12	Severe	Right	6 YO	Inflatable belt / 9.5mm CLL/ anchor- PT	Inflatable belt
0228-02	Severe	Right	6 YO	4pt belt/ 8mm CLL/ retractor-PTx2/ buckle-PTx2/ DLT	None
0070-18	Severe	Right	6 YO	3pt belt/ 9.5mm CLL/ retractor-PT	BiR
0228-11	Severe	Left	6 YO	3pt belt/ 8mm CLL/ retractor-PT/ anchor-PT/ DLT	SCaRAB
0228-03	Severe	Left	5th	3pt belt/ 10 mm PLL/ retractor-PT / anchor-PT/ DLT	None
0228-10	Severe	Left	5th	Inflatable belt / 9.5mm CLL/ anchor- PT/ DLT	Inflatable belt
0228-03	Severe	Right	5th	4pt belt/ 8mm CLL/ retractor-PTx2/ buckle-PTx2/ DLT	None
0228-15	Severe	Right	5th	3pt belt/ 8mm CLL/ retractor-PT/ anchor-PT/ DLT	BiR
0228-10	Severe	Right	5th	3pt belt/ 8mm CLL/ retractor-PT/ anchor-PT	SCaRAB
0070-19	Severe	Left	THOR	3pt belt/ 10.5 mm CLL/ retractor-PT / buckle-PT	None
0348-04	Severe	Right	THOR	Inflatable belt / 9.5mm CLL/ anchor- PT/ DLT	Inflatable belt
0070-13	Severe	Right	THOR	4pt belt/ 8mm CLL/ retractor-PTx2	None
0070-11	Severe	Right	THOR	3pt belt/ 9.5mm CLL/ retractor-PT	BiR
0070-12	Severe	Right	THOR	3pt belt/ 9.5mm CLL/ retractor-PT	SCaRAB
0070-18	Severe	Left	95th	3pt belt/ 10.5 mm PLL/ retractor-PT / buckle-PT	None
0228-11	Severe	Right	95th	Inflatable belt / 9.5mm CLL/ anchor- PT	Inflatable belt
0228-01	Severe	Right	95th	4pt belt/ 8mm CLL/ retractor-PTx2/ buckle-PTx2/ DLT	None
0070-17	Severe	Right	95th	3pt belt/ 9.5mm CLL/ retractor-PT	BiR
0228-12	Severe	Left	95th	3pt belt/ 8mm CLL/ retractor-PT/ anchor-PT/ DLT	SCaRAB

Table 4. Sled test matrix for the final series with the optimized restraints

No.	Pulse	Side	ATD	Belt	Airbag
0045-02	Soft	Right	6 YO	3pt belt/ 9mm CLL/ retractor-PT/ anchor-PT / DLT	SCaRAB
0045-05	Soft	Left	6 YO	3pt belt/ 10.5mm CLL/ retractor-PT/ anchor-PT / DLT	None
0045-03	Severe	Right	6 YO	3pt belt/ 10.5mm CLL/ retractor-PT/ anchor-PT / DLT	None
0045-04	Severe	Left	6 YO	3pt belt/ 9mm CLL/ retractor-PT/ anchor-PT / DLT	SCaRAB
0045-07	Soft	Right	5th	3pt belt/ 9mm CLL/ retractor-PT/ anchor-PT / DLT	SCaRAB
0045-09	Soft	Left	5th	3pt belt/ 10.5mm CLL/ retractor-PT/ anchor-PT / DLT	None
0045-08	Severe	Right	5th	3pt belt/ 10.5mm CLL/ retractor-PT/ anchor-PT / DLT	None
0045-10	Severe	Left	5th	3pt belt/ 9mm CLL/ retractor-PT/ anchor-PT / DLT	SCaRAB
0045-09	Soft	Right	THOR	3pt belt/ 9mm CLL/ retractor-PT/ anchor-PT / DLT	SCaRAB
0045-07	Soft	Left	THOR	3pt belt/ 10.5mm CLL/ retractor-PT/ anchor-PT / DLT	None
0045-10	Severe	Right	THOR	3pt belt/ 10.5mm CLL/ retractor-PT/ anchor-PT / DLT	None
0045-08	Severe	Left	THOR	3pt belt/ 9mm CLL/ retractor-PT/ anchor-PT / DLT	SCaRAB
0045-05	Soft	Right	95th	3pt belt/ 9mm CLL/ retractor-PT/ anchor-PT / DLT	SCaRAB
0045-06	Soft	Left	95th	3pt belt/ 10.5mm CLL/ retractor-PT/ anchor-PT / DLT	None
0045-04	Severe	Right	95th	3pt belt/ 10.5mm CLL/ retractor-PT/ anchor-PT / DLT	None
0045-03	Severe	Left	95th	3pt belt/ 9mm CLL/ retractor-PT/ anchor-PT / DLT	SCaRAB

Computational Models

MADYMO ATD models representing THOR 50th, H-III 5th, 95th and 6 YO ATDs were used in this study. Two THOR 50th models, a THOR-alpha 50th and a THOR-NT 50th model, were used in this study, because the THOR-NT 50th model developed by TASS became available toward the end of this study. As a result, the THOR-alpha 50th model was used in the validation runs against the baseline sled tests, while the THOR-NT 50th model was used in the validation runs against sled tests with advanced restraints and the final parametric simulations. Compared to the THOR-alpha 50th model, the THOR-NT 50th model included more realistic geometry and impact characteristics. The H-III 6 YO MADYMO model has been improved by incorporating more accurate pelvis and abdomen geometries (Wu et al., 2012).

Four sets of environment models were developed along with the ATD models as shown in Figure 4. Simulations were set up to match the baseline test configurations with these 4 sets of models and 2 crash pulses (soft/severe). Besides the ATD models, the major components of the crash environment developed in MADYMO were the rear seats, the front seats, and the seat belt systems. The seat geometry and seat belt anchorage locations were based on CAD data of the baseline vehicle provided by ZF-TRW. Facet mesh was used for the seat models to achieve a better representation of the geometry. The seat belt webbing and retractor models, which have been validated at the component level, were provided by ZF-TRW. Baseline stiffness values of the rear seat cushion and front seat back were selected based on generic contact stiffness curves and compared to the related data reported by Prasad and Weston (2011) and Arbogast et al. (2012). The stiffness values were scaled up and down during the validation process to match the baseline test data. The front seat back rotational characteristics were also tuned to match the baseline test results.

The model validation process closely followed those from our previous studies (Hu et al., 2012a; Wu et al., 2012), in which sensitivity analyses and optimization techniques were used to validate ATD models at different sizes against multiple sled tests. In the current study, optimizations were used to determine model parameters that provide the best match to the ATD responses in 8 baseline sled test conditions. ModeFRONTIER (ESTECO), a multi-objective optimization software program, was coupled with MADYMO to conduct the optimizations.

Model parameters optimized in the model validation process against the baseline tests included rear seat parameters (cushion stiffness, damping, and friction), front seat parameters (back stiffness and damping), seat belt parameters (shoulder and lap belt slacks), and ATD parameters (chest and abdomen contact characteristics of the old-THOR 50th model). Because the seat belt webbing and retractor models were validated previously at the component level by ZF-TRW, those parameters were not tuned in the model validation process. Similarly, because the H-III ATD models were validated previously against ATD tests, no parameters of the H-III ATD models were adjusted in the model validation process. The THOR-alpha 50th MADYMO model was less valid, therefore the abdomen contact characteristics were scaled to achieve the best match between test and simulation results.

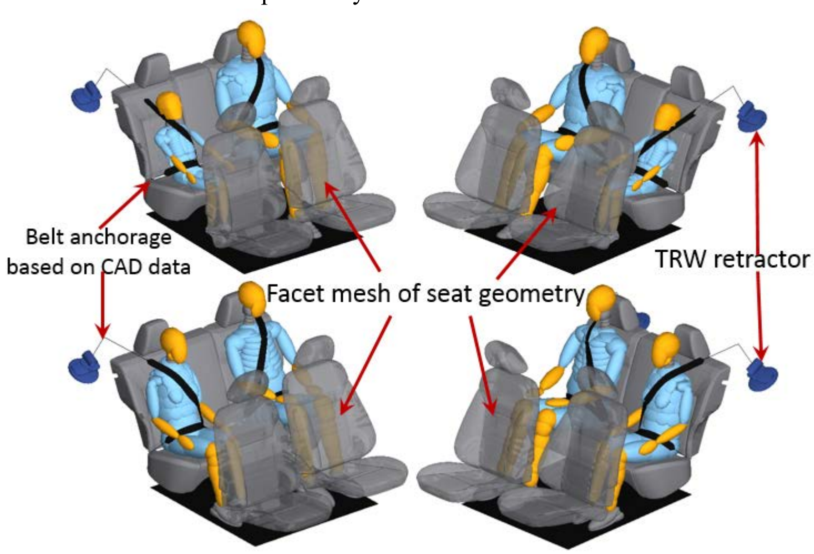

Figure 4. Four sets of models developed for model validation against baseline tests

A total of nine impact responses for each ATD in each test were used for model validation, including the accelerations in X-, and Z-directions at the ATD head center of gravity (CG), chest, and pelvis, as well as chest deflection and shoulder and lap belt loads. In each optimization, the sum of normalized errors of the nine impact responses (Eq. 1) for each ATD at each test conditions were defined as the objective function to evaluate the differences between the tests and simulations. Equal weights on different types of signals and different body regions were used.

$$Objective(Test_x ATD_y) = \sum_{i=1}^{data\ channel}\left(\sqrt{\sum_{j=1}^{\text{data point}} \frac{\left(\text{Sim}_{i,j}-\text{Test}_{i,j}\right)^2}{\text{Test}_{\max}^2 \times \text{Data point}}}\right) \quad (1)$$

In Eq. 1, data channel represents the total channel numbers in each test for model validation, and data point is the total number of points in each data channel depending on the sampling frequency. In the model validation of this project, a 1-kHz sample rate was chosen for calculating the objective function in each optimization.

Optimization was conducted for each ATD in each of the tests. In each optimization, a total of 200 simulations with different combinations of model parameters sampled by the Uniform Latin Hypercube method were performed first. Response surface models (RSMs) based on radial basis functions were generated to quantify the relationship between the model parameters and the sum of normalized errors across test signals given by Eq. 1. Virtual optimizations using the RSMs were conducted to achieve the best combination of model parameters. A genetic algorithm NSGA-II (Non-dominated Sorting Genetic Algorithm II) was used in the optimization to minimize the sum of normalized errors. Compared with gradient methods, the genetic algorithm reduces the chance of identifying a local optimum. More than 50 generations were performed in an optimization with 50 designs in each generation.

To evaluate the goodness of fit between the test and simulation results, statistical assessments were performed in addition to visual comparisons between the test and simulation results. CORrelation and Analysis (CORA) scores were calculated for each measurement of the tests to evaluate the model quality. A CORA score of 1.0 represents a perfect match between the test and simulation, while a CORA score of 0.0 represents no correlation between the test and simulation results.

Since the ATD model, seat belt model, and the vehicle seat models have been validated at the component level as well as against baseline sled tests, the models with advanced restraints were further validated against the sled tests with advanced restraints. These models included 3-point seat belt with pre-tensioner(s), load limiter(s), and/or dynamic locking tongue, 4-point belt, BiR, and SCaRAB. A booster seat model with geometry similar to those used in the tests was also developed. The models were tuned manually to match the test data for each selected testing condition.

Computational Design Optimizations

Based on the results of the second series sled test, design optimizations were performed for the 3-point belt (with pre-tensioner and load limiter), 3-point belt with a BiR, and 3-point belt with SCaRAB using the objective function and constraints shown in Table 5.

A parametric study based on the full factorial design for the 3-point belt with a CLL and retractor pre-tensioner was conducted. The input parameters are crash pulse (severe/soft), ATD (6 YO/5th/THOR 50th/95th), CLL torsion bar (8.0/8.5/9.0/9.5/10.0/10.5 mm), buckle pre-tensioner (Yes/No), anchor pre-tensioner (Yes/No), DLT (Yes/No). A total of 384 (2*4*6*2*2*2*2) simulations were conducted, and injury measures in Table 5 for all the simulations were output for evaluation.

Table 5. Objective function and constraints in the design optimizations

	Head			Neck			Chest
	Excursion (mm)	HIC	BrIC	NeckT (kN)	NeckC (kN)	Nij	Chest D
H-III 6 YO	<480	<700	<0.87	<1.49	<1.82	<1.0	<40 mm
H-III 5th	<500	<700	<0.87	<2.62	<2.52	<1.0	Minimize
THOR 50th	<580	<700	<0.87	<4.17	<4.00	<1.0	Minimize
H-III 95th	<600	<700	<0.87	<5.44	<5.44	<1.0	Minimize
Combined Probability of Chest Injury for 5th, THOR 50th, & 95th							Minimize

Note: All injury measures should be less than those in the baseline tests

Simulations with airbags only focused on crashes with the severe crash pulse. Parametric studies based on the full factorial design for the BiR and SCaRAB with a CLL and retractor pre-tensioner were also conducted. The input parameters are occupant side (driver/passenger), ATD (6 YO/5th/THOR 50th/95th), CLL torsion bar (8.0/8.5/9.0 mm), buckle pre-tensioner (Yes/No), anchor pre-tensioner (Yes/No), DLT (Yes/No). A total of 96 (2*4*3*2*2) simulations were conducted for each airbag design (BiR or SCaRAB). Note that the BiR and SCaRAB design parameters (e.g. airbag location, mass flow, vent size, etc.) were also tuned through separate parametric studies before these parametric runs.

RESULTS

Baseline Sled Tests

The results of the baseline sled tests have been reported previously (Hu et al. 2015). However, for completeness, the main findings are presented here. Results in the baseline sled series showed that crash pulse and occupant size were the two dominating factors affecting the ATD kinematics and injury measurements, while impact angle and front seat location did not produce significant effects. Although no head-to-front seat contact occurred in any of the tests, in general, a severe crash pulse would result in chest deflections exceeding the injury criteria for adult ATDs and higher ATD head excursions than for the soft crash pulse. These results are consistent with those from the field data (Kuppa et al., 2005), in that chest injuries are the most common serious injuries in rear seat adult occupants. The H-III 6 YO ATD submarined in all the tests conducted without a booster seat due to the slouching pre-crash posture. Submarining also occurred for the HIII 5th ATD in all the tests under a severe crash pulse, indicating that smaller occupants may be more likely to submarine than larger occupants.

Baseline Model Validations

Figure 5 summarizes the CORA evaluation results for each impact response on each ATD, and a summary of the CORA evaluation results are shown in Appendix C. In general, all the models provided good correlations to the test results, although H-III 5th and 95th ATD models produced better correlations to the test data than the THOR 50th and H-III 6 YO ATD models. The correlations for the chest Z accelerations were generally poor because of the small magnitudes and two peaks (one positive and one negative) in all the tests. Examples of model correlations are shown in Appendix C as well.

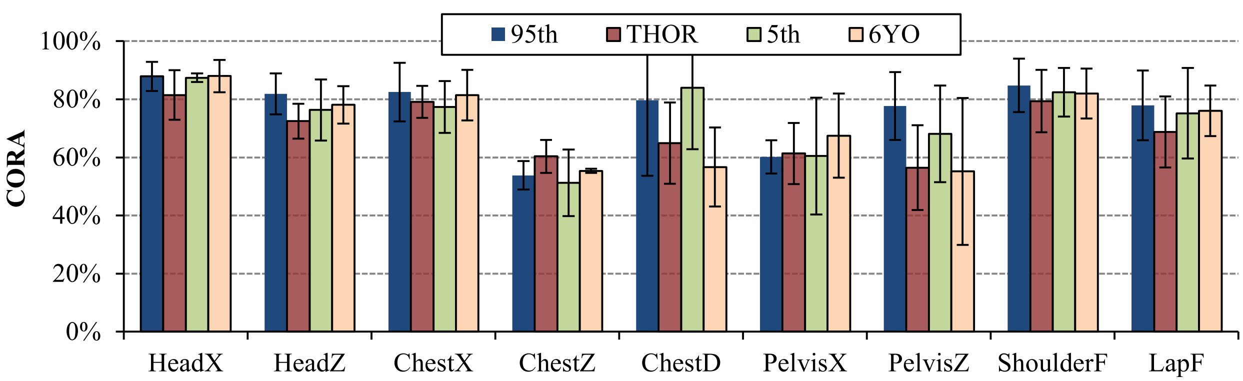

Figure 5. Summary of the CORA scores for the model validation against baseline tests

Sled Tests with Advanced Restraints

H-III 5th ATD Test Results

The injury measures and ATD kinematics with the 5th ATD using different restraint systems are shown in Figure 6. Compared to the baseline 3-pt belt system, advanced restraint systems generally reduced the injury measures. However, the 3-point belt with pre-tensioner and load limiter and the inflatable belt did not reduce the HIC, BrIC, and neck tension to values below the associated IARVs, while the 4-point belt, BiR, and the SCaRAB reduced all the injury measures below the IARVs. Since the chest is the most commonly injured body region for adults according to recent literature discussed above, the BiR and SCaRAB airbags were considered good options for reducing the chest injury risks for the 5th ATD. The seat belt loads also showed that the BiR and SCaRAB reduced crash loads on ATD chests (shoulder belt forces) by more than 50% when compared to those in the baseline tests, while the 3-point belt with load limiter only reduced the loads on the chest by less than 20% when compared to those in the baseline tests. This is because BiR and SCaRAB can prevent hard contacts between the head and front seat, which has allowed a lower shoulder belt load limit to be applied. In the sled tests, an 8-

mm torsion bar was used in the load limiter with BiR or SCaRAB, and a 10-mm torsion bar was used for the 3-point belt only conditions. If an 8-mm torsion bar was used without BiR or SCaRAB, head contact with the front seat may have occurred due to increased head excursion. ATD submarining did not occur in any of the tests with advanced restraint designs, mainly because an anchor/buckle pre-tensioner was used while keeping the same seat belt anchorage locations in all the tests.

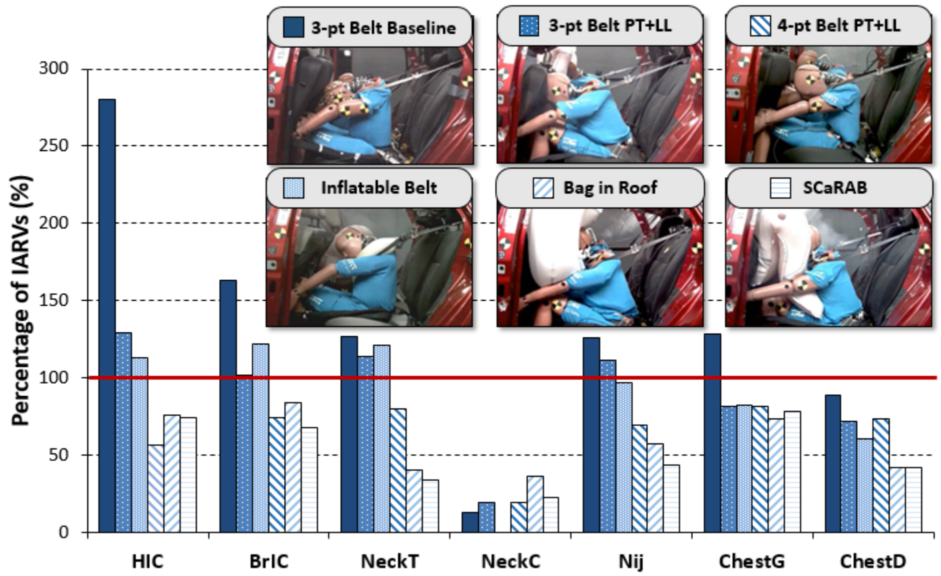

Figure 6. Injury measures and kinematics of the 5th ATD with different restraints

H-III 6 YO ATD Test Results

The injury measures and ATD kinematics with the 6 YO ATD using different restraint systems are shown in Figure 7. Compared to the baseline 3-pt belt system, advanced restraint systems generally reduced the injury measures. However, none of the advanced restraints reduced all the injury measures below the IARVs. All the restraint systems failed to meet the IARV for BrIC. The 3-point belt with pre-tensioner and load limiter, the inflatable belt, and the 4-point belt did not reduce the neck tension below the associated IARVs, while the inflatable belt and the 4-point belt increased the chest deflection from the baseline test and failed to meet the IARVs for the chest deflection. Because of the usage of the booster seat, submarining did not occur in any of the tests in the second series.

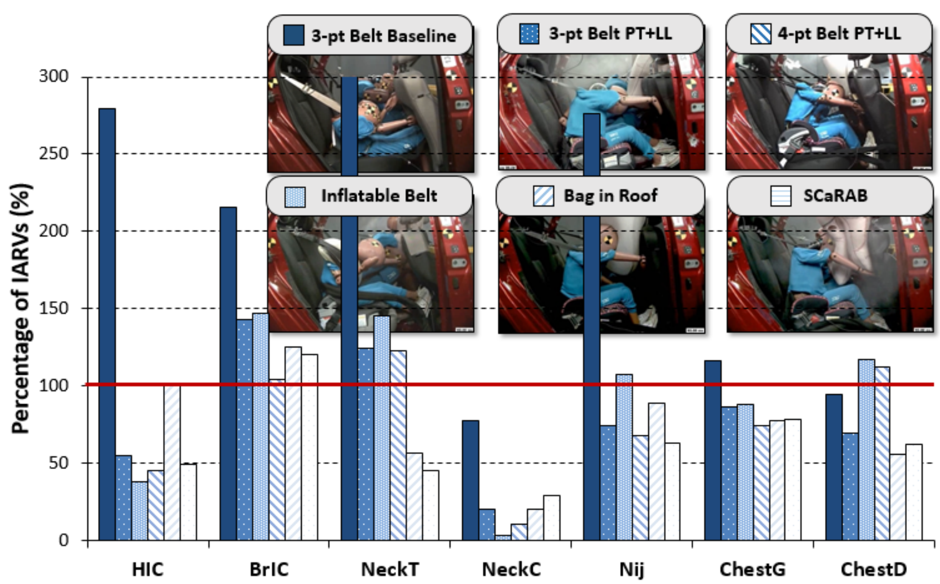

Figure 7. Injury measures and kinematics of the 6 YO ATD with different restraints

THOR 50th ATD Test Results

The injury measures and ATD kinematics with the THOR 50th using different restraint systems are shown in Figure 8. Compared to the baseline 3-pt belt system, advanced restraint systems generally reduced the injury measures. However, none of the advanced restraints reduced all of the injury measures below the IARVs. The 3-point belt with pre-tensioner and load limiter met all the IARVs except for the BrIC; the 3-point belt with SCaRAB met all the IARVs except for chest deflection; and all the other designs exceeded at least two IARVs. Even though lower load limits were used for the tests with 4-point belt, BiR and SCaRAB, the THOR 50th chest deflections with those advanced restraints were higher than the baseline tests, which was not consistent with the results using other ATDs. Tests with airbags (BiR or SCaRAB) generally reduced the neck injury measures. However the HIC with BiR was high, and based on the kinematics it seems that the BiR stiffness should have been reduced to allow better cushioning.

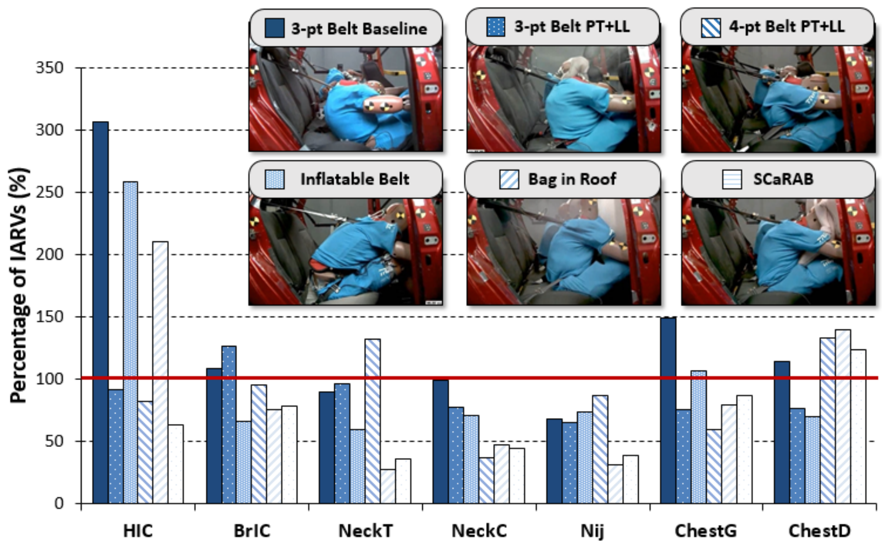

Figure 8. Injury measures and kinematics of the THOR 50th with different restraints

H-III 95th ATD Test Results

The injury measures and ATD kinematics with the 95th ATD using different restraint systems are shown in Figure 9. Compared to the baseline 3-pt belt system, advanced restraint systems generally reduced the injury measures. However, none of the advanced restraints reduced all of the injury measures below the IARVs. Based on the test results, the SCaRAB only exceeded the Nij IARV, which provided the best occupant protection among all the designs.

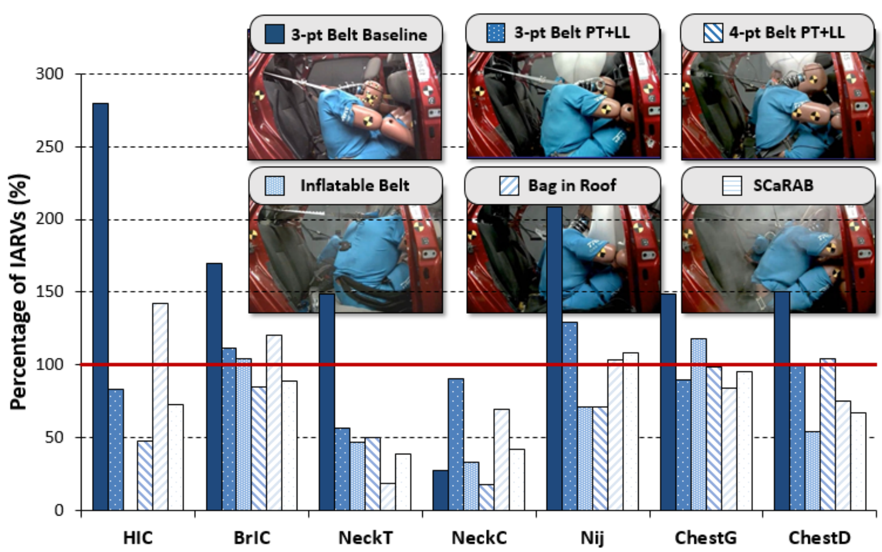

Figure 9. Injury measures and kinematics of the 95th ATD with different restraints

Model Validation against Sled Tests with Advanced Restraints

Examples of comparisons of occupant kinematics between the tests and simulations are shown in Figure 10. Correlations between the tests and simulations on occupant responses were attached in Appendix C. Reasonably good correlations were achieved.

Computational Design Optimizations

The results for the parametric study with 3-point belt-only designs showed that the constraint violations limited the number of designs that can be considered. In particular, only 5 designs were able to meet all the constraints under the soft crash pulse, while no designs could meet all the constraints under the severe crash pulse. The design constraint passing rates as well as the final designs that can meet all the constraints in the soft crash pulse are shown in Tables 6 and 7. It was clear that a 9.0 or 9.5 mm torsion bar and a buckle pre-tensioner were needed to pass all the design constraints under the soft pulse crash.

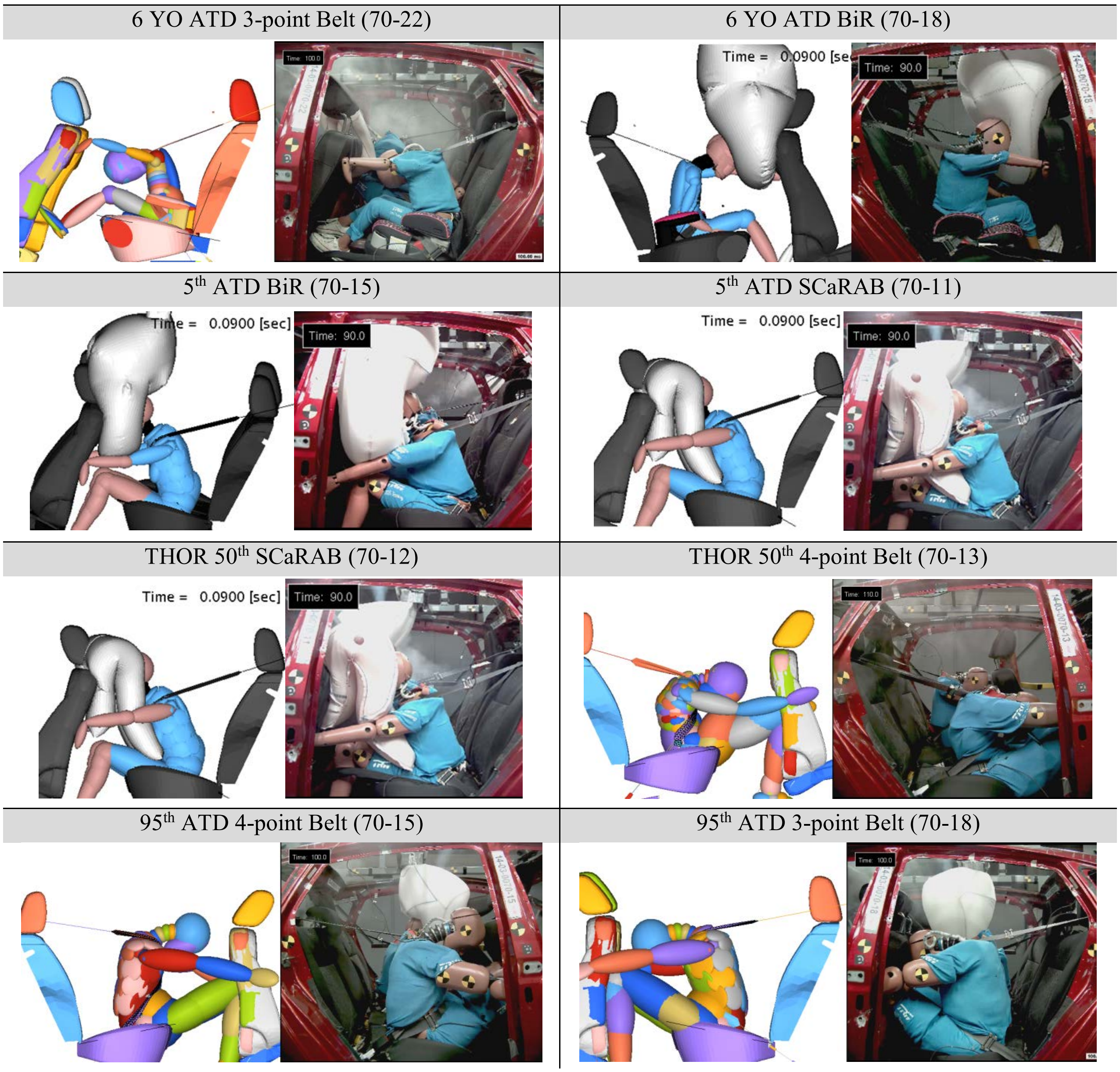

Figure 10. Comparison of ATD kinematics between the tests and simulations with advanced restraints

Table 6. Percentage of 3-point belt only designs able to meet the design constraints in Table 5

Pulse	6 YO	5th	THOR 50th	95th	Combined
Severe	0%	0%	0%	3%	0%
Soft	41%	69%	94%	100%	28%

Table 7. 3-point only designs able to meet all the design constraints in Table 5

Run No	Anchor PT	Buckle PT	DLT	Pulse	Angle	Torsion Bar	Total Chest Probability
26	Yes	Yes	Yes	Soft	0°	9.0 mm	10%
122	No	Yes	Yes	Soft	0°	9.0 mm	13%
98	No	Yes	No	Soft	0°	9.0 mm	14%
123	No	Yes	Yes	Soft	0°	9.5 mm	15%
99	No	Yes	No	Soft	0°	9.5 mm	20%

A retractor pre-tensioner was used in all the simulations.

The model-predicted ATD kinematics with one of the advanced belt-only designs (design 122 in Table 7) are shown in Figure 11, in which no head-to-front-seat contact occurred while the ATDs sustained good kinematics (torso pitching forward without submarining).

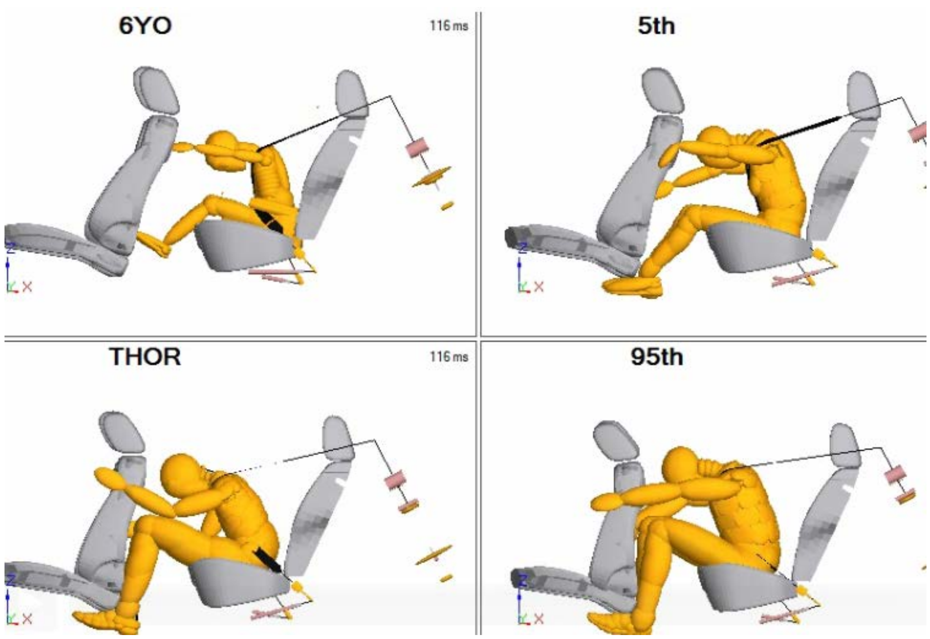

Figure 11. ATD kinematics with the belt-only design 122 under soft crash pulse

The percentages of designs including an airbag (BiR or SCaRAB) that were able to meet all the design constraints for each ATD under the severe crash pulse are shown in Table 8, and the designs that met all the constraints for all the ATDs are shown in Table 9. Interestingly, the designs that met all of the constraints are all with a SCaRAB and an 8.5 or 9.0 mm torsion bar. The model-predicted ATD kinematics with one of the advanced designs (design 68 in Table 9) are shown in Figures 12 and 13.

Table 8. Percentage of airbag designs that can meet the design constraints in Table 5

Designs	6 YO	5th	THOR	95th	Comb
SCaRAB	94%	79%	58%	88%	48%
BiR	58%	98%	23%	100%	21%

Table 9. Designs with an airbag that can meet all the design constraints in Table 5

Run No	Restraints	Anchor PT	Buckle PT	DLT	Load Limiter Level	Comb Chest Probability
56	SCaRAB	Yes	Yes	Yes	9.0 mm	41.5%
68	SCaRAB	Yes	No	Yes	9.0 mm	44.4%
55	SCaRAB	Yes	Yes	Yes	8.5 mm	46.9%
50	SCaRAB	Yes	Yes	No	9.0 mm	48.5%
62	SCaRAB	Yes	No	No	9.0 mm	49.0%
49	SCaRAB	Yes	Yes	No	8.5 mm	50.7%

A retractor pre-tensioner was used in all the simulations.

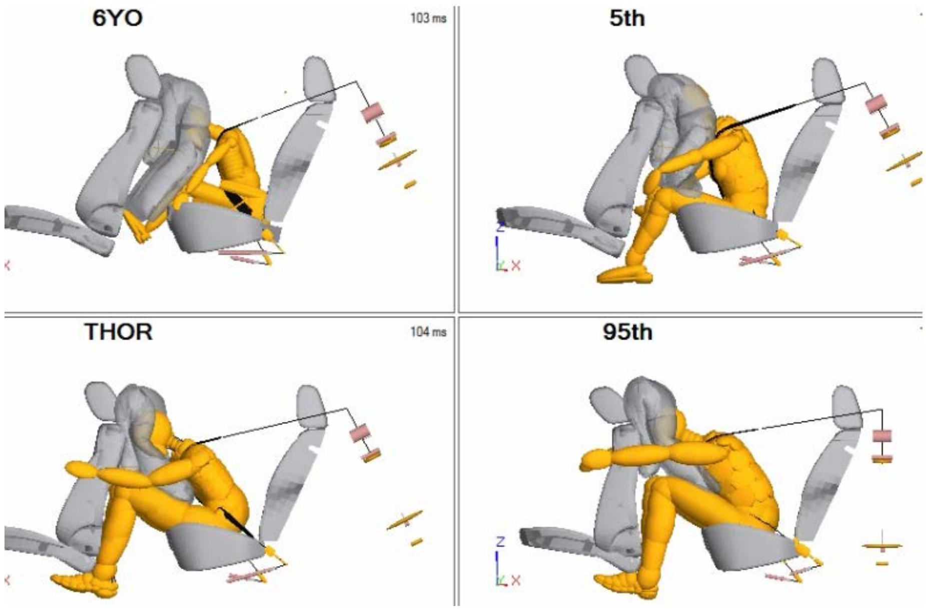

Figure 12. Driver side ATD kinematics with an advanced belt system (3-point belt with 9.0 mm torsion bar, retractor and anchor pre-tensioners) and a SCaRAB under severe crash pulse

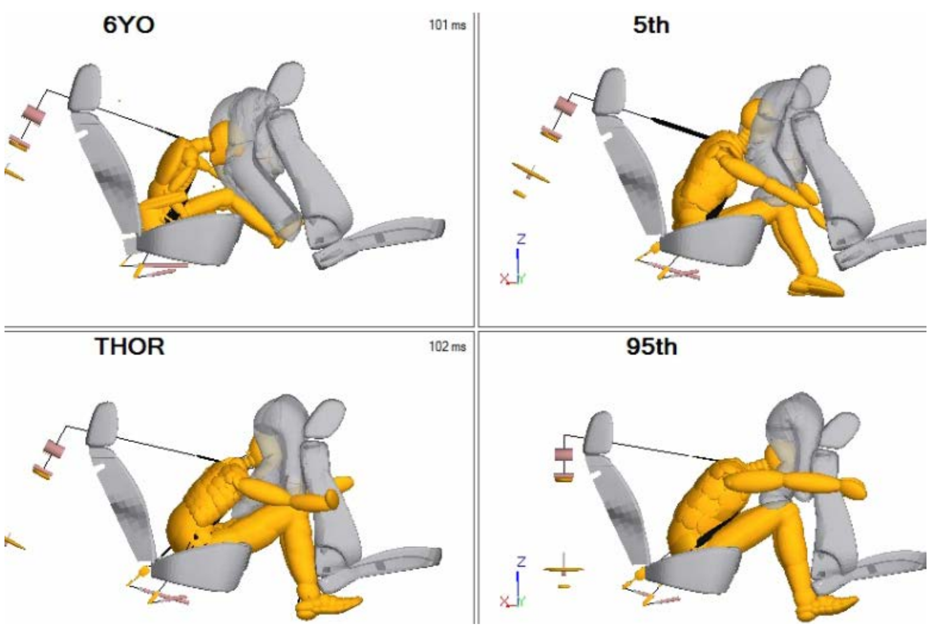

Figure 13. Passenger side ATD kinematics with an advanced belt system (3-point belt with 9.0 mm torsion bar, retractor and anchor pre-tensioners) and a SCaRAB under severe crash pulse

Final Series of Sled Tests with Advanced Restraints

Detailed injury measures and belt forces for all the tests in the baseline and final sled series are shown in Appendix D. The term "bag" or "airbag" in this section refers to SCaRAB.

H-III 6 YO ATD

The kinematics and injury measures of the 6 YO ATD with 4 different restraint systems (baseline belt without booster, baseline belt with booster, advanced-belt only, and advanced-belt with SCaRAB) and under 2 crash pulses (soft vs. severe) are shown in Figure 14. With the advanced-belt and SCaRAB, all the injury measures were below the IARVs; while with the advanced-belt only design, all the injury measures were below the IARVs except for the neck tension and BrIC. Adding the booster significantly improved the kinematics of the 6 YO ATD, and prevented submarining. However, without advanced restraint features, most injury measures are still over the IARVs.

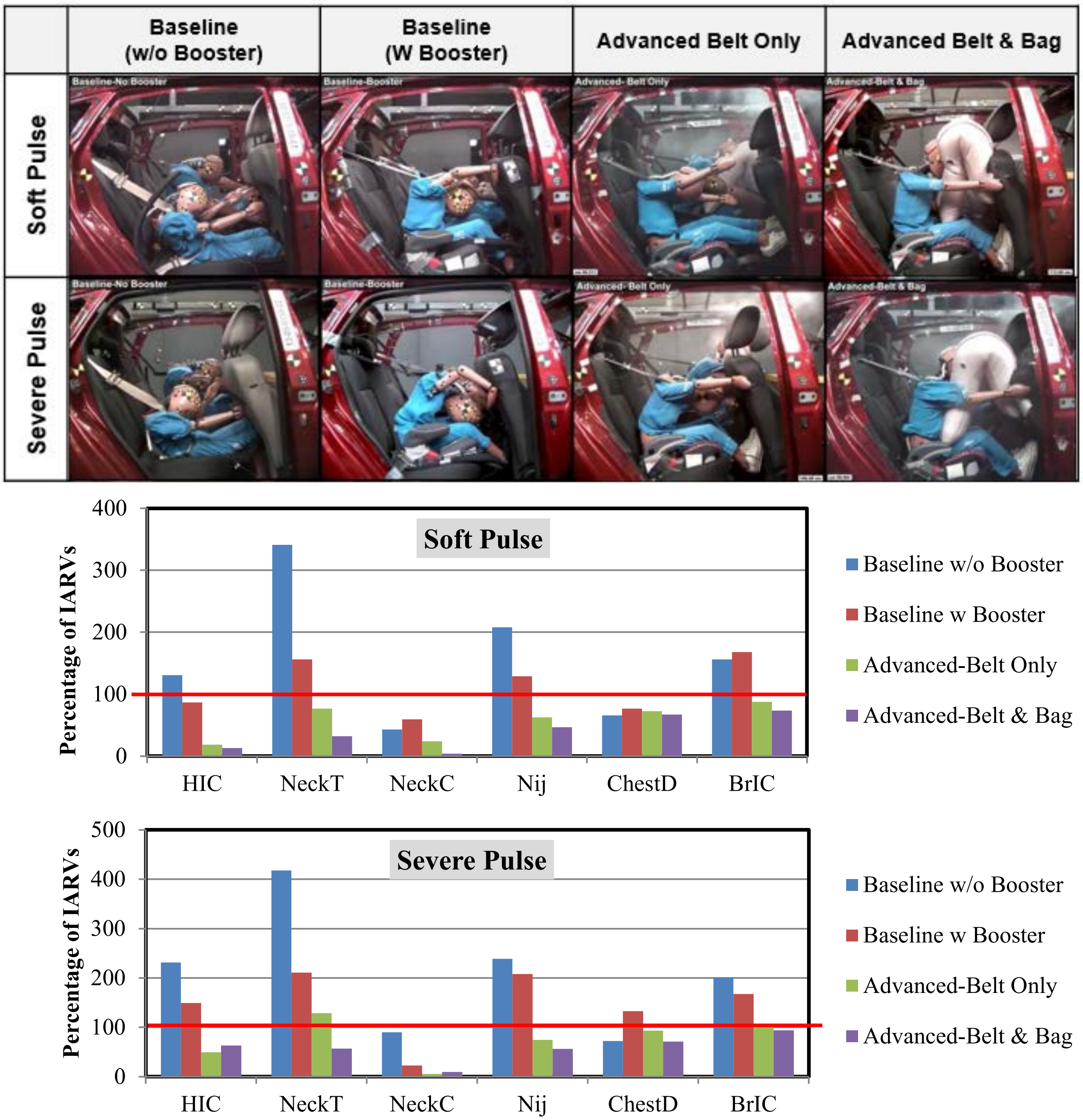

Figure 14. 6 YO ATD kinematics and injury measures with 4 restraints under 2 crash pulses
Images for left passenger were all mirrored, and red lines represent 100% of IARVs.

H-III 5th female ATD

The kinematics and injury measures of the 5th ATD with 3 restraints (baseline belt, advanced-belt only, and advanced-belt with SCaRAB) under 2 crash pulses (soft vs. severe) are shown in Figure 15. With the two advanced restraints, all the injury measures were below the IARVs. The design with SCaRAB reduced almost all the injury measures more than the belt-only design.

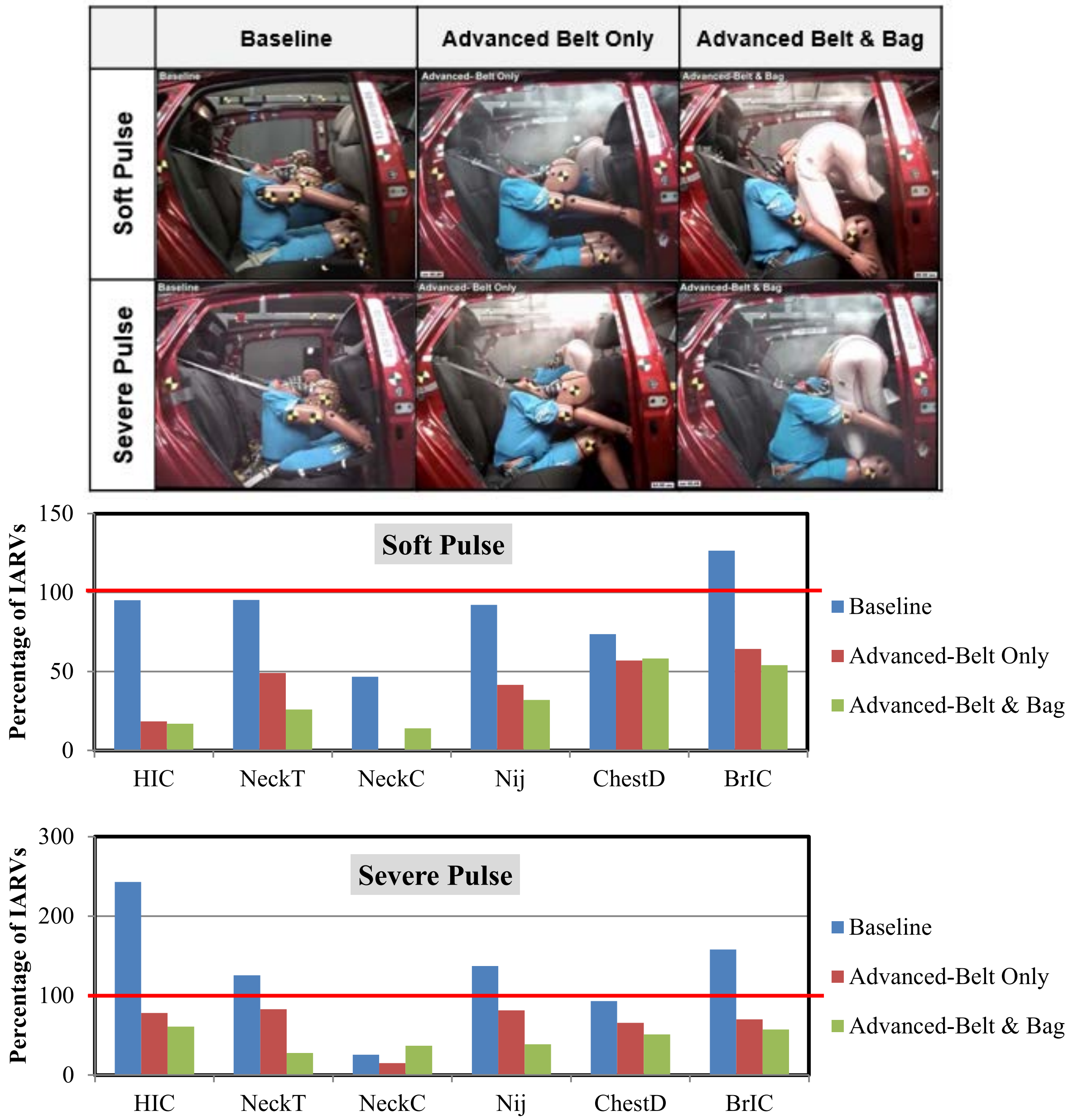

Figure 15. 5th ATD kinematics and injury measures with 3 restraints under 2 crash pulses
Images for left passenger were all mirrored, and red lines represent 100% of IARVs.

THOR 50th male ATD

The kinematics and injury measures of the THOR 50th with 3 restraints (baseline belt, advanced-belt only, and advanced-belt with SCaRAB) under 2 crash pulses (soft vs. severe) are shown in Figure 16. Under the soft crash pulse, both advanced restraints were able to reduce all the injury measures below the IARVs. However, under the severe crash pulse, it was common for the IARVs to be exceeded for the advanced-belt only design. In general, the advanced restraint designs did not reduce the chest deflection from the baseline tests. With the advanced-belt only design, the head of THOR contacted the knee, resulting in a very high HIC value.

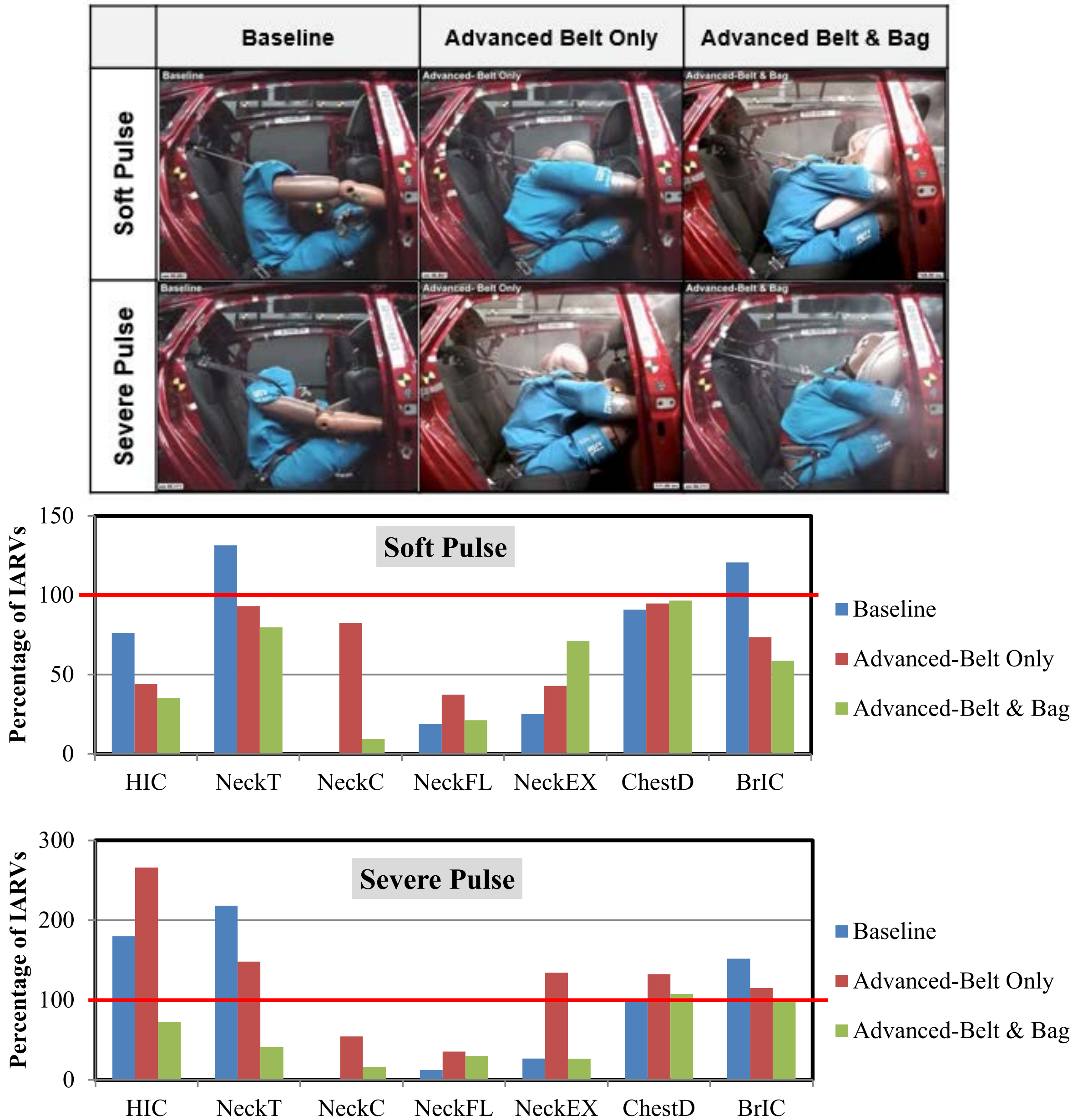

Figure 16. THOR 50th kinematics and injury measures with 3 restraints under 2 crash pulses Images for left passenger were all mirrored, and red lines represent 100% of IARVs.

The chest deflection results at 4 locations of the THOR 50th are shown in Figure 17. It is clear that the maximal chest deflection was always at the location near the buckle, which was not affected by the restraint designs. On the other hand, the chest deflections on the upper chest showed reduction by using the two advanced restraints. Note that 63 mm (chest deflection IARV for the H-III 50th ATD) was used as the IARV for chest deflection of the THOR 50th. Because the THOR 50th uses different chest injury risk curves than the H-III 50th ATD, a 63 mm IARV for the H-III 50th ATD would likely under-estimate the actual chest injury risks predicted by the THOR 50th.

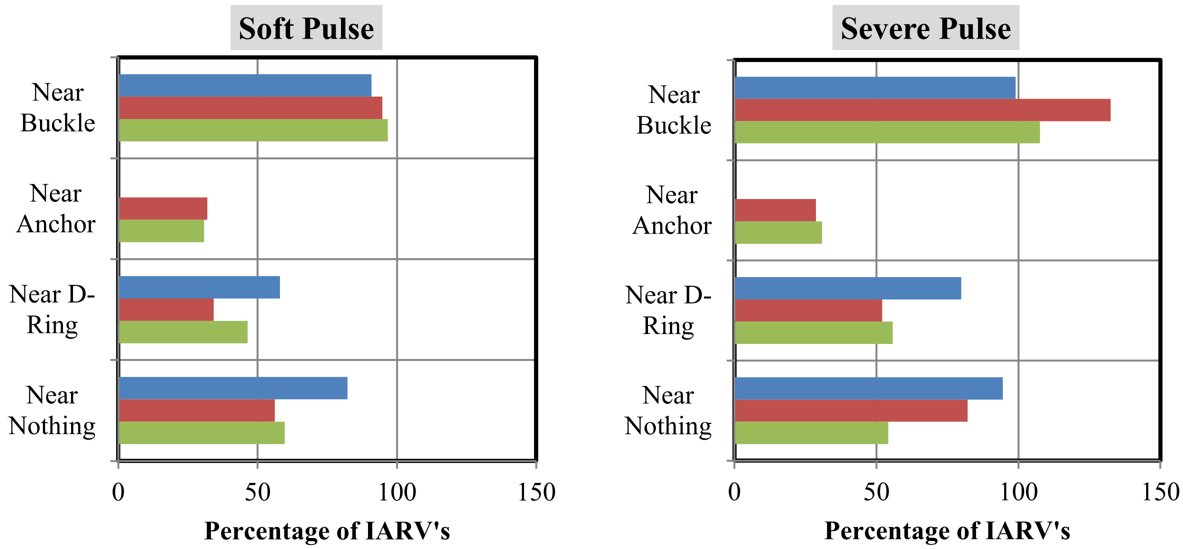

Figure 17. THOR 50th chest deflections at 4 locations with 3 restraints under 2 crash pulses
Note: Among the four chest deflection measures, three of them are corresponding to the three anchorage locations, while "near nothing" is not corresponding to any of the belt anchorage locations.

H-III 95th male ATD

The kinematics and injury measures of the 95th ATD with 3 restraint configurations (baseline belt, advanced-belt only, and advanced-belt with SCaRAB) under 2 crash pulses (soft vs. severe) are shown in Figure 18. With the advanced belt and SCaRAB, all the injury measures were below the IARVs. With the advanced belt only design, all the injury measures were below the IARVs except for the HIC and BrIC under severe crashes due to a head to front seat contacts.

Table 10 shows the injury risk reductions for the 4 ATDs from the baseline restraint to the two optimized advanced restraints. The injury risks were calculated based on the injury risk curves associated with AIS3+ injuries to the head (brain), neck, and chest (Prasad et al., 2010; Takhounts et al., 2013), and the injury risk reductions were calculated as the injury risk differences between the baseline restraint and the advanced restraints. A negative sign indicates a decrease in the injury risk from the baseline tests and vice versa.

Generally speaking, compared to the results from the baseline tests, the two advanced restraint designs (advanced-belt only design and the advanced-belt with SCaRAB design) both reduced the injury measures for all the ATDs under all 4 crash conditions. The only exceptions are all associated with the THOR 50th.

Both advanced restraint systems reduced the injury risks from the baseline tests substantially in 6 YO, 5th, and 95th ATDs regardless of the injury measure. However, for the THOR 50th with the advanced belt only design, the injury risks based on HIC and chest deflection increased from the baseline tests; and with the advanced belt and SCaRAB design, the injury risks based on chest deflection also increased slightly from the baseline tests. Because the injury risks derived from the neck compression were near zero in the baseline tests, the injury risk reductions based on neck compression were also near zero. The high HIC values in the THOR 50th with the advanced belt only design and under the severe crash pulse were due to a head-to-knee contact, which did not occur in the baseline tests. Because among the 4 chest deflection measures on the THOR 50th, the maximal chest deflection always occurred at the lower chest near the buckle point, and the load limiters could only reduce the chest deflections at the upper chest but not the lower chest region, THOR 50th chest injury risks cannot be effectively reduced by the load limiters in the current test scenarios. In contrast, H-III 6 YO, 5th, and 95th ATDs measured the chest deflection only at the center of the sternum, thus load limiters effectively reduced their chest injury risks in the tests.

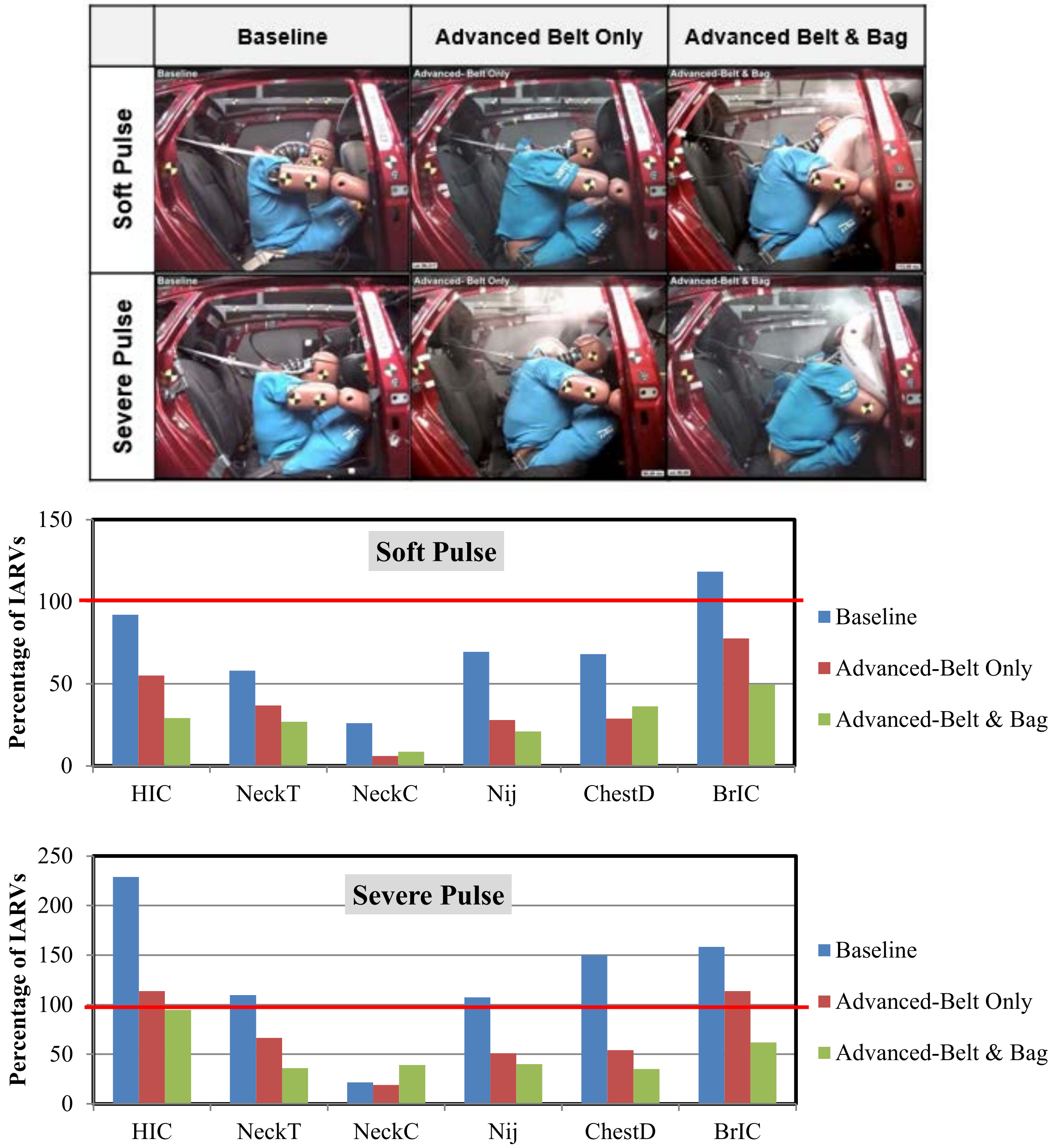

Figure 18. 95th ATD kinematics and injury measures with 3 restraints under 2 crash pulses
Images for left passenger were all mirrored, and red lines represent 100% of IARVs.

Table 10. Injury risk changes by using two optimized advanced restraints

ATD	Pulse	Restraint	HIC	Neck T	Neck C	Nij	Chest D	BrIC
H-III 6 YO	Soft	Belt Only	-7.90%	-95.60%	-2.10%	-21.40%	-4.00%	-57.30%
		Belt & Bag	-7.90%	-98.90%	-2.10%	-24.40%	-8.90%	-69.90%
	Severe	Belt Only	-23.50%	-14.70%	0.00%	-55.70%	-38.60%	-40.30%
		Belt & Bag	-21.70%	-99.50%	0.00%	-59.70%	-63.80%	-50.50%
H-III 5th	Soft	Belt Only	-9.90%	-17.10%	-0.10%	-11.30%	-12.60%	-56.20%
		Belt & Bag	-9.90%	-17.30%	-0.10%	-12.70%	-11.90%	-62.90%
	Severe	Belt Only	-43.30%	-74.70%	0.00%	-20.70%	-29.60%	-69.80%
		Belt & Bag	-46.30%	-80.60%	0.10%	-29.30%	-37.90%	-78.80%
THOR 50th	Soft	Belt Only	-4.70%	-73.70%	0.00%	-	1.90%	-44.30%
		Belt & Bag	-5.30%	-84.10%	0.00%	-	2.50%	-55.40%
	Severe	Belt Only	20.50%	-2.40%	0.00%	-	0.60%	-25.20%
		Belt & Bag	-28.60%	-99.90%	0.00%	-	0.60%	-40.70%
H-III 95th	Soft	Belt Only	-7.00%	-0.40%	0.00%	-7.10%	-14.40%	-38.90%
		Belt & Bag	-9.00%	-0.50%	0.00%	-7.80%	-13.50%	-58.70%
	Severe	Belt Only	-31.30%	-45.10%	0.00%	-14.90%	-83.00%	-28.90%
		Belt & Bag	-36.30%	-46.20%	0.00%	-16.70%	-88.20%	-75.90%
Mean	**Soft**	**Belt Only**	**-7.38%**	**-46.70%**	**-0.55%**	**-13.27%**	**-7.28%**	**-49.18%**
		Belt & Bag	**-8.03%**	**-50.20%**	**-0.55%**	**-14.97%**	**-7.95%**	**-61.73%**
	Severe	**Belt Only**	**-19.40%**	**-34.23%**	**0.00%**	**-30.43%**	**-37.65%**	**-41.05%**
		Belt & Bag	**-33.23%**	**-81.55%**	**0.03%**	**-35.23%**	**-47.33%**	**-61.48%**

DISCUSSION

Advanced Restraint Technologies

In this study evaluating frontal impacts with two crash pulses, we found that advanced restraints generally reduced the injury measures for rear seat occupants. Pre-tensioners engaged the ATDs earlier and reduced the chest deflections and head excursions. Although it is difficult to evaluate the effect of the DLT in this study, in general it can help limit pelvis excursion and reduce chest deflection. With a seat belt only system, different limits have to be set for the load limiter for different ATDs so that they can help reduce the chest injury but at the same time help prevent head-to-front-seat contact. These findings are widely consistent to the previous studies on rear seat occupant protection (Forman et al., 2009; Forman et al., 2008; Kent et al., 2007).

This study introduced a variety of new restraint designs for rear seat occupant protection. Our test results showed that the inflatable belt tightened the belt quickly and had similar effects as those from a retractor pre-tensioner. However, the effect of inflatable belt on spreading the load on the chest was not clear, likely due to the fact that the H-III ATDs only measure the chest deflection at a single point. The 4-point belt showed slightly better results than those from the 3-point belt and inflatable belt in terms of the injury measures for the H-III 5th ATD, but it did not reduce the chest deflections compared to the 3-point belt with pre-tensioner(s) and load limiter. Other airbag concepts, such as the BiR and SCaRAB, allowed further reduction of the retractor torsion bar diameter in the seat belts (from 10 mm to 8 mm in the current study) without a hard head contact to the front seat, so that the shoulder belt load and the chest deflection can be reduced from a 3-point belt only design. The SCaRAB design showed great potential because it can adapt to the space between the occupant and the front seat back.

Submarining

Booster seats were used in the second and final series of sled tests with advanced restraints for the 6 YO ATD, although they were not used in the first baseline sled series. Because the booster seats changed the ATD seating posture and belt fit, the kinematic differences of the 6 YO ATD between the two sled series and the baseline series are likely due in part to the boosters, not necessarily the advanced restraints. Without a booster, the initial slouching posture of the 6 YO ATD would likely induce submarining even with the advanced restraints. Previous computational studies (Hu et al., 2013a; Hu et al., 2013b) have shown that reducing the length of the seat cushion may be a possible solution to reduce the submarining risk for the 6 YO without boosters. However, a short seat cushion may compromise the protection to adult occupants and infants in child seats (Hu et al., 2013a). Further investigations are necessary to determine the best ways to reduce submarining risks for children smaller than adults who sit on the vehicle seat without a booster. Furthermore, combinations of seat belt and seat designs should be explored to reduce the likelihood of submarining risks for rear seated adult occupants as well.

In this study, anchor and/or buckle pre-tensioner(s) were used in some of the tests in the second sled series. The current H-III ATDs cannot be used to assess whether such features are likely to cause abdominal injuries, especially for older children. To fully evaluate those possible injuries, ATDs with a modified abdomen (Hu et al., 2012a) or computational human models would be needed.

Design Optimization for Rear Seat Restraint System

The major challenge of the design optimization was to meet all the design constraints, that is, to make sure that all the injury measures of all the ATDs were below the IARVs. The 3-point belt-only designs only met these constraints under the soft crash pulse; no belt-only design met all injury measure constraints under the severe crash pulse. This finding suggests that airbags may be needed to provide added protection for rear seat occupants when the crash is severe.

Because no head-to-front-seat contact occurred in any of the baseline tests, the head injury measures (HIC and BrIC) and neck injury measures (neckC, neckT, and Nij) were mainly induced by the whipping of the head, while the chest deflections were mainly induced by the seat belt loading. To reduce all the injury measures, pre-tensioners were necessary to engage the seat belt to the occupant earlier, and a load limiter was necessary to reduce the load to the chest, which had the side effect of allowing the head to travel further forward. However, such kinematics increased the risk of head contact to the back of the front seat, violating the head excursion constraint. As a result, only relatively high load limits could be applied to ensure that no head-to-front-seat contact occurred, but such high load limits may have caused the head and neck injury measures to exceed the IARVs. Under the soft crash pulse, a relatively low load limit could be chosen without causing any head-to-front-seat contact and ensure that the head and neck injury measures are below the IARVs. However, under the severe crash pulse, the conflicting effects between the chest deflection and the head and neck injury measures prevented any designs with 3-point belt only to meet all the design constraints.

With the introduction of airbag designs (BiR or SCaRAB), the head and neck injury measures were caused by the occupant-to-airbag contact. Therefore, with airbags which are designed properly, the head and neck injury measures can be potentially reduced below those without an airbag. In that case, the 3-point belt load limit can be reduced without worrying about a hard head contact. Consequently, the airbag design has the potential of reducing not only the head and neck injury measures but also the chest deflections (indirectly). The simulation results in this study demonstrated that the SCaRAB was effective in ensuring that all the injury measures were below the IARVs for the severe crash pulse.

It should also be noted that all the advanced designs used in the final sled series are not FMVSS No. 209 compliant, because the type 2 seat belt assembly elongation requirement was not considered in this study. It is expected that if FMVSS No. 209 compliance is considered, stiffer seatbelt will be needed, which might result in higher chest deflection and more head whipping motion.

Limitations

In this study, only a single vehicle rear seat compartment based on a compact vehicle was used. Therefore, the findings from this study may not be generalized for all the vehicles. Additional simulations could determine whether the compartment size and belt geometry can affect the advanced restraint design solutions.

In this study, we found that lowering the shoulder belt load limit is not effective in reducing the maximal chest deflection of THOR. This may be a controversial finding, which requires further investigation. The rear-seat compartment size, the belt geometry, the crash pulse, the seat stiffness, the usage of DLT, and many other factors may be associated with this finding. Therefore, it may not be generalized for other crash conditions. This result may also indicate the differences between HIII ATDs and THOR in measuring the relationship between restraint characteristics and injury measures, which also needs further investigation.

CONCLUSION

In this study, three series of frontal-impact sled tests (baseline tests, advanced restraint trial tests, and final tests), MADYMO model validations against a subset of the sled tests, and design optimizations using the validated models were conducted to investigate rear seat occupant protection with 4 Anthropomorphic Test Devices (ATDs) and 2 crash pulses.

The results of the first two sled series demonstrated significant safety issues with the baseline 3-point belt system, showed the significance of crash pulse and occupant size in predicting injury risks, and verified the potential of advanced restraint features for better protecting the rear-seat occupants in frontal crashes. Good correlations between the tests and simulations were achieved through a combination of optimization and manual fine-tuning, as determined by a correlation method. Parametric simulations showed that optimized belt-only designs (3-point belt with pre-tensioner and load limiter) met all of the injury assessment reference values (IARVs) under the soft crash pulse but not the severe crash pulse, while the optimized belt and SCaRAB design met all the IARVs under both the soft and severe crash pulses.

Two physical prototype restraint systems, namely an “advanced-belt only” design and an “advanced-belt and SCaRAB” design, were then tested in the final sled series. With the soft crash pulse, both advanced restraint systems were able to reduce all the injury measures below the IARVs for all four ATDs. Both advanced restraint systems also effectively reduced almost all the injury measures for all ATDs under the severe crash pulse, except for THOR. The design with the advanced-belt and SCaRAB generally provided lower injury measures than those using the advanced belt-only design.

This study highlighted the potential benefit of using advanced seatbelt and airbag systems for rear-seat occupant protection in frontal crashes.

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APPENDIX A: ATD INSTRUMENTATION LIST

Table A1. ATD instrumentation

Body Region	Number of Data Channels		
	Instrumentation	THOR 50th	5th/95th/6 YO
Head	Triax Accelerometer	3	3
	Triax Angular Velocity Sensor	3	3
Neck	Upper Neck Load Cell	6	6
	Lower Neck Load Cell	6	6
	Front Neck Cable Load Cell	1	-
	Rear Neck Cable Load Cell	1	-
	Head Rotation Potentiometer	1	-
Thorax	Left Clavicle Load Cell	4	-
	Right Clavicle Load Cell	4	-
	UL CRUX unit	3	-
	UR CRUX unit	3	-
	LL CRUX unit	3	-
	LR CRUX unit	3	-
	Chest Deflection	-	1
	Triax Accelerometer	3	3
Lower Abdomen	Left DGSP Unit	3	-
	Right DGSP Unit	3	-
Spine	T1 - Triax Accelerometer	3	-
	T12 - Triax Accelerometer	3	-
	T12 - Load Cell	5	5
Pelvis	Left Acetabulum Load Cell	3	-
	Right Acetabulum Load Cell	3	-
	Left Iliac Crest Load Cell	2	2
	Right Iliac Crest Load Cell	2	2
	Triax Accelerometer	3	3
Femur	Left Femur 6-axis Load Cell	6	1
	Right Femur 6-axis Load Cell	6	1

Note: CRUX is the chest deflection instrumentation, and DGSP is the lower abdomen deflection instrumentation

APPENDIX B: DESIGN SPECIFICATIONS FOR ADVANCED RESTRAINTS

Design	Specifications
CLL/PLL	The 8, 9.5, 10, and 10.5 mm CLLs are approximately equivalent to 1.8, 3, 3.6, and 4.2 kN load limiters. The PLL starts increasing the load limit (up to 3kN additional force) when the webbing is pulled out by 175 mm.
Pre-tensioner(s)	The stroke of the buckle pre-tensioner ranges from 15 to 45 mm, while the strokes of the anchor and retractor pre-tensioner range from 40 to 80 mm, depending on the ATD and the number of pre-tensioners used in the test. The retractor pre-tensioner was fired at 10 ms, and the buckle/anchor pre-tensioner was fired at 14 ms.
Inflatable Belt	127 mm diameter
BiR	Inflator output: 500kPa, bag volume: 110 liters, vent diameter 70 mm, 470 dtx nylon uncoated material
SCaRAB	Inflator output: 230kPa, bag volume: 45 liters, vent diameter 25 mm x2, 700 dtx nylon silicon coated material

All airbags were fired at 14 ms.

APPENDIX C: MODEL VALIDATION RESULTS

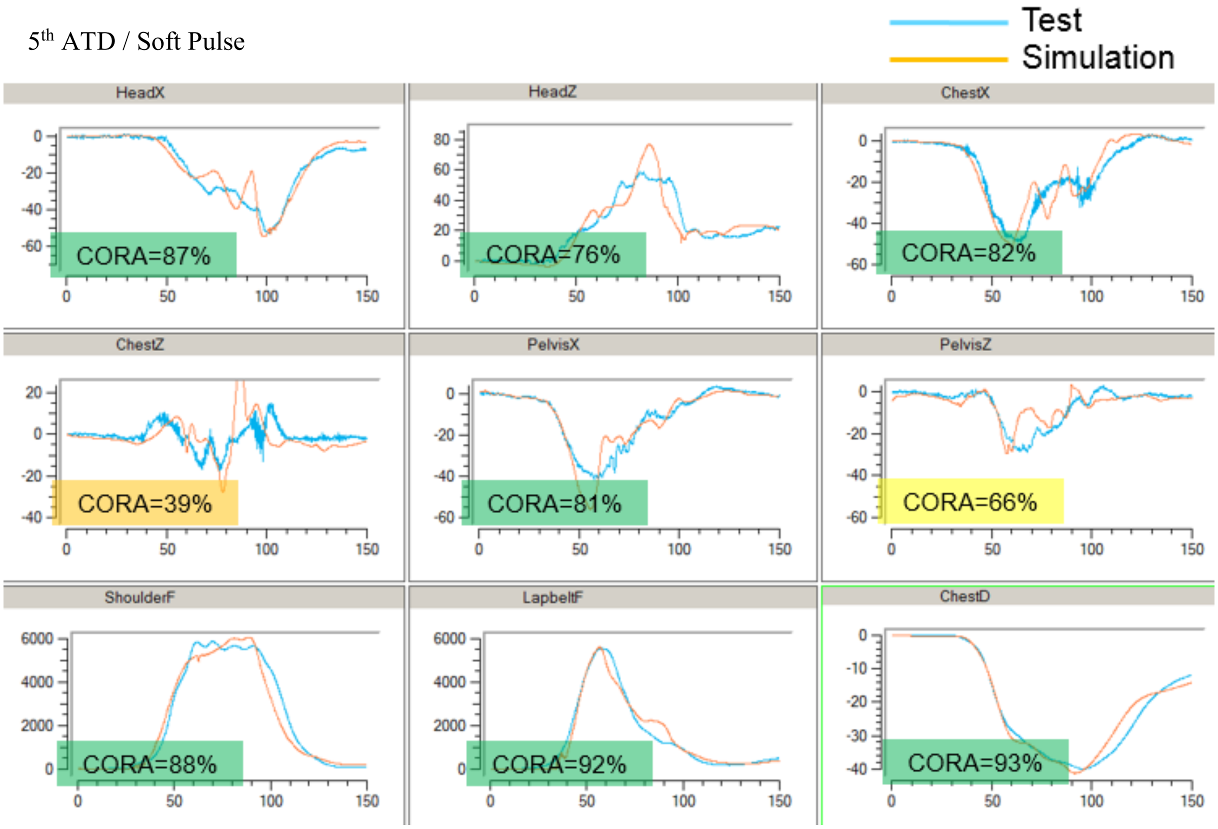
Table B1: CORA results for all the model validations against baseline tests

Test #	ATD	HeadX	HeadZ	ChestX	ChestZ	ChestD	PelvisX	PelvisZ	ShoulderF	LapF
01	95th	81.8%	75.5%	86.3%	55.7%	98.0%	-	61.1%	93.4%	91.1%
01	6 YO	75.5%	71.6%	73.4%	67.2%	62.0%	58.4%	67.4%	69.4%	60.1%
02	95th	89.1%	89.4%	67.5%	46.6%	-	64.5%	81.0%	91.4%	63.0%
02	6 YO	-	72.6%	80.9%	56.2%	73.8%	56.7%	61.6%	80.5%	65.8%
03	6 YO	-	63.6%	72.3%	63.4%	69.0%	33.3%	45.6%	76.6%	61.4%
03	95th	93.8%	86.3%	89.3%	55.6%	61.3%	53.7%	88.2%	80.1%	74.6%
04	6 YO	-	65.5%	76.3%	62.9%	77.3%	53.5%	62.0%	73.7%	62.4%
04	95th	86.8%	76.2%	86.7%	57.4%	-	62.3%	80.4%	74.1%	82.8%
05	THOR	87.5%	80.2%	86.0%	55.1%	46.4%	76.8%	34.9%	93.9%	86.8%
05	5th	86.3%	76.1%	82.8%	37.6%	98.8%	81.7%	65.6%	87.6%	93.4%
06	THOR	82.7%	73.4%	69.4%	54.5%	45.2%	82.7%	36.0%	73.5%	76.9%
06	5th	69.8%	71.6%	69.0%	40.0%	92.2%	49.6%	67.8%	87.5%	50.2%
07	5th	84.0%	81.5%	81.6%	42.2%	80.0%	82.4%	59.1%	93.5%	91.2%
07	THOR	60.0%	72.7%	83.7%	48.2%	48.7%	66.1%	35.3%	88.0%	80.1%
08	5th	64.1%	87.3%	81.1%	50.3%	95.0%	-	56.5%	90.1%	86.1%
08	THOR	56.3%	65.8%	69.0%	-	47.3%	61.3%	38.9%	71.3%	78.8%

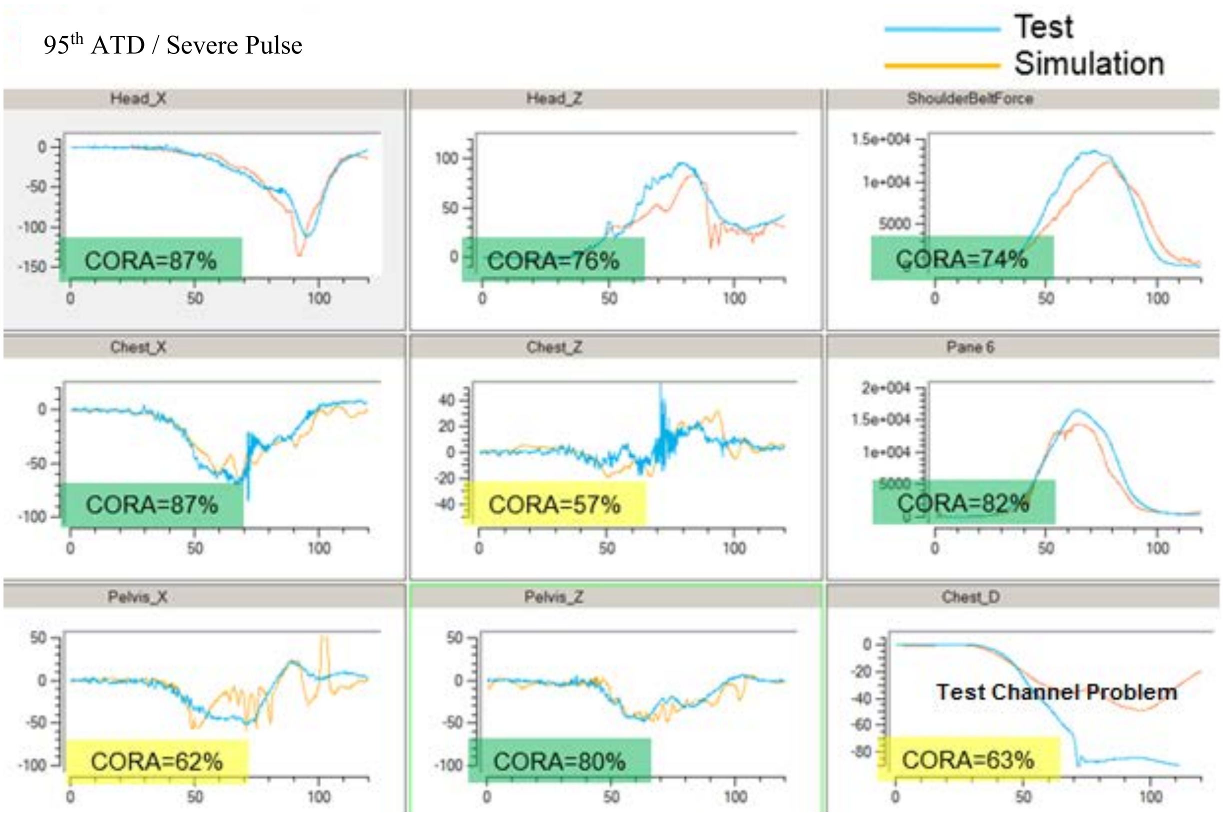
"-" indicates that the channel was lost or had problem
Green: CORA>=70%, Good
Yellow: 50%<=CORA<70%, Marginal
Orange: 25%<=CORA<50%, Poor

Examples of model validation against baseline sled tests

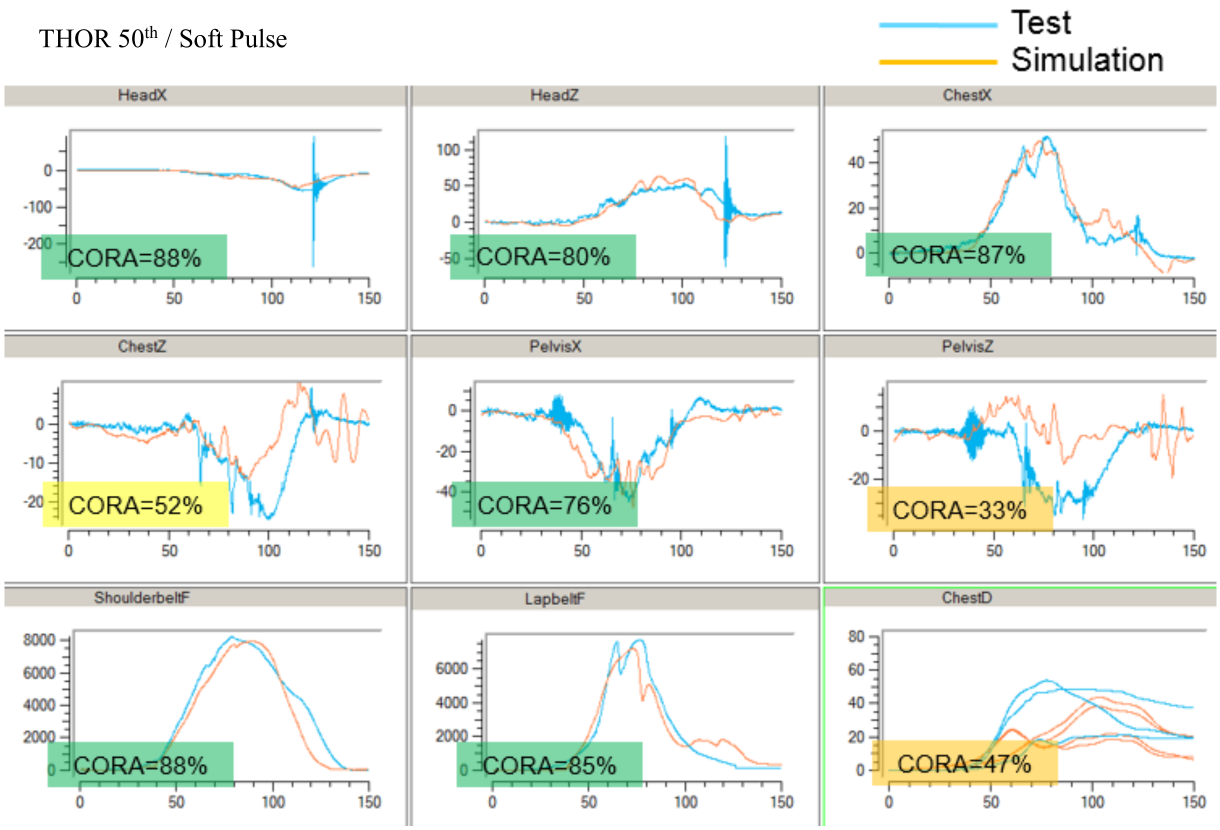
5th ATD / Soft Pulse



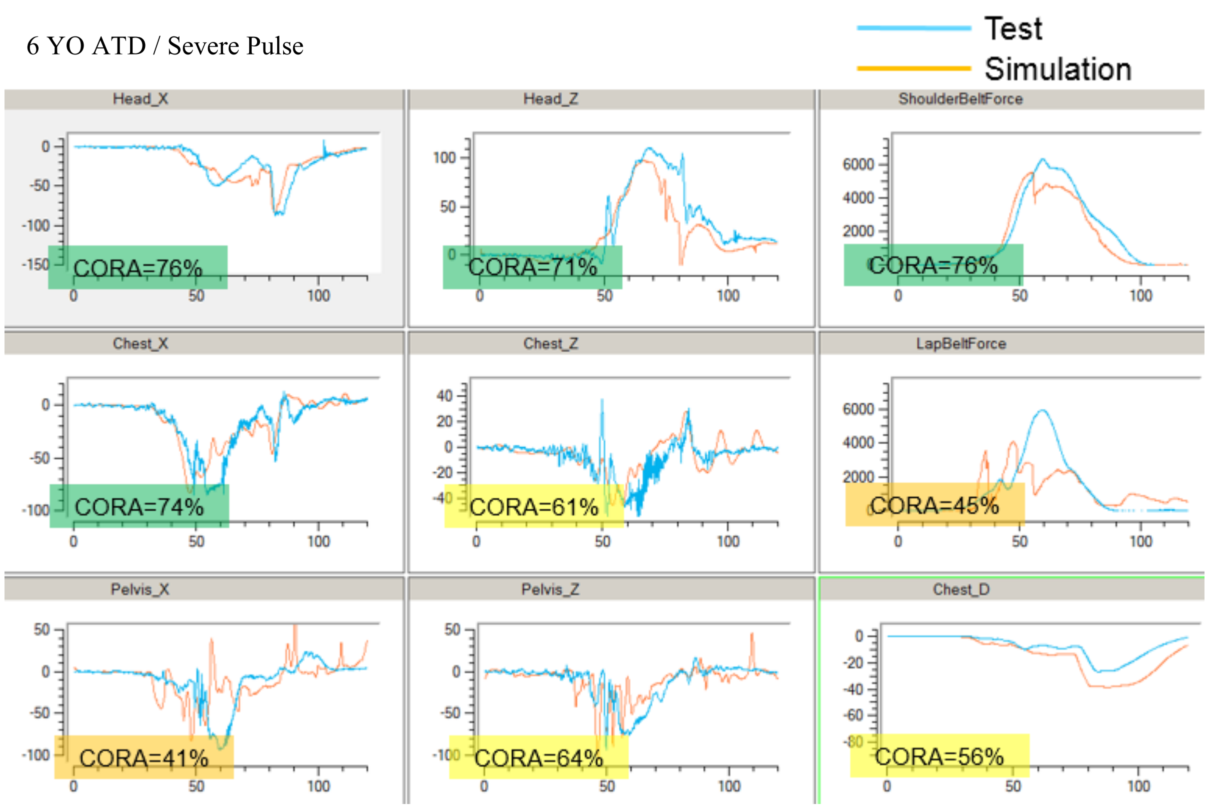
95th ATD / Severe Pulse



THOR 50th / Soft Pulse

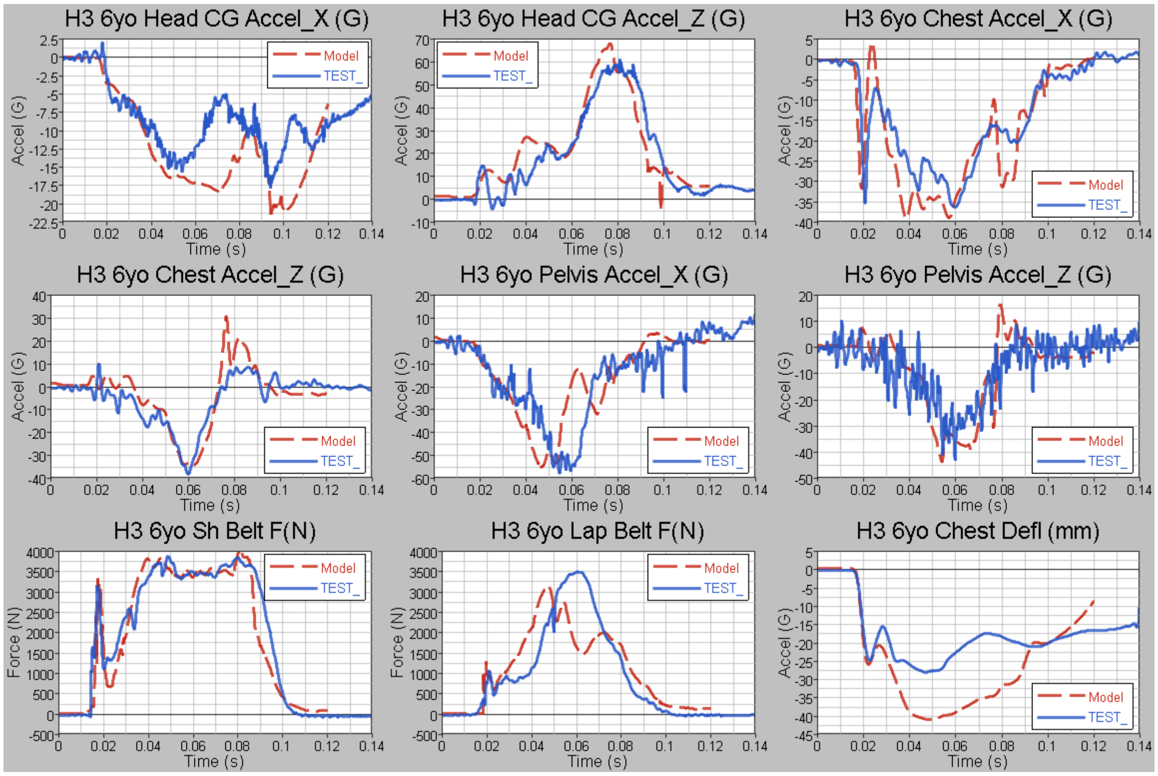


6 YO ATD / Severe Pulse

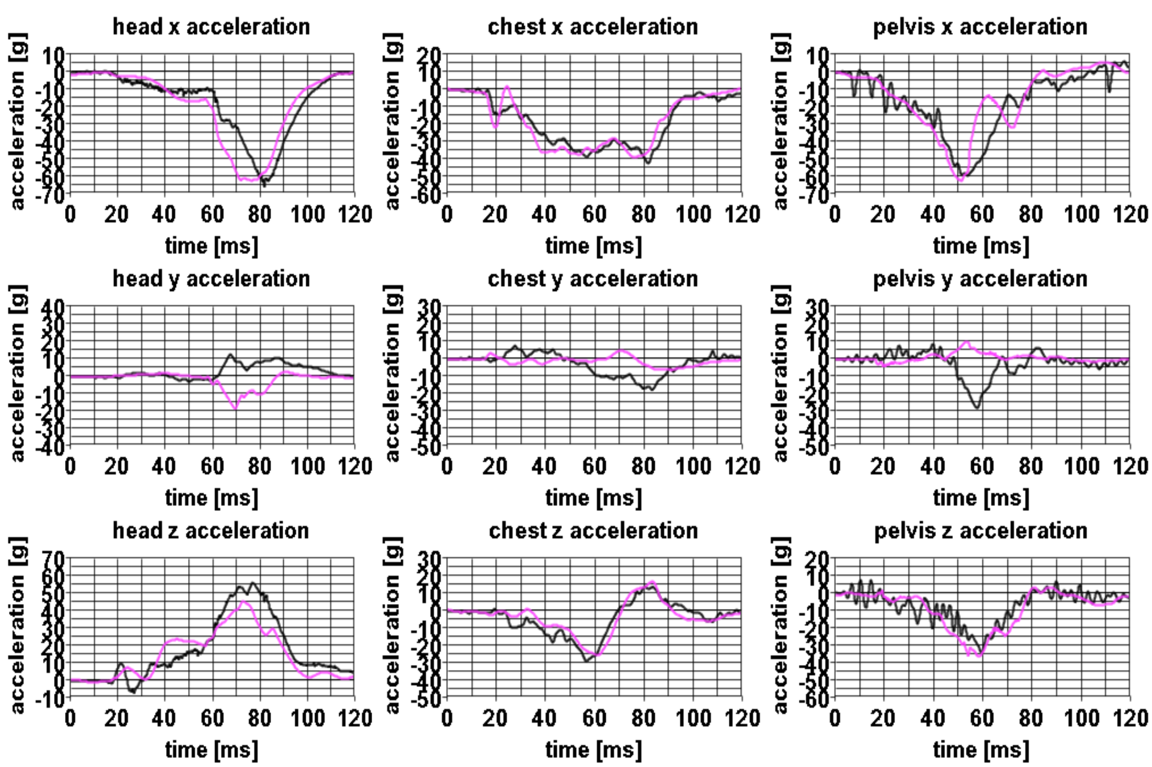


Examples of Model Validation against Sled Tests with Advanced Restraints

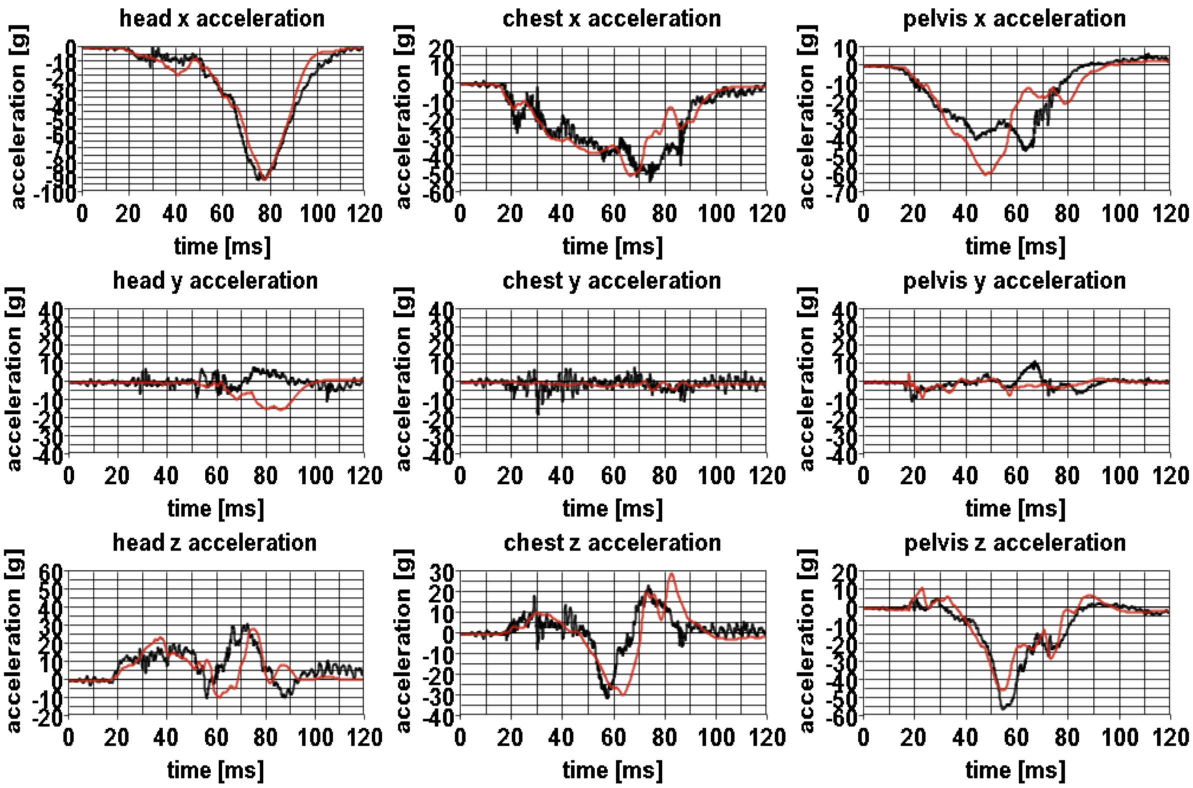
6 YO 3-point Belt



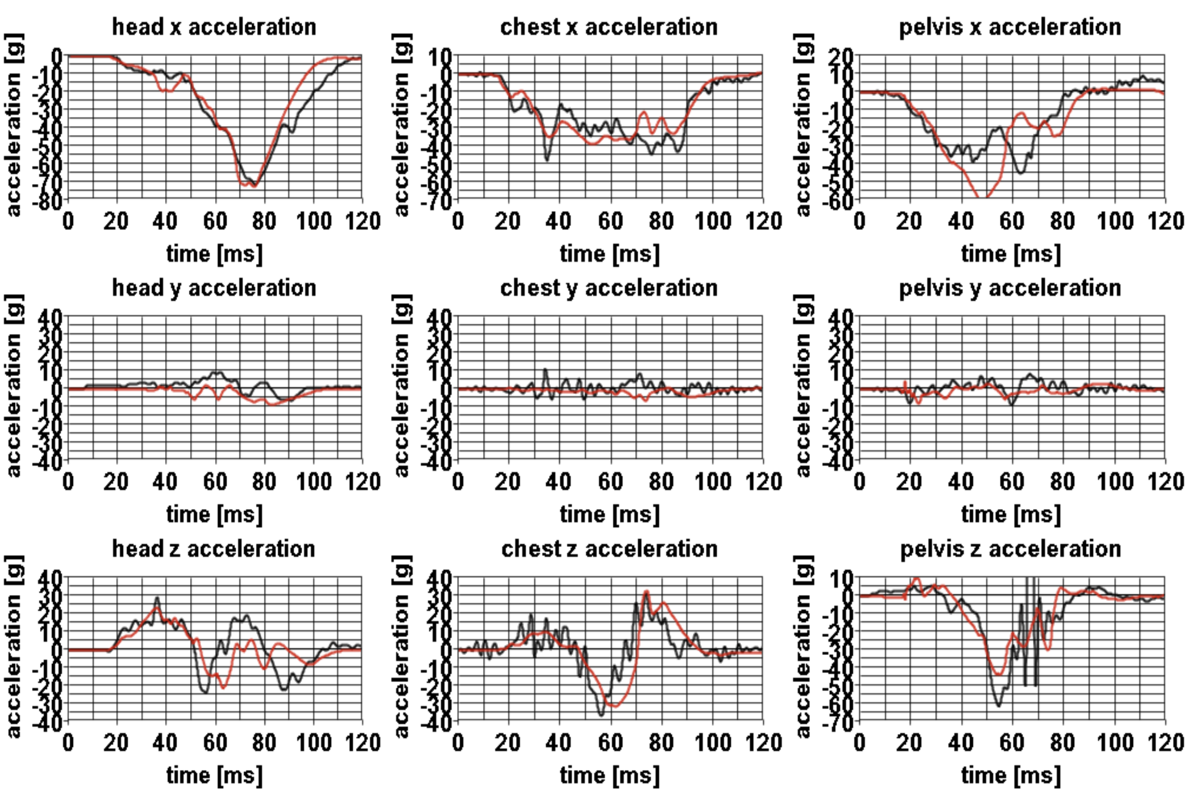
6 YO BiR



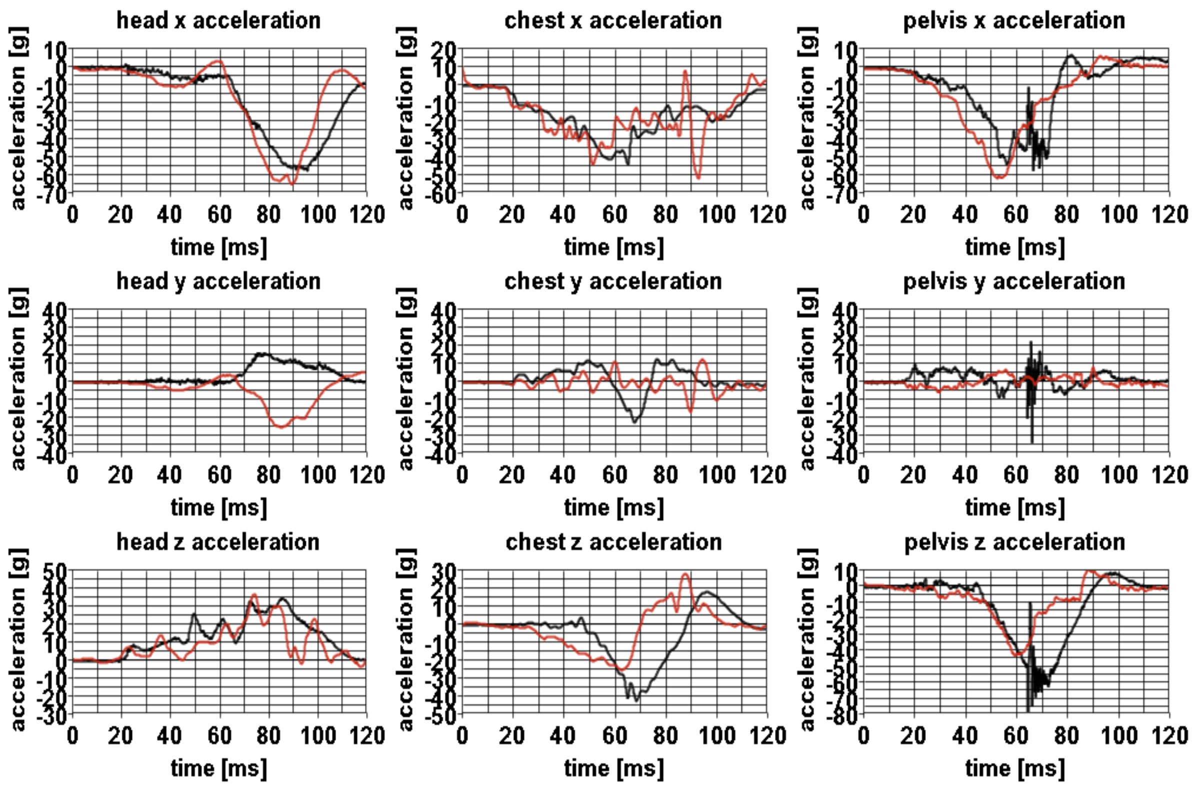
5th ATD BiR



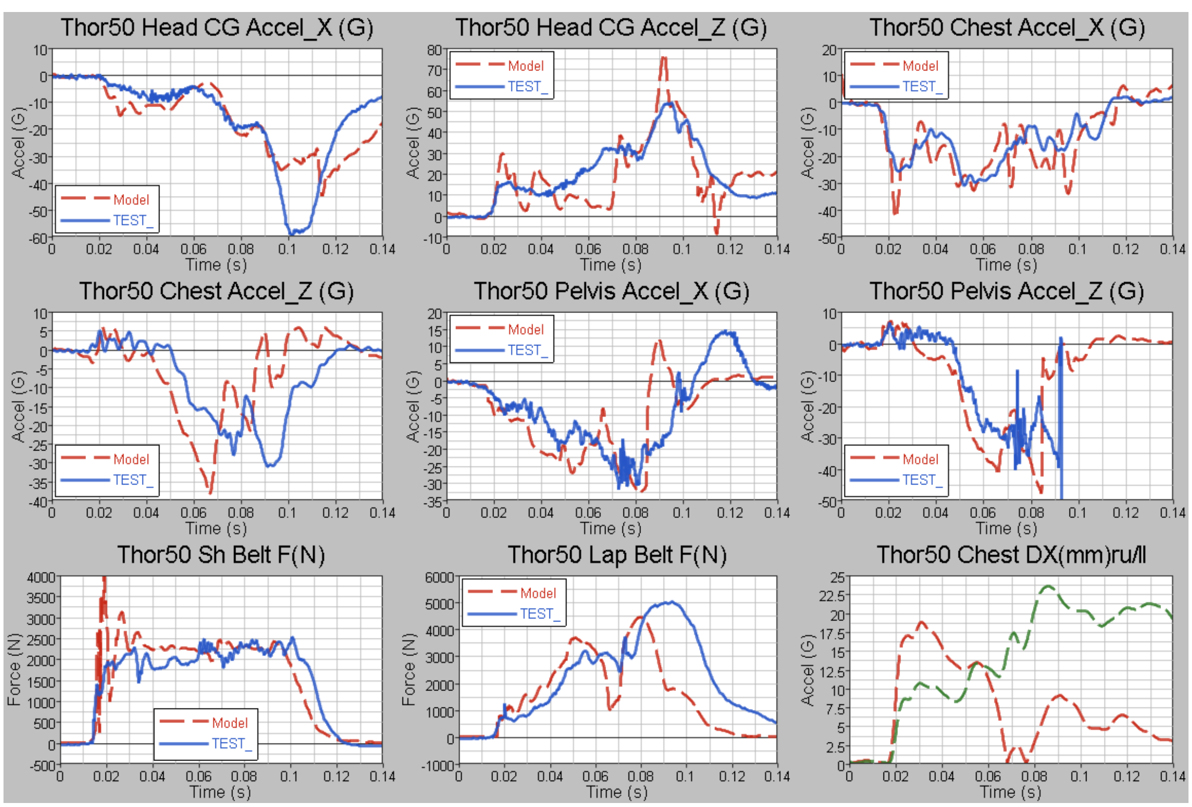
5th ATD SCaRAB



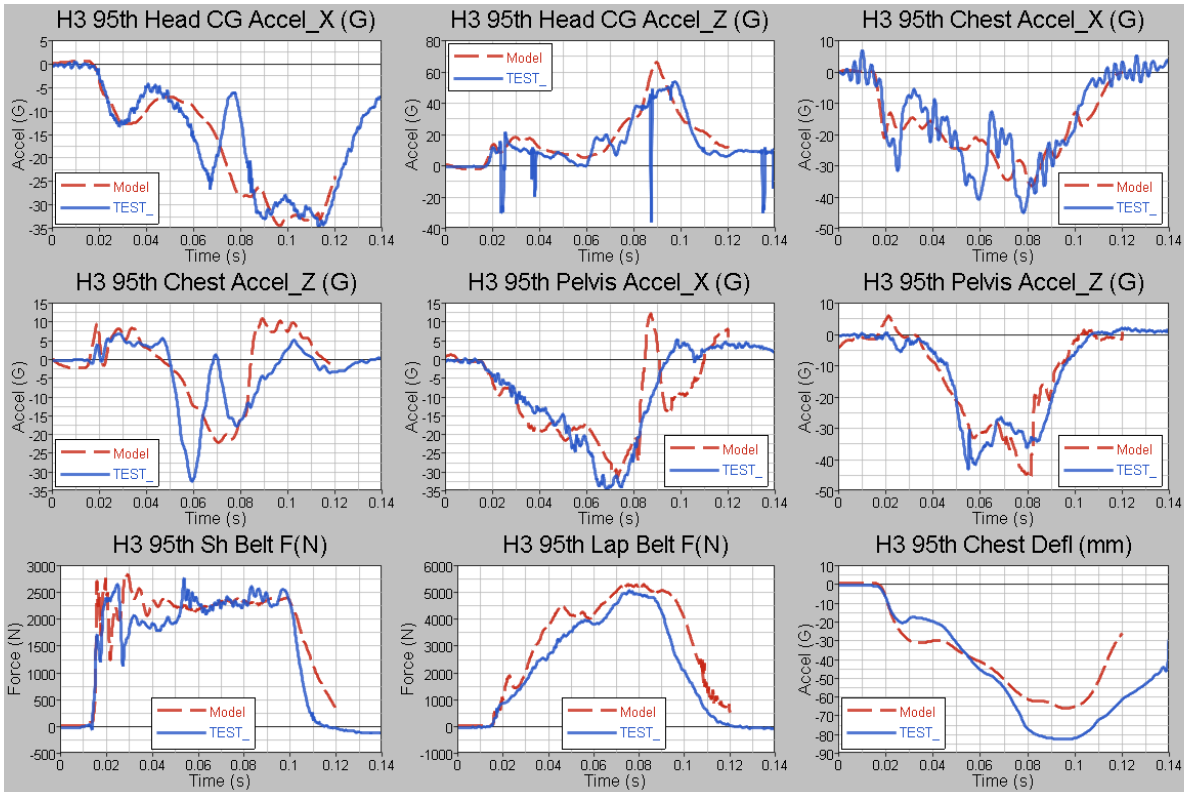
THOR 50th SCaRAB



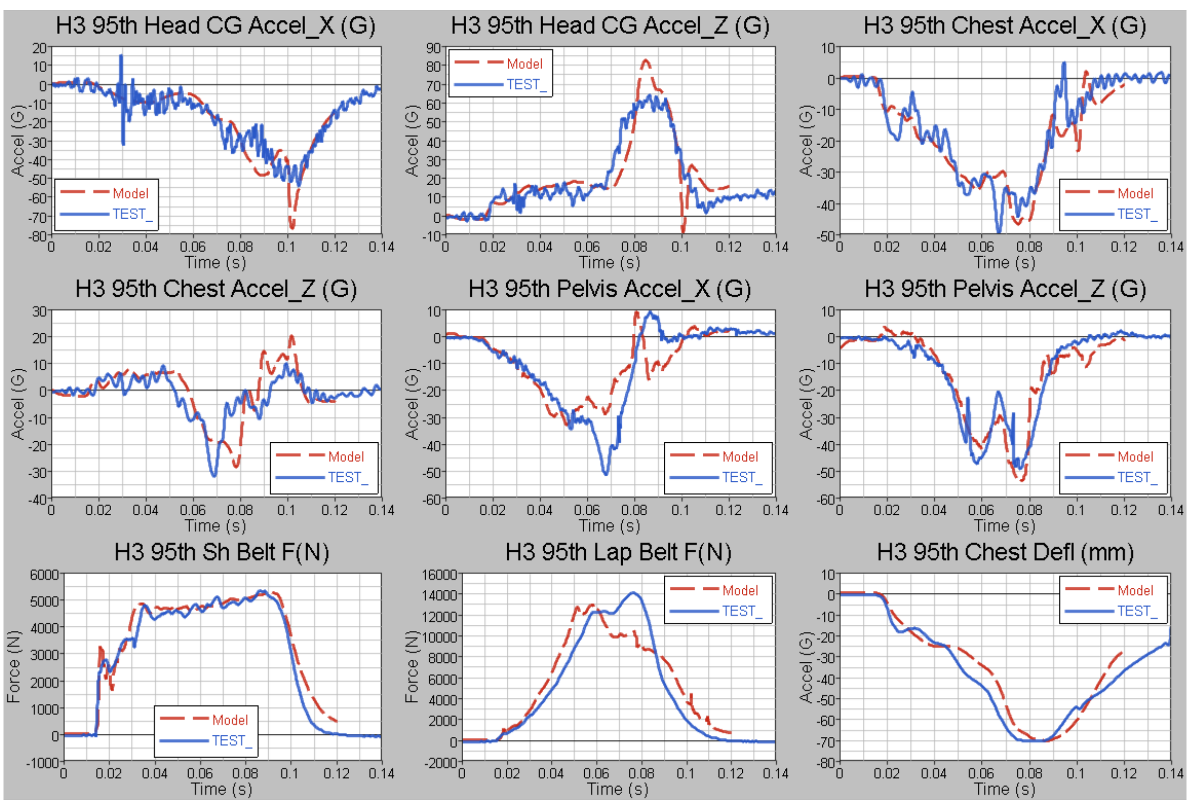
THOR 50th 4-point Belt



95th ATD 4-point Belt



95th ATD 3-point Belt



APPENDIX D: BASELINE AND FINAL TEST RESULTS

All the injury measures are reported as the percentage of associated IARVs.

Red>IARV, IARV>=Orange>80% IARV, 80% IARV>=Yellow>60% IARV, 60% IARV>=white

Table D1. Baseline test results

Test #		ATD	Condition		Head		Neck			Chest		Sub-marine	Belt Force (kN)	
Series #	ID		Pos.	Pulse	HIC	BrIC	NeckT	NeckC	N_{ij}	ChestG	ChestD		Sh.	Lap
13-05-0159	01	95^{th}	Left	Soft	83	103	51	29	81	77	64	No	8.9	8.6
13-05-0159	02	95^{th}	Left	Severe	279	170	149	27	209	149	150	No	12.6	13.9
13-05-0159	03	95^{th}	Right	Soft	101	135	57	18	104	80	73	No	9.7	11.7
13-05-0159	04	95^{th}	Right	Severe	237	161	83	30	151	119	150	No	13.5	16.5
13-05-0159	19	THOR	Right	Soft	106	82	63	27	55	76	86	Yes	8.1	7.1
13-05-0159	20	THOR	Right	Severe	306	108	90	99	68	149	114	Yes	10.6	8.3
13-05-0159	05	THOR	Left	Soft	73	108	63	16	56	85	86	Yes (Right)	8.2	7.8
13-05-0159	06	THOR	Left	Severe	130	130	195	33	-	121	108	Yes	11.9	9.5
13-05-0159	05	5^{th}	Right	Soft	76	130	96	44	93	81	77	Yes (Left)	5.8	5.6
13-05-0159	06	5^{th}	Right	Severe	206	153	125	39	149	115	98	Yes	8.5	8.1
13-05-0159	07	5^{th}	Left	Soft	114	123	95	50	92	80	70	No	6.4	5.2
13-05-0159	08	5^{th}	Left	Severe	281	163	126	13	126	128	88	Yes	8.2	8.7
13-05-0159	01	6YO	Right	Soft	84	139	222	36	129	82	51	Yes	4.1	2.9
13-05-0159	02	6YO	Right	Severe	231	201	418	90	239	134	72	Yes	6.5	5.9
13-05-0159	03	6YO	Left	Soft	131	156	341	43	208	89	66	Yes	4.6	3.9
13-05-0159	04	6YO	Left	Severe	280	216	483	77	276	116	94	Yes	6.2	6.2

Table D2. Final test results

Test #		ATD	Condition		Head		Neck				Chest		Sub-marine	Belt Force (kN)	
Series #	ID		Pos.	Pulse	HIC	BrIC	NeckT	NeckC	Nij/ NeckF (THOR)	NeckE (THOR)	ChestG	ChestD		Sh.	Lap
15-02-0045	03	95^{th}	Left	Severe	95	62	36	39	40		97	35	No	4.3	10.2
15-02-0045	04	95^{th}	Right	Severe	114	114	67	19	51		159	54	No	5.0	13.0
15-02-0045	05	95^{th}	Right	Soft	29	49	27	9	21		82	36	No	4.2	8.2
15-02-0045	06	95^{th}	Left	Soft	55	73	37	11	28		78	29	No	4.7	7.5
15-02-0045	07	THOR	Left	Soft	44	74	93	82	37	43	76	60	No	4.5	6.1
15-02-0045	08	THOR	Left	Severe	73	99	41	16	30	26	100	68	No	4.9	7.8
15-02-0045	09	THOR	Right	Soft	35	59	80	9	21	71	112	61	No	3.5	8.8
15-02-0045	10	THOR	Right	Severe	266	115	148	55	36	134	117	83	No	5.4	11.5
15-02-0045	07	5^{th}	Right	Soft	17	54	26	14	32		51	58	No	4.4	2.7
15-02-0045	08	5^{th}	Right	Severe	78	70	83	15	81		75	66	No	4.7	5.6
15-02-0045	09	5^{th}	Left	Soft	19	64	49	1	42		44	57	No	3.9	2.9
15-02-0045	10	5^{th}	Left	Severe	61	58	28	37	40		80	51	No	4.2	5.9
15-02-0045	02	6 YO	Right	Soft	13	74	32	4	47		51	67	No	2.8	2.9
15-02-0045	03	6 YO	Right	Severe	50	105	129	6	75		83	94	No	4.4	2.9
15-02-0045	04	6 YO	Left	Severe	63	94	57	10	56		88	71	No	2.9	3.0
15-02-0045	05	6 YO	Left	Soft	19	88	77	24	63		45	73	No	4.0	1.7