U.S. Department
of Transportation

National Highway
Traffic Safety
Administration

NHTSA

DOT HS 812 248 March 2016

Rear Seat Restraint Optimization Considering The Needs From a Diverse Population

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Suggested APA Format Citation:

Hu, J., Rupp, J., Reed, M. P., Fischer, K., Lange, P., & Adler, A. (2016, March). *Rear seat restraint optimization considering the needs from a diverse population* (Report No. DOT HS 812 248). Washington, DC: National Highway Traffic Safety Administration.

Technical Report Documentation Page

1. Report No. DOT HS 812 248	2. Government Accession No.	3. Recipients's Catalog No.
4. Title and Subtitle Rear Seat Restraint Optimization Considering the Needs From a Diverse Population		5. Report Date March 2016
		6. Performing Organization Code 071638
7. Authors Jingwen Hu, Jonathan Rupp, Matthew P. Reed, Kurt Fischer, Paul Lange, Angelo Adler		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Michigan Transportation Research Institute 2901 Baxter Rd., Ann Arbor MI 48109 TRW Vehicle Safety Inc. 4505 26 Mile Rd, Washington, MI 48094		10. Work Unit No. (TRAIS)n code
		11. Contract of Grant No. DTNH22-12-C-00272
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE. Washington, DC 20590		13. Type of Report and Period Covered Final, October 2012-April 2015
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

In this study, three series of sled tests (baseline tests, advanced restraint trial tests, and a final series of tests), two series of model validations (against each of the first two series of sled tests), and design optimizations using the validated computational models were conducted to investigate rear seat occupant protection with four anthropomorphic test devices (ATDs) (Hyrbrid-III[(H-III] 6-Year-Old (YO)/H-III 5th percentile female/Test Device for Human Occupant Restraint (THOR) 50th percentile male/H-III 95th percentile male), 2 crash pulses (soft and severe), 2 impact angles (0 deg and 15 deg), and 2 front seat locations (driver and passenger).

In the baseline tests, crash pulse and occupant size were two dominating parameters affecting occupant injury risks, while impact angle and front seat location did not have statistically significant effects. The second series of sled tests and design optimizations showed that advanced belt-only designs (3-point belt with pretensioner and load limiter) could meet all of the injury assessment reference value (IARV) constraints under the soft crash pulse, but an advanced belt with a self-conforming rear seat air bag (called SCaRAB) was needed to meet all the IARV constraints under the severe crash pulse.

An “advanced-belt-only” design and an “advanced-belt-and-SCaRAB” design were used in the final sled series. With the soft crash pulse, both advanced restraint systems were able to reduce all the injury measures below the IARV constraints for all four ATDs. Both advanced restraint systems also substantially reduced almost all the injury measures for the H-III 6YO, 5th, and 95th ATDs under the severe crash pulse. The design with the SCaRAB generally provided lower injury measures than those using the advanced belt-only design. However, neither of the advanced restraints reduced the chest deflections for the THOR 50th, because the maximal chest deflection of the THOR 50th always occurred at the lower chest location close to the buckle, which is not sensitive to the load limiter in the crash scenarios of the current study.

17. Key Words rear seat, crash test, crash simulation, restraint system, design optimization, seat belt, air bag, head injury, chest injury		18. Distribution Statement Document is available to the public from the National Technical Information Service www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 76	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Acknowledgments

This study was funded by National Highway Transportation Safety Administration under Contract No: DTNH22-12-C-00272. The authors would like to thank James Saunders, Stephen Summers, Dan Parent, and Matthew Craig from NHTSA for their tremendous support of this project.

TABLE OF CONTENTS

List of Figures

List of Tables

Executive Summary

The objective of this study was to design, optimize, and fabricate prototype advanced restraint systems to provide protection for rear seat occupants of a wide range of sizes in frontal crashes with different crash pulses and impact directions.

In the first phase of this study, 16 baseline sled tests were conducted with four anthropomorphic test devices (ATDs), the Hybrid-III 6-Year-Old (HIII6YO or just 6YO), the H-III 5th percentile female, the Test Device for Human Occupant Restraint (THOR) 50th percentile male, and the H-III 95th percentile male; two crash pulses (soft/severe), two crash angles (0 deg/15 deg), and two front seat locations (driver/passenger). The two pulses selected in this study were based on a comparison of 2011-2012 B-Segment NCAP crash pulses from 25 small cars. The test matrix for this set of sled tests can be found in Table 1. Crash pulse and occupant size were two dominating parameters affecting occupant injury risks, while impact angle and front seat location (occupant side) did not have statistically significant effects.

Because field data shows that the chest is the most commonly injured body region for rear-seated adult occupants, an attempt was made to reduce the chest loading while managing head excursion. This was done using a second series of sled tests conducted using prototype countermeasures including 3-point belts with pretensioner and load limiter, 4-point belts, dynamic locking tongue (DLT), inflatable belts, the “bag-in-roof” (BiR) concept, and the self-conforming rear seat air bag (called SCaRAB) concept. The test matrix for this series can be found in Table 7. In this series, only the most severe testing condition (0 deg and severe pulse) in the first sled series was used to focus on the most extreme cases. Reductions in occupant loading were shown with these advanced restraint systems, especially the air bag features.

The results of the two sled series were used to develop and validate a set of MADYMO (MAthematical DYnamic MOdels software package from TASS International Software and Services, Helmond, the Netherlands) models for use in further refinement of countermeasure design. Good correlations between the tests and simulations were achieved through a combination of optimization and manual fine-tuning, as determined by a correlation method. The validated models were then used to perform design optimizations. It was found that advanced-belt-only designs (3-point belt with pretensioner and load limiter) met all of the injury assessment reference value (IARV) constraints under the soft crash pulse but not the severe crash pulse, while the advanced belt and SCaRAB met all the IARV constraints 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 third and final sled series. The matrix for these 16 tests can be found in Table 14. With the soft crash pulse, both advanced restraint systems were able to reduce all the injury measures below the IARV constraints for all four ATDs. Both advanced restraint systems also effectively reduced almost all the injury measures for the 6YO, 5th, and 95th ATDs under the severe crash pulse. The design with the advanced-belt-and-SCaRAB generally provided lower injury measures than those using the advanced-belt-only design. However, neither of the advanced restraints reduced the chest deflections for the THOR 50th, because the maximal chest deflection of THOR 50th always occurred at the lower chest location close to the buckle, which is not sensitive to the load limiter in the crash scenarios of the current study.

1 Introduction

1.1 Rear Seat Occupant Safety

In recent years, advanced restraint technologies have become widely available in front row seating positions, but they are less frequently available in the rear seat environment. Although previous field data analyses have estimated that rear seat occupants are at lower risk of serious injury and fatality than front seat occupants in motor vehicle crashes, some previous studies have also shown that the rear seat's safety advantage may be diminishing, especially for elderly occupants, in newer vehicle models (Kent, Forman, Parent, & Kuppa, 2007; Kuppa et al., 2005; Sahraei, Soudbakhsh, & Digges, 2009; Smith & Cummings 2006).

Kuppa et al. (2005) conducted a double-paired comparison study using FARS data, 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 and older. Smith and Cummings (2006) confirmed the findings from Kuppa's study by a matched-cohort analysis of FARS data and further found that the relative effectiveness of rear seats to mitigate fatality decreased with increased occupant age. They also suggested that when front passenger air bags are present and occupants are belted, putting adults in front and children in back will enhance child safety without sacrificing adult safety.

Kent, Forman, Parent, and Kuppa (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. Similarly, Sahraei, Soudbakhsh, and Digges (2009) also 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. Bilston et al. (2010) conducted a matched-cohort analysis of the NASS-CDS data, and concluded that the safety for front seat occupant occupants has improved over the last decade, to the point where, for occupants older than 15, the front seat is safer than the rear seat. While the benefit of rear-seated children 9 to 15 years old has decreased over time, they are still at lower risk in the rear seat.

1.2 Age Distribution and Injury Pattern of Rear Seat Occupants

The design of a vehicle rear seat compartments for protecting occupants is challenging because of the wide range of occupant 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 harness restraints and older children using belt-positioning booster seats and vehicle belts alone. More than half of the rear seat occupants in motor vehicle crash data (Figure 1) are children under 12, about 40 percent of whom are older children between 6 and 12 years old (Huang & Reed 2006). Previous studies have shown that most U.S. children 6 to 12 are riding without boosters, even if 100 percent compliance with the current booster laws is assumed because booster laws generally only apply to 8 and younger. Because most 6- to 12-year-old children are smaller in body size than adults, the slouched posture that these children typically assume in vehicle seats results in poor belt fit that may significantly increase the risk of submarining (Klinich, Pritz, Beebe,& Welty, 1994; Reed, Ebert-Hamilton, & Schneider, 2005). Trowbridge and Kent (2009) conducted an analysis to quantify the rear seat occupant exposure and found that the annual rear seat travel exposure is similar among children under 12 and teens and adults from 13 to 64 years old (18.9 versus 19.1 billion person-trips), suggesting that child protection, especially for older children 6 to 12 who use vehicle restraints directly, should be considered in rear seat advanced restraint system designs. If we combined these results with the higher injury risk for the elderly population in rear seats than in front seats, *in addition to protecting mid-size male occupants, rear seat advanced restraint system designs should also provide improved protection to occupants of all ages and sizes, such as school-age children and older occupants.*

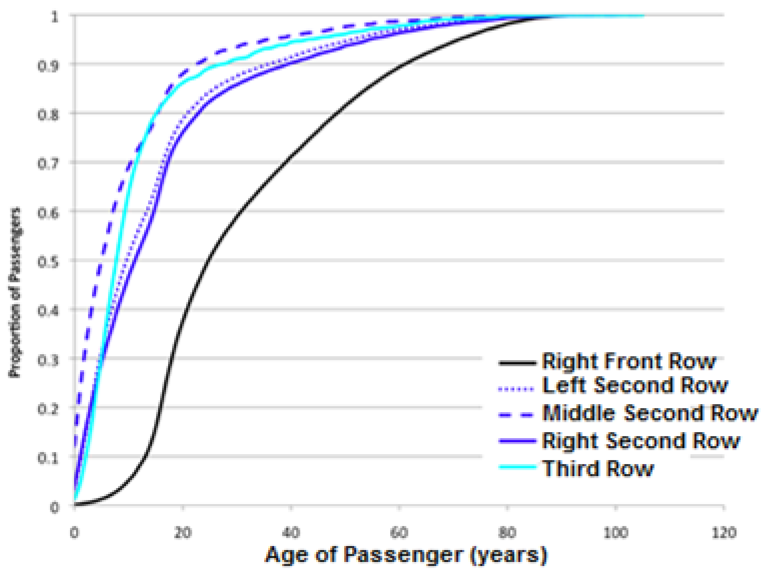

Figure 1: Age distribution of rear seat occupants involved in motor vehicle crashes.

Interestingly, the injury patterns for the rear-seated older children and adult populations are different. For belted children, the most frequently injured body region is the head. 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. 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. 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.

1.3 Previous Studies on Rear Seat Advanced Restraint Systems

Compared with the front seat, relatively few studies have focused on rear seat advanced restraint systems. However, some researchers have performed crash tests and computational simulations to evaluate the feasibility of introducing seat belt features, such as load limiters and pretensioners, for enhancing rear seat occupant protection.

Zellmer, Luhrs, & Bruggemann (1998) used three sled tests to validate a MADYMO ATD model in a rear seat environment. This model was further used to explore the protective effects of load limiters and pretensioners. They found that chest loading was significantly reduced with pretensioners and load limiters, but they also suggested that the optimal load limiter level depends on occupant size and the space available for ride-down.

Kent, Forman, Parent, and Kuppa (2007) conducted a parametric simulation study of rear seat restraint designs to assess chest deflection and head excursion trends for various seatbelt load limits, pretensioner locations and strokes, and impact severities with the H-III 50th and 5th ATD MADYMO models. The results showed that even though there is a tradeoff between chest deflection and head excursion, they can be reduced at the same time with seat belt load limiters and pretensioners even in the absence of an air bag and knee bolster for load sharing.

Forman et al. (2008) performed sled tests with H-III 6YO, 5th percentile female and 50th percentile male ATDs as well as THOR 50th to investigate the protective effects from load limiters and pretensioners for rear seat occupants. They found that load limiters and pretensioners 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 pretensioners can improve the kinematics (increase forward torso rotation) of rear seat occupants with reduced belt load and chest acceleration.

More recently, the University of Michigan Transportation Research Institute (UMTRI) conducted several series of sled tests and computational simulations focusing on optimizing the rear seat and belt geometries for 6- to 12-year-old children, mid-size adults, and infants in rear-facing child restraints (Hu, Reed, & Klinich, 2012; Hu, Wu, Klinich, Reed, Rupp, & Cao, 2013; Hu, Wu, Reed, Klinich, & Cao, 2013). It was found that the optimal belt anchorage locations and seat designs 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. In these studies, rear seat spaces for different vehicles were also quantified to compare the head excursions of older children from 6 to 12 in a range of impact severities and directions. The findings provided a reference for determining the areas and structures that should be padded in the rear seat compartment to reduce head injury risk for older children. However, in these studies, only one crash pulse was used, and advanced restraint features were not investigated.

1.4 Future Trends and Considerations in Rear seat Restraint System Designs

The aging of the U.S. population and the increased use of lightweight vehicles may adversely affect traffic safety (Kent, Henary, & Matsuoka, 2005; Kent, Trowbridge, Lopez-Valdes, Ordoyo, & Segui-Gomez,; NHTSA, 1997). Over the next 20 years, the first trend will result in a growing number of vulnerable occupants, and the second is driven by fleet fuel economy requirements, which may result in stiffer crash pulses due to a smaller crushing zone in front of a small vehicle. Unfortunately, both of these trends tend to increase injury and fatality risks for rear seat occupants. In addition, increased attention on child occupant safety worldwide may also affect the restraint system performance (Durbin, 2011). Therefore, it is important to consider these trends in the rear seat advanced restraint system designs.

Because air bags are generally not available in rear seat environments, the seat belt is by far the most important device for managing the impact energy. While load limiter and pretensioner combinations have demonstrated considerable benefit for rear seat occupant protection, other seat belt technologies available for front seat occupants, such as 4-point belt and inflatable belt, can also be used in the rear seat environment. However, the benefits from those designs for rear seat occupants have not been fully established. Furthermore, rear seat occupant protection largely depends on occupant size and occupant compartment geometry, with the available space varying significantly between vehicles and within the same vehicle depending on front seat position. Even with a frontal impact air bag in the rear seat, its reaction surface may depend on the location of the front seat. Therefore, to achieve a reliable protective effect from rear seat restraints, a good understanding of the rear seat occupant compartment geometry and adaptive features that can be adjusted for a range of occupant size and compartment geometry is necessary.

1.5 Objective and Tasks

The objective of this study was to identify, design, optimize, fabricate, test, and demonstrate prototype advanced restraint systems for protecting rear seat occupants with a range of body sizes and multiple frontal crash conditions. This project established the baseline performance of a non-advanced restraint system and demonstrated the occupant safety improvements offered by the advanced restraint systems.

As shown in Figure 2, five ***Tasks*** were conducted in this study through a partnership between UMTRI and TRW.

Task 1. Establish the baseline performance of a baseline rear seat restraint system using sled tests.

Task 2. Develop and validate computational models against results from the baseline tests.

Task 3. Propose technologies for advanced restraint systems that are suitable for rear seat occupant protection.

Task 4. Develop and validate the computational models for the proposed advanced restraint technologies and combine and optimize these technologies into a single advanced restraint system that minimizes the risk of injuries across the rear seat population.

Task 5. Fabricate and test the proposed advanced restraint systems and demonstrate the occupant safety improvement.

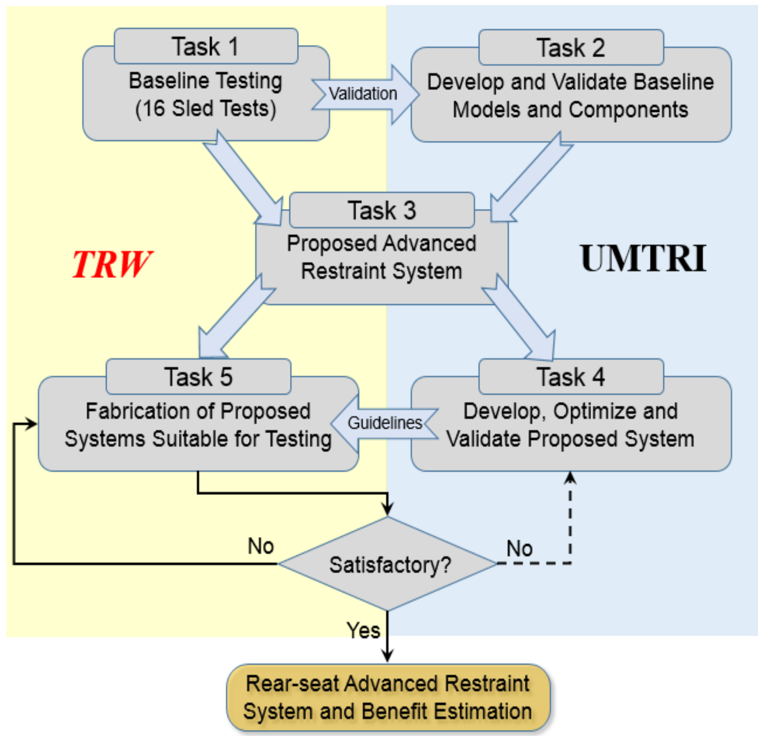

Figure 2: Overall technical schematic for developing advanced rear seat restraint system

2 Baseline testing

2.1 Goal

The goal of the baseline testing was to establish the baseline crash performance of a typical, non-advanced restraint system in a variety of frontal crash scenarios with a variety of occupant sizes.

2.2 Methods

The baseline test series included 16 sled tests (Table 1) with two impact angles (0 deg and 15 deg), two sled pulses (soft and severe), and two ATDs in each test. Considering the increase of light-weight vehicles driven by fleet fuel economy requirements, the sled buck was built to represent a current compact vehicle. Four ATDs, including THOR 50th male, H-III 5th female, 95th male and 6YO ATDs were used. In the 15 deg tests, the sled buck was rotated to the right to simulate a left/driver side impact. A standard rear seat belt system was used in all the tests in the baseline series. These standard rear seat belts do not include any advanced features, such as a pretensioner, load limiter, or dynamic locking tongue (DLT) in the latch plate. A webbing-mounted buckle and a free falling latch plate were used in all the baseline tests, which is consistent with the restraint system used in the selected compact vehicle. In all the baseline 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 ECE R14 anchorage zone. Examples of belt and anchor locations relative to the ATDs in the rear seat are shown in Figure 3a to 3c. 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 as shown in Figure 3d. This allowed for easy replacement if it was deformed during testing. It also helped ensure a more repeatable series. It should be noted that only the larger occupants (50th and 95th) deformed the sheet metal replacement.

Table 1. Baseline sled test matrix

No.	Sled Angle	Sled Pulse	Left Passenger	Right Passenger
01	0	Soft	THOR 50th	H-III 5th
02	0	Severe	THOR 50th	H-III 5th
03	0	Soft	H-III 5th	THOR 50th
04	0	Severe	H-III 5th	THOR 50th
05	0	Soft	H-III 95th	H-III 6YO
06	0	Severe	H-III 95th	H-III 6YO
07	0	Soft	H-III 6YO	H-III 95th
08	0	Severe	H-III 6YO	H-III 95th
09	15 left	Soft	THOR 50th	H-III 5th
10	15 left	Severe	THOR 50th	H-III 5th
11	15 left	Soft	H-III 5th	THOR 50th
12	15 left	Severe	H-III 5th	THOR 50th
13	15 left	Soft	H-III 95th	H-III 6YO
14	15 left	Severe	H-III 95th	H-III 6YO
15	15 left	Soft	H-III 6YO	H-III 95th
16	15 left	Severe	H-III 6YO	H-III 95th

a) THOR 50th on the left side

b) 5th ATD on the right side

c) Buckle location

d) Modified rear seat cushion supporting structure

Figure 3: Belt position relative to the ATDs and modified rear seat cushion supporting structure

The 6YO ATD was positioned based on UMTRI procedure, which allows the knee to bend naturally and in turn induces a slouching posture when used on a seat that is long relative to the ATD thigh. This procedure is based on measured child postures reported by Reed, Ebert-Hamilton, Manary, Klinich, and Schneider (2006). No booster seat was used for the 6YO ATD in this baseline series. However, booster seats were used for the 6YO ATD in all the sled tests with advanced restraint systems, and the baseline conditions with the 6YO ATD using booster seats were also conducted in the final sled series to quantify the effects from booster seat on the occupant injury measures, which will be described in the following sections. All the other sizes of the ATDs were positioned based on the IIHS seating procedure for rear seat occupants (IIHS 2012). For THOR 50th, the lower thoracic pitch mechanism set was in the “slouched” position in all the tests. 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 seat location relative to the knees for each occupant size evaluated. Table 2 shows the front seat location for each ATD and each side of the test buck.

Table 2. Front seat locations in the tests

ATD size	Left		Right	
	Seat Back Angle*	Seat Position (Knee/Seat Offset)	Seat Back Angle*	Knee/Seat Offset
6YO	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.

The crash pulses used in this study are shown in Figure 4. The proposed soft pulse was the "fleet soft" and the proposed severe pulse was the "fleet severe" based on NCAP 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 5, in which OLC++ 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". In 15 deg oblique sled tests, the same pulses were used as those in the pure frontal tests. In addition, during 15 deg oblique sled tests, a diagonally oriented side bar simulating the side door structure was used to better represent occupant-to-door interaction.

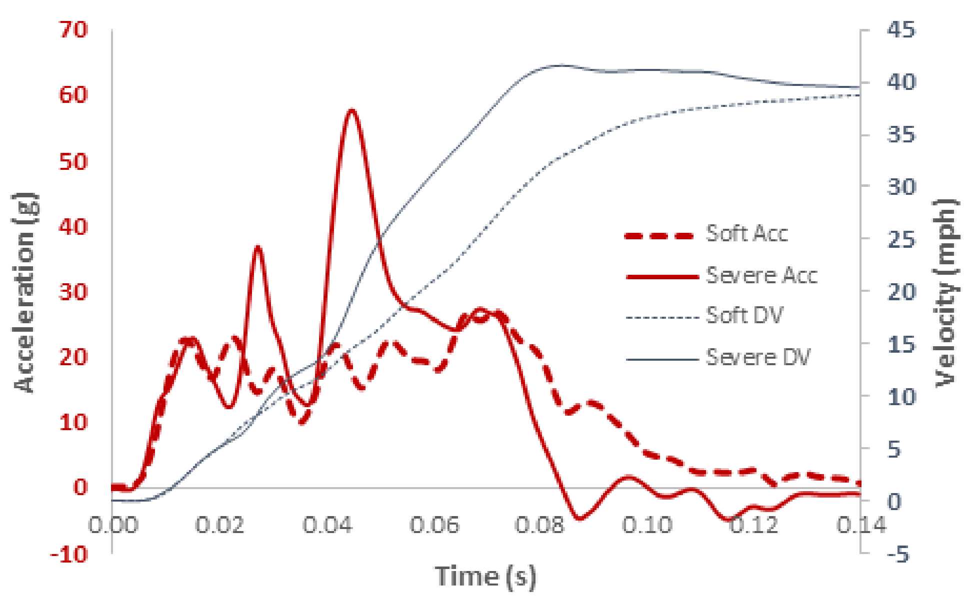

Figure 4: Soft and severe crash pulses based on NCAP tests

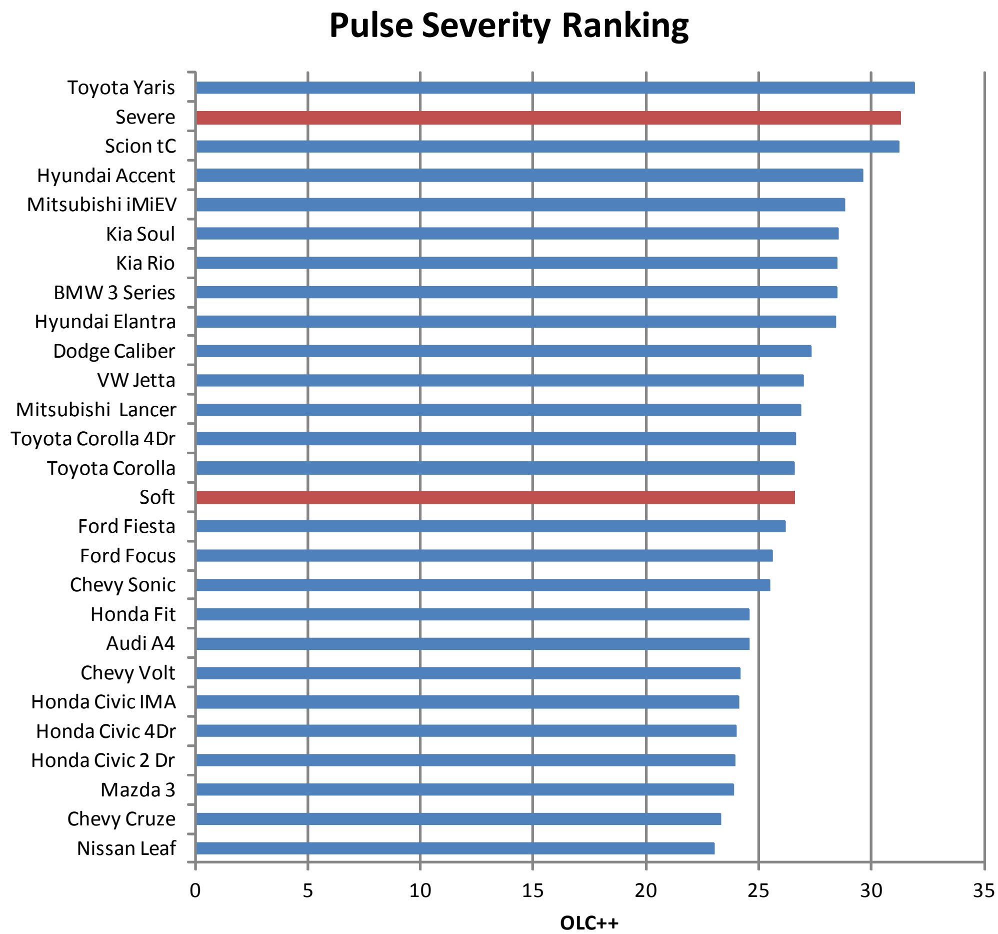

Figure 5: NCAP pulse severity ranking based on 25 small cars

The ATD instrumentation used in each test on the THOR 50th, H-III 5th, 95th and 6YO ATDs are shown in Table 3. 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.

Table 3. ATD instrumentation

Body Region	Number of Data Channels		
	Instrumentation	**THOR 50th**	**5th/95th/6YO**
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

In all the tests, the injury measures and their associated injury assessment reference values (IARVs) are shown in Table 4. 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). Brian 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, 3795.85, 3234.35, and 2456.27 deg/s were used for ω_{xc}, ω_{yc}, and ω_{zc}, and BrIC of 0.87 corresponded to 50 percent of AIS 3+ brain injury risk (Takhounts et al., 2013).

Table 4. Target IARVs for different sizes of the ATD

Occupant	HIC	BrIC	Neck T (N)	Neck C (N)	Nij	Chest G (g)	Chest C (mm)
6YO	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 percent risk for a 6YO.

** 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.

In this study, ATD submarining was determined by the evaluation of the iliac loads and the visual inspections of the testing videos. Examples of the iliac loads and ATD kinematics with and without submarining are shown in Figure 6.

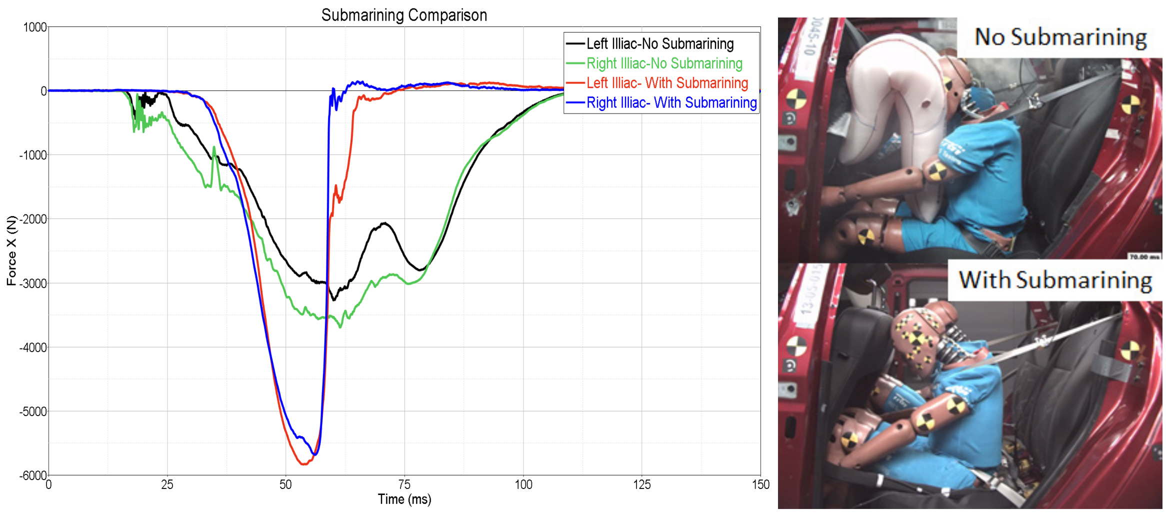

Figure 6: Examples of iliac loads and ATD kinematics with and without submarining

2.3 Results

2.3.1 H-III 95th male ATD

The mean and standard deviation of all injury measures for the 8 tests with the H-III 95th male ATD with respect to the occupant seating side (driver/passenger), crash pulse (soft/severe), and crash angle (0 deg/15 deg) are shown in Figure 7. Crash pulse was the dominating parameter that affected the injury outcomes, while seating side and impact angle were not statistically significant. In tests with a severe crash pulse, all the mean values of injury measures, except the neck compression force, were over the associated IARVs. ATDs on the right side showed slightly lower injury measures than the left side, but it is not statistically significant. ATDs sustained slightly lower injury measures, except BrIC, in 15 deg crashes than those in 0 deg crashes, but this effect is not significant either.

Figure 7 also shows the H-III 95th male ATD kinematics when the maximum head excursions occurred. Tests with the severe pulse sustained slightly higher head excursions than those with the soft pulse, and tests under 0 deg impacts sustained higher head excursions in the fore-aft direction than 15 deg impacts. In the passenger side (right side) the ATD motions were similar to those in the driver side (left side). However, because the front seat was further away from the ATDs on the passenger side, the head was further away from the front seat than on the driver side. Head-to-front-seat contact did not occur in any of the tests. The H-III 95th male ATD did not submarine in any of the tests.

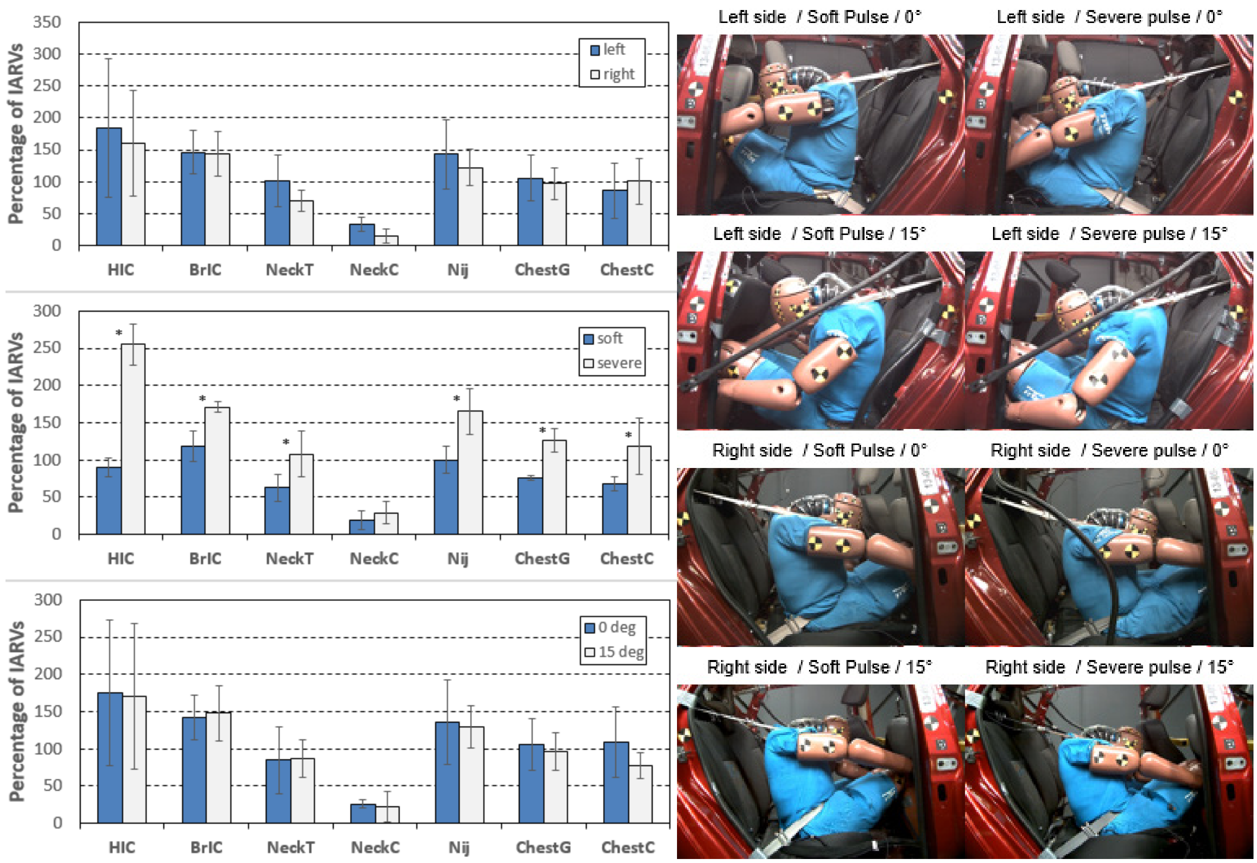

Figure 7: 95th ATD injury measures and kinematics at maximum head excursion

(103 ms for soft pulse, and 88 ms for severe pulse)
(* highlights the statistical significance based on T-tests)

2.3.2 THOR 50th male ATD

The mean and standard deviation of all injury measures for the tests with the THOR 50th with respect to the occupant seating side (left/right), crash pulse (soft/severe), and crash angle (0 deg/15 deg) are shown in Figure 8. Due to a testing mishap, no test data are available for this

ATD in the two 15 deg severe crash tests. Moreover, head angular velocity data were lost in one of the 15 deg soft crash tests, and Nij was lost in one of the severe crash tests. For these reasons, statistical tests were not conducted for THOR 50th male ATD due to the small sample size. However, based on the mean values, similar to the results from the H-III 95th male ATD, crash pulse was the dominating parameter that affected the injury outcomes, while seating side and impact angle were not significant. In tests with the severe crash pulse, many injury measures exceeded the associated IARVs.

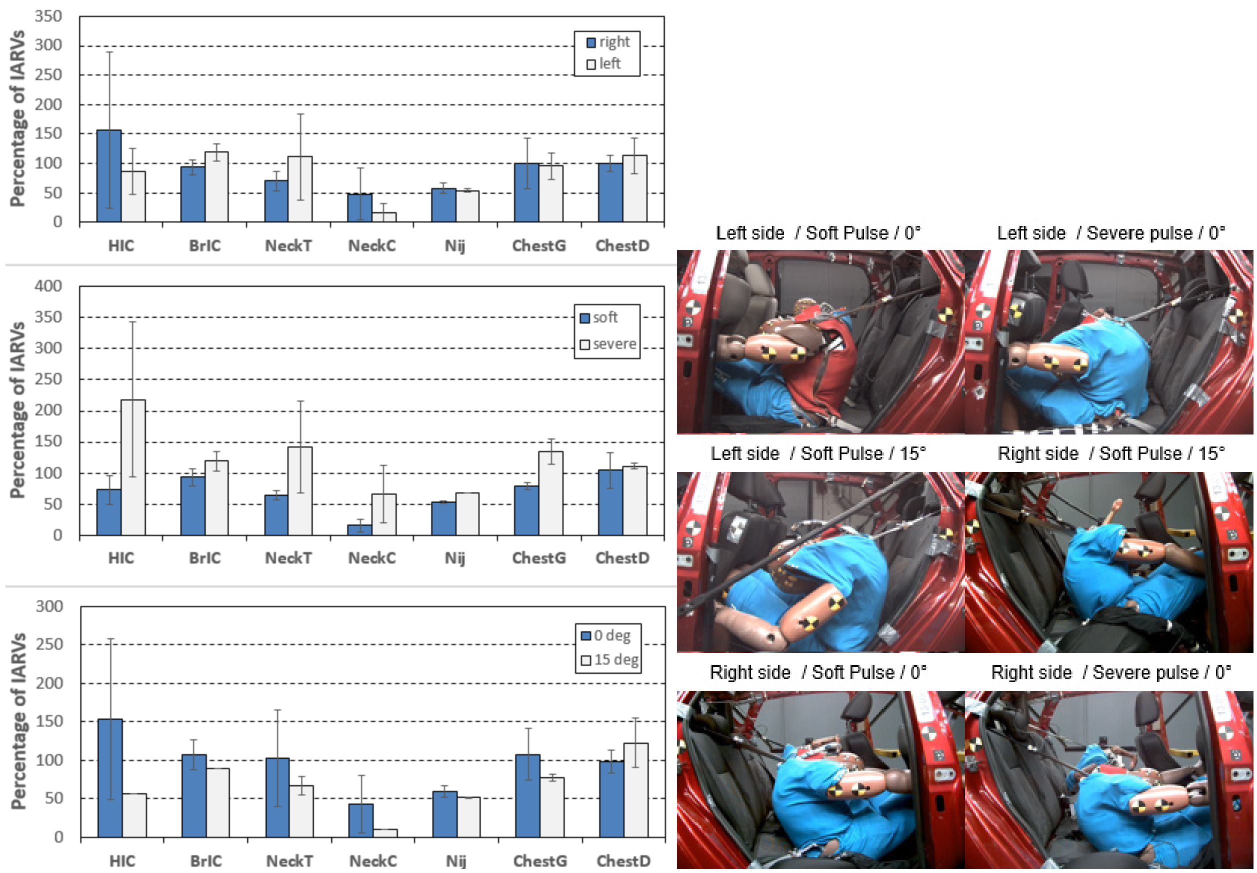

Figure 8: THOR 50th injury measures and kinematics at maximum head excursion

(110ms for soft pulse, and 92ms for severe pulse)
(T-test was not conducted due to small sample size)

Figure 8 also shows the THOR 50th kinematics when the maximum head excursions occurred. Tests with the severe pulse resulted in higher head and pelvic excursions than those with the soft pulse, and tests under 0 deg impacts resulted in higher head excursions in the fore-aft direction than 15 deg impacts. In the passenger side (right side) the ATD motions were similar to those on the driver side (left side). The head did not contact the front seat in any of the tests. Based on the iliac load cell data visual inspection, submarining was found in all but one of the tests with the THOR 50th. Submarining did not occur when the THOR 50th was on the driver side (left side) with a soft 15 deg crash pulse. In the tests where it was determined that the THOR 50th submarined, the submarining occurred on both sides of the pelvis, except for the test with the THOR 50th on the driver side under a soft 0 deg crash pulse, in which the submarining occurred only on the right side of the pelvis.

2.3.3 H-III 5th female ATD

The mean and standard deviation of all injury measures for the 8 tests with the H-III 5th female ATD with respect to the occupant seating side (left/right), crash pulse (soft/severe), and crash angle (0 deg/15 deg) are shown in Figure 9. Similar to the other ATDs, crash pulse was the dominating parameter that affects the injury outcomes, while seating side and impact angle were not significant. In all the tests with the severe pulse, all the injury measures, except the neck compression force, were at or above the associated IARVs.

Figure 9 also shows the 5th ATD kinematics when the maximum head excursions occurred. Tests with the severe pulse produced higher head excursions than those with the soft pulse, and 0 deg impacts produced higher head excursions in the fore-aft direction than 15 deg impacts. On the passenger side, the ATD motions were similar to those on the driver side. The ATD head did not contact the front seat in any of the tests. With the soft pulse, the 5th ATD submarined in 1 of the 4 tests, and the submarining occurred on the left side of the pelvis only. With the severe pulse, the 5th ATD submarined in all 4 tests on both sides of the pelvis.

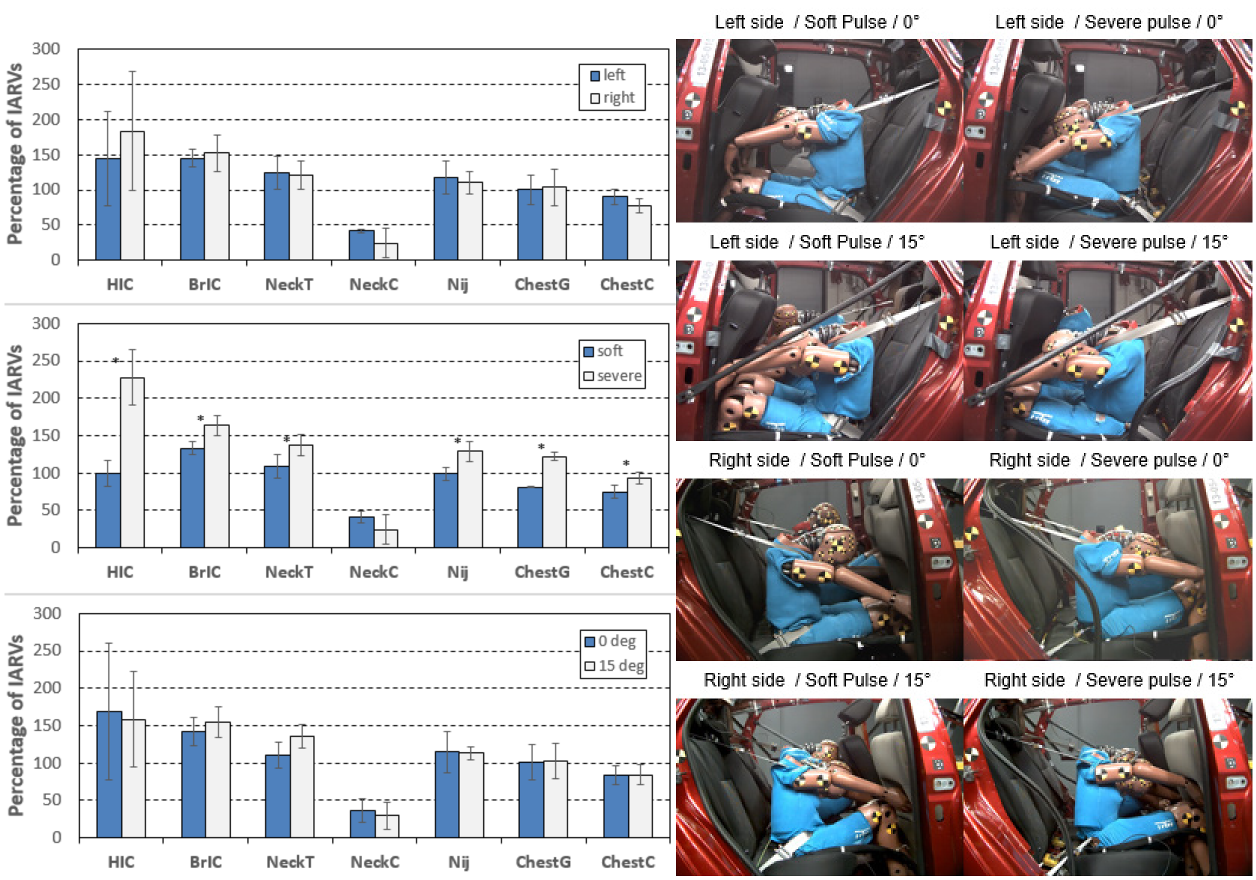

Figure 9: 5th ATD injury measures and kinematics at maximum head excursion

(92 ms for soft pulse, and 82 ms for severe pulse)
(* highlights the statistical significance based on T-tests)

2.3.4 H-III 6YO ATD

The mean and standard deviation of all injury measures for the 8 tests with the H-III 6YO ATD with respect to the occupant seating side (left/right), crash pulse (soft/severe), and crash angle (0 deg/15 deg) are shown in Figure 10. Crash pulse was the dominating parameter that affected the injury outcomes, while seating side and impact angle were not statistically significant. In tests with the severe crash pulse, all the injury measures were at or above the associated IARVs. The neck tension force for the 6YO was more than three times the IARV in most tests.

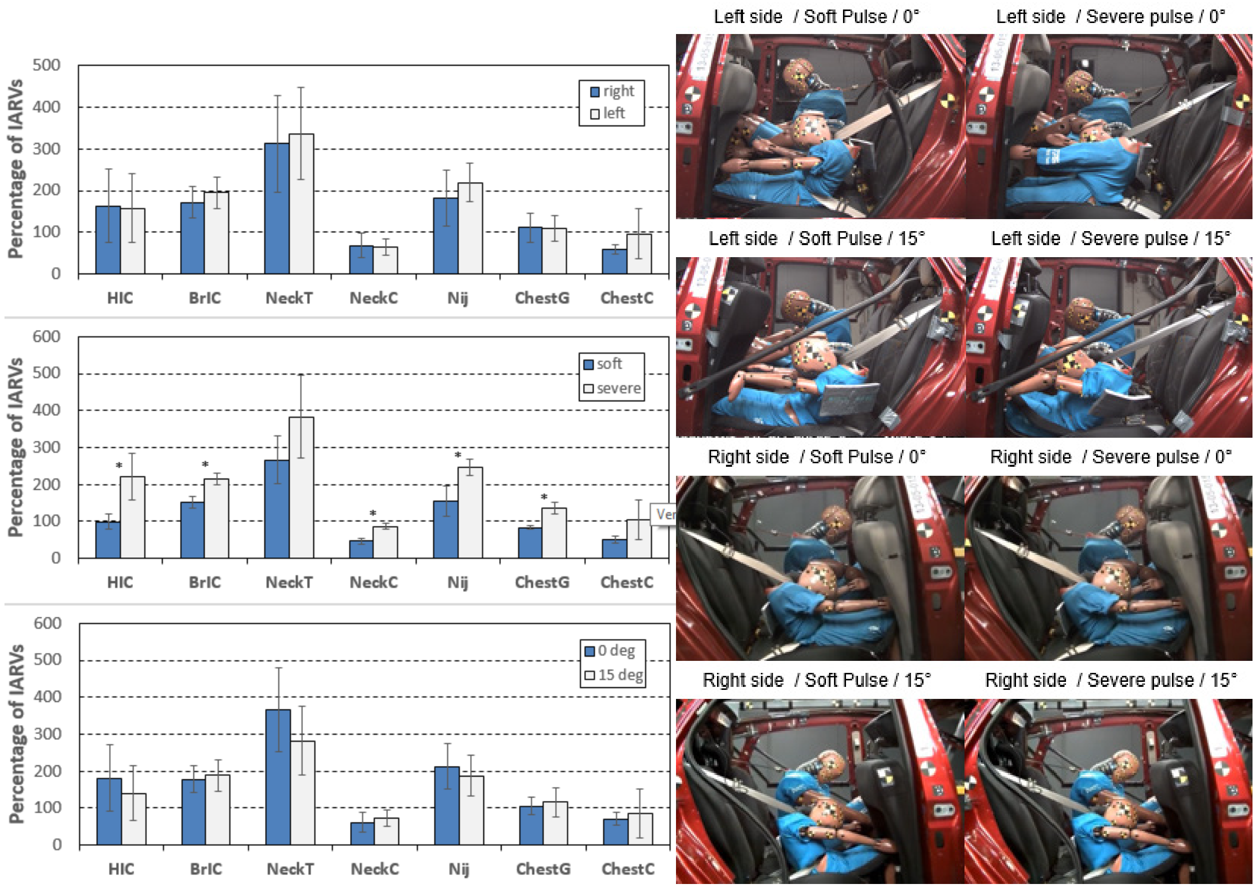

Figure 10: 6YO ATD injury measures and kinematics at maximum head excursion

(89 ms for soft pulse, and 78 ms for severe pulse)
(* highlights the statistical significance based on T-tests)

Figure 10 also shows the 6YO ATD kinematics when the maximum head excursions occurred. Tests with severe pulse sustained higher excursions than those with soft pulse, and 0 deg impacts produced higher head excursions in the fore-aft direction than 15 deg impacts. On the passenger side, the ATD motions were similar to those on the driver side. The ATD head did not contact the front seat in any of the tests. Because the 6YO ATD was in a slouching posture before the crash, submarining occurred in every test.

2.4 Discussion

2.4.1 Crash pulse, impact angle, and front seat location

In this study using a small vehicle buck, several crash parameters were investigated in the first series of sled tests for their effects on rear seat occupant injury risks with a baseline 3-point belt. Crash pulse was the dominating parameter affecting the occupant injury risks, while impact angle and front seat proximity to the second row occupant (represented by the occupant side in this study) are not statistically significant. With the severe crash pulse, most injury measures exceeded the IARVs. Although the HIC values were generally high in all the tests, no head contact was found for any ATD in any test. In the field, head injuries for rear seat occupants, especially older children, are generally caused by the contact to the back of the front seat or the B-pillar. The HIC injury risk function was developed from short duration head impact data. Therefore, one should use caution when interpreting the HIC values from this study where head contact was not present.

2.4.2 Occupant size effects

Consistent with previous studies, occupant size had a strong effect on occupant kinematics. Smaller occupants (6YO and 5th) in the real world tend to slouch in rear seats (Reed, Ebert-Hamilton, Manary, Klinich, & Schneider, 2006), which increases the potential for submarining. Submarining occurred in 8 of 8 tests with H-III 6YO ATD, 5 of 8 tests with H-III 5th female ATD and 5 of 6 tests with the THOR 50th, while no submarining occurred in any of the tests with the 95th ATD. Submarining is associated with higher knee excursion and lower head excursion (Hu, Wu, Klinich, Reed, Rupp, & Cao, 2013; Hu, Wu, Reed, Klinich, & Cao, 2013). In general, in the current sled testing conditions, such kinematics would result in higher HIC and Nij, because no head contact was involved and the HIC and Nij were due to the head whipping. However, as mentioned earlier, one should be cautious in using HIC to estimate head injury risks without a head contact. In addition, Nij may over-estimate the neck injury risk. The submarining effects on the chest deflection were not clear based on the current ATD results. However, intuitively, submarining has the potential to increase the occupant chest injury risk due to less engagement with the clavicle and belt penetration into the abdomen and lower thorax. Theoretically, larger occupants have a greater potential for head-to-front seat contact. However, no head-to-front seat contact was found in any tests with all the ATDs. The knees of larger occupants (95th and 50th) may push the back of the front seat slightly forward, which may help reduce the chance of head contact. The lack of head contact in all the baseline tests is contrary to the field data, which showed that the head is the most commonly injured body region for children. These results suggested that head injuries in the field may be associated with poor shoulder belt fit, belt misuse, or more complex seated postures and crash kinematics. The ATDs also may not adequately represent human kinematics. Previous studies (Ash et al., 2009; Lopez-Valdes et al., 2009; Sherwood et al., 2003) have shown that the H-III 6YO ATD may over-predict head and neck rotations in frontal crashes, resulting in higher HIC and Nij values than human cadavers or volunteers. However, evaluating the biofidelity of the ATDs for rear-seated occupants is out of the scope of this study and needs further investigation in the future.

3 Baseline Model Development and Validation

3.1 Goal

The goal of this task was to develop and validate a set of computational models against results from the sled tests.

3.2 Methods

MADYMO ATD models (Figure 11) representing THOR 50th, H-III 5th, 95th and 6YO ATDs were used in this study. Two THOR 50th models, an old THOR 50th and a new/improved THOR 50th model, were used in this study, because the improved THOR 50th model developed by TASS became available toward the end of the project. As a result, the old THOR 50th model was used in the validation runs against the baseline sled tests, while the improved THOR 50th model was used in the validation runs against sled tests with advanced restraints and the final parametric simulations. Compared to the old THOR 50th model, the improved THOR 50th model included more realistic geometry and impact characteristics. The H-III 6YO MADYMO model has been improved recently at UMTRI by incorporating more accurate pelvis and abdomen geometries (Wu, Hu, Reed, Klinich, & Cao, 2012).

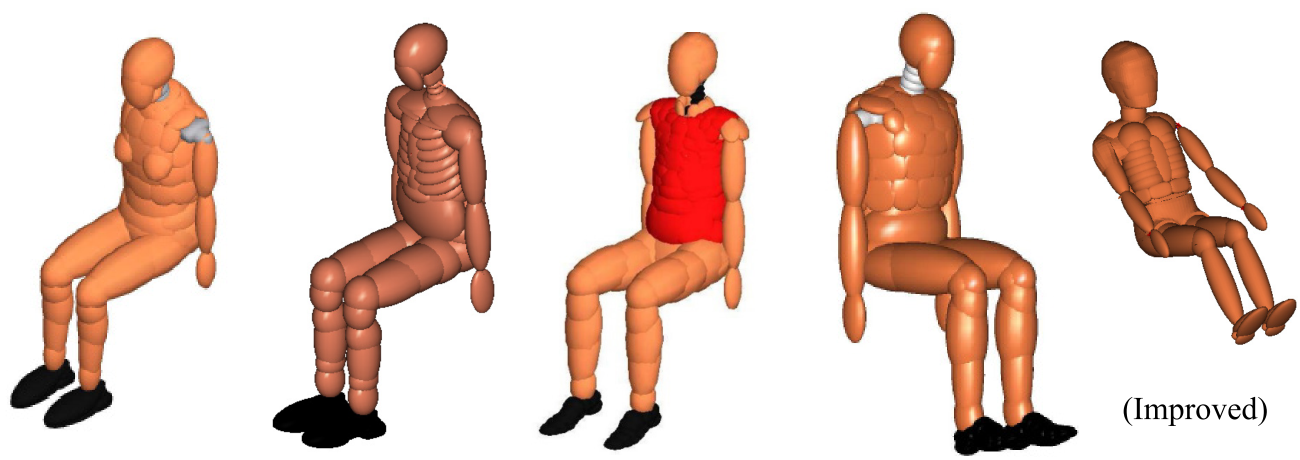

Figure 11: ATD models used in this study

Four sets of environment models were developed along with the ATD models as shown in Figure 12: 95th (left) & 6YO (right), 6YO (left) & 95th (right), THOR 50th (left) & 5th (right), and 5th (left) & THOR 50th (right). Simulations were set up to match the 16 baseline test configurations with these 4 sets of models, two crash pulses (soft/severe) and two impact angles (0 deg/15 deg). 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 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 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.

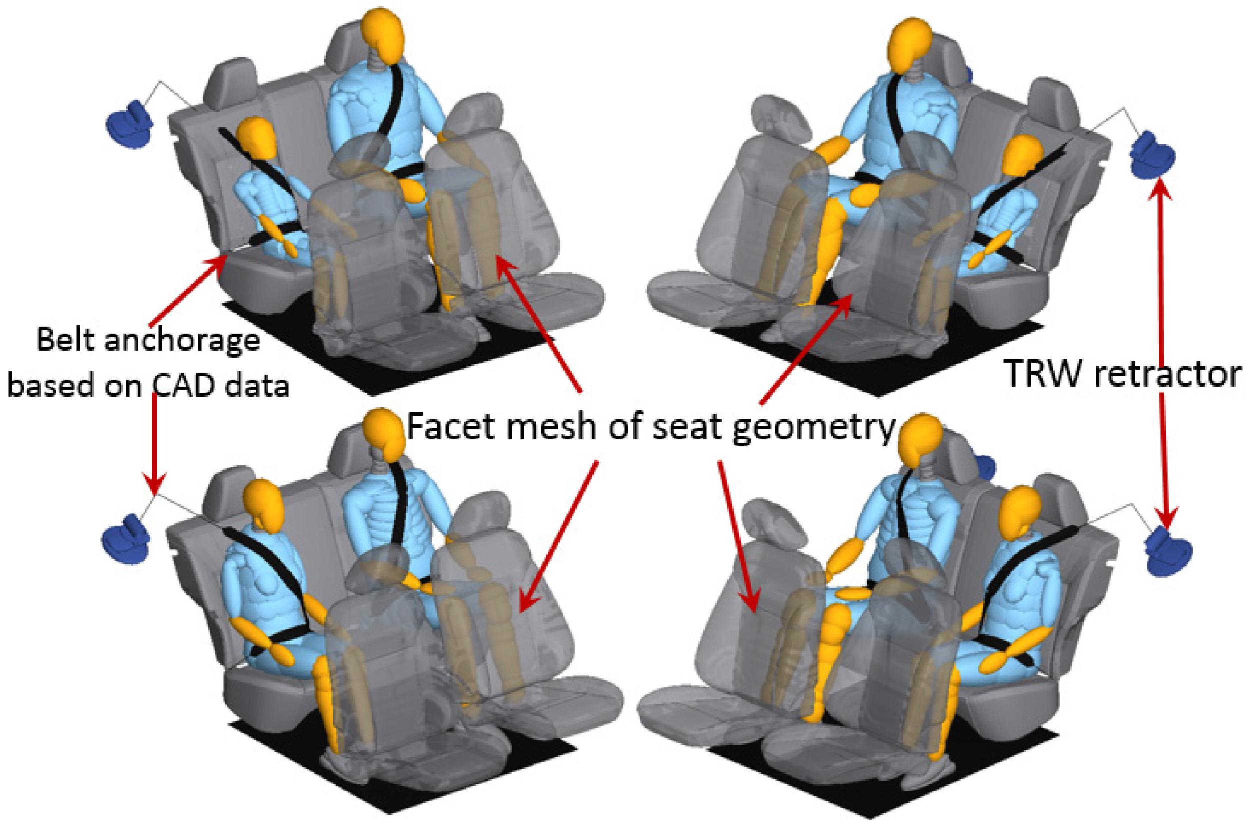

Figure 12: Four sets of models developed for model validation against baseline tests

The model validation process closely followed those from previous UMTRI studies (Hu, Klinich, Reed, Kokkolaras, & Rupp, 2012; Wu, Hu, Reed, Klinich, & Cao, 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 under 0 deg crash conditions, while the optimal parameters in the 0 deg crashes were applied to the corresponding 15 deg crashes. ModeFRONTIER, a multi-objective optimization software program from ESTECO, in Trieste, Italy, was coupled with MADYMO to conduct the optimizations.

Model parameters optimized in the model validation process 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 TRW, those parameters were not tuned in the model validation process. Similarly, because the ATD models were validated previously against ATD tests, no parameters of the ATD models were adjusted in the model validation process. The old THOR 50th MADYMO model was less valid, therefore chest and abdomen contact characteristics were scaled to achieve the best match between test and simulation results.

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 (Equation 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.

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

In Equation 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 at 0 deg. In each optimization, 200 MADYMO 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 equation 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, non-global 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.

3.3 Results

A summary of the CORA evaluation results are shown in Table 5, in which channels with CORA score>=70% were highlighted in green, channels with 50%<=CORA<70% were highlighted in yellow, while channels with 25%<=CORA<50% were highlighted in orange. No channel had a CORA less than 25 percent. The test numbers in Table 5 correspond to those in Table 1. Figure 13 summarizes the CORA evaluation results for each impact response on each ATD. 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-III6YO ATD models. The correlations for the Z accelerations were generally poor because of the small magnitudes and two peaks (one positive and one negative) in all the tests. The THOR 50th model did not provide good correlations on the chest deflection and pelvis Z accelerations, while the

H-III6YO ATD did not provide good correlation on the pelvis X acceleration due to the severe submarining of the ATD. Examples of model correlations are shown in Appendix A.

Table 5. 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	6YO	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	6YO	-	72.6%	80.9%	56.2%	73.8%	56.7%	61.6%	80.5%	65.8%
03	6YO	-	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	6YO	-	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%
09	THOR	64.9%	68.1%	69.5%	57.1%	37.6%	88.7%	39.3%	71.8%	68.8%
09	5th	75.7%	68.1%	69.7%	44.0%	89.9%	-	-	64.2%	66.3%
10	5th	82.5%	78.0%	73.9%	57.6%	95.8%	71.3%	49.3%	75.7%	67.4%
11	5th	77.1%	92.0%	86.2%	41.2%	96.9%	79.8%	64.2%	87.0%	74.2%
11	THOR	64.3%	70.5%	81.3%	51.4%	46.3%	62.8%	37.4%	84.5%	62.5%
12	5th	72.6%	72.7%	75.6%	50.6%	90.3%	69.3%	74.0%	85.7%	70.3%
13	95th	50.3%	76.2%	81.6%	46.3%	64.4%	85.5%	63.1%	69.1%	80.1%
13	6YO	62.0%	65.2%	69.2%	47.9%	-	45.9%	57.7%	60.6%	55.9%
14	95th	88.9%	78.6%	83.2%	58.1%	75.2%	71.7%	68.1%	64.4%	80.4%
14	6YO	73.0%	68.4%	80.5%	64.3%	61.1%	50.0%	67.3%	88.5%	54.8%
15	6YO	75.6%	61.6%	74.7%	47.8%	46.5%	40.6%	51.1%	70.0%	63.8%
15	95th	77.0%	80.2%	86.8%	31.0%	61.6%	53.8%	80.6%	69.3%	69.8%
16	6YO	68.4%	62.1%	76.1%	55.6%	-	32.3%	51.3%	89.6%	54.7%
16	95th	84.3%	73.3%	88.4%	52.2%	65.1%	57.9%	81.5%	73.2%	74.1%
	Total	75.3%	74.1%	78.4%	51.7%	70.2%	62.7%	59.5%	79.3%	71.6%

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

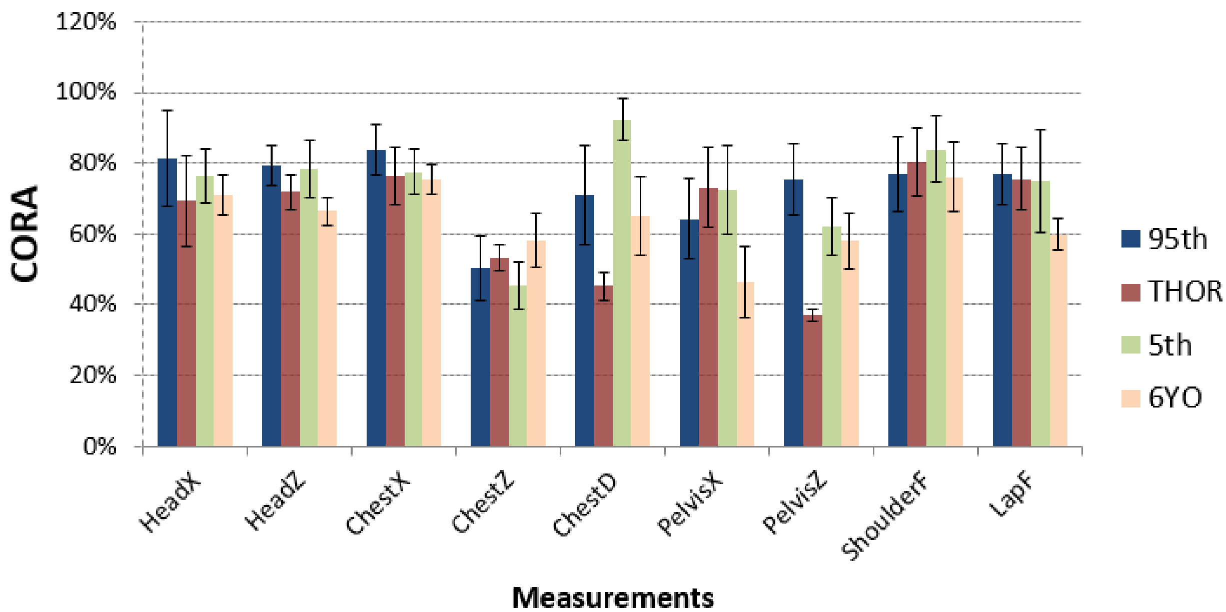

Figure 13: Summary of the CORA scores for the model validation against baseline tests

4 Advanced Restraint Selection

4.1 Goal

The goal of this task was to identify combinations of advanced restraint system technologies suitable for rear seat occupants.

4.2 Proposed State-of-the Art Technologies for Rear seat Restraint System

To investigate the effects of advanced restraints, 3-point seat belts with pretensioners, 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 SCaRAB concept (Figure 14) were used in the second series of sled tests.

a) DLT b) BiR c) SCaRAB d) 4-point belt e) Inflatable belt

Figure 14: 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. Pretensioners were used to engage the occupant early by moving the onset of belt force earlier in a crash. A retractor pretensioner, the most common form of pretensioner, helped to reduce the slack in the shoulder portion of the belt system. An anchor pretensioner reduced slack in the lap portion, and a buckle pretensioner added pretension to both the lap and shoulder segments of the belt system. All of these pretensioner configurations were evaluated in this study.

In general once a pretensioner 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 (Figure 14a) 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.

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 air bag. Two air bag concepts were investigated in the study. The BiR (Figure 14b) deploys from the roof of the vehicle between the rear seat occupant and front seat back. The SCaRAB (Figure 14c) 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 air bag for the front seat. In comparison, the SCaRAB inflator output and bag volume are relatively small, similar to a driver air bag and less than half the size of the BiR.

A further option with a belt only system was the 4-point belt (Figure 14d). Two retractor pretensioners 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.

An inflatable belt (Figure 14e) 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.

A summary of the possible technologies as well as their estimated benefit on rear seat occupant protection based on engineering judgment is shown in Table 6.

Table 6. Restraint Technologies and estimated benefits (--: negative, +: positive, 0: neutral)

Restraint Technology	Minimize Excursion	Reduce Chest Loading	Reduce Head Loading	Adaptability Occupant Size
Constant Load Limiter	--	+	0	0
Progressive Load Limiter	--	+	0	+
Switchable Load Limiter	0	++	0	++
Retractor Pretensioner	+	+	0	0
Anchor Pretensioner	+	+	0	0
Buckle Pretensioner	+	+	0	0
Four Point Mounting	+	+	0	0
Dynamic Locking Tongue	+	+	0	0
Inflatable Belt	+	+	0	0
SCaRAB	++	0	++	0
BiR	++	0	++	0

5 Design Optimizations for Advanced Restraint Systems

5.1 Goal

The goals of this task were to conduct sled tests with advanced restraint technologies, validate the computational models against those tests, and conduct design optimizations for the proposed advanced restraint system.

5.2 Sled tests with advanced restraint technologies

5.2.1 Methods

The test matrix for the selected sled tests in the second series with advanced restraint technologies is shown in Table 7, and the design specifications for the advanced restraints used in the second sled series are shown in Table 8. The second series focused on testing various combinations of advanced restraints for computer models to validate against. For tests with the 6YO ATD, a Graco Backless TurboBooster was used to reduce the potential for submarining. Based on the results from the first series of tests, all the sled tests in the second series were conducted at a 0 deg angle with the severe crash pulse, which is the most severe test condition. The seat belt anchorage locations in the second series of tests were the same as those in the baseline tests. In the second series of tests with advanced restraint features, the FMVSS No. 209 type 2 seat belt assembly elongation requirement was not considered.

Table 7. Sled test matrix with advanced restraint designs in the second sereies

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

Note that all the tests in this series are at 0 deg angle with the severe crash pulse.

Table 8. 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.
Pretensioners	The stroke of the buckle pretensioner ranges from 15 to 45 mm, while the strokes of the anchor and retractor pretensioner range from 40 to 80 mm, depending on the ATD and the number of pretensioners used in the test. The retractor pretensioner was fired at 10 ms, and the buckle/anchor pretensioner 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 air bags were fired at 14 ms.

5.2.2 H-III 5th ATD test results

The injury measures with the 5th ATD using different restraint systems are shown in Figure 15, and the ATD kinematics are shown in Figure 16. Compared to the baseline 3-pt belt system, advanced restraint systems generally reduced the injury measures. However, the 3-point belt with pretensioner and load limiter and the inflatable belt did not reduce the HIC, BrIC, and neck tension to a value 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 (Appendix C and D) also showed that the BiR and SCaRAB reduced crash loads on ATD chests (shoulder belt forces) by more than 50 percent 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 percent when compared to those in the baseline tests. This is because BiR and SCaRAB prevented hard contacts between the head and front seat, which 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 pretensioner was used while keeping the same seat belt anchorage locations in all the tests.

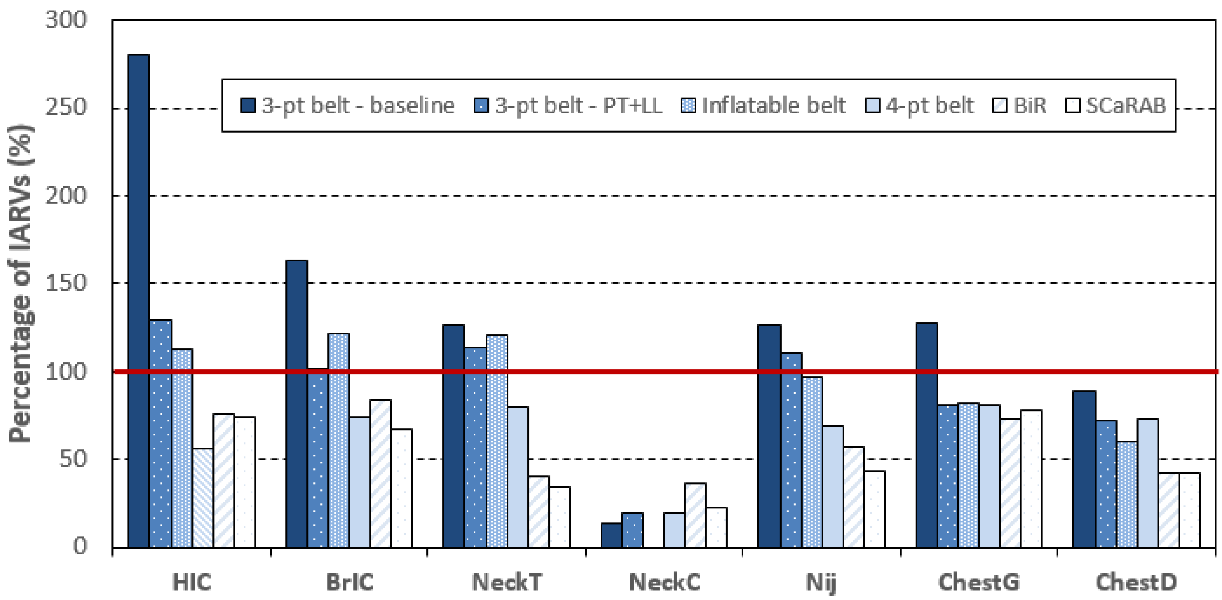

Figure 15: Injury measures for the 5th ATD with different restraint systems

Figure 16: 5th ATD kinematics with different restraint systems

5.2.3 H-III 6YO ATD test results

The injury measures with the 6YO ATD using different restraint systems are shown in Figure 17, and the ATD kinematics are shown in Figure 18. 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 pretensioner 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. Based on the seat belt load data (Appendix C and D), advanced restraints reduced the loads on the 6YO ATD by about 30-50 percent.

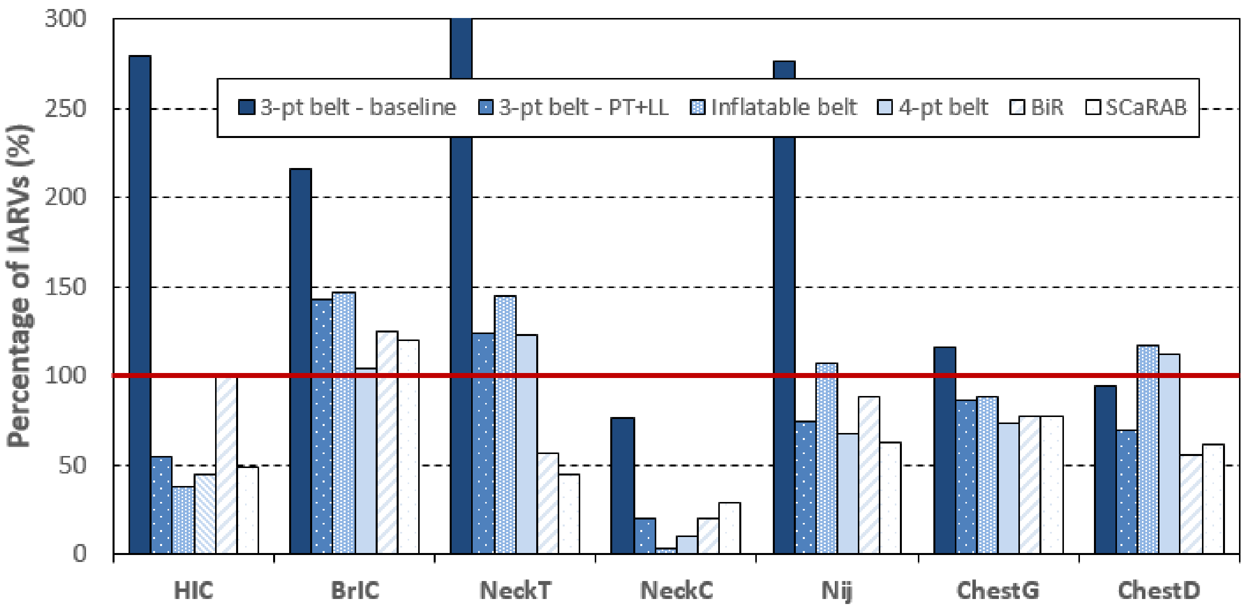

Figure 17: Injury measures for the 6YO ATD with different restraint systems

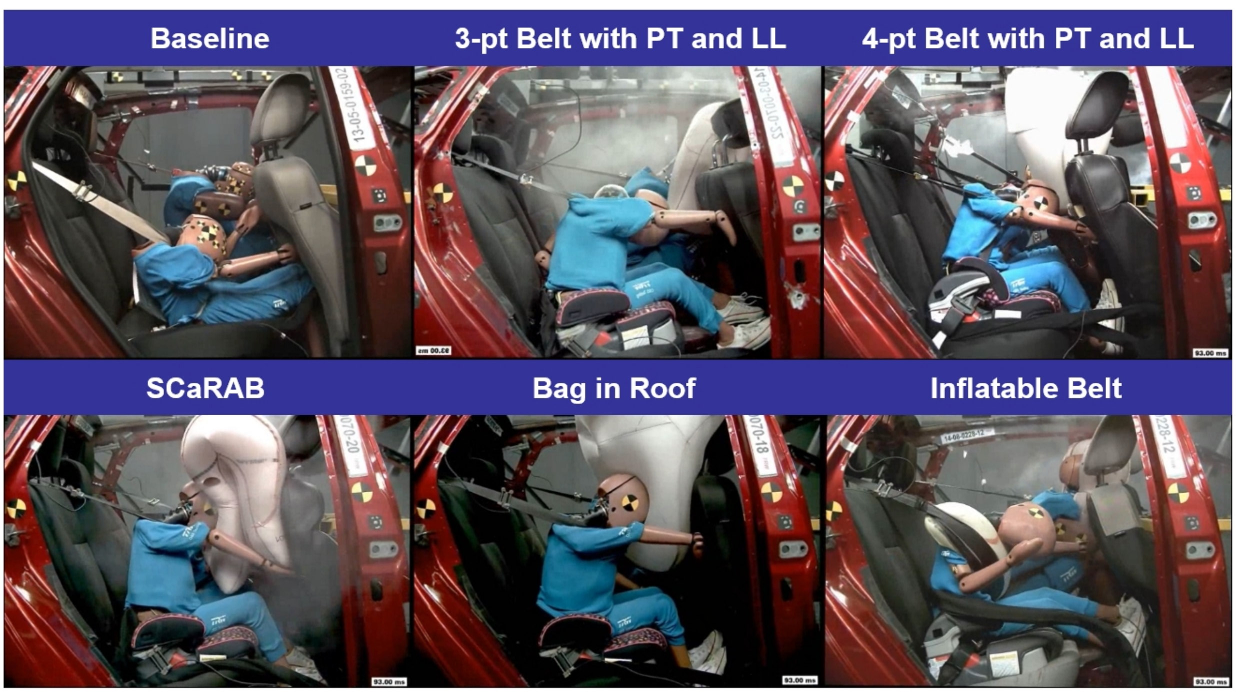

Figure 18: 6YO ATD kinematics with different restraint systems

5.2.4 THOR 50th ATD test results

The injury measures with the THOR 50th using different restraint systems are shown in Figure 19, and the THOR 50th kinematics are shown in Figure 20. 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 pretensioner 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 air bags (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.

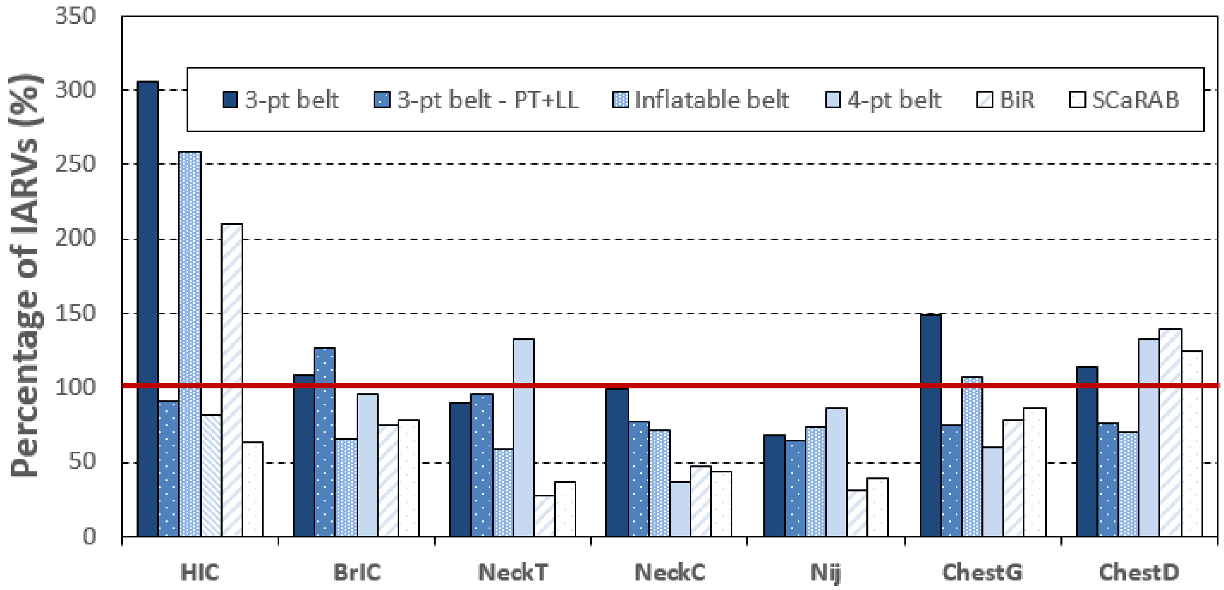

Figure 19: Injury measures for the THOR 50th with different restraint systems

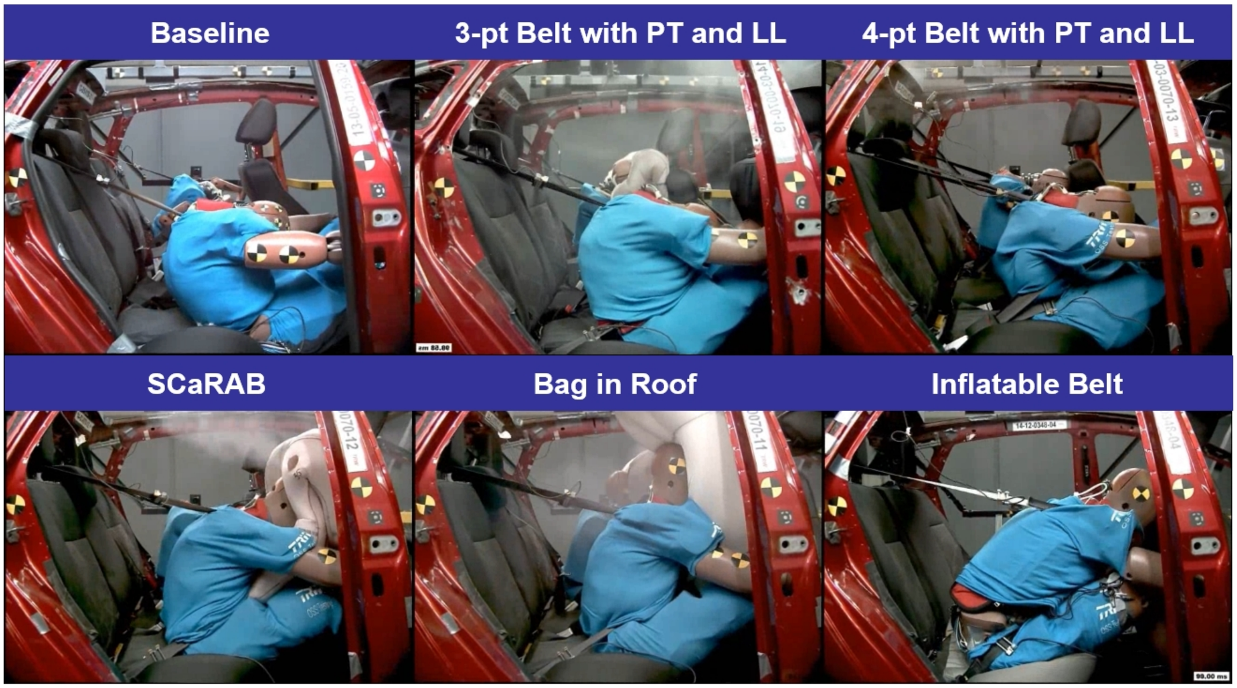

Figure 20: THOR 50th kinematics with different restraint systems

5.2.5 H-III 95th ATD test results

The injury measures of the 95th ATD using different restraint systems are shown in Figure 21, and the ATD kinematics are shown in Figure 22. 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.

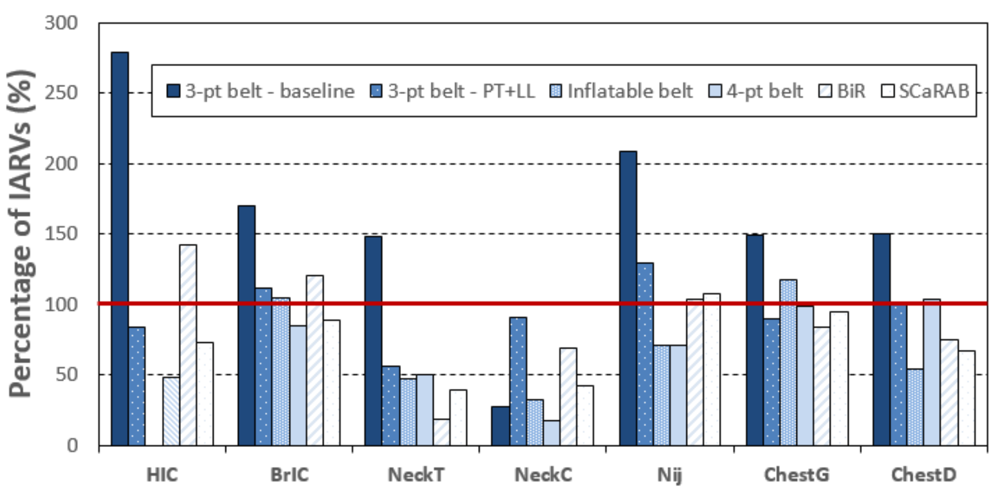

Figure 21: Injury measures for the 95th ATD with different restraint systems

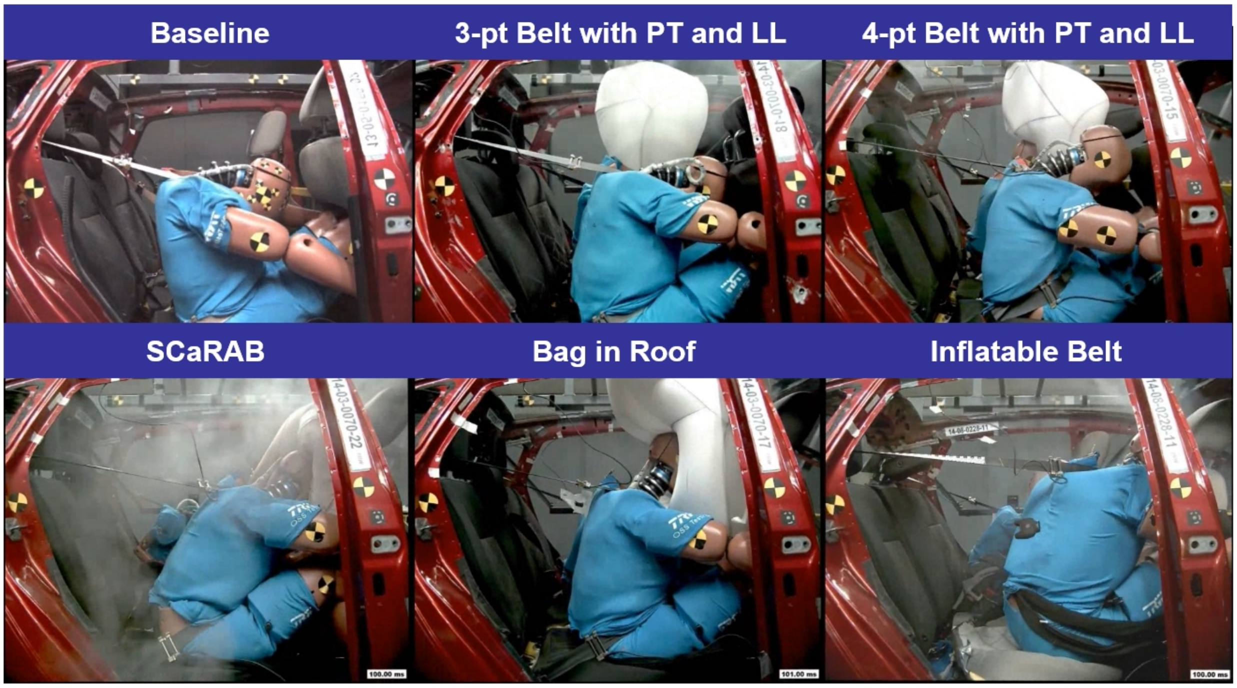

Figure 22: 95th ATD kinematics with different restraint systems

5.2.6 Discussion on Second Series of Sled Tests with Advanced Restraints

Different advanced restraints were investigated in a second sled series. In general, advanced restraints reduced the injury measures. Pretensioners 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 prevent excessive 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. Our test results showed that the inflatable belt tightened the belt quickly and had similar effects as those from a retractor pretensioner. 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 pretensioner and load limiter. Other air bag concepts, such as the BiR and SCaRAB, may allow 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. However, the advanced restraints tested in the current study were conceptual designs, and further design optimization would be needed for a production system. Booster seats were used in the second sled series with advanced restraints for the 6YO 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 6YO ATD between the two sled series are likely due in part to the boosters, not necessarily the advanced restraints. Without a booster, the initial slouching posture of the 6YO ATD would likely induce submarining even with the advanced restraints. Previous computational studies (Hu, Wu, Klinich, Reed, Rupp, & Cao, 2013; Hu, Wu, Reed, Klinich, & Cao, 2013) have shown that reducing the length of the seat cushion may be a possible solution to reduce the submarining risk for the 6YO without boosters. However, a short seat cushion may compromise the protection to adult occupants and infants in child seats (Hu, Wu, Klinich, Reed, Rupp, & Cao, 2013). 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 pretensioners 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, Klinich, Reed, Kokkolaras, & Rupp, 2012) or computational human models could be needed.

5.3 Further Validation of Computational Models With Advanced Restraints

5.3.1 Methods

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 pretensioner, load limiter, 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.

5.3.2 Model validation results against sled tests with advanced restraints

Examples of comparisons of occupant kinematics between the tests and simulations are shown in Figure 23. Correlations between the tests and simulations on occupant responses were attached in Appendix B. Reasonably good correlations were achieved.

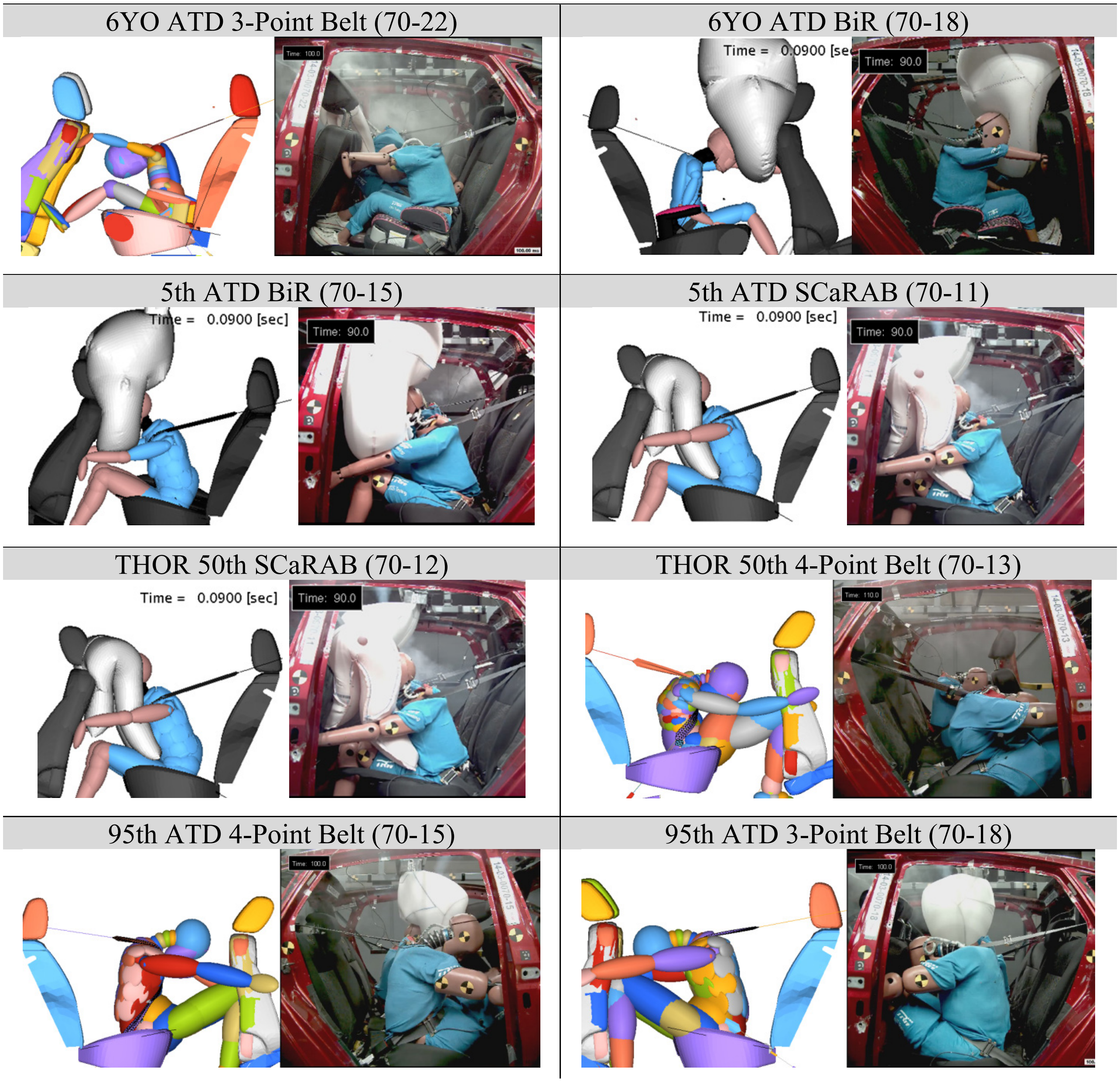

Figure 23: Comparison of ATD kinematics between the tests and simulations with advanced restraints

5.4 Design Optimizations

5.4.1 Methods

Based on the results of sled tests in the second series, design optimizations were performed for the 3-point belt, 3-point belt with a BiR, and 3-point belt with SCaRAB.

Table 9. Objective function and constraints in the design optimizations

	Head			**Neck**			**Chest**
	Excursion (mm)	**HIC**	**BrIC**	**Neck T (kN)**	**Neck C (kN)**	**Nij**	**Chest D**
H-III6YO	<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

A parametric study based on the full factorial design for the 3-point belt with a CLL and retractor pretensioner was conducted. The input parameters are crash pulse (severe/soft), crash angle (0 deg/15 deg), ATD (6YO/5th/THOR 50th/95th), CLL torsion bar (8.0/8.5/9.0/9.5/10.0/10.5 mm), buckle pretensioner (Yes/No), anchor pretensioner (Yes/No), DLT (Yes/No). A total of 768 (2*2*4*6*2*2*2*2) simulations were conducted, and injury measures in Table 9 for all the simulations were output for evaluation.

Simulations with air bags only focused on crashes at 0 deg with the severe crash pulse. Parametric studies based on the full factorial design for the BiR and SCaRAB with a CLL and retractor pretensioner were also conducted. The input parameters are occupant side (driver/passenger), ATD (6YO/5th/THOR 50th/95th), CLL torsion bar (8.0/8.5/9.0 mm), buckle pretensioner (Yes/No), anchor pretensioner (Yes/No), DLT (Yes/No). A total of 96 (2*4*3*2*2) simulations were conducted for each air bag design (BiR or SCaRAB). Note that the BiR and SCaRAB design parameters (air bag location, mass flow, vent size, etc.) were also tuned through separate parametric studies before these parametric runs.

5.4.2 Results

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 at 0 deg angle, 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 10 and 11. It was clear that a 9.0 or 9.5 mm torsion bar and a buckle pretensioner were needed to pass all the design constraints under the soft pulse crash. The material cost of such restraint system is about twice the cost of the baseline seat belt system based on TRW estimation.

Table 10. Percentage of 3-point belt only designs able to meet the design constraints in Table 9

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

Table 11. 3-point only designs able to meet all the design constraints in Table 9

Run No	Anchor PT	Buckle PT	DLT	Pulse	Angle	Load Limiter Torsion Bar	Comb Chest Probability	System Costs
26	Yes	Yes	Yes	Soft	0 deg	9.0 mm	10%	285%
122	No	Yes	Yes	Soft	0 deg	9.0 mm	13%	206%
98	No	Yes	No	Soft	0 deg	9.0 mm	14%	190%
123	No	Yes	Yes	Soft	0 deg	9.5 mm	15%	206%
99	No	Yes	No	Soft	0 deg	9.5 mm	20%	190%

The model-predicted ATD kinematics with one of the advanced belt-only designs (design 122 in Table 11 9.0mm torsion bar/DLT/retractor PT/buckle PT) are shown in Figure 24, in which no head-to-front-seat contact occurred while the ATDs sustained good kinematics (torso pitching forward without submarining).

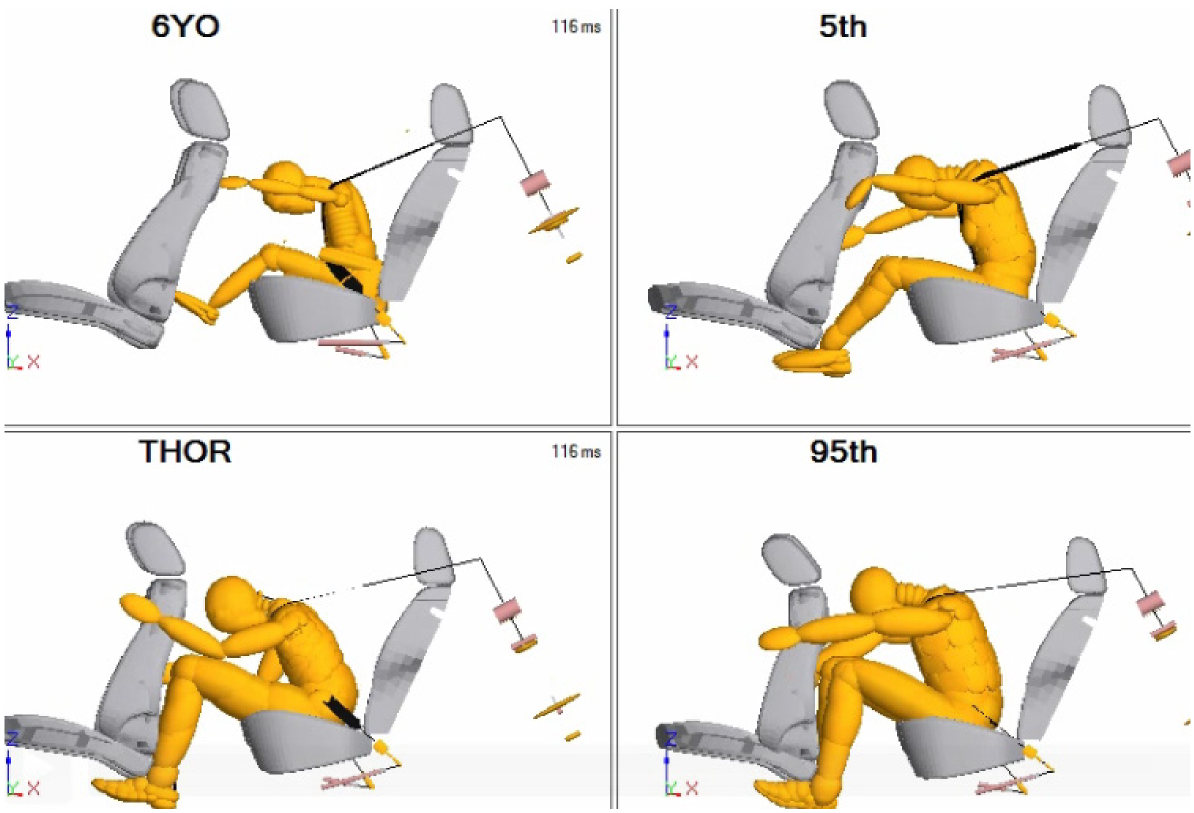

Figure 24: ATD kinematics with the belt-only design 122 (3-point belt with 9.0 mm torsion bar, DLT, and retractor and buckle pretensioners) under soft crash pulse at 0 deg crash angle

The percentages of designs including an air bag (BiR or SCaRAB) that were able to meet all the design constraints for each ATD under the severe crash pulse at 0 deg angle are shown in Table 12, and the designs that met all the constraints for all the ATDs are shown in Table 13. 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 cost of such a system is about four times the cost of the baseline system, based on TRW estimation.

Table 12. Percentage of air bag designs that can meet the design constraints in Table 9

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

Table 13. Designs with an air bag that can meet all the design constraints in Table 9

Run No	Restraints	Anchor PT	Buckle PT	DLT	Load Limiter Level	Comb Chest Probability	System Costs
56	SCaRAB	Yes	Yes	Yes	9.0 mm	41.5%	520%
68	SCaRAB	Yes	No	Yes	9.0 mm	44.4%	442%
55	SCaRAB	Yes	Yes	Yes	8.5 mm	46.9%	520%
50	SCaRAB	Yes	Yes	No	9.0 mm	48.5%	504%
62	SCaRAB	Yes	No	No	9.0 mm	49.0%	426%
49	SCaRAB	Yes	Yes	No	8.5 mm	50.7%	504%

The model-predicted ATD kinematics with one of the advanced designs (design 68 in Table 13 9.0mm torsion bar/DLT/retractor PT/anchor PT/SCaRAB) are shown in Figures 25 and 26.

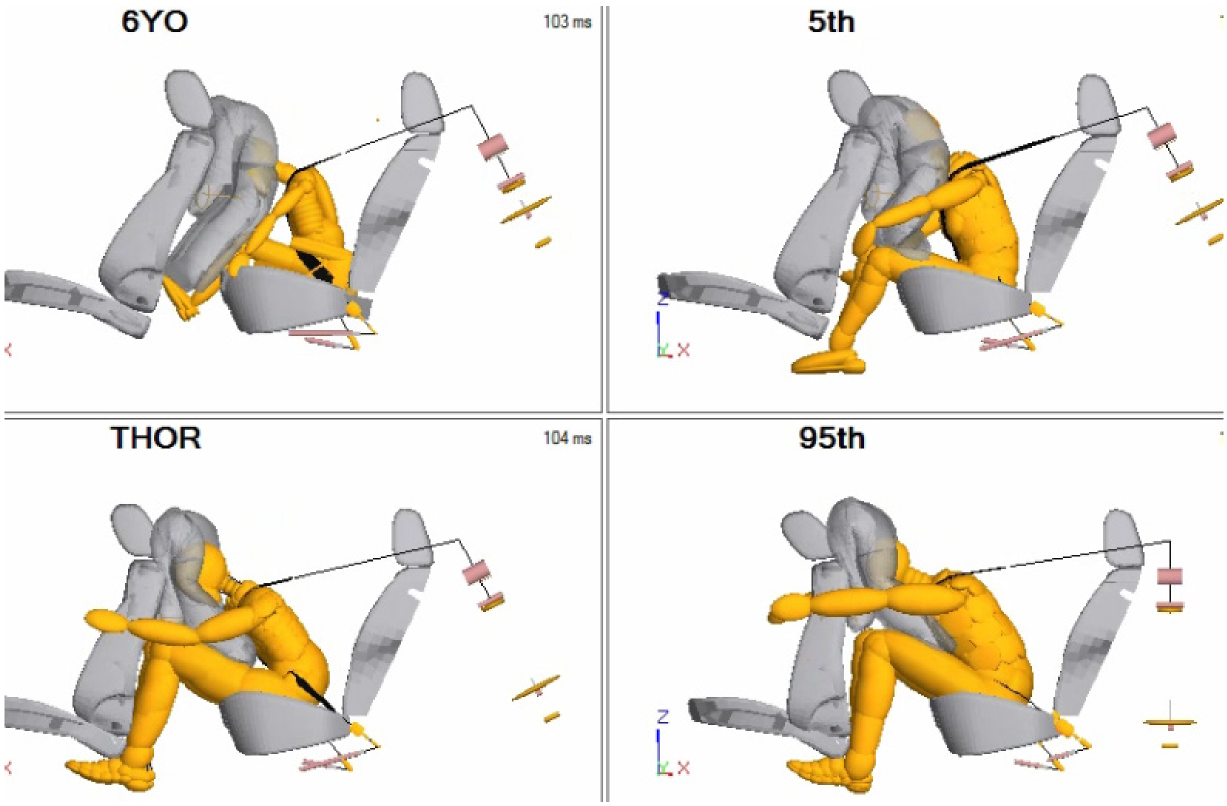

Figure 25: Driver side ATD kinematics with an advanced belt system (3-point belt with 9.0 mm torsion bar, retractor and anchor pretensioners) and a SCaRAB under severe crash pulse at 0 deg crash angle

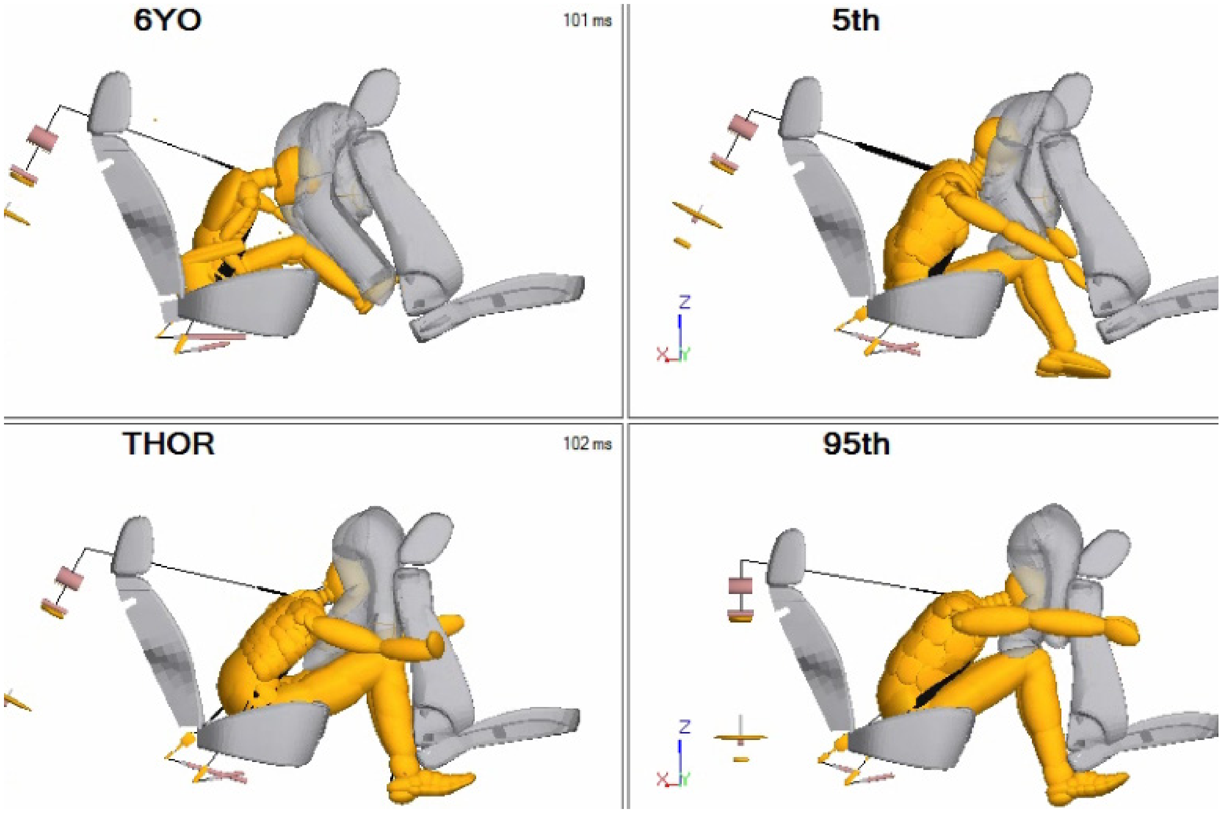

Figure 26: Passenger side ATD kinematics with an advanced belt system (3-point belt with 9.0 mm torsion bar, retractor and anchor pretensioners) and a SCaRAB under severe crash pulse at 0 deg crash angle

5.4.3 Discussion on 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 air bags 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, pretensioners 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 air bag designs (BiR or SCaRAB), the head and neck injury measures were caused by the occupant-to-air bag contact. Therefore, with air bags which are designed properly, the head and neck injury measures can be potentially reduced below those without an air bag. In that case, the 3-point belt load limit can be reduced without worrying about a hard head contact. Consequently, the air bag 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.

6 Final Series of Sled Tests With Advanced Restraints

6.1 Goal

The goal of this task was to fabricate the prototype advanced restraint systems optimized in the first two phases for rear seat occupants and to conduct sled tests to demonstrate the improvements from these systems.

6.2 Methods

Two advanced designs (a 3-point belt only design and a 3-point belt with SCaRAB) were identified through computational simulations for the soft crash pulse and severe crash pulse, respectively. However, because the proposed 3-point belt only design was optimal for the soft pulse, this design would be expected to allow too much head excursion with the severe crash pulse, leading to a head-to-front-seat contact and an increase in the head and neck IARVs. To address this problem, another belt-only design (3-point belt with a 10.5mm torsion bar, DLT, and retractor and anchor pretensioners) was developed for the final sled series. The increased load limit was expected to reduce head excursion with the severe crash pulse, thus minimizing the probability of head contact with the front seat. Note that neither of the final advanced designs can meet the FMVSS No. 209 type 2 seat belt assembly elongation requirement.

The test matrix for the final sled series is shown in Table 14. In the 0 deg tests, both soft and severe crash pulses were used, while in the 15 deg tests, only severe crash pulses were used so that the left and right side occupant responses could be compared. Note that in all the tests with the H-III6YO ATD, the same booster seat from the second sled series was used. For comparison purpose, sled tests with the 6YO ATD on booster seats using the baseline seatbelt system were also conducted to quantify the effects from booster seat on occupant injury measures.

Table 14. Test matrix for the final sled series

Sled No.	Sled Angle	Sled Pulse	Left Passenger	Left System	Right Passenger	Right System
1	0	Soft	H-III 95th	Belt Only	H-III6YO	Belt & Bag
2	0	Severe	H-III 95th	Belt & Bag	H-III6YO	Belt Only
3	0	Soft	H-III6YO	Belt Only	H-III 95th	Belt & Bag
4	0	Severe	H-III6YO	Belt & Bag	H-III 95th	Belt Only
5	0	Soft	THOR 50th	Belt Only	H-III 5th	Belt & Bag
6	0	Severe	THOR 50th	Belt & Bag	H-III 5th	Belt Only
7	0	Soft	H-III 5th	Belt Only	THOR 50th	Belt & Bag
8	0	Severe	H-III 5th	Belt & Bag	THOR 50th	Belt Only
9	15	Severe	THOR 50th	Belt Only	H-III 5th	Belt & Bag
10	15	Severe	THOR 50th	Belt & Bag	H-III 5th	Belt Only
11	15	Severe	H-III 5th	Belt Only	THOR 50th	Belt & Bag
12	15	Severe	H-III 5th	Belt & Bag	THOR 50th	Belt Only
13	15	Severe	H-III 95th	Belt Only	H-III6YO	Belt & Bag
14	15	Severe	H-III 95th	Belt & Bag	H-III6YO	Belt Only
15	15	Severe	H-III6YO	Belt Only	H-III 95th	Belt & Bag
16	15	Severe	H-III6YO	Belt & Bag	H-III 95th	Belt Only

System	Anchor PT	DLT	Retractor PT	Load Limiter	Air bag
Belt Only	X	X	X	10.5 mm	None
Belt & Bag	X	X	X	9 mm	SCaRAB

6.3 Results

6.3.1 H-III 6YO ATD

The kinematics and injury measures of the 6YO ATD with four different restraint systems (baseline belt without booster, baseline belt with booster, advanced-belt only, and advanced-belt with SCaRAB) and under 4 crash conditions (0 deg soft pulse, 0 deg severe pulse, 15 deg right passenger, and 15 deg left passenger) are shown in Figures 27 and 28. Note that all of the 15 deg crashes were performed with the severe crash pulse. 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.

Figure 27: 6YO ATD kinematics with four restraints at four crash conditions
Images for left passenger were all mirrored.

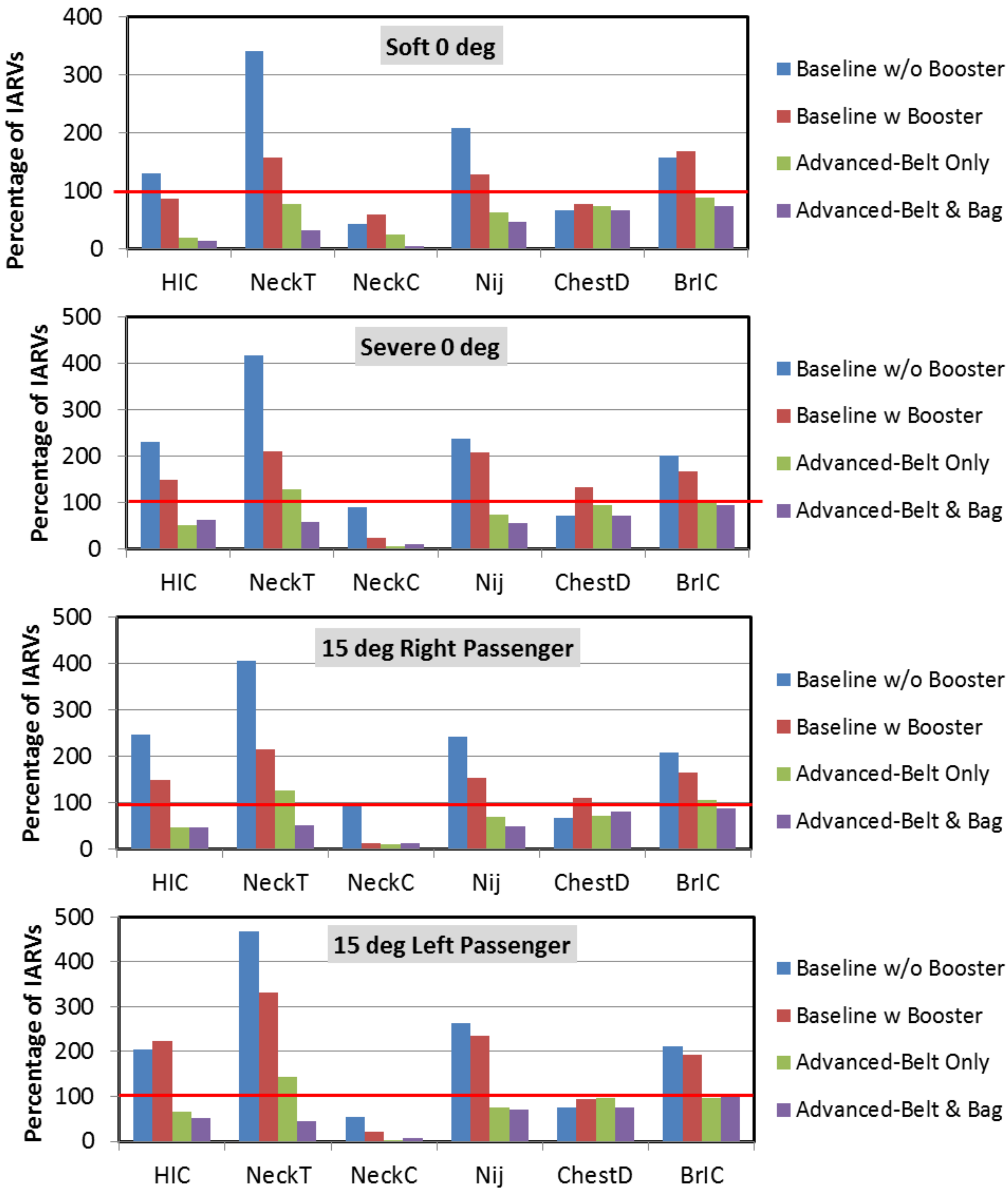

Figure 28: 6YO ATD injury measures with four restraints at four crash conditions
Red lines represent 100 percent of IARVs.

6.3.2 H-III 5th female ATD

The kinematics and injury measures of the 5th ATD with three restraints (baseline belt, advanced-belt only, and advanced-belt with SCaRAB) under four crash conditions (0 deg soft pulse, 0 deg severe pulse, 15 deg right passenger, and 15 deg left passenger) are shown in Figures 29 and 30. Note that all the 15 deg crashes were performed with the severe crash pulse. 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 BrIC under 15 deg crashes. Compared to the belt-only design, the design with SCaRAB reduced almost all the injury measures.

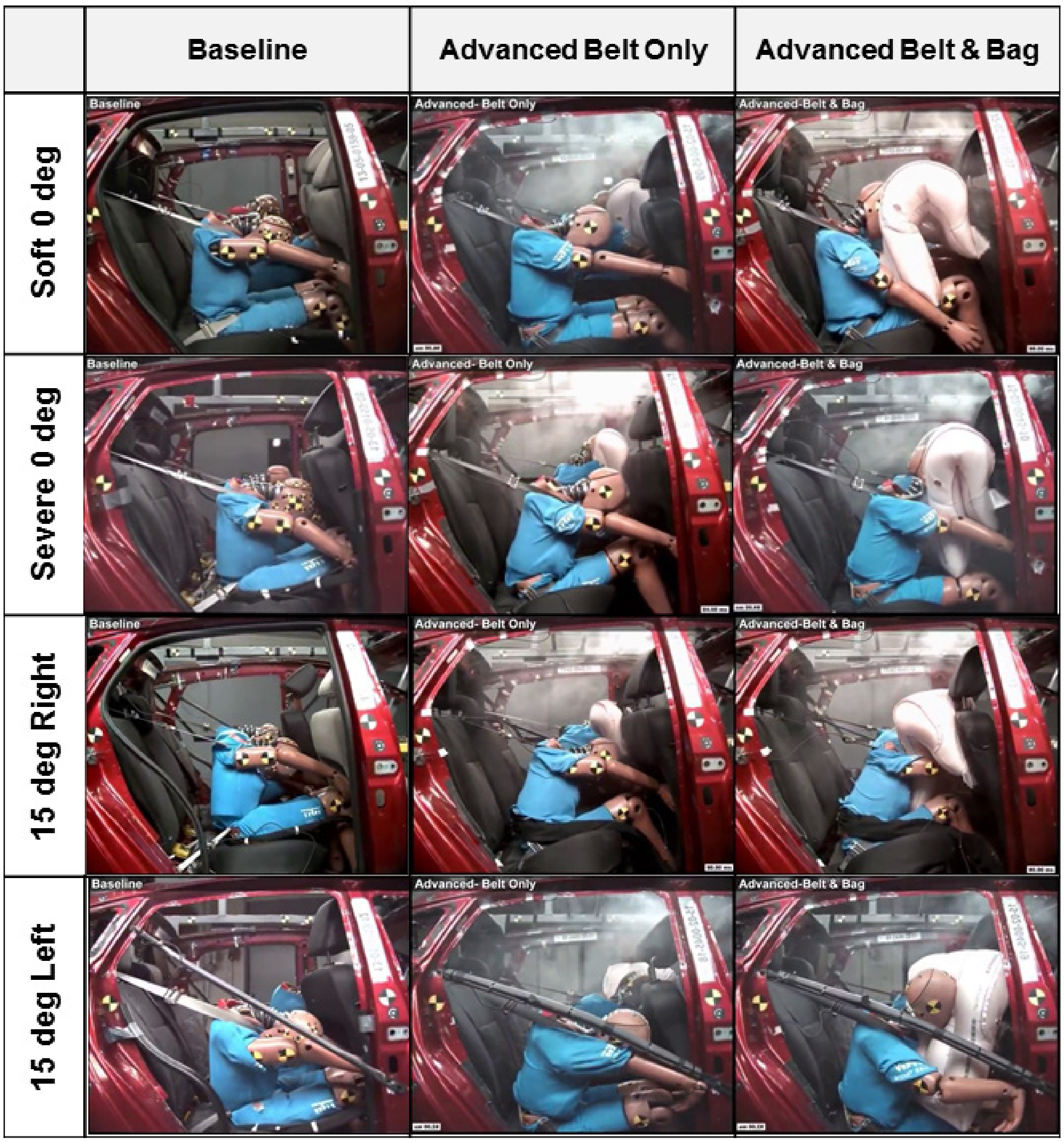

Figure 29: 5th ATD kinematics with three restraints at four crash conditions
Images for left passenger were all mirrored.

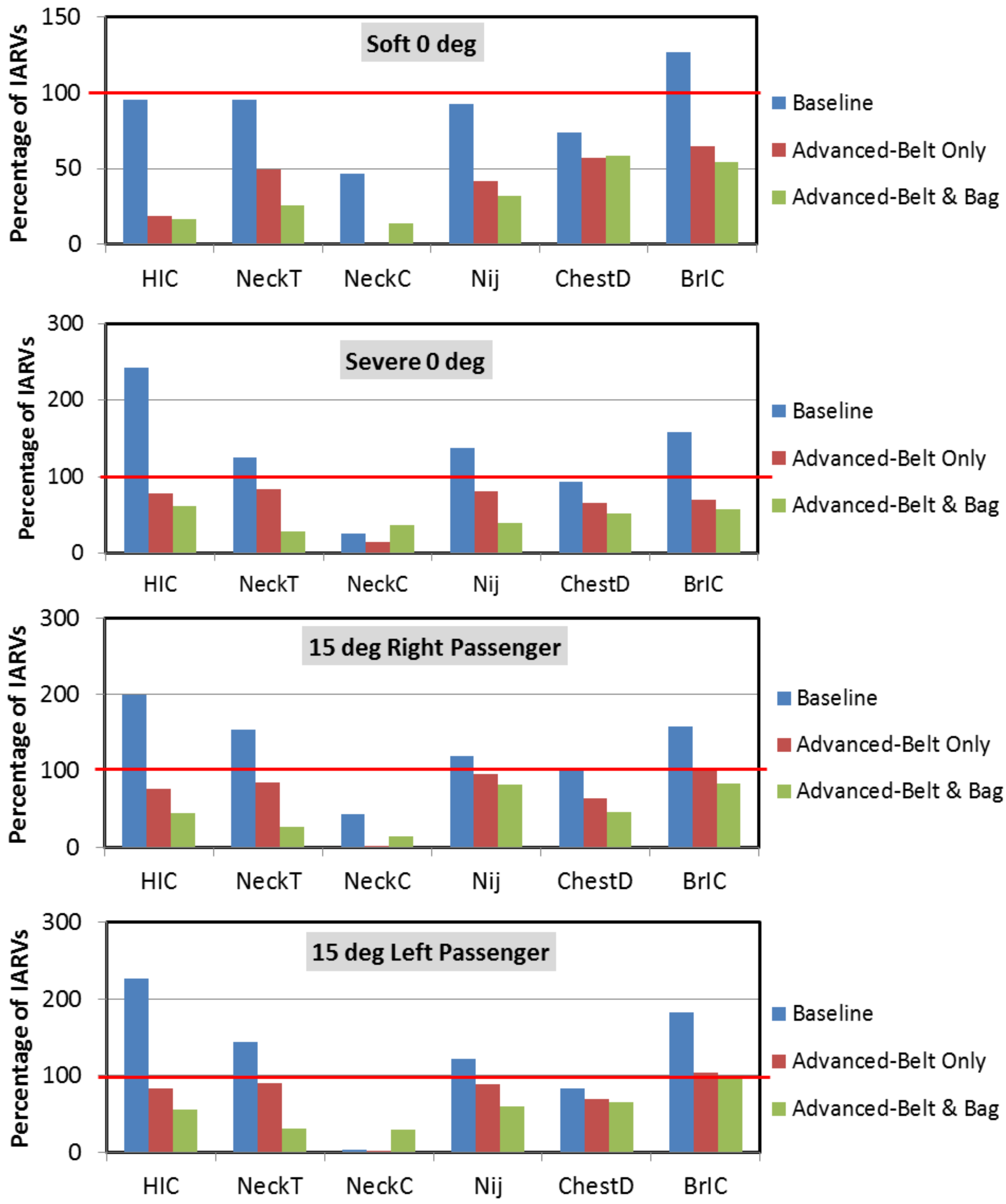

Figure 30: 5th ATD injury measures with three restraints at four crash conditions
Red lines represent 100 percent of IARVs.

6.3.3 THOR 50th male ATD

The kinematics and injury measures of the THOR 50th with three restraints (baseline belt, advanced-belt only, and advanced-belt with SCaRAB) under four crash conditions (0 deg soft pulse, 0 deg severe pulse, 15 deg right passenger, and 15 deg left passenger) are shown in Figures 31 and 32. Note that all the 15 deg crashes were performed with the severe crash pulse. 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 both advanced designs, and the HIC and neck tension with advanced-belt only design were much higher than the IARVs. In general, the advanced restraint designs did not reduce the chest deflection and neck extension from the baseline tests.

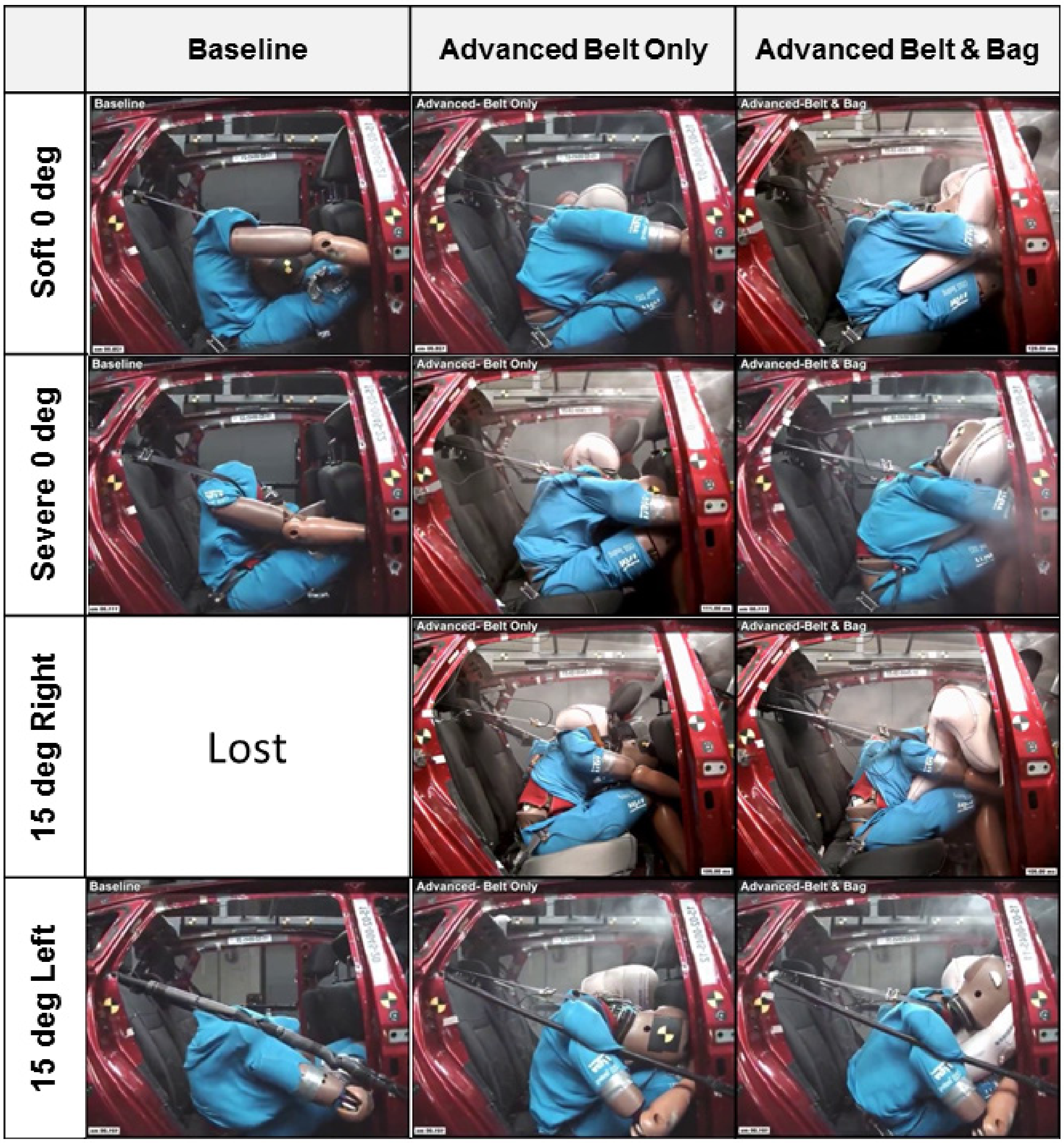

Figure 31: THOR 50th kinematics with three restraints at four crash conditions
Images for left passenger were all mirrored.

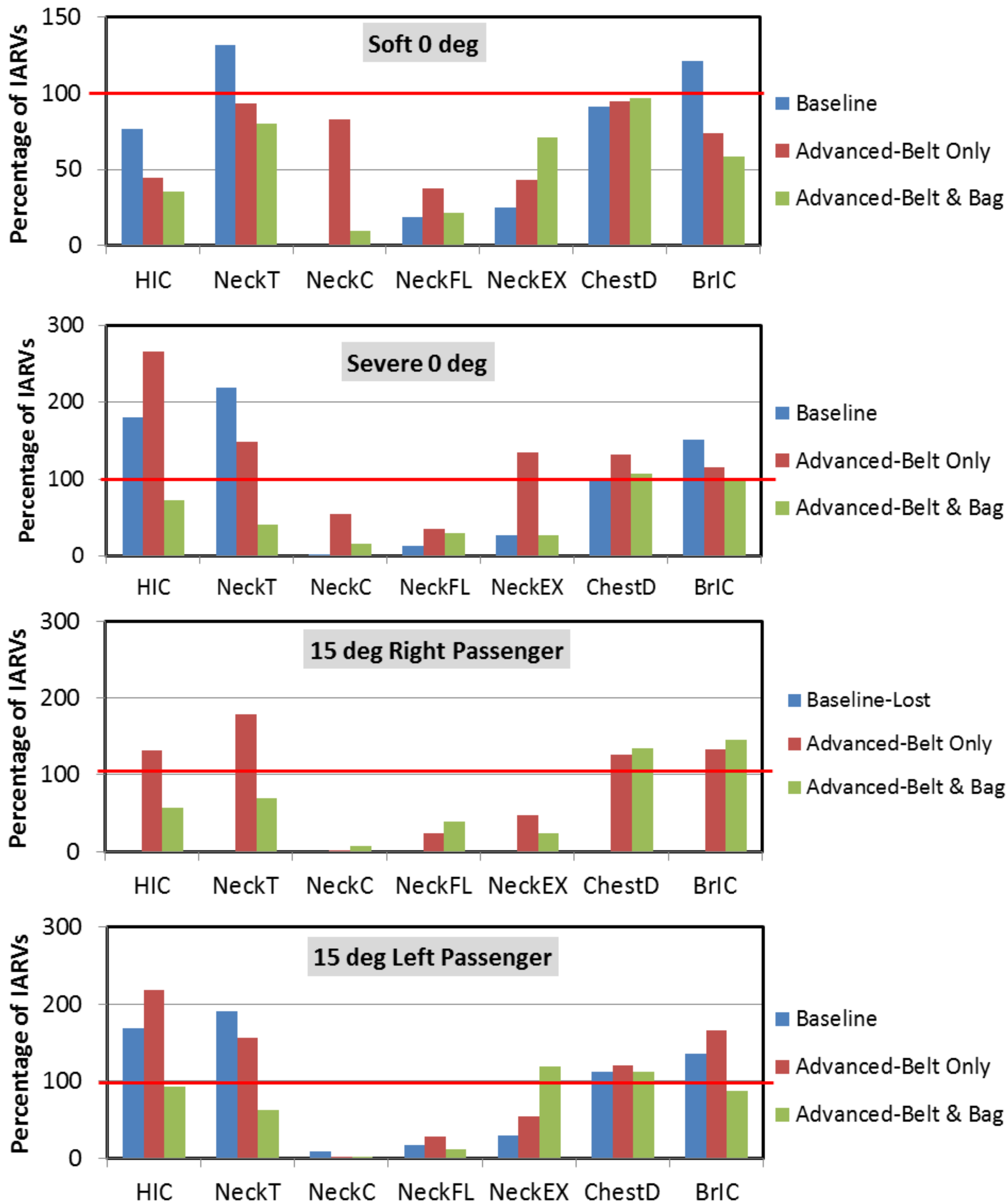

Figure 32: THOR 50th injury measures with three restraints at four crash conditions
Red lines represent 100 percent of IARVs.

The chest deflection results at four locations of the THOR 50th are shown in Figure 33. It is clear that the maximal chest deflection is 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.

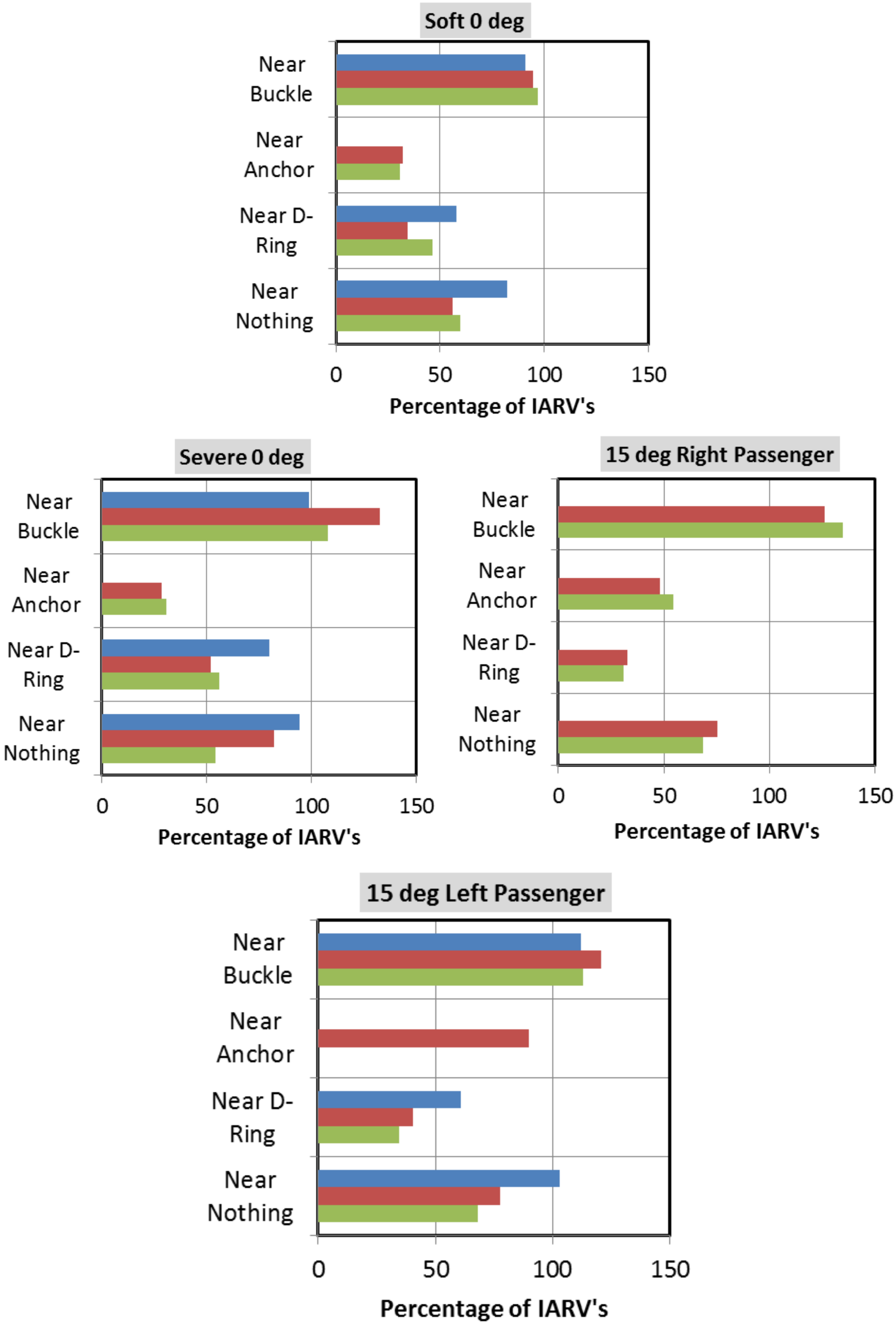

Figure 33: THOR 50th chest deflections at four locations with three restraints at four crash conditions

6.3.4 H-III 95th male ATD

The kinematics and injury measures of the 95th ATD with three restraint configurations (baseline belt, advanced-belt only, and advanced-belt with SCaRAB) under four crash conditions (0 deg soft pulse, 0 deg severe pulse, 15 deg right passenger, and 15 deg left passenger) are shown in Figures 34 and 35. Note that all the 15 deg crashes were performed with the severe crash pulse. With the advanced belt and SCaRAB, all the injury measures were below the IARVs except for one, BrIC. With the advanced belt only design, all the injury measures were below the IARVs except for the HIC and BrIC under severe crashes. Compared to the belt-only design, the advanced belt design with SCaRAB reduced almost all the injury measures.

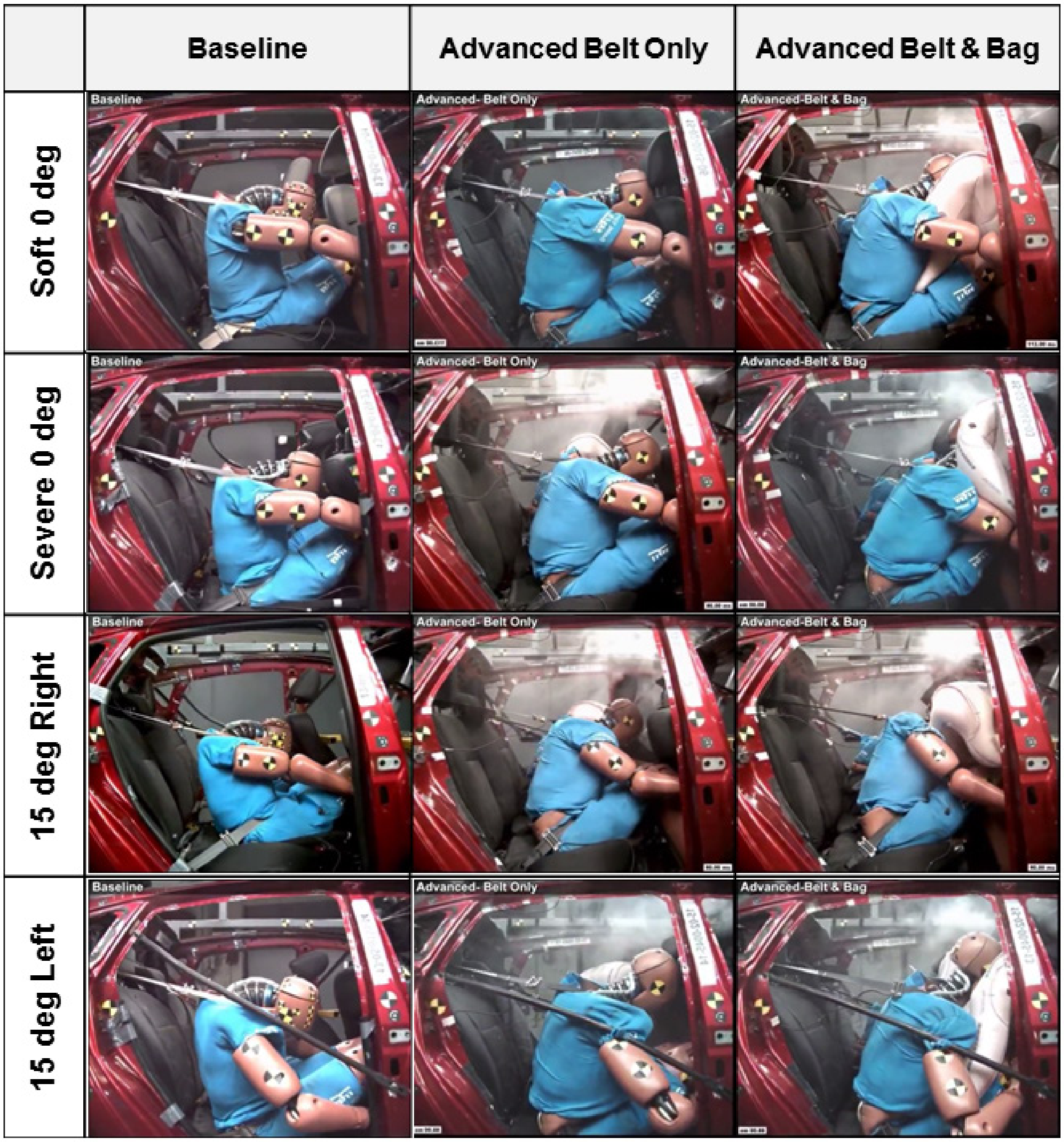

Figure 34: 95th ATD kinematics with three restraints at four crash conditions

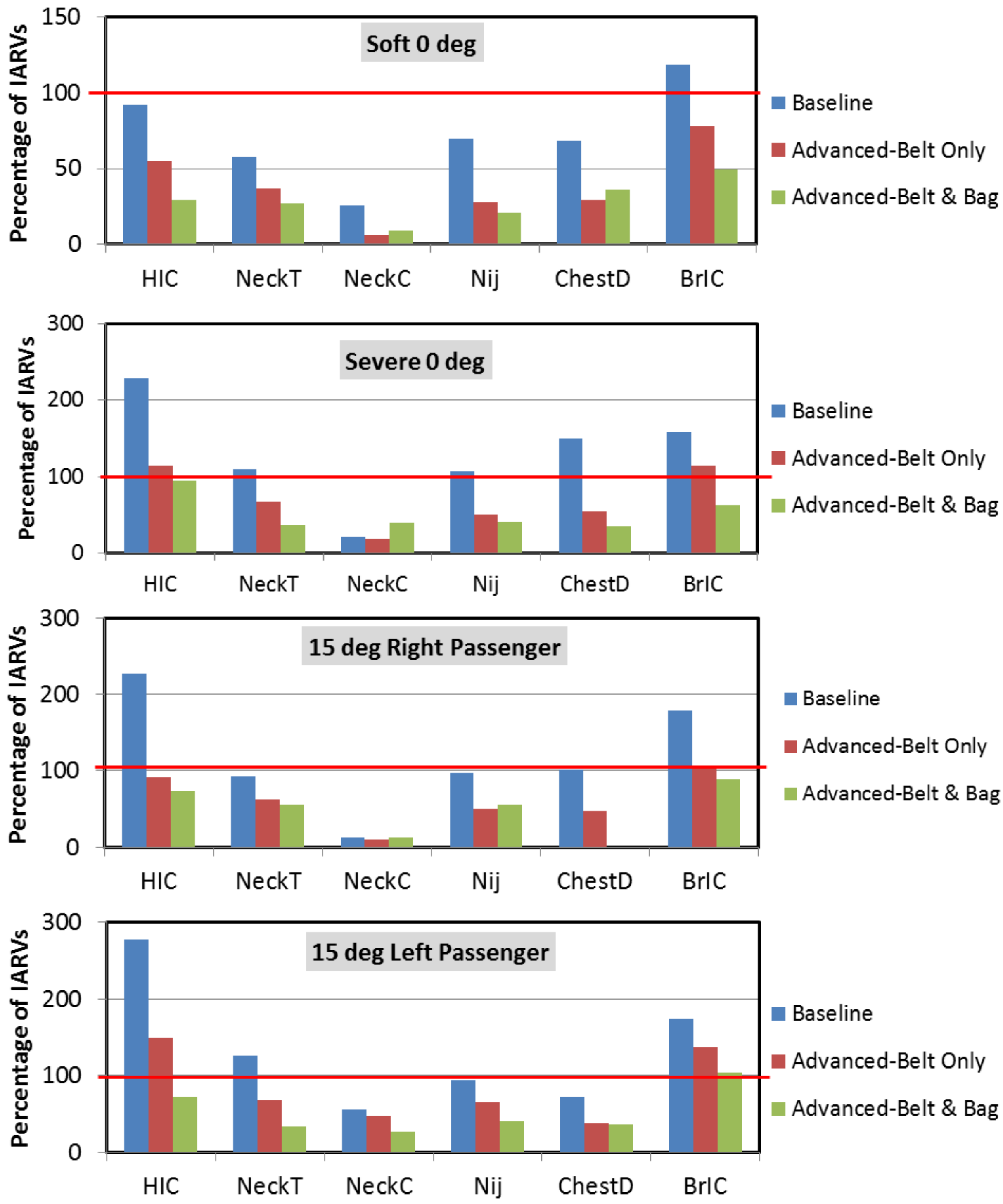

Figure 35: 95th ATD injury measures with three restraints at four crash conditions
Red lines represent 100 percent of IARVs.

6.4 Summary of the comparison between the baseline and final sled series

Tables 15 to 18 show the injury risk reductions for the four ATDs from the baseline restraint to the two advanced restraints. The injury risks were calculated based on the injury risk curves associated with each injury measure, 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 four crash conditions. The only exceptions are all associated with the THOR 50th.

Under the soft crash pulse, all the injury measures were reduced from the baseline design to be below the IARVs with both advanced restraint countermeasure configurations. Under the severe crash pulse, a majority of the injury measures were reduced to be below the IARVs. For the advanced belt without SCaRAB design, IARVs were exceeded for the neck tension and BrIC for the 6YO, BrIC for the 5th HIC, Nij, chest deflection, and BrIC for the THOR 50th, and HIC and BrIC for the 95th ATD. For the design with the SCaRAB, the IARVs were exceeded for chest deflection and BrIC for the THOR 50th, and BrIC for the 95th ATD. In general, the design with the SCaRAB had lower injury measures than the advanced-belt only design.

Table 15. Injury risk reductions for the 6YO ATD by using two advanced restraints

Condition		Injury Risk Reduction	HIC	Neck T	Neck C	Nij	Chest D	BrIC
6YO	Soft 0 deg	Belt Only	-7.9%	-95.6%	-2.1%	-21.4%	-4.0%	-57.3%
		Belt & Bag	-7.9%	-98.9%	-2.1%	-24.4%	-8.9%	-69.9%
	Severe 0 deg	Belt Only	-23.5%	-14.7%	0.0%	-55.7%	-38.6%	-40.3%
		Belt & Bag	-21.7%	-99.5%	0.0%	-59.7%	-63.8%	-50.5%
	15 deg Right	Belt Only	-23.7%	-18.7%	0.0%	-31.0%	-43.4%	-38.8%
		Belt & Bag	-23.7%	-99.7%	0.0%	-35.5%	-35.1%	-55.5%
	15 deg Left	Belt Only	-41.1%	-4.1%	0.0%	-65.0%	3.9%	-51.1%
		Belt & Bag	-43.0%	-99.8%	0.0%	-66.4%	-20.8%	-48.6%
	Mean	**Belt Only**	**-24.1%**	**-33.3%**	**-0.5%**	**-43.3%**	**-20.5%**	**-46.9%**
		Belt & Bag	**-24.1%**	**-99.5%**	**-0.5%**	**-46.5%**	**-32.2%**	**-56.1%**

Table 16. Injury risk reductions for the 5th ATD by using two advanced restraints

Condition		Injury Risk Reduction	HIC	Neck T	Neck C	Nij	Chest D	BrIC
5th	Soft 0 deg	Belt Only	-9.9%	-17.1%	-0.1%	-11.3%	-12.6%	-56.2%
		Belt & Bag	-9.9%	-17.3%	-0.1%	-12.7%	-11.9%	-62.9%
	Severe 0 deg	Belt Only	-43.3%	-74.7%	0.0%	-20.7%	-29.6%	-69.8%
		Belt & Bag	-46.3%	-80.6%	0.1%	-29.3%	-37.9%	-78.8%
	15 deg Right	Belt Only	-33.1%	-91.5%	-0.1%	-8.7%	-41.0%	-39.6%
		Belt & Bag	-37.7%	-98.6%	-0.1%	-12.6%	-50.0%	-58.6%
	15 deg Left	Belt Only	-38.4%	-85.3%	0.0%	-11.8%	-14.9%	-44.2%
		Belt & Bag	-43.2%	-96.3%	0.0%	-19.0%	-18.0%	-47.6%
	Mean	**Belt Only**	**-31.2%**	**-67.2%**	**-0.1%**	**-13.1%**	**-24.5%**	**-52.5%**
		Belt & Bag	**-34.3%**	**-73.2%**	**0.0%**	**-18.4%**	**-29.5%**	**-62.0%**

Table 17. Injury risk reductions for the THOR 50th by using two advanced restraints

Condition		Injury Risk Reduction	HIC	Neck T	Neck C	Chest D (27YO)	Chest D (60YO)	BrIC
THOR 50th	Soft 0 deg	Belt Only	-4.7%	-73.7%	0.0%	6.9%	1.9%	-44.3%
		Belt & Bag	-5.3%	-84.1%	0.0%	10.3%	2.5%	-55.4%
	Severe 0 deg	Belt Only	20.5%	-2.4%	0.0%	42.2%	0.6%	-25.2%
		Belt & Bag	-28.6%	-99.9%	0.0%	15.4%	0.6%	-40.7%
	15 deg Right*	Belt Only	-	-	-	-	-	-
		Belt & Bag	-	-	-	-	-	-
	15 deg Left	Belt Only	12.9%	-1.1%	0.0%	11.5%	0.0%	13.7%
		Belt & Bag	-21.2%	-99.1%	0.0%	1.6%	0.0%	-43.1%
	Mean	**Belt Only**	**9.6%**	**-25.7%**	**0.0%**	**20.2%**	**0.8%**	**-18.6%**
		Belt & Bag	**-18.4%**	**-94.4%**	**0.0%**	**9.1%**	**1.0%**	**-46.4%**

*The baseline test for the THOR 50th on the right side and under 15 deg severe crash pulse was not successful.

Table 18. Injury risk reductions for the 95th ATD by using two advanced restraints

Condition		Injury Risk Reduction	HIC	Neck T	Neck C	Nij	Chest D	BrIC
95th	Soft 0 deg	Belt Only	-7.0%	-0.4%	0.0%	-7.1%	-14.4%	-38.9%
		Belt & Bag	-9.0%	-0.5%	0.0%	-7.8%	-13.5%	-58.7%
	Severe 0 deg	Belt Only	-31.3%	-45.1%	0.0%	-14.9%	-83.0%	-28.9%
		Belt & Bag	-36.3%	-46.2%	0.0%	-16.7%	-88.2%	-75.9%
	15 deg Right	Belt Only	-36.5%	-12.8%	0.0%	-11.5%	-47.2%	-44.8%
		Belt & Bag	-40.5%	-13.2%	0.0%	-10.4%	-	-57.8%
	15 deg Left	Belt Only	-31.7%	-79.8%	0.0%	-7.8%	-16.7%	-14.6%
		Belt & Bag	-51.6%	-81.2%	0.0%	-12.5%	-17.1%	-42.8%
	Mean	**Belt Only**	**-26.6%**	**-34.5%**	**0.0%**	**-10.3%**	**-40.3%**	**-31.8%**
		Belt & Bag	**-34.4%**	**-35.3%**	**0.0%**	**-11.9%**	**-39.6%**	**-58.8%**

Based on the injury risk reduction shown in Tables 15 to 18, both advanced restraint systems reduced the injury risks from the baseline tests substantially in 6YO, 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 four 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 6YO, 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.

7 Summary

In this study, three series of sled tests (baseline tests, advanced restraint trail tests, and a final series of tests), two series of model validations (against each of the first two series of sled tests), and design optimizations using the validated computational models were conducted to investigate rear seat occupant protection with a range of occupant sizes, crash pulses, impact angles, and front seat locations.

7.1 Baseline Tests

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, in that chest injuries are the most common serious injuries in rear seat adult occupants. The H-III 6YO ATD submarined in all the tests conducted without a booster seat due to the slouching pre-crash posture. No head-to-front seat contact occurred in any of the tests with the 6YO ATD, which is contrary to field data analyses showing that the head is the most commonly injured body region for children. In the field, head injuries in children may be generally associated with poor shoulder belt fit, certain types of belt misuse, or crash kinematics different from those evaluated. However, further investigations are needed. Submarining also occurred for the HIII 5th H-IIIATD in all the tests under a severe crash pulse in the first sled series, indicating that smaller occupants may be more likely to submarine than larger occupants.

7.2 Advanced Restraint Trial Tests

Compared to the baseline rear seat belt series, in the second sled series tests were conducted with only the 0 deg severe crash pulse, which is the most severe crash condition. The advanced restraints generally resulted in reduced injury measures for rear seat occupants. Pretensioners were very effective in helping the seat belt engage the ATD earlier and in turn reduce the chest deflection and head excursion. Submarining did not occur in any tests in the second sled series with 6YO or 5th H-III ATD. For the 6YO ATD, this was likely due to the use of a booster seat, while for the 5th H-III, it is mainly a result of using anchor/buckle pretensioner, DLT, and load limiter. Because only a few advanced restraint design prototypes were tested with little tuning, specific conclusions on which type of advanced restraints served the best for the rear seat occupant responses could not be drawn from this test series. However, the results showed that inflatable belts provided similar, but not better restraint to the 6YO and 5th ATDs, and 50th ATD than the 3-point belt with pretensioners and load limiter. The 4-point belt generally performed well for all the ATDs. However, it generated slightly higher chest deflection with all the ATDs than that obtained with the 3-point belt with pretensioners and load limiter. Because of their cushion ability, air bag concepts, including BiR and SCaRAB, have the potential to allow further reduction of the torsion bar diameter in the retractor (resulting in a reduction in load limit) in the seat belts without producing a hard head contact to the front seat. This would allow both shoulder belt load and chest deflection to be reduced with additional system optimization when compared to 3-point belt only designs. However, the chest deflection of the THOR 50th was not sensitive to any of the advanced restraints, because the highest chest deflection always occurred at the lower chest close to the buckle and the load limiter was only effective to reduce the deflections on the upper chest region.

7.3 Model Development and Validation

A set of MADYMO models, including four ATD models, rear seat model, front seat models, and restraint system models, were developed and integrated. Model validations were conducted against both the baseline sled tests and the second series of tests with advanced restraints. The seat contact characteristics and belt slacks were tuned through optimizations based on the baseline tests, and the models were further adjusted to match the test results with advanced restraints. Good correlations between the tests and simulations were achieved.

7.4 Design Optimizations

Design optimizations were conducted for the 3-point belt only design, and 3-point belt with either the BiR or the SCaRAB. The combined chest injury risks of three adult ATDs was considered as the objective function of the optimization, while all the other injury measures were considered as the optimization constraints, which were required to be below the corresponding IARVs. None of the 3-point belt only design met all the constraints under the severe crash pulse, and five 3-point belt only designs met all the constraints under a soft crash pulse. Under the severe crash pulse, six designs with SCaRAB met all constraint requirements. During the optimization process, direct conflict between the head excursion and chest deflection was found for all H-III ATDs without an air bag, as lower load limits generally reduced the chest deflection they increased the head excursion to potentially cause a head-to-front seat contact. Although adding an air bag cannot reduce the chest deflection directly, it may reduce the hard contact to the head, which allows a lower load limit to be used, decreasing chest deflection.

7.5 Final Sled Series

Two advanced restraint designs were selected for the final sled series. The advanced belt-only design included a 3-point belt with retractor and anchor pretensioners, a 10.5 mm torsion bar for load limiting, and a DLT. The advanced belt plus bag design included a 3-point belt with retractor and anchor pretensioners, a 9.0 mm torsion bar for load limiting, a DLT, and a SCaRAB. Neither of the final advanced designs can meet the FMVSS No. 209 type 2 seat belt assembly elongation requirement. The final sled series allowed a direct comparison of the performance between the baseline, advanced-belt only, and advanced-belt and bag designs under different crash conditions.

Under the soft crash pulse, both the advanced restraints were able to reduce all the injury measures below the IARVs for all the four ATDs. Both advanced restraints also reduced almost all the injury measures for the 6YO, 5th, and 95th ATDs under the severe crash pulse. The design with the SCaRAB generally provided lower injury measures than those using the advanced belt-only design. However, neither of the advanced restraints reduced the peak chest deflections for the THOR 50th, because among the chest deflection measures at the four locations the highest chest deflection always occurred at the lower chest location close to the buckle. In these tests, the load limiter reduced the chest deflections of the THOR 50th only at the upper chest locations.

7.6 Limitation

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.

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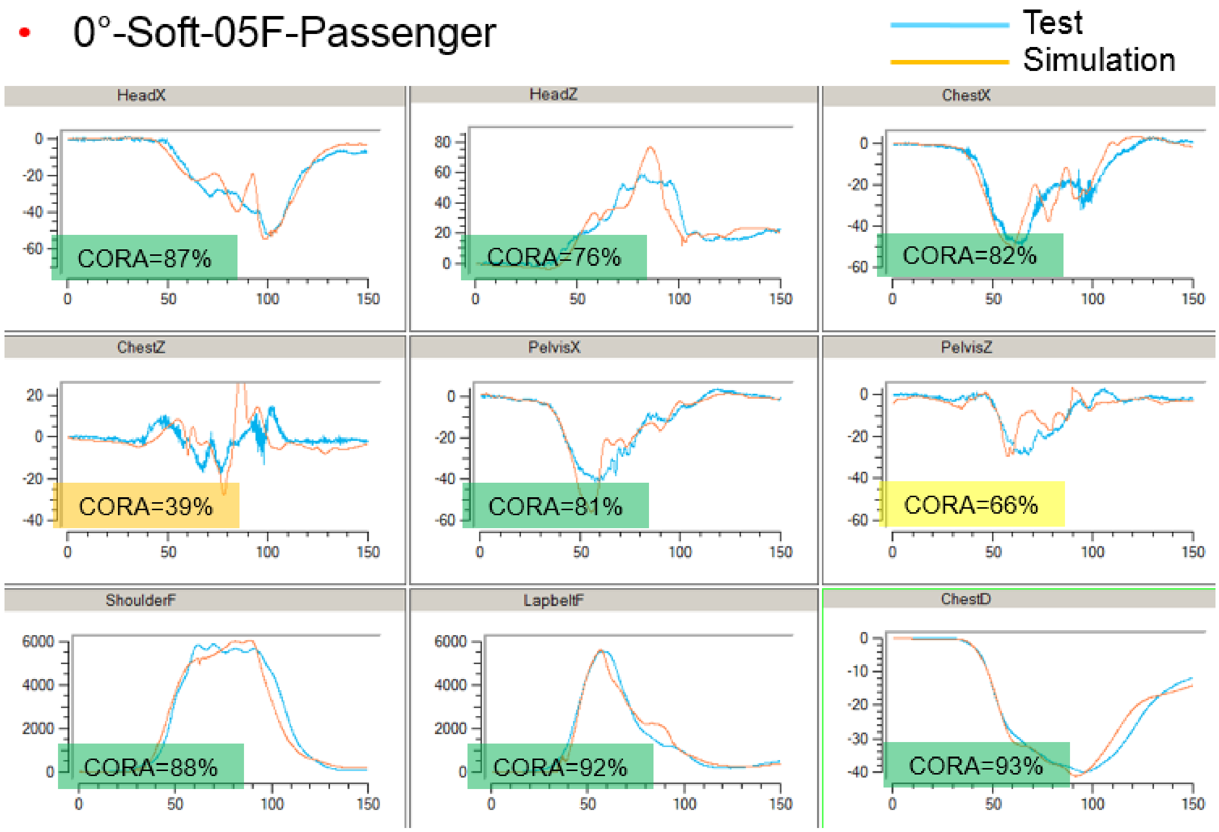
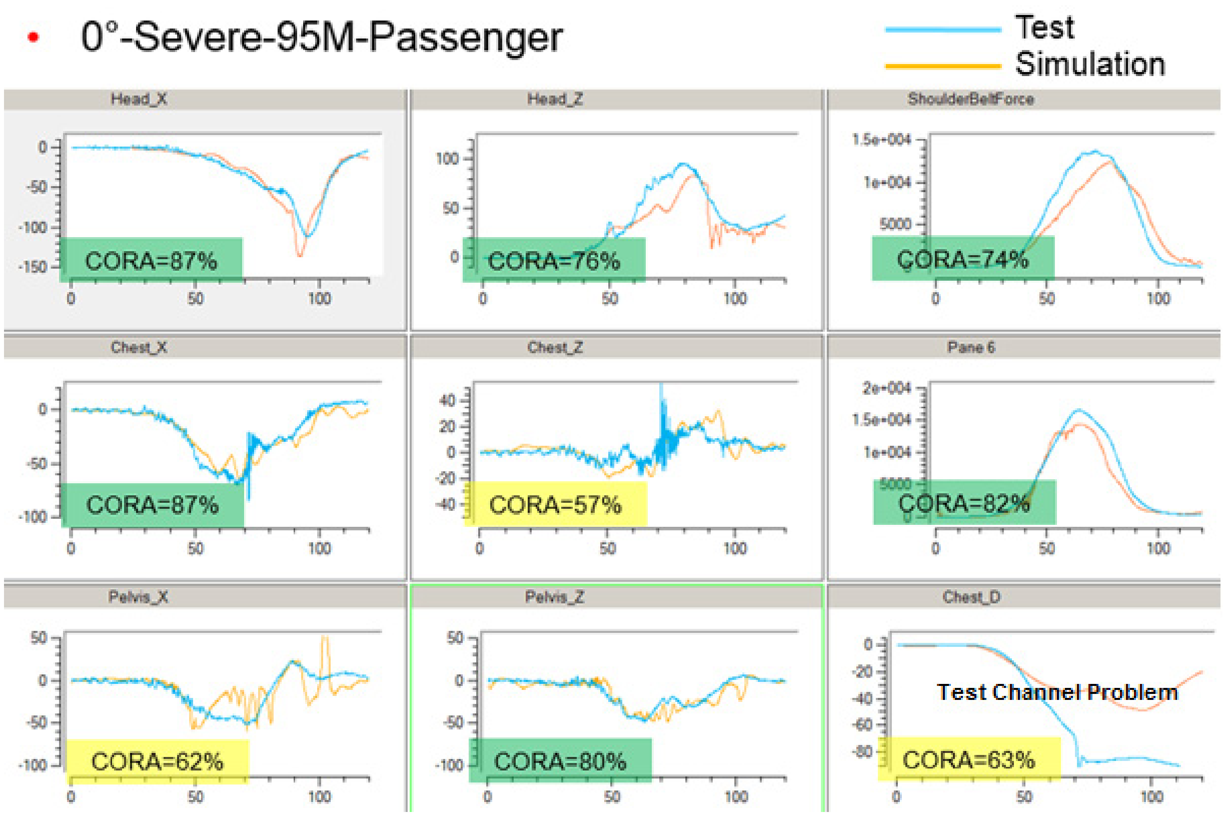
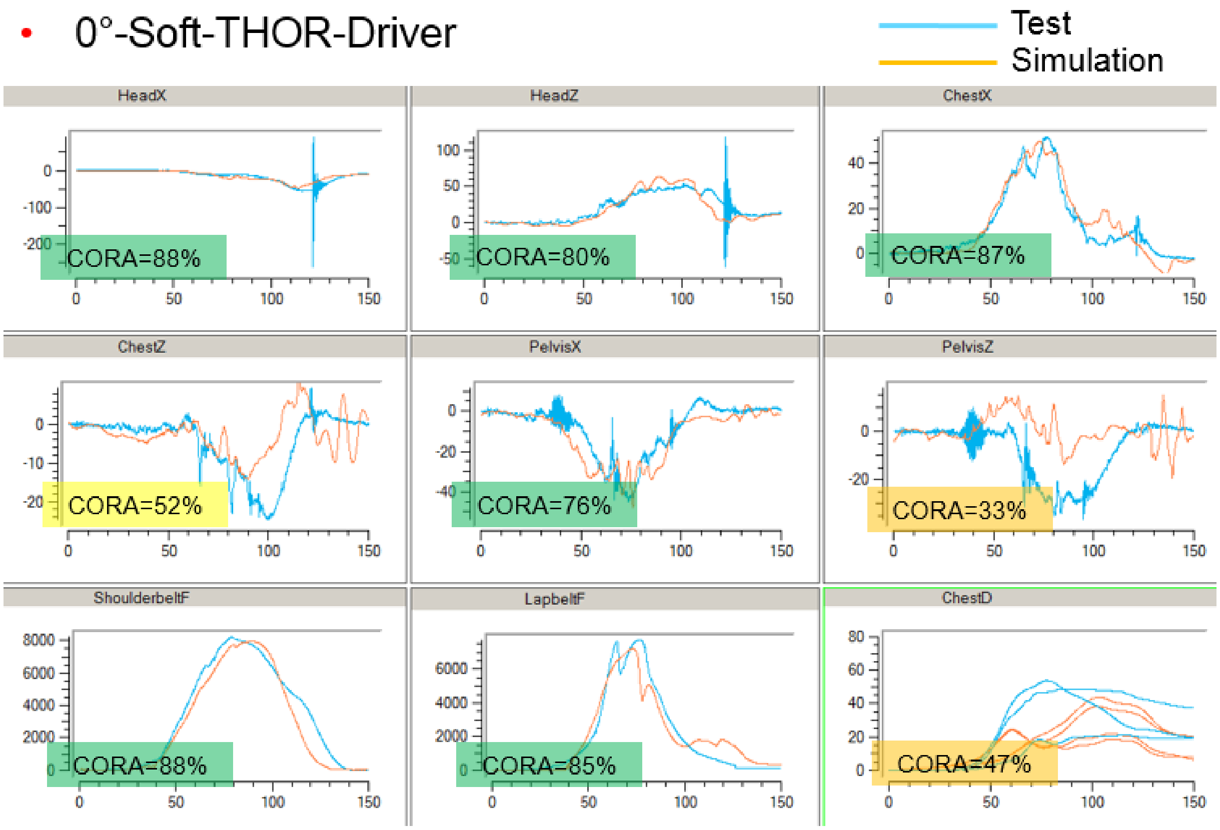
Appendix A: Examples of baseline model validation



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Test
Simulation
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CORA=88%
HeadZ
CORA=80%
ChestX
CORA=87%
ChestZ
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PelvisX
CORA=76%
PelvisZ
CORA=33%
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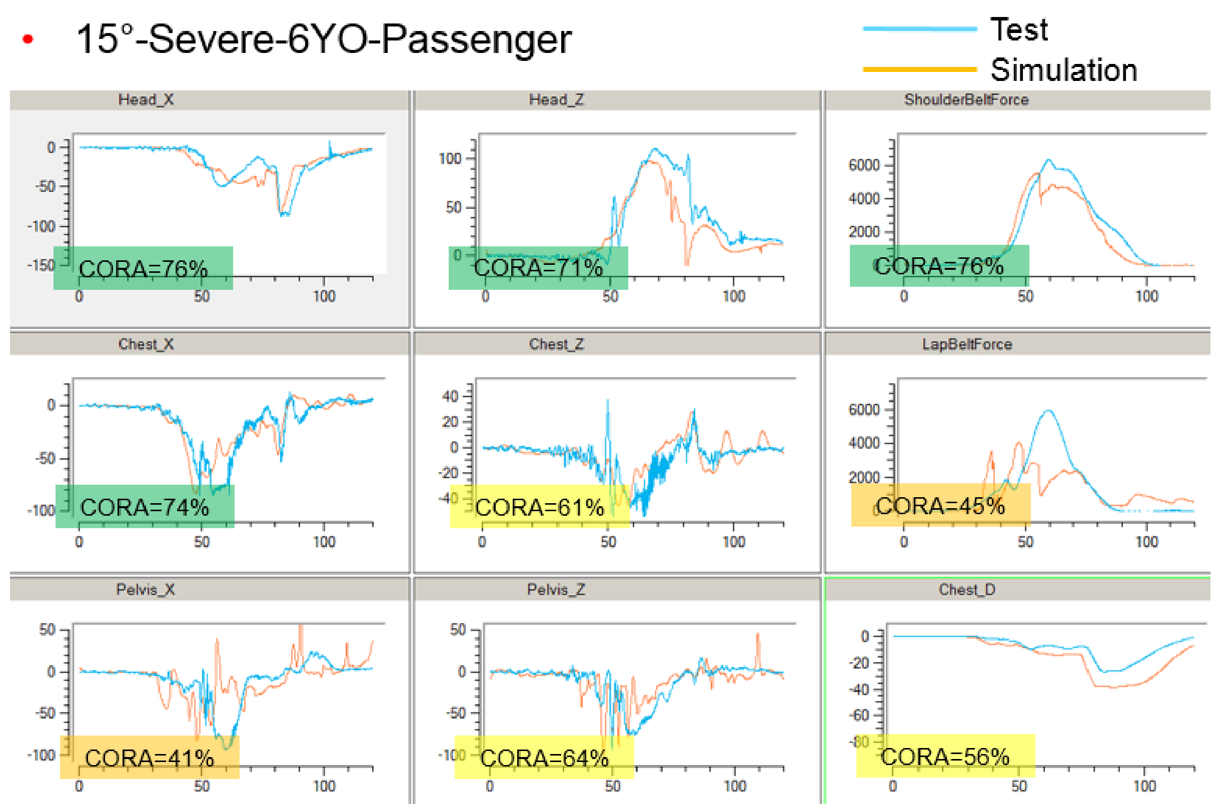
CORA=88%
LapbeltF
CORA=85%
ChestD
CORA=47%


15°-Severe-6YO-Passenger
Test
Simulation
Head_X
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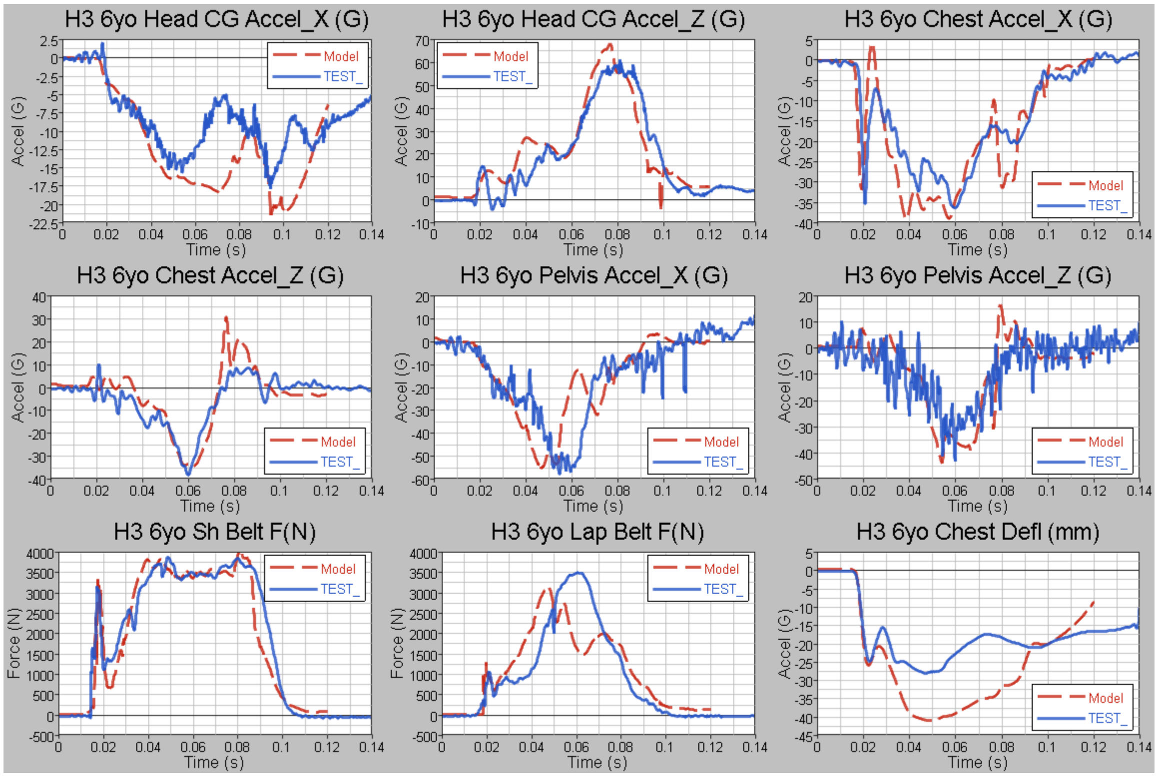
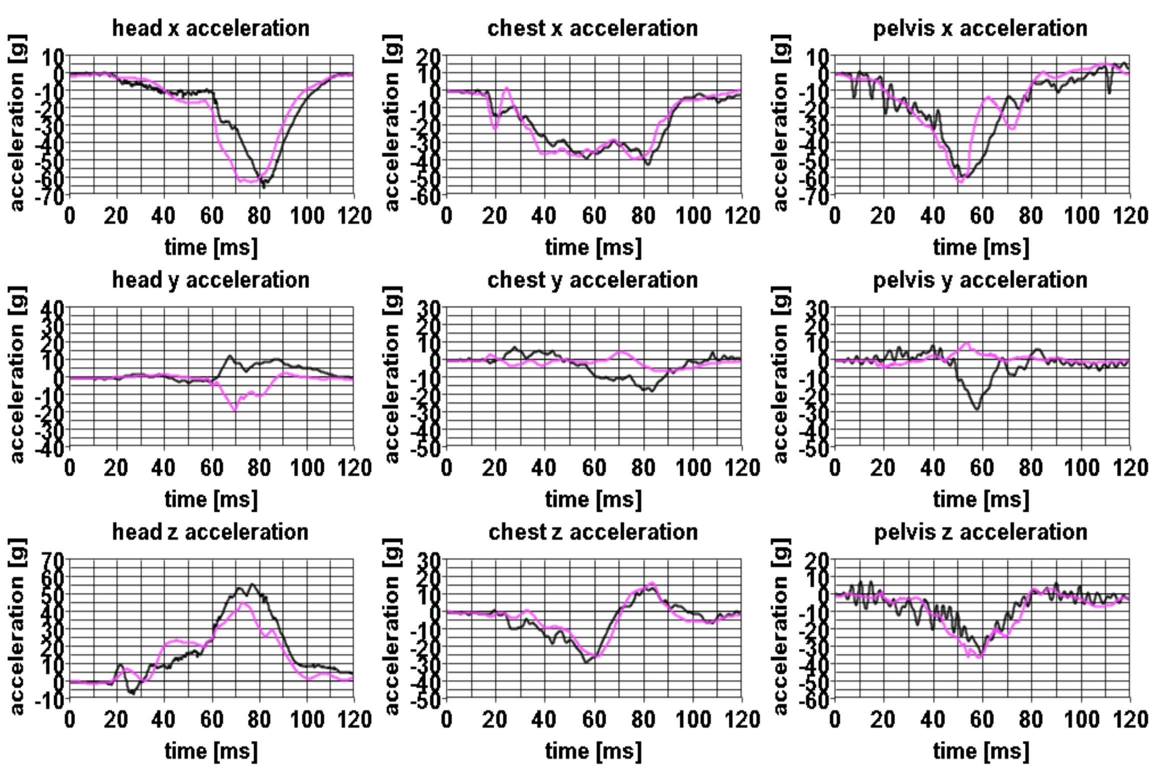
Head_Z
CORA=71%
ShoulderBeltForce
CORA=76%
Chest_X
CORA=74%
Chest_Z
CORA=61%
LapBeltForce
CORA=45%
Pelvis_X
CORA=41%
Pelvis_Z
CORA=64%
Chest_D
CORA=56%

Appendix B: Examples of model validation against sled tests with advanced restraints

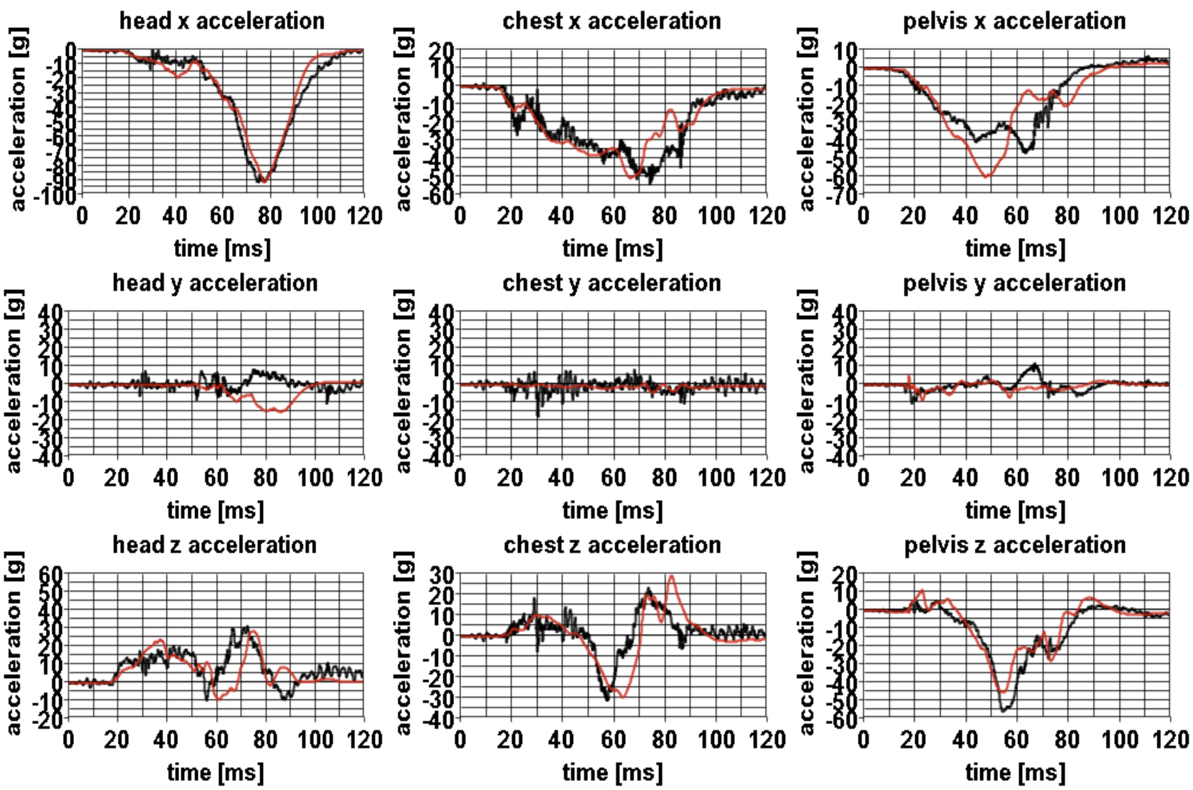
6YO 3-point Belt



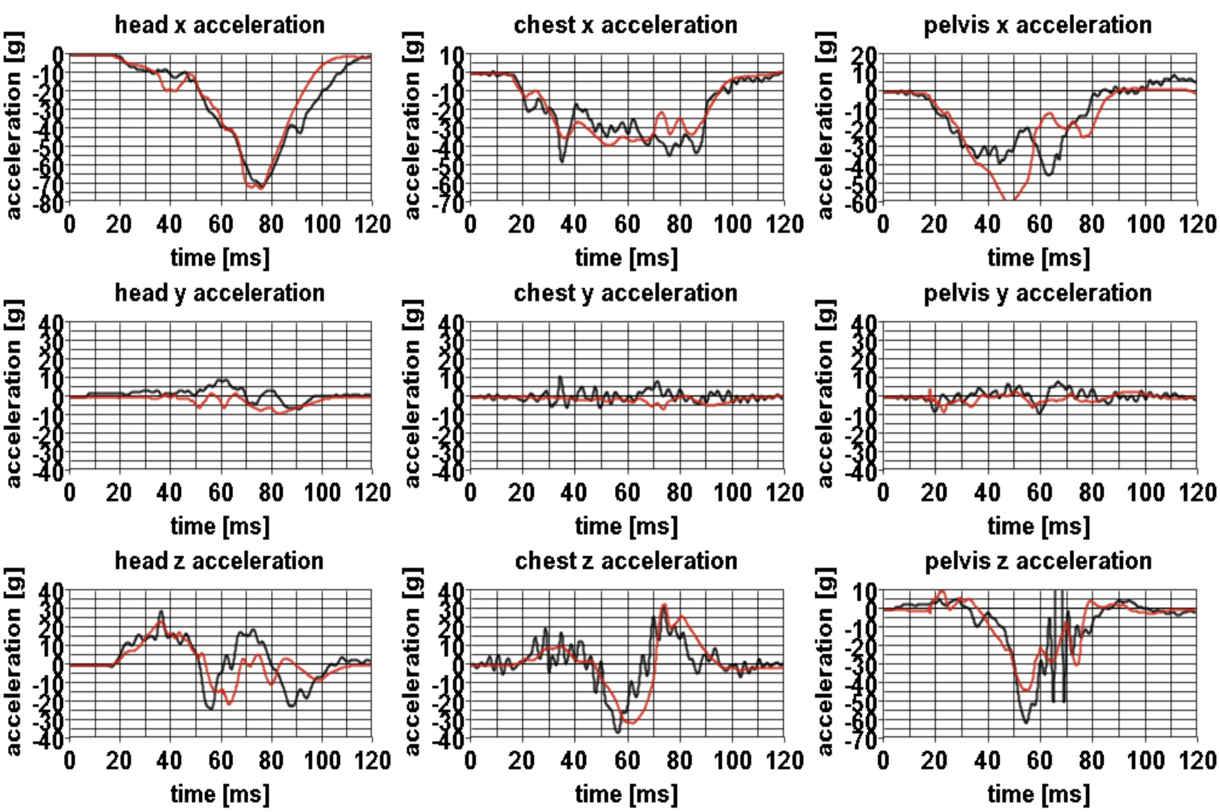
6YO BiR



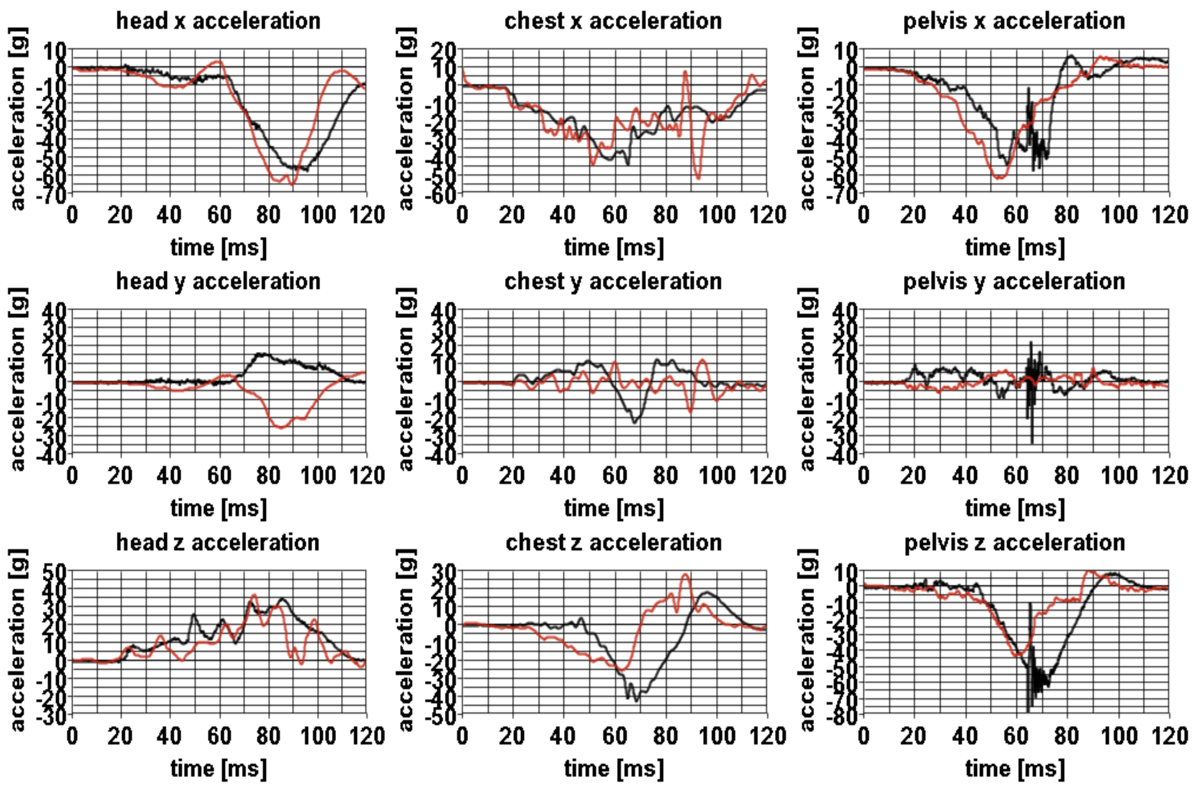
5th ATD BiR



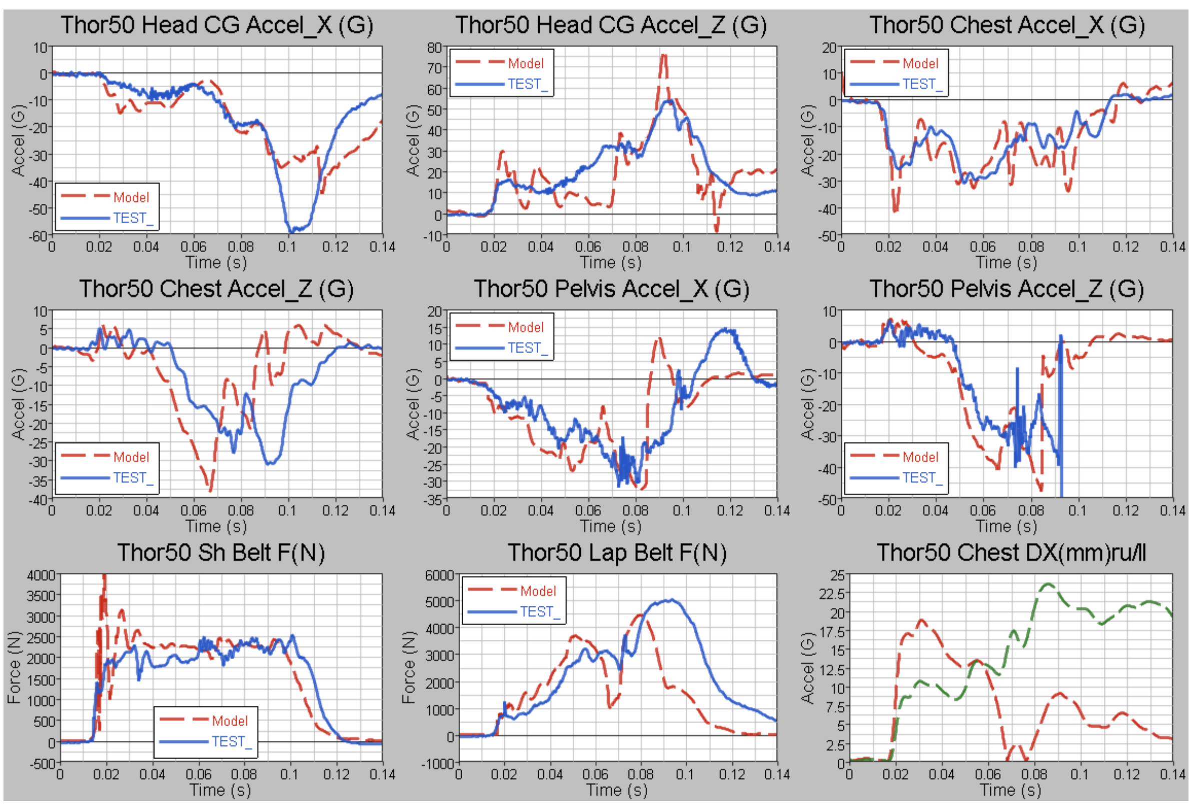
5th ATD SCaRAB



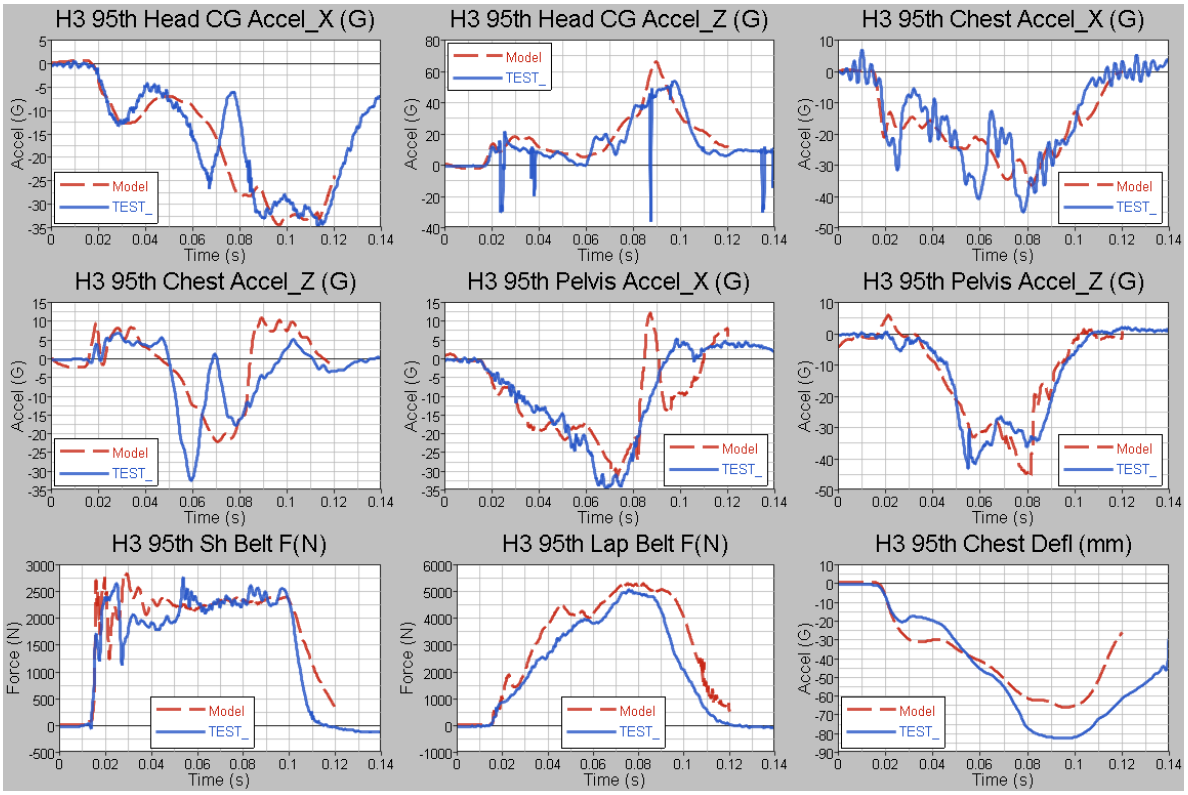
THOR 50th SCaRAB



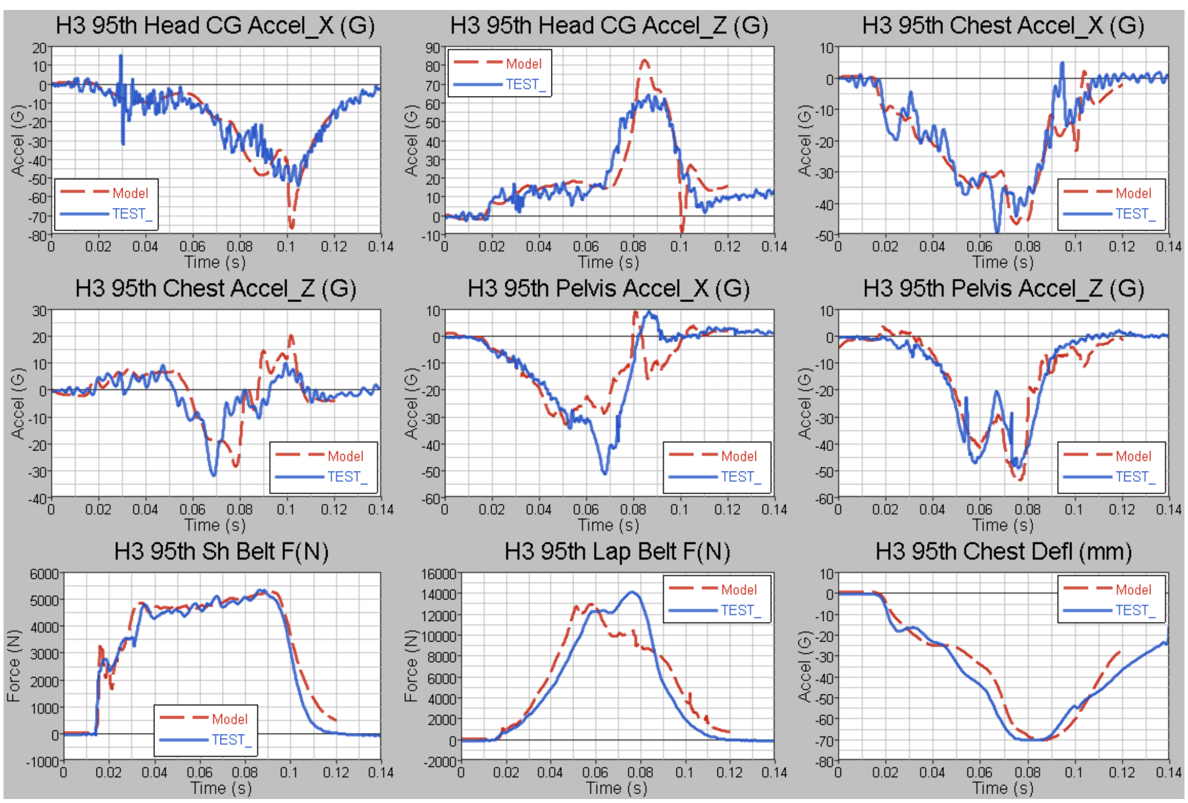
THOR 50th 4-Point Belt



95th ATD 4-Point Belt



THOR 50th 3-Point Belt



Appendix C: Baseline test results

Note: All the baseline tests were conducted using a baseline rear seat belt system without pretensioners, load limiter, or dynamic locking tone. All the injury measures are reported as the percentage of associated IARVs.

Test #		ATD	Condition			Head		Neck				Chest		Sub-marine	Belt Force (kN)	
Series #	ID		Pos.	Pulse	Angle	HIC	BrIC	NeckT	NeckC	N_{ij}/ NeckF (THOR)	NeckE (THOR)	ChestG	ChestD		Sh.	Lap
13-05-0159	01	95th	Left	Soft	0 deg	83	103	51	29	81		77	64	No	8.9	8.6
13-05-0159	02	95th	Left	Severe	0 deg	279	170	149	27	209		149	150	No	12.6	13.9
13-05-0159	03	95th	Right	Soft	0 deg	101	135	57	18	104		80	73	No	9.7	11.7
13-05-0159	04	95th	Right	Severe	0 deg	237	161	83	30	151		119	150	No	13.5	16.5
13-05-0159	13	95th	Left	Soft	15 deg	99	138	90	27	123		76	58	No	8.8	6.4
13-05-0159	14	95th	Left	Severe	15 deg	279	175	117	49	159		121	72	No	12.1	11.6
13-05-0159	15	95th	Right	Soft	15 deg	77	100	54	2	92		73	79	No	8.7	10.2
13-05-0159	16	95th	Right	Severe	15 deg	227	178	85	11	141		116	101	No	13.3	17.0
13-05-0159	19	THOR	Right	Soft	0 deg	106	82	104	0	46	5	76	86	Yes	8.1	7.1
13-05-0159	20	THOR	Right	Severe	0 deg	306	108	149	2	54	15	149	114	Yes	10.6	8.3
13-05-0159	05	THOR	Left	Soft	0 deg	73	108	103	1	42	8	85	86	Yes (Right)	8.2	7.8
13-05-0159	06	THOR	Left	Severe	0 deg	130	130	195	33	322	4	121	108	Yes	11.9	9.5
13-05-0159	18	THOR	Right	Soft	15 deg	57	90	97	0	39	4	74	100	Yes	8.1	6.6
13-05-0159	17	THOR	Left	Soft	15 deg	57	Lost	124	0	32	5	80	146	No	Lost	Lost
15-02-0045	19	THOR	Right	Severe	15 deg	Lost	Lost	Lost	Lost	Lost	Lost	Lost	Lost	No	10.8	11.5
15-02-0045	20	THOR	Left	Severe	15 deg	169	136	192	9	17	30	133	70	No	11.3	11.6
15-02-0045	21	THOR	Left	Soft	0 deg	76	121	131	0	19	25	84	57	No	8.1	7.6
15-02-0045	22	THOR	Left	Severe	0 deg	180	152	218	0	13	27	128	62	No	12.8	13.1
13-05-0159	05	5th	Right	Soft	0 deg	76	130	96	44	93		81	77	Yes (Left)	5.8	5.6
13-05-0159	06	5th	Right	Severe	0 deg	206	153	125	39	149		115	98	Yes	8.5	8.1
13-05-0159	07	5th	Left	Soft	0 deg	114	123	95	50	92		80	70	No	6.4	5.2
13-05-0159	08	5th	Left	Severe	0 deg	281	163	126	13	126		128	88	Yes	8.2	8.7
13-05-0159	09	5th	Right	Soft	15 deg	97	139	125	42	110		83	86	No	6.3	6.5
13-05-0159	10	5th	Right	Severe	15 deg	199	158	154	43	119		121	101	Yes	11.8	11.5
13-05-0159	11	5th	Left	Soft	15 deg	112	141	120	31	101		81	67	No	6.4	4.7
13-05-0159	12	5th	Left	Severe	15 deg	227	183	144	3	122		125	84	Yes	8.0	8.2
13-05-0159	01	6YO	Right	Soft	0 deg	84	139	222	36	129		82	51	Yes	4.1	2.9
13-05-0159	02	6YO	Right	Severe	0 deg	231	201	418	90	239		134	72	Yes	6.5	5.9
13-05-0159	03	6YO	Left	Soft	0 deg	131	156	341	43	208		89	66	Yes	4.6	3.9
13-05-0159	04	6YO	Left	Severe	0 deg	280	216	483	77	276		116	94	Yes	6.2	6.2
13-05-0159	13	6YO	Right	Soft	15 deg	93	139	203	52	119		82	47	Yes	4.5	3.6
13-05-0159	14	6YO	Right	Severe	15 deg	246	207	406	97	241		150	67	Yes	6.2	5.9
13-05-0159	15	6YO	Left	Soft	15 deg	91	171	299	54	167		83	45	Yes	4.4	3.6
13-05-0159	16	6YO	Left	Severe	15 deg	133	238	223	84	226		149	182	Yes	6.4	5.3

Appendix D: Final test results with advanced restraints

Note: All the baseline tests were conducted using a baseline rear seat belt system without pretensioners, load limiter, or dynamic locking tone. All the injury measures are reported as the percentage of associated IARVs.

Test #		ATD	Condition			Head		Neck				Chest		Sub-marine	Belt Force (kN)	
Series #	ID		Pos.	Pulse	Angle	HIC	BrIC	NeckT	NeckC	Nij/NeckF (THOR)	NeckE (THOR)	ChestG	ChestD		Sh.	Lap
15-02-0045	01	95th	Left	Soft	0 deg	55	82	36	1	28		62	29	No	4.8	8.3
15-02-0045	03	95th	Left	Severe	0 deg	95	62	36	39	40		97	35	No	4.3	10.2
15-02-0045	04	95th	Right	Severe	0 deg	114	114	67	19	51		159	54	No	5.0	13.0
15-02-0045	05	95th	Right	Soft	0 deg	29	49	27	9	21		82	36	No	4.2	8.2
15-02-0045	06	95th	Left	Soft	0 deg	55	73	37	11	28		78	29	No	4.7	7.5
15-02-0045	13	95th	Left	Severe	15 deg	73	104	33	27	40		116	36	No	3.7	9.7
15-02-0045	14	95th	Left	Severe	15 deg	149	137	68	47	66		118	38	No	4.7	9.8
15-02-0045	15	95th	Right	Severe	15 deg	91	102	62	10	50		116	47	No	5.1	14.3
15-02-0045	16	95th	Right	Severe	15 deg	73	89	55	12	56		114	Lost	No	4.5	13.4
15-02-0045	07	THOR	Left	Soft	0 deg	44	74	93	82	37	43	76	60	No	4.5	6.1
15-02-0045	08	THOR	Left	Severe	0 deg	73	99	41	16	30	26	100	68	No	4.9	7.8
15-02-0045	09	THOR	Right	Soft	0 deg	35	59	80	9	21	71	112	61	No	3.5	8.8
15-02-0045	10	THOR	Right	Severe	0 deg	266	115	148	55	36	134	117	83	No	5.4	11.5
15-02-0045	11	THOR	Left	Severe	15 deg	93	87	63	1	12	119	95	71	No	3.7	7.3
15-02-0045	12	THOR	Left	Severe	15 deg	218	166	156	0	28	55	124	76	No	5.1	8.5
15-02-0045	17	THOR	Right	Severe	15 deg	132	133	178	0	23	47	97	80	No	5.0	11.8
15-02-0045	18	THOR	Right	Severe	15 deg	57	146	70	7	39	23	107	85	No	3.9	10.8
15-02-0045	07	5th	Right	Soft	0 deg	17	54	26	14	32		51	58	No	4.4	2.7
15-02-0045	08	5th	Right	Severe	0 deg	78	70	83	15	81		75	66	No	4.7	5.6
15-02-0045	09	5th	Left	Soft	0 deg	19	64	49	1	42		44	57	No	3.9	2.9
15-02-0045	10	5th	Left	Severe	0 deg	61	58	28	37	40		80	51	No	4.2	5.9
15-02-0045	11	5th	Right	Severe	15 deg	78	88	83	1	81		75	66	No	4.5	6.9
15-02-0045	12	5th	Right	Severe	15 deg	44	99	27	26	82		69	46	No	3.6	7.4
15-02-0045	18	5th	Left	Severe	15 deg	83	103	90	1	89		73	70	No	4.3	4.5
15-02-0045	19	5th	Left	Severe	15 deg	56	100	31	29	60		76	66	No	4.5	4.0
15-02-0045	02	6YO	Right	Soft	0 deg	13	74	32	4	47		51	67	No	2.8	2.9
15-02-0045	03	6YO	Right	Severe	0 deg	50	105	129	6	75		83	94	No	4.4	2.9
15-02-0045	04	6YO	Left	Severe	0 deg	63	94	57	10	56		88	71	No	2.9	3.0
15-02-0045	05	6YO	Left	Soft	0 deg	19	88	77	24	63		45	73	No	4.0	1.7
15-02-0045	13	6YO	Right	Severe	15 deg	47	105	126	11	70		79	73	No	4.4	2.9
15-02-0045	14	6YO	Right	Severe	15 deg	46	88	52	12	48		84	81	No	3.1	3.1
15-02-0045	15	6YO	Left	Severe	15 deg	52	89	Lost	Lost	Lost		82	87	No	3.2	3.1
15-02-0045	16	6YO	Left	Severe	15 deg	65	98	143	2	76		74	96	No	4.3	2.7
15-02-0045	17	6YO	Left	Severe	15 deg	52	100	45	8	71		82	75	No	3.4	2.3

DOT HS 812 248
March 2016

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12124-030116-v2a