Potential Benefit of a 3+2 Criss Cross Seat Belt System in Frontal and Oblique Crashes

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Abstract Chest injuries are one of the most frequent injuries in frontal and frontal oblique car crashes, especially for the senior population due to increased physical frailty. This study was conducted to assess a seat-integrated, 3+2 Criss Cross (3+2 CC) seat belt system's ability to reduce AIS2+ chest injuries compared to a seat-integrated three-point seat belt. This was accomplished by quantifying the reduction of chest deflection in a numerical LS-Dyna simulation of both the Test device for Human Occupant Restraint version 1.0 (THOR) and Autoliv Total HUman body Model for Safety (THUMS) for full frontal impact, and of the THORv1.0 only for frontal oblique impacts. The reduction of chest deflection and corresponding injury risk was then used to calculate the system's effectiveness for the 3+2 CC seat belt to reduce the risk to the occupant of sustaining an AIS2+ chest injury. Using weighted National Automotive Sampling System Crashworthiness Data System (NASS CDS) and German In-depth Accident Study (GIDAS) data, a real world benefit estimation of reduced AIS2+ injuries was performed, assuming that the total vehicle fleet was equipped with the 3+2 CC seat belt. It was shown that 22% and 25% of all AIS2+ injuries could be prevented in the USA and Germany, respectively.

Keywords Chest injury, Frontal impact, Frontal oblique impact, THOR, 3+2 Criss Cross seat belt.

I. INTRODUCTION

Occupant fatalities and injuries in vehicle crashes are global health issues. Even if road safety has improved, road crashes still result in 1.3 million deaths annually, and 78.2 million non-fatal injuries warranting medical care [1]. Frontal crashes are the most frequent crash mode, with the chest and head being the most commonly injured body regions [2-3]. Front-seat occupants sustain head injuries from bottoming out of the airbag, or from sliding out of the belt, thereby impacting interior structures. Chest injuries are sustained as a result of compression of the chest due to loading by the seat belt, or impacting a hard structure, e.g. the steering-wheel rim [2-5]. Typical head injuries are concussion, skull fracture and brain injuries, while typical chest injuries are rib and sternum fractures, or injuries to thoracic organs.

In current frontal consumer tests crash test dummies, such as the Hybrid III (HIII) 5th and 50th percentile, are used to evaluate occupant injury risk [6-8]. The evaluation includes the risk for sustaining chest injuries, which is assessed by dummy chest deflection measurement. A new dummy, Test device for Human Occupant Restraint (THOR), will be introduced in Euro NCAP starting in 2020 [9], and is proposed to be introduced in US-NCAP for model year (MY) 2020 and subsequent MYs [2, 10]. Previous studies have shown that the THOR shows a more human-like response to frontal and frontal oblique loading compared to the HIII [3, 10-13]. When comparing the two dummies, it was also shown that THOR is able to distinguish between a stiff and a soft restraint system with regards to chest injury [14-15]. In order to assess chest injuries, injury risk curves (IRCs) for THOR have been proposed by the EU THORAX project [16] and by NHTSA [17]. The IRCs proposed by the EU THORAX project are based on X_{max} deflection, i.e. peak rib deflection in x-direction of the ribs, while the IRCs proposed by NHTSA are based on R_{max}, i.e. peak rib deflection of the resultant of x, y and z directions. Another difference between the two IRCs is that EU THORAX IRCs predict AIS2+ risks, while NHTSA IRCs predict AIS3+ risks. In both sets of IRCs the risks for both 45-year-old and 65-year-old occupants can be evaluated.

Seat belts are the most efficient way to reduce the risk of injury in frontal crashes. The history of improving seat belts is long, beginning in the 1950s with a three-point shoulder/lap belt. In combination with frontal

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airbags, the three-point seat belt provides a 73% injury reduction of MAIS2+ injuries [18]. However, chest injuries are still frequent in the field data, and it is believed that by using the new crash test dummy THOR, the effectiveness of the seat belt, or a seat belt and airbag system, can be further improved.

By MY 2008 all new cars and LTVs (Light Truck & Van) sold in the USA were equipped with pre-tensioners and load limiters for the driver and right passenger seats [19]. Advanced seat belts can also be equipped with an adaptive function called Load Limiter Adaptive (LLA), whereby the load limiter level can be switched to a lower level during a crash [20]. Other advanced seat belts are variants of multipoint belts [21-22]. Ruahana et al 2003 [21] showed that a V-shaped four-point belt resulted in a lower chest compression since load from the chest was shifted to the clavicles and pelvis. By this design it was possible to reduce the chest deflection of a HIII by a factor of two. The principle of distributing the load from the seat belt to the chest with advanced seat belt geometry was demonstrated by Bostrom et al. [23] using Autoliv Total HUman body Model for Safety (THUMS). It was concluded that the kinematics of the occupant may contribute to the loading of the chest, i.e. by reducing the twisting of the chest less chest deflection was observed. The Renault Twizy is an example where a four-point belt, as a supplementary belt, is installed in the vehicle. This extra two-point belt requires the occupant to slip an arm under it, and then buckle the three-point seat belt as usual.

Most advanced seat belt studies have been performed using HIII, Human Body Models or Post Mortem Human Subjects. There is a lack of investigating a 3+2 Criss Cross (3+2 CC) seat belt system using THOR. The introduction of THOR in future rating procedures makes it relevant to investigate the potential chest deflection when introducing a multipoint belt system.

The objective of this study was to quantify the expected real world benefit of a seat-integrated 3+2 CC seat belt compared to a seat-integrated three-point belt, based on crash statistics and numerical simulations using THOR and Autoliv THUMS and THOR IRCs from EU THORAX.

II. METHODS

Method overview of total benefit calculation

A holistic approach was used to assess the benefit of the 3+2 CC seat belt system compared to the standard three-point belt. The basis for the benefit estimation was real life crash statistics of a determined group of crashes in order to understand the crash scenarios, i.e. load cases and associated injury types, here called *data collection* (Fig. 1). The next step was to quantify the *benefit* by reducing one or more injury measurements (in the present study, chest deflection) in the determined load cases by either numerical simulations and/or physical tests of the proposed restraint system compared to a baseline system (Fig. 1). This was followed by quantifying the *effectiveness* of the proposed restraint system, which was done by comparing the injury risk for the new system to the baseline. Finally, the *real world benefit* was calculated by assuming that the full vehicle fleet in the data collection was equipped with the proposed restraint system.

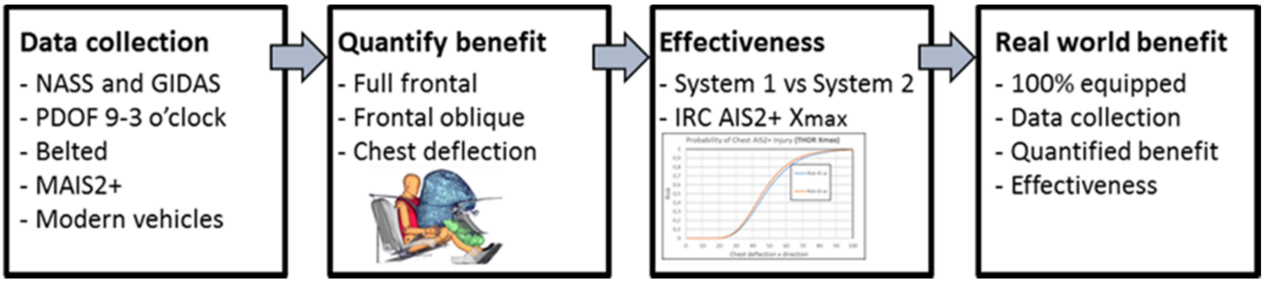


Fig. 1. Method overview of total benefit calculation.

Data collection

Data was collected from the National Automotive Sampling System (NASS) Crashworthiness Data System (CDS), a nationwide crash data-collection program sponsored by the U.S. Department of Transportation [24], and also from the German In-Depth Accident Study (GIDAS) in Dresden, Hanover, and environs [25-26]. Data from both NASS and GIDAS databases were used to give a general overview, considered the differences in vehicle fleet, i.e. more LTV and Sport Utility Vehicles in US, and legal and rating crash tests in the two countries, i.e. full frontal crash test in the US and offset deformable barrier in Germany. In the present study, the NASS CDS (2007–2014) and GIDAS databases (2005–2015) were used. The data extracted were belted front-seat occupants, both drivers and passengers 13 years or older including cases with and without airbag deployment, sustaining a MAIS2+ injury (AIS2008). Data were limited to non-rollover crashes with the Principal Direction of Force (PDOF) between 9 and 3 o'clock from modern passenger car vehicles, MY 2007 and later for NASS, and MY 2005 and later for GIDAS. MY 2005 instead of MY 2007 was used for GIDAS as a compromise to increase the number of cases. Data were extracted on a personal level, and not on a vehicular or injury level. The inclusion criteria resulted in 543 NASS CDS cases, and 108 GIDAS cases.

To reflect national statistics for the USA and Germany, the data was weighted. The NASS data were weighted according to weighting factors provided in the NASS CDS. The GIDAS data were weighted for crash severity and crash type to reflect German national crash statistics for 2014, which include all police reported injury crashes that occurred in Germany involving at least one motorised vehicle.

The weighted data were stratified into seven groups, which were defined by PDOF and occupant position (Fig. 2). Left oblique and right oblique crashes were similar in that the occupants' trajectories were not straight ahead relative to the vehicle's interior, but the side of obliquity results in the near-side and far-side occupant experiencing different conditions. A driver would be considered a near-side occupant in a left oblique crash, while the right front passenger would be a far-side occupant (see arrows in Fig. 2). The seven groups were as follows.

1. Full frontal and partial overlap crashes, 12 o'clock, i.e. +/-15°.
2. Frontal oblique near-side, 1 or 11 o'clock, i.e. +/-15-45°.
3. Frontal oblique far-side, 1 or 11 o'clock, i.e. +/-15-45°.
4. Side oblique near-side 10 or 2 o'clock, i.e. +/-45-75°.
5. Side oblique far-side 10 or 2 o'clock, i.e. +/-45-75°.
6. Side near-side 9 or 3 o'clock, i.e. +/-75-105°.
7. Side far-side 9 or 3 o'clock, i.e. +/-75-105°.

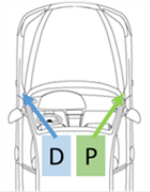
	Frontal	Frontal oblique near side	Frontal oblique far side	Side obligue near side	Side obligue far side	Side near side	Side far side
							
	[km/h]	**[km/h]**	**[km/h]**	**[km/h]**	**[km/h]**	**[km/h]**	**[km/h]**
Low	0-32	0-32	0-32	N/A	N/A	N/A	N/A
Mid	32-80	32-80	32-80	0-50	0-50	0-50	0-50
High	80+	80+	80+	50+	50+	50+	50+

Fig. 2. Crash types and crash severity definitions.

In this study, only the full frontal and frontal oblique groups were considered for the 3+2 CC seat belt benefit evaluation. However, to understand the full potential of a modification to the restraint system, the distribution of the different side load cases was also calculated. Therefore, all groups were stratified, with respect to crash severity, into three sub groups: low-severity crashes; mid-severity crashes; and high-severity crashes. The speed intervals were set due to the assumed potential for the 3+2 CC seat belt to reduce chest injury. Low-severity was set to delta v 0–32 km/h, mid-severity 32–80 km/h, and high-severity 80 km/h or above. The delta v of 32 km/h was chosen due to the assumption that loading to the chest at lower velocities would be minor, and thereby result in a low risk for chest injuries. The delta v of 80 km/h was chosen as the upper limit due to the assumption that the compartment would partly collapse at higher speeds, resulting in multiple trauma, e.g. intrusion-related head injuries. For side and side oblique crashes it was assumed that there was no low-severity crash level due to that side impacts often result in injuries already at low speeds. Instead, mid and high severity were used, being 0–50 km/h delta v and above 50 km/h delta v, respectively (Fig. 2).

The data for low and medium crash severity were analysed according to injury. The injured persons were divided into five groups, depending on the body part with the AIS2+ injury.

1. Both head and chest injuries (includes injuries to the head, face, chest and abdomen).
2. Only head injury (includes injuries to the head and face).
3. Only chest and abdomen injuries (includes injuries to the chest and abdomen).
4. No head or chest injury (includes injuries other than head, face, chest and abdomen).
5. Head or chest injury unknown.

Quantifying benefit using computational modelling

Numerical LS-Dyna simulations were performed using a generic vehicle interior geometry representing a mid-size sedan MY 2010, and using both the THOR v1.0 CAE dummy model (Humanetics Innovative Solutions, Inc.) for full frontal and frontal oblique load cases, and the human body model Autoliv THUMS for the full frontal load case. The Autoliv THUMS was derived from the THUMS model v1.4 [27-28]. The THOR and Autoliv THUMS models were positioned as close as possible to the HIII position defined by FMVSS 208, aligning H-point, pelvic angle, head and knee positions to a HIII position.

The generic vehicle system model was equipped with a seat with a force penetration function for the seat pan, and a rigid seat-back. The rigid seat-back was used since the purpose of the simulations was to identify and study the effect of two seat-integrated belt systems, and allowing the seat-back to deform could make the effect of the two belt systems more difficult to interpret, as they would have deformed differently. As described for the seat pan, the carpet and the instrument panel were also modelled with force penetration functions.

The THOR and the Autoliv THUMS were restrained with a seat-integrated three-point seat belt as a baseline, and a seat-integrated 3+2 CC seat belt system (Fig. 4). A seat-integrated three-point seat belt was chosen as baseline instead of a B-pillar mounted three-point seat belt to be able to direct compare the belt systems without the difference in belt routing geometry that would follow with different installation positions. The performance of the restraint systems was evaluated for two load cases: full frontal rigid barrier 56 km/h impact (current US-NCAP); and variants of a frontal oblique 90 km/h impact. Both near-side and far-side impacts were evaluated with an impact angle of 15° (Table I).

TABLE I

SIMULATED LOAD CASES THOR AND AUTOLIV THUMS

Load case	**Occupant**	**Belt configuration**
Full Frontal Rigid Barrier 56 km/h	THOR v1.0	Three-point seat belt
Full Frontal Rigid Barrier 56 km/h	THOR v1.0	3+2 CC seat belt
Full Frontal Rigid Barrier 56 km/h	Autoliv THUMS	Three-point seat belt
Full Frontal Rigid Barrier 56 km/h	Autoliv THUMS	3+2 CC seat belt
Frontal Oblique Near-side 90 km/h	THOR v1.0	Three-point seat belt
Frontal Oblique Near-side 90 km/h	THOR v1.0	3+2 CC seat belt
Frontal Oblique Far-side 90 km/h	THOR v1.0	Three-point seat belt
Frontal Oblique Far-side 90 km/h	THOR v1.0	3+2 CC seat belt

The baseline restraint system was a seat-integrated three-point seat belt with a constant 4 kN load limiter (LL) equipped with a retractor pre-tensioner (PT), an outer lap belt PT, and a Crash Locking Tongue (CLT). The CLT function locks the belt slip between lap and diagonal parts. A passenger airbag (PAB) with a volume of 110l and 2 vents with Ø45mm each, and a 12l knee airbag (KAB) without ventilation, were used for both seat belt systems. Characteristics for PT, LL functions and airbags were taken from current production hardware with no variations, and were thereby validated CAE models (Fig. 3). For restraint system details, see Appendix A.

In the 3+2 CC seat belt system, the total resulting force that acted on the dummy chest were the sum of both the normal three-point seat belt and the extra +2 part. Therefore, the load limiter levels needed to be lower so as not to increase chest deflection. The 3+2 CC seat belt system was equipped with adaptive load limiter (LLA) retractor instead of the constant LL retractor. The setting of the LLA was 2.5 kN/1.3 kN, and the LL switch was activated at 66 ms in the full frontal load case. The position of the extra belt was fully symmetrical, with the normal three-point seat belt to cross the chest in the same way (Fig. 4). In addition, the position of the extra buckle was varied in the full frontal load case for the 3+2 CC seat belt system with THOR. One position was at the same x-coordinate as the three-point seat belt buckle and the second position moved 120 mm forward in the model (Fig. 6). The forward position was used in all frontal oblique simulations and for full frontal with Autoliv THUMS. Except for those two modifications, LLA and buckle position, the same settings were used in the 3+2 CC seat belt system as in the baseline three-point seat belt system, i.e. the same PT levels and airbag settings.

In the full frontal simulations, the retractor PT was activated at 8 ms after T0, the lap belt PT was activated with a delay of 7 ms, i.e. at 15 ms. Passenger Airbag (PAB) 1st stage activated at 8 ms, 2nd stage at 13 ms, and the Knee Airbag (KAB) at 8 ms. In the frontal oblique load cases, all systems were activated 10 ms later than in the full frontal load case.

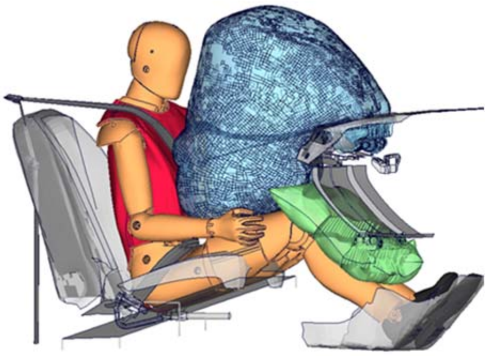


Fig. 3. System model at 40 ms.

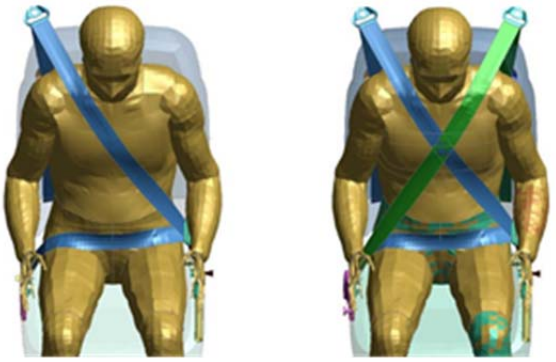


Fig. 4. Seat belt layout for three-point seat belt (left) and 3+2 CC seat belt (right).

Chest deflections for Autoliv THUMS were extracted at similar positions as the THOR (Fig. 5) with a fixed coordinate system at the spine for the relative chest deflections. For simplicity, only the passenger position was simulated in full frontal rigid barrier 56 km/h and in frontal oblique impact 90 km/h, but the results were assumed to be valid for both the driver and passenger, and for the whole mid-severity crash interval, delta v 32–80 km/h.

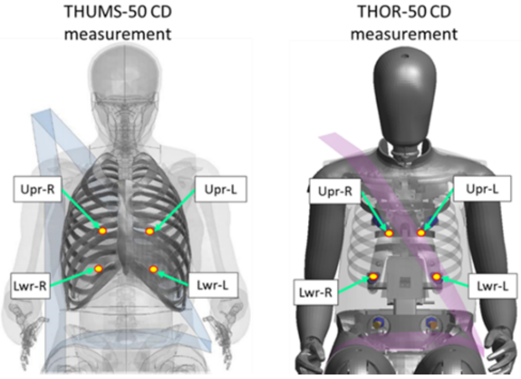


Fig. 5. Chest deflection measuring points for Autoliv THUMS (left) and THOR (right).

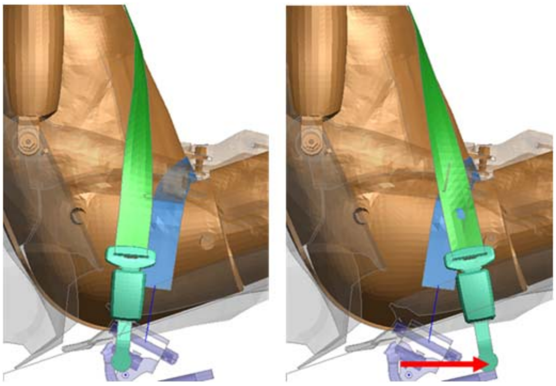


Fig. 6. Extra buckle at original position (left) and moved forward 120 mm (right).

Chest injury risk for THOR and Autoliv THUMS

The AIS2+ chest injury risk for THOR was evaluated by using X_{max} rib deflection and IRCs presented by Davidsson *et al*. [16] (Fig. 7). This injury criteria and corresponding IRCs were chosen due to the hypothesis that deflection in x is a stronger criteria for rib fracture compared to the resultant measurement due to the biofidelic uncertainty of how the ribs in THOR move during loading in a y- and z-direction.

For the Autoliv THUMS model, the risk for rib fracture was evaluated by a probabilistic analytical method [29]. An age-adjusted ultimate strain distribution was used to estimate local rib fracture probabilities within the FE model. These local probabilities were combined to predict injury risk and severity within the whole ribcage. In this study, probabilities of the two or more rib fractures corresponding to an AIS2+ injury for ages 45yo and 65yo were evaluated.

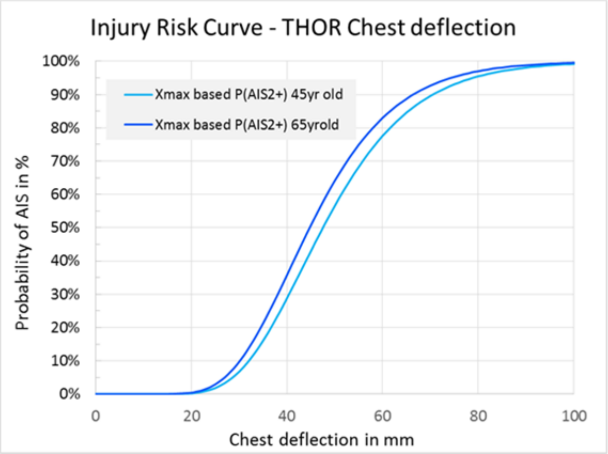


Fig. 7. IRC AIS2+ chest injury risk for THOR for a 45yo and 65yo occupant (Davidsson et al.).

System effectiveness using THOR

The system effectiveness regarding AIS2+ chest injury risk reduction was obtained by a standard method. The THOR numerical simulation of the baseline belt system and the 3+2 CC seat belt resulted in a reduced chest deflection for the 3+2 CC seat belt system. IRCs for THOR were used to calculate the new risks of being injured with the new restraint system. The system effectiveness was defined as E=1–R'/R, where R was the risk of sustaining an AIS2+ chest injury based on the chest deflection value for the baseline belt system, and R' was the risk corresponding to the chest deflection of the 3+2 CC seat belt system. Effectiveness was calculated using THOR results only for both frontal and frontal oblique (both near-side and far-side). It was assumed that the 3+2 CC seat belt reduces chest deflection in mid-severity frontal and frontal oblique crashes as defined above, hence simulations were carried out only for these load cases.

Real world benefit

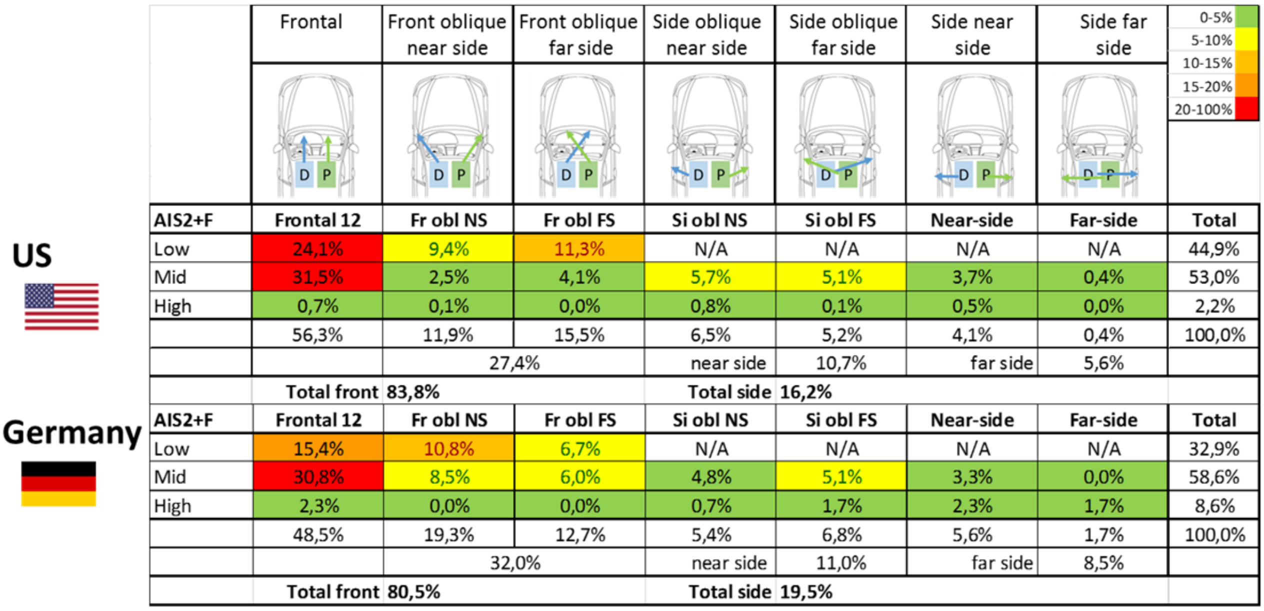
The real world benefit estimations were calculated by assuming that the vehicle fleet in the data collection were equipped with the 3+2 CC seat belt system. The number of AIS2+ chest injuries in mid-severity crashes, delta v 32-80 km/h, were multiplied by the system effectiveness per load case, and then summarised to give the potential reduction of AIS2+ injuries in the mid-severity crash interval. Finally, these values were multiplied by the percentage of mid-severity crashes from the full data collection to give the percentage of reduced AIS2+ injuries in the full data collection.

III. RESULTS

Data collection

The data collection included 543 NASS CDS cases, 199 low-severity, 313 mid-severity and 31 high-severity crashes and 108 GIDAS cases, 36 low-severity, 62 mid-severity and 10 high-severity crashes (Table II). These were weighted to national statistics, and both the US and German data showed an approximate distribution of AIS2+ injuries of 80% front crashes and 20% side crashes (Fig. 8). The colour code in Fig. 8, 0-5% green, 5-10% yellow, 10-15% light orange, 15-20% dark orange and 20-100% red, were used to high light the different percentages.

Frontal 12 o'clock PDOF mid-severity crashes was found to be the most frequent load case, representing 31.5% of the AIS2+ injuries in the USA and 30.8% in Germany. The second most common crash scenario was Frontal 12 o'clock PDOF low-severity crash, with 24.1% in the USA and 15.4 % in Germany. At delta v less than 32 km/h, frontal and frontal oblique represented 44.9% of all AIS2+ injuries in the USA, and 32.9 % in Germany, which could be compared to the mid-severity crash distribution of 53.0% in the USA and 58.6% in Germany. The high-severity distribution was 2.2% in the USA, and 8.6% in Germany.



US

	Frontal	Front oblique near side	Front oblique far side	Side oblique near side	Side oblique far side	Side near side	Side far side	
AIS2+F	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Total**
Low	24,1%	9,4%	11,3%	N/A	N/A	N/A	N/A	44,9%
Mid	31,5%	2,5%	4,1%	5,7%	5,1%	3,7%	0,4%	53,0%
High	0,7%	0,1%	0,0%	0,8%	0,1%	0,5%	0,0%	2,2%
	56,3%	11,9%	15,5%	6,5%	5,2%	4,1%	0,4%	100,0%
		27,4%		near side	10,7%	far side	5,6%	
	Total front	**83,8%**		**Total side**	**16,2%**			

Germany

AIS2+F	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Total**
Low	15,4%	10,8%	6,7%	N/A	N/A	N/A	N/A	32,9%
Mid	30,8%	8,5%	6,0%	4,8%	5,1%	3,3%	0,0%	58,6%
High	2,3%	0,0%	0,0%	0,7%	1,7%	2,3%	1,7%	8,6%
	48,5%	19,3%	12,7%	5,4%	6,8%	5,6%	1,7%	100,0%
		32,0%		near side	11,0%	far side	8,5%	
	Total front	**80,5%**		**Total side**	**19,5%**			

Fig. 8. Weighted distributions of the US (top) and German (bottom) crashes.

The average age was also calculated for the different severity groups, (Table II). For both NASS and GIDAS data the low severity group showed the oldest average age, 48.5yo far NASS and 56.6yo for GIDAS.

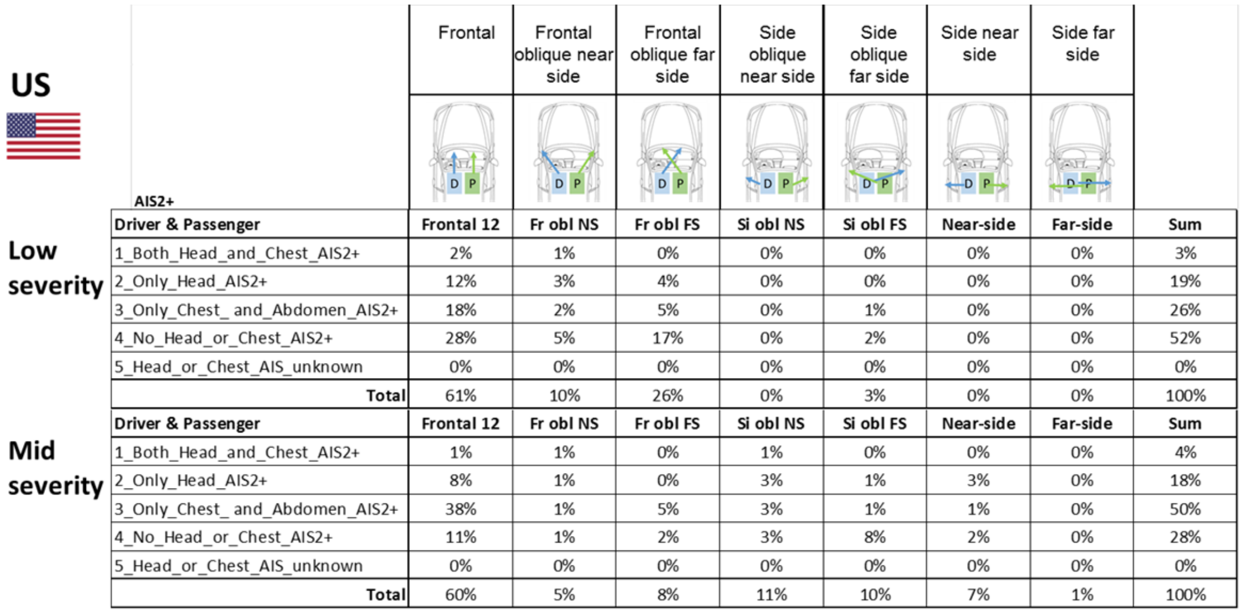
TABLE II

AVERAGE AGE PER CRASH SEVERITY LEVEL FOR GIDAS AND NASS

Database	**Crash severity**	**Number of MAIS2+**	**Average age**
GIDAS	Low	36	56.6
GIDAS	Mid	62	46.6
GIDAS	High	10	39.7
NASS	Low	199	48.5
NASS	Mid	313	47.5
NASS	High	31	35.9

The distributions of injured body regions for the five groups and the seven load cases for low-severity and mid-severity are presented in Fig. 9 and Fig. 10. The percentages are based for the USA on 196/312 (low/mid) cases, and for Germany on 34/58 cases. High severity crashes represented too few cases, 31 for NASS and 10 for GIDAS and are not presented. It was found that for both the USA and Germany cases where the occupants sustained chest and abdomen injuries dominated the frontal mid-severity dataset, with values above 30%. The inclusion of frontal oblique, chest and abdomen injuries represents over 40% in both the US and Germany.

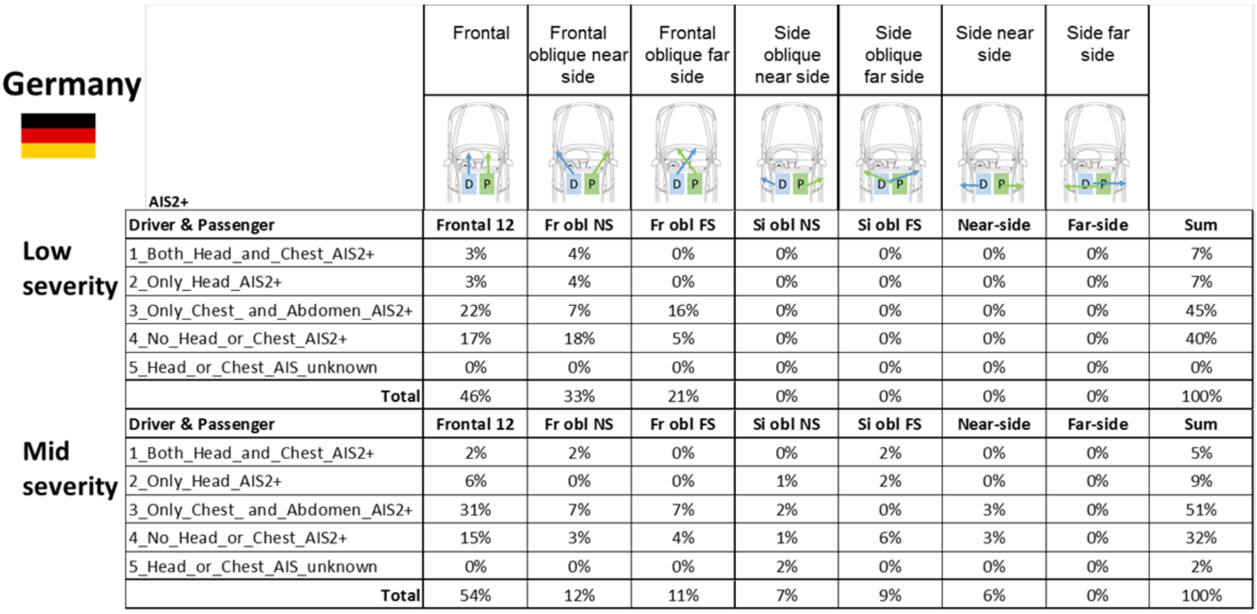
Similar distributions was seen in low-severity crashes, but with a higher number for the frontal oblique cases. In low speed crashes, the class “no head or chest injury” increased compared to mid-severity crashes.



US

	AIS2+	Frontal	Frontal oblique near side	Frontal oblique far side	Side oblique near side	Side oblique far side	Side near side	Side far side	
	Driver & Passenger	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Sum**
Low severity	1_Both_Head_and_Chest_AIS2+	2%	1%	0%	0%	0%	0%	0%	3%
	2_Only_Head_AIS2+	12%	3%	4%	0%	0%	0%	0%	19%
	3_Only_Chest_ and_Abdomen_AIS2+	18%	2%	5%	0%	1%	0%	0%	26%
	4_No_Head_or_Chest_AIS2+	28%	5%	17%	0%	2%	0%	0%	52%
	5_Head_or_Chest_AIS_unknown	0%	0%	0%	0%	0%	0%	0%	0%
	Total	61%	10%	26%	0%	3%	0%	0%	100%
	Driver & Passenger	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Sum**
Mid severity	1_Both_Head_and_Chest_AIS2+	1%	1%	0%	1%	0%	0%	0%	4%
	2_Only_Head_AIS2+	8%	1%	0%	3%	1%	3%	0%	18%
	3_Only_Chest_ and_Abdomen_AIS2+	38%	1%	5%	3%	1%	1%	0%	50%
	4_No_Head_or_Chest_AIS2+	11%	1%	2%	3%	8%	2%	0%	28%
	5_Head_or_Chest_AIS_unknown	0%	0%	0%	0%	0%	0%	0%	0%
	Total	60%	5%	8%	11%	10%	7%	1%	100%

Fig. 9. Weighted distribution of injured body regions in the US low- and mid-severity crashes.



Germany

	AIS2+	Frontal	Frontal oblique near side	Frontal oblique far side	Side oblique near side	Side oblique far side	Side near side	Side far side	
	Driver & Passenger	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Sum**
Low severity	1_Both_Head_and_Chest_AIS2+	3%	4%	0%	0%	0%	0%	0%	7%
	2_Only_Head_AIS2+	3%	4%	0%	0%	0%	0%	0%	7%
	3_Only_Chest_ and_Abdomen_AIS2+	22%	7%	16%	0%	0%	0%	0%	45%
	4_No_Head_or_Chest_AIS2+	17%	18%	5%	0%	0%	0%	0%	40%
	5_Head_or_Chest_AIS_unknown	0%	0%	0%	0%	0%	0%	0%	0%
	Total	46%	33%	21%	0%	0%	0%	0%	100%
	Driver & Passenger	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Sum**
Mid severity	1_Both_Head_and_Chest_AIS2+	2%	2%	0%	0%	2%	0%	0%	5%
	2_Only_Head_AIS2+	6%	0%	0%	1%	2%	0%	0%	9%
	3_Only_Chest_ and_Abdomen_AIS2+	31%	7%	7%	2%	0%	3%	0%	51%
	4_No_Head_or_Chest_AIS2+	15%	3%	4%	1%	6%	3%	0%	32%
	5_Head_or_Chest_AIS_unknown	0%	0%	0%	2%	0%	0%	0%	2%
	Total	54%	12%	11%	7%	9%	6%	0%	100%

Fig. 10. Weighted distribution of injured body regions in Germany low- and mid-severity crashes severity.

Quantifying benefit using computational modelling

In the numerical simulations using THOR, in full frontal load case, the reference belt system resulted in 41.5 mm peak deflection in x direction. The 3+2 CC seat belt system with the buckle in original position resulted in 29.8 mm peak deflection, while with the extra buckle moved forward 120 mm the peak deflection was 25.4 mm. The maximum values are taken from one of the four measurement points in the THOR, as presented in Fig.11.

For a 45yo and a 65yo occupant the deflections correspond to 33.1% and 40.0% risk of a AIS2+ chest injury for the baseline system, and a 6.5%/9.3% and 2.1%/3.3% risk for the 3+2 CC seat belt system with the buckle in the original position and in the forward moved position, respectively (Table III).

The forward displacement of the head, chest and pelvis from the full frontal load case, are presented in Fig. 12. THOR with 3+2 CC seat belt and the buckle moved 120 mm forward resulted in longer forward displacements than the 3+2 CC seat belt system with the buckle in original position, but both 3+2CC seat belt systems resulted in less forward displacement than the baseline 3-point seat belt system.

For same load case using the Autoliv THUMS model, corresponding chest deflection results were 34.5 mm peak deflection for the reference system and 25.8 mm for the 3+2 CC seat belt system, with the buckle only in the forward position (Table III). The probability function for two or more rib fractures resulted in an AIS2+ chest injury risk of 100% for the reference system, and 11.0% risk for the 3+2 CC seat belt system for a 45yo occupant (Table III). The 3+2 CC seat belt system resulted in a 37% risk of AIS2+ chest injury for a 65yo occupant. For Autoliv THUMS, chest deflection time history showed not only positive (compression) but also negative (expansion) deflection values, which was not observed in the THOR model (see Appendix A).

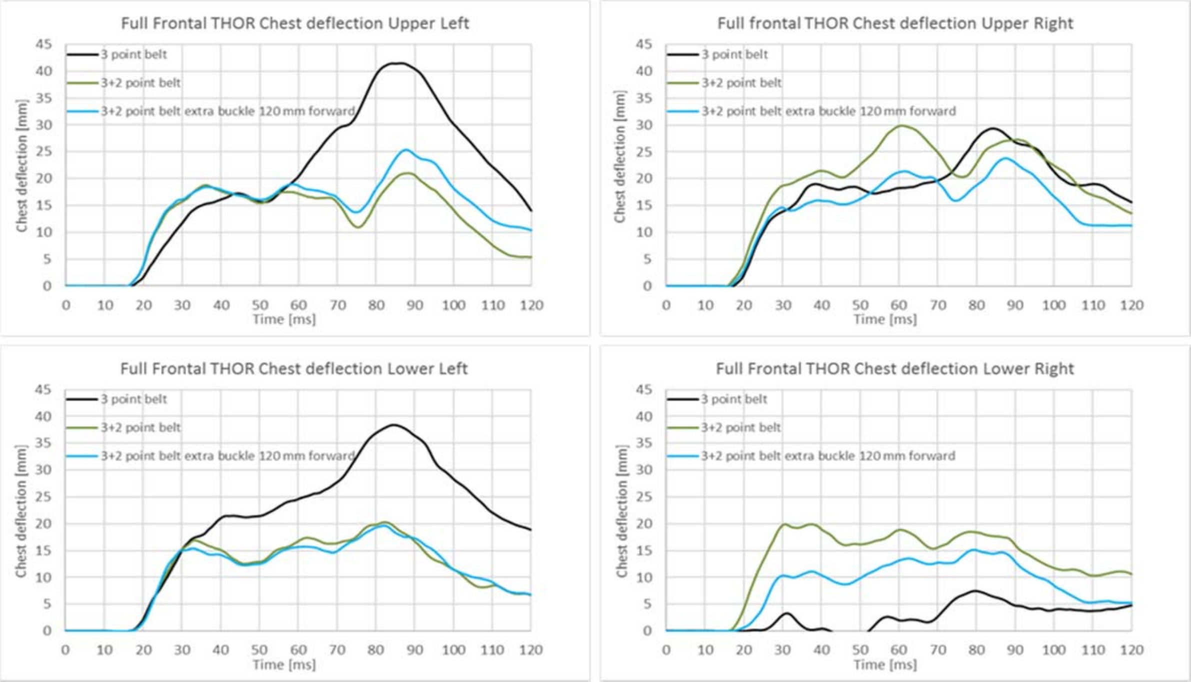
In the frontal oblique load cases the reference system resulted in 39.9 mm and 38.0 mm peak deflection in x direction for near-side and far-side loading, respectively (Table III), and the THOR showed a tendency to slide out of the belt. The 3+2 CC seat belt system resulted in 26.2 mm and 25.5 mm for the near- and far-side loading, and no tendency to slide out of the belt was noticed.

For a 45yo and a 65yo occupant the deflections correspond to 28.6% and 23.4% risk of an AIS2+ chest injury for the 45yo for frontal oblique near-side and frontal oblique far-side respectively and 35.6% and 29.7% risk of an AIS2+ chest injury for the 65yo for the baseline system. For the same load case with the 3+2 CC seat belt system corresponding risks were 2.7% and 2.1% for the 45yo in frontal oblique near-side and frontal oblique far-side respectively and for the 65yo the risk of an AIS2+ chest injury was 4.1% and 3.4%. (Table III).

TABLE III

CHEST DEFLECTION AND RISK FOR AIS2+ FOR SIMULATED LOAD CASES

Load case	Occupant	Belt configuration	Chest deflection X_{max}	Risk for AIS2+ 45yo	Risk for AIS2+ 65yo
Full Frontal	THOR v1.0	3 point	41.5 mm	33.1%	40.0%
Full Frontal	THOR v1.0	3+2 point	29.8 mm	6.5%	9.3%
Full Frontal	THOR v1.0	3+2 point +2 buckle forw	25.4 mm	2.1%	3.3%
Full Frontal	Autoliv THUMS	3 point	34.5 mm	100%	100%
Full Frontal	Autoliv THUMS	3+2 point +2 buckle forw	25.8 mm	11.0%	37.0%
Frontal Oblique Near-side	THOR v1.0	3 point	39.9 mm	28.6%	35.6%
Frontal Oblique Near-side	THOR v1.0	3+2 point +2 buckle forw	26.2 mm	2.7%	4.1%
Frontal Oblique Far-side	THOR v1.0	3 point	38.0 mm	23.4%	29.7%
Frontal Oblique Far-side	THOR v1.0	3+2 point +2 buckle forw	25.5 mm	2.1%	3.4%


Full Frontal THOR Chest deflection Upper Left

Full frontal THOR Chest deflection Upper Right

Full Frontal THOR Chest deflection Lower Left

Full Frontal THOR Chest deflection Lower Right

Fig. 11. THOR full frontal 56 km/h chest deflection for each of the four measurement points in THOR.

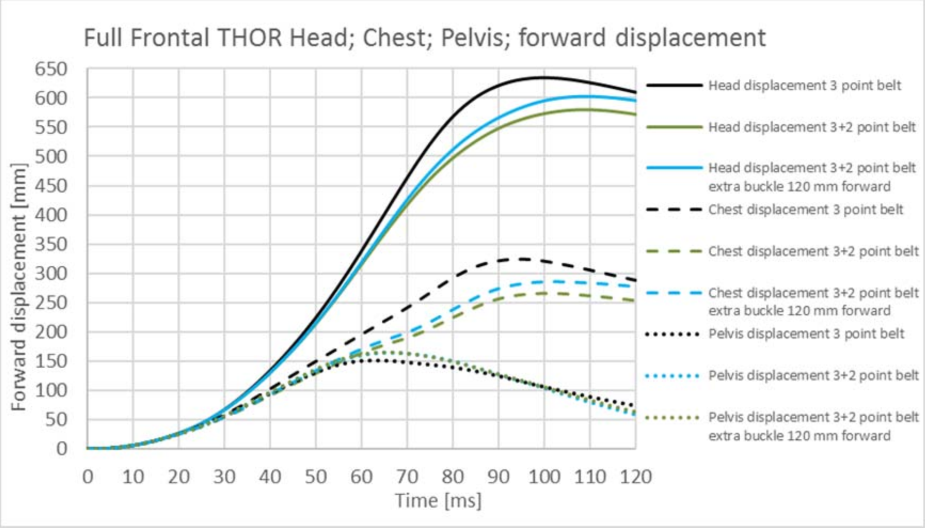


Fig. 12. THOR full frontal forward displacement of head, chest and pelvis.

System effectiveness

The reduced risks, calculated as effectiveness of the systems for THOR, see “System effectiveness using THOR” above, are shown in Table IV. The 3+2 CC seat belt system resulted in an effectiveness between 90% and 94% for a 45yo occupant, and between 88% and 92% for a 65yo occupant, depending on the load case.

TABLE IV
SYSTEM EFFECTIVENESS BASED ON THOR IRC FOR 45YO AND 65YO

Load case	**System Effectiveness 45yo**	**System Effectiveness 65yo**
Full Frontal	93.7%	91.9%
Frontal Oblique Near-side	90.7%	88.5%
Frontal Oblique Far-side	90.8%	88.7%

Real world benefit

The real world benefit estimation was calculated by assuming that the whole vehicle fleet in the data collection was equipped with the 3+2 CC seat belt system. As shown in Fig. 9 and Fig. 10, chest AIS2+ injury correspond to 38% + 1% + 5% = 44% (full frontal, frontal oblique near-side and front oblique far-side) for the USA, and 31% + 7% + 7% = 45% for Germany of all AIS2+ injuries in the mid-severity interval (Table V). With the system effectiveness for 45yo from Table IV multiplied by these distributions, 41.1% in the USA and 41.8% in Germany of the AIS2+ injuries could be removed from the mid-severity crashes. Fig. 8 shows that mid-severity stands for 53.0% for the USA and 58.6% for Germany of all AIS2+ injuries. This results in a total reduction of 41.1% *53.0% = 21.8% for the USA, and 41.8% * 58.6% = 24.5% for Germany of all AIS2+ injuries if a 3+2 CC seat belt system had been used in all vehicles.

TABLE V
EFFECTIVENESS AND INJURY REDUCTION MID-SEVERITY CRASHES

Load case	**Country**	**Effectiveness 45yo**	**% of AIS2+ chest injuries**	**AIS2+ chest injury reduction**
Full Frontal	USA	93.7%	38%	35.6%
Frontal Oblique Near-side	USA	90.7%	1%	0.9%
Frontal Oblique Far-side	USA	90.8%	5%	4.5%
All load cases	USA		44%	41.1%
Full Frontal	Germany	93.7%	31%	29.0%
Frontal Oblique Near-side	Germany	90.7%	7%	6.3%
Frontal Oblique Far-side	Germany	90.9%	7%	6.4%
All load cases	Germany		45%	41.8%

IV. DISCUSSION

In this study the potential of a well-balanced 3+2 CC seat belt system to reduce AIS2+ chest injuries in full frontal rigid barrier 56 km/h pulses and in frontal oblique 90 km/h pulses was demonstrated by means of numerical simulations using THOR and Autoliv THUMS. The 3+2 CC seat belt system was balanced for LL levels and the geometry of belt routing over the chest, i.e. symmetrical routing over the chest to obtain similar loading to the left and right sides, and the position of the extra buckle. It was shown that the position of the extra buckle was an important factor in reducing peak chest deflection for THOR. By direct comparison of 3-point belt and 3+2 CC with buckles in same position a substantial reduction of Cd was achieved. To show the potential of the 3+2 CC system, optimizations were made to the position of the extra buckle and that configuration was then used for the rest of the simulations. The effect of moving the extra buckle forward can be explained by that the normal buckle is forced forward in the crash by its lap portion when the pelvis is moving forward, while the extra buckle only takes loading from the diagonal belt, i.e. the chest. By these loading differences the extra belt induces greater forces to the right side of the chest, resulting in higher deflection. This was compensated by moving the buckle further forward. Results of this are seen in Fig. 11, where left and right, upper IRTRACC (Infrared Telescope Rod for Assessment of Chest Compression) resulted in similar peak deflections with the buckle in the forward position, but higher right upper peak deflection with the buckle in the original position.

Similar to THOR, Autoliv THUMS also reflected more balanced loading, comparing left and right sides with the 3+2 CC seat belt to the baseline system (see Appendix A). Comparing the strain per rib, which shows the maximal rib strain on the left and right side of the chest, it is also obvious that the 3+2 CC seat belt provides a more evenly distributed loading to the rib cage (see Appendix A).

The effectiveness of the proposed system was between 90% and 94% in the evaluated load cases for a 45yo occupant, and between 88% and 92% for a 65yo occupant. Applying the system’s effectiveness for a 45yo occupant on the vehicle fleet, a reduction of 22% in the USA and 25% in Germany of all AIS2+ injuries could be achieved. It was also observed that the forward head displacement was shorter with the proposed system, Fig. 12. This indicates a better possibility of reducing the likelihood of bottoming out of the airbag if, for example, crash severity is increased. The above, in combination with the increased possibility of avoiding sliding out of the seat belt in frontal oblique far-side crashes with a 3+2 CC seat belt, implies that such a system has the potential to also reduce head injuries in real life crashes. Surprisingly, the data collection shows very few cases of head only, or head and chest injuries, in mid-severity crashes. Moreover, the 3+2 CC seat belt can also keep the occupant in position in far-side crashes, and thus avoid head impact to the interior or to the other occupant [30].

The benefit calculation considered only the mid crash severity and *“Only chest and abdomen injuries”* cases. Even if the chest injury could be solved in the class “*Both head and chest”*, it was decided not to include them in the calculation because the occupant will still sustain an AIS2+ injury to the head. In either case, chest injuries to the “both head and chest” group could probably also be solved with the proposed system, and thereby the reduce the number of AIS2+ chest injuries even more.

From the data collection, it was shown that of the AIS2+ injuries, more than 30% in Germany and 40% in the USA come from crashes with a delta v of less than 32 km/h. In the body injury distribution of low speed crash severity, it was shown that 45% in Germany and 26% in the USA were “*chest and abdomen only”* injuries. This shows that there is a potential to further reduce the number of chest injuries with the 3+2 CC seat belt system. However, this has not been addressed in this evaluation since crash simulation was performed only in mid crash severity.

One reason for the many injuries at the low speed crash severity can be occupant age. The average age was higher in the group with low crash severity compared to mid and high crash severities. People currently live longer, and therefore the population age shifts. In coming years, many drivers and passengers will be 65 year and older. Typically, older vehicle occupants are less able to withstand crash forces than younger occupants when involved in a crash. In 2013 the NHTSA proposed a silver rating in its document [31]: ‘Ultimately, older consumers could use NCAP silver car rating information to help them select and purchase vehicles that would be potentially safer for them.’ The 3+2 CC seat belt may be a suitable restraint system for elderly people because it distributed loading and resulted in less deflection to the chest. To reduce both low and mid crash severity cases a dual mode test is proposed: one at low speed, with delta v at 32 km/h and low acceptance for chest deflection; and one at high speed, with delta v of 56 km/h and with more moderate acceptance for chest deflection. Similar ideas have been proposed by D. Hynd *et. al* 2016 [32].

Strengths and limitations

It is a strength of the findings that both NASS and GIDAS data shows very similar results when comparing both the injury distribution of modern vehicles and that the potential with the potential with the 3+2 CC seat belt system is valid both in the US and in Germany.

A limitation of this study is that the restraint evaluation is based on numerical data only. However, the numerical model consists of component models that are presently in production, and they have been validated on a component level. Anyhow, representing real-world impacts with a limited number of simulations will by nature only give a rough estimation due to the wide variation of crash types, occupant position etc. in real world crashes.

Another strength with the investigation is that both the THOR and Autoliv THUMS show similar trends and responses to the two systems in the full frontal load cases: that a 3+2 CC seat belt can substantially reduce chest deflection. It should be noted that the THOR model used in the study was version 1 from Humanetics Innovative Solutions Inc. Later versions, i.e. 1.3 [33] and later, have a more flexible spine. This will affect dummy kinematics, and thereby also chest deflection values. This was not known at the time this investigation was performed.

For simplicity of the study only passenger occupants have been simulated in full frontal rigid barrier 56km/h and frontal oblique 90 km/h. The results are then used to evaluate both driver and passenger performance in the speed intervals 32 km/h to 80 km/h delta v.

The LL levels were set with the condition that the seat-back was rigid. In a real implementation, the seat-back will flex during loading. This will affect the chosen LLs, but the effect will probably be less with the 3+2 CC seat belt compared to a three-point seat belt due to the symmetrical loading to the seat.

Consideration for implementation

The 3+2 CC seat belt shows significant potential to reduce the number of chest injuries in frontal collisions, but many issues remain to be resolved before it can be considered for production vehicles. Examples of such issues include the possibility to unbuckle with a single button (ECE R 16 requirement), to integrate with the seat, and acceptance by the users to always use both the three-point belt and the +2 part. This is necessary because the 3+2 CC seat belt system's normal three-point belt part has a LL too low to work alone.

V. CONCLUSIONS

Using both THOR and Autoliv THUMS in simulated full frontal and THOR in frontal oblique impact conditions, the 3+2 CC seat belt system showed a reduction in chest deflection and risk for thoracic injury compared to a seat integrated three-point seat belt system with a constant load limiter. These results show the potential for designing new belt systems that distribute the load to the chest, in order to reduce chest injuries in real world crashes.

Based on the NASS and GIDAS database analysis, it was estimated that for approximately 22% (USA) and 25% (Germany) of the vehicle occupants of the extracted cases the AIS2+ injuries could be reduced with a 3+2 CC or similar belt system.

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[

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Appendix A CAE settings and CAE results

Load cases

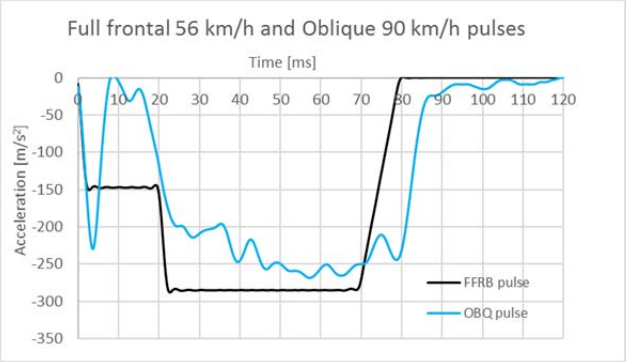


Fig. A1. Vehicle pulses, Full frontal and frontal oblique.

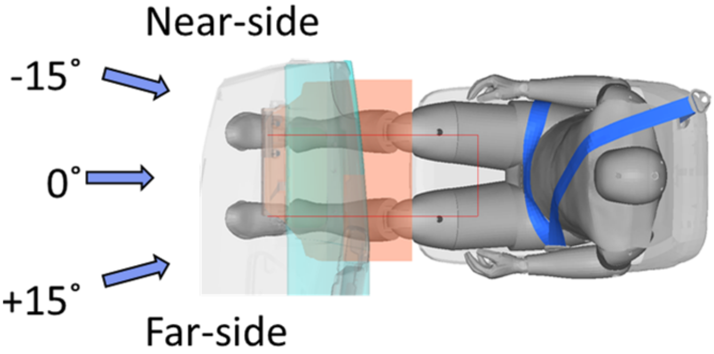


Fig. A2. Impact angles for frontal oblique.

Restraint system

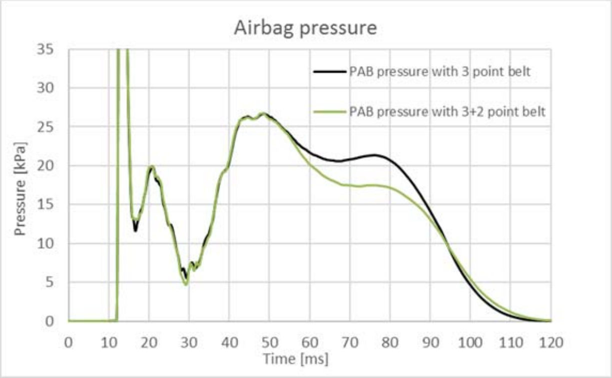


Fig. A3. Passenger airbag pressure, THOR full front 56 km/h.

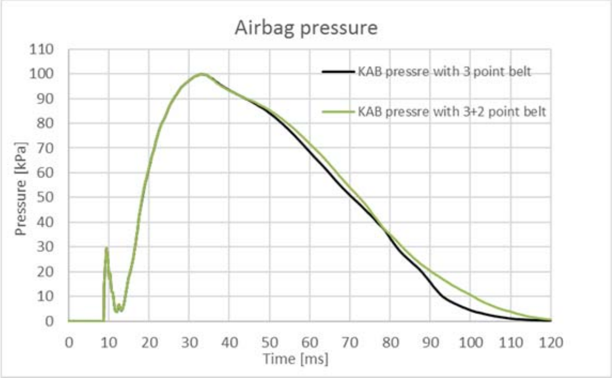


Fig. A4 Knee airbag pressure, THOR full front 56 km/h.

Belt forces diagonal belt and lap belt forces

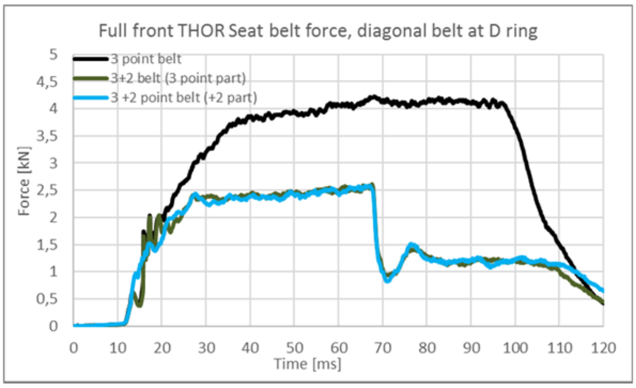


Fig. A5. THOR full frontal diagonal belt forces.

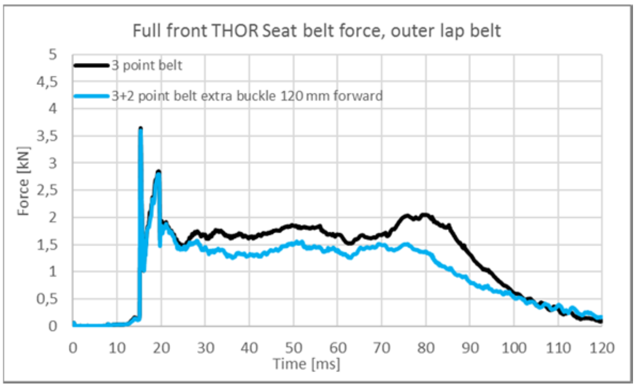


Fig. A6. THOR full frontal lap belt forces.

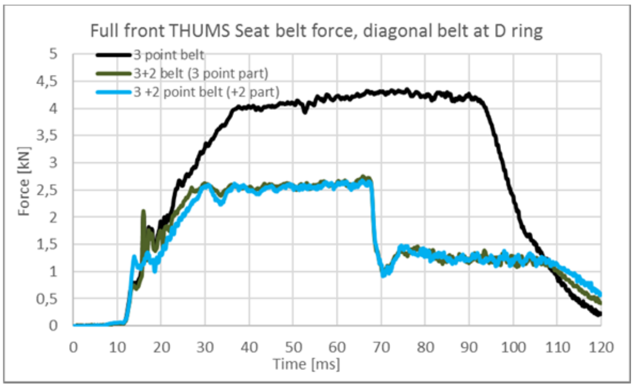


Fig. A7. Autoliv THUMS full frontal diagonal belt forces.

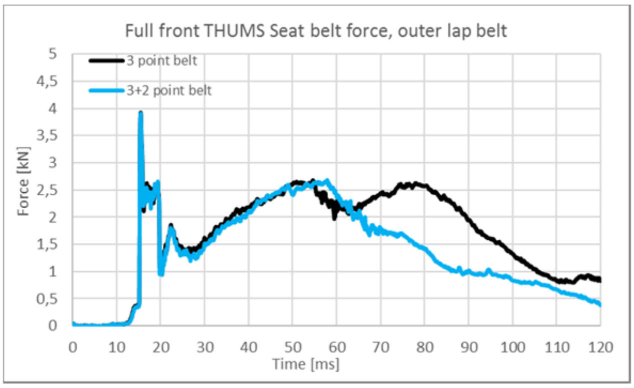


Fig. A8. Autoliv THUMS full frontal lap belt forces.

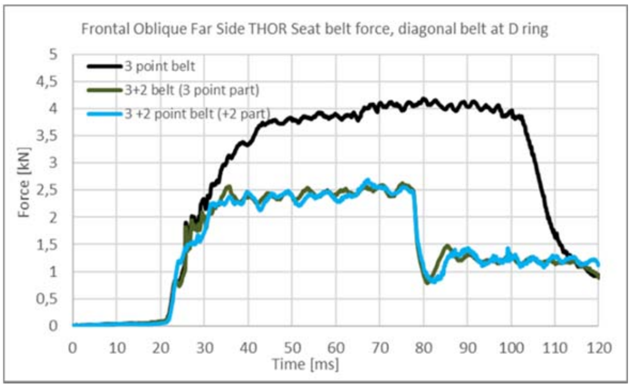


Fig. A9. THOR frontal oblique far side diagonal belt forces.

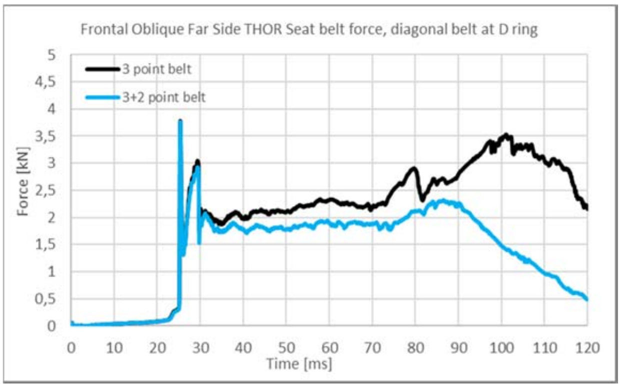


Fig. A10. THOR frontal oblique far side diagonal belt forces.

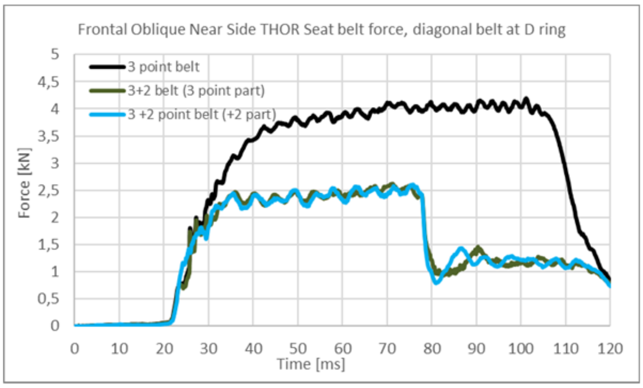


Fig. A11. THOR frontal oblique far side diagonal belt forces.

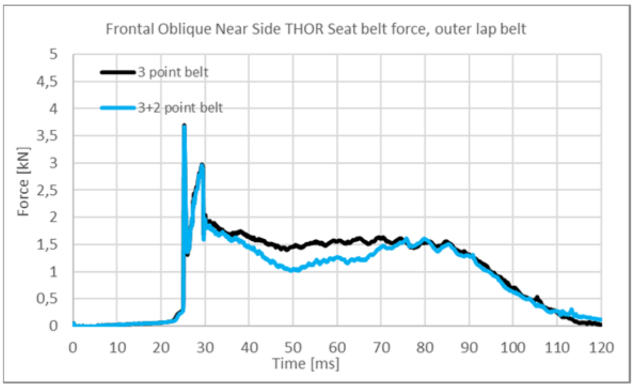


Fig. A12. THOR frontal oblique far side diagonal belt forces.

Chest deflection measurements

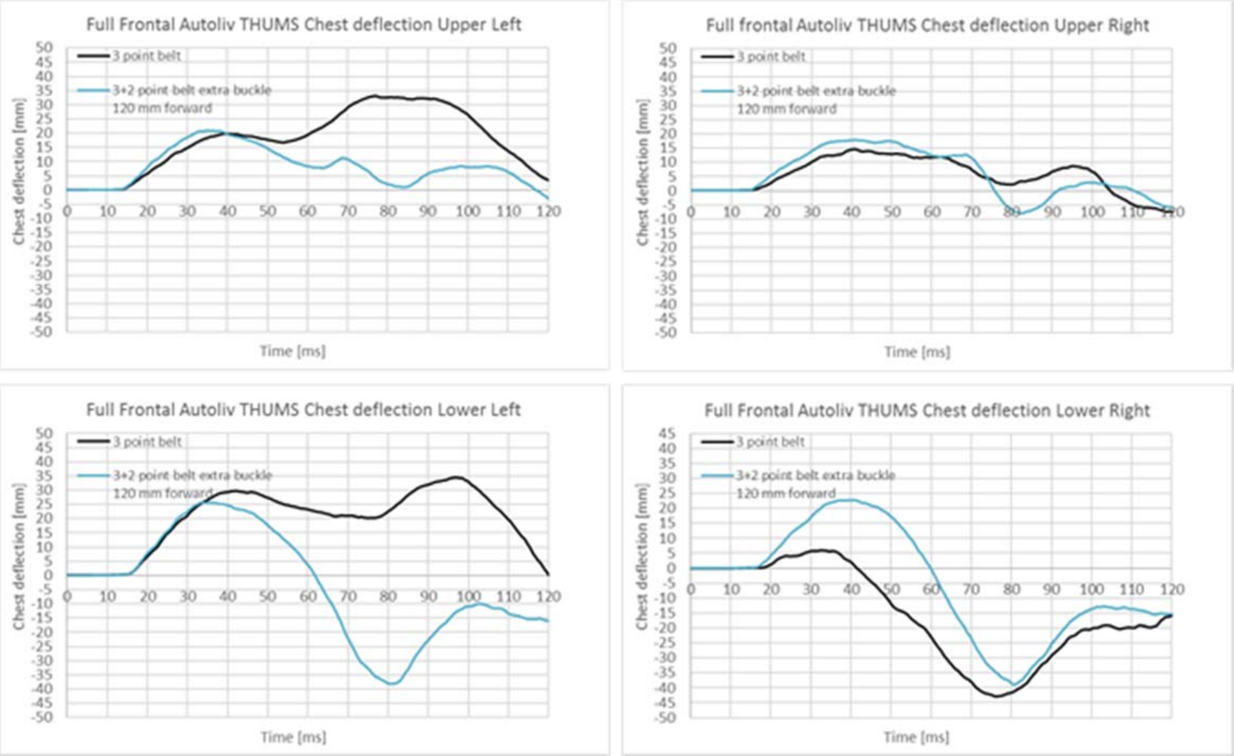


Fig. A13. Autoliv THUMS full frontal 56 km/h chest deflections.

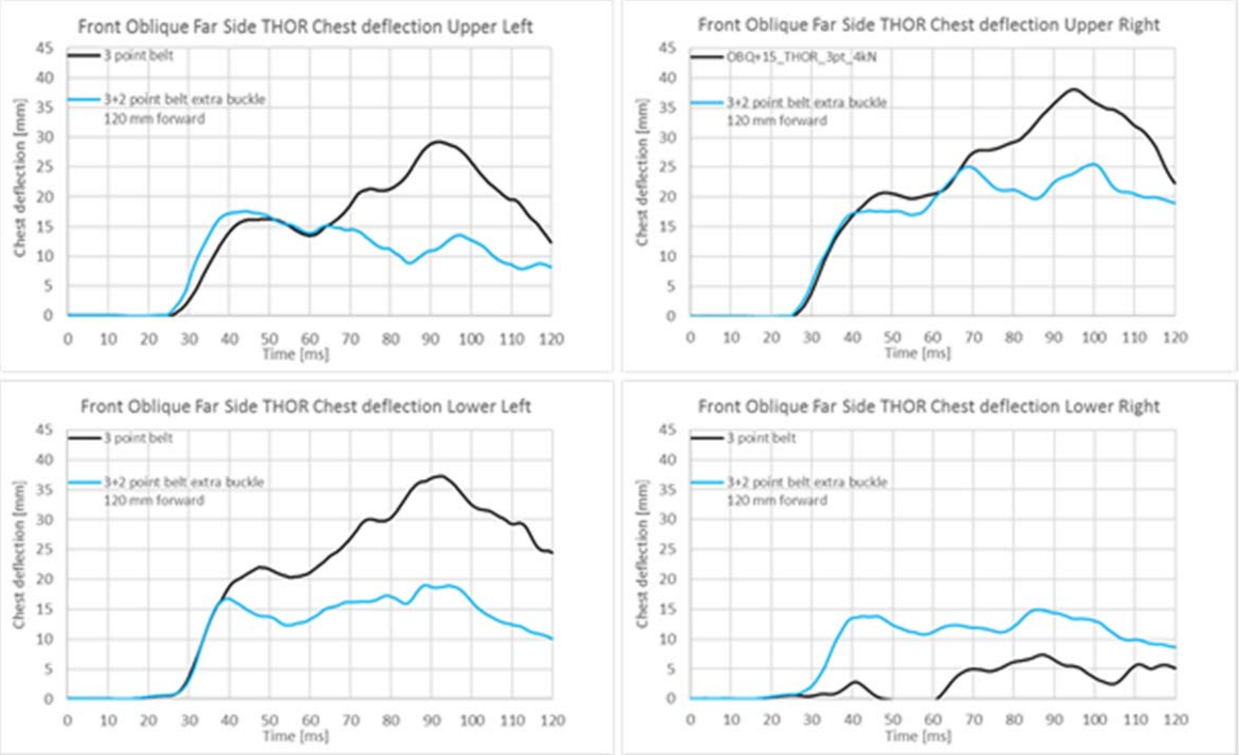


Fig. A14. THOR Frontal Oblique Far side chest deflections.

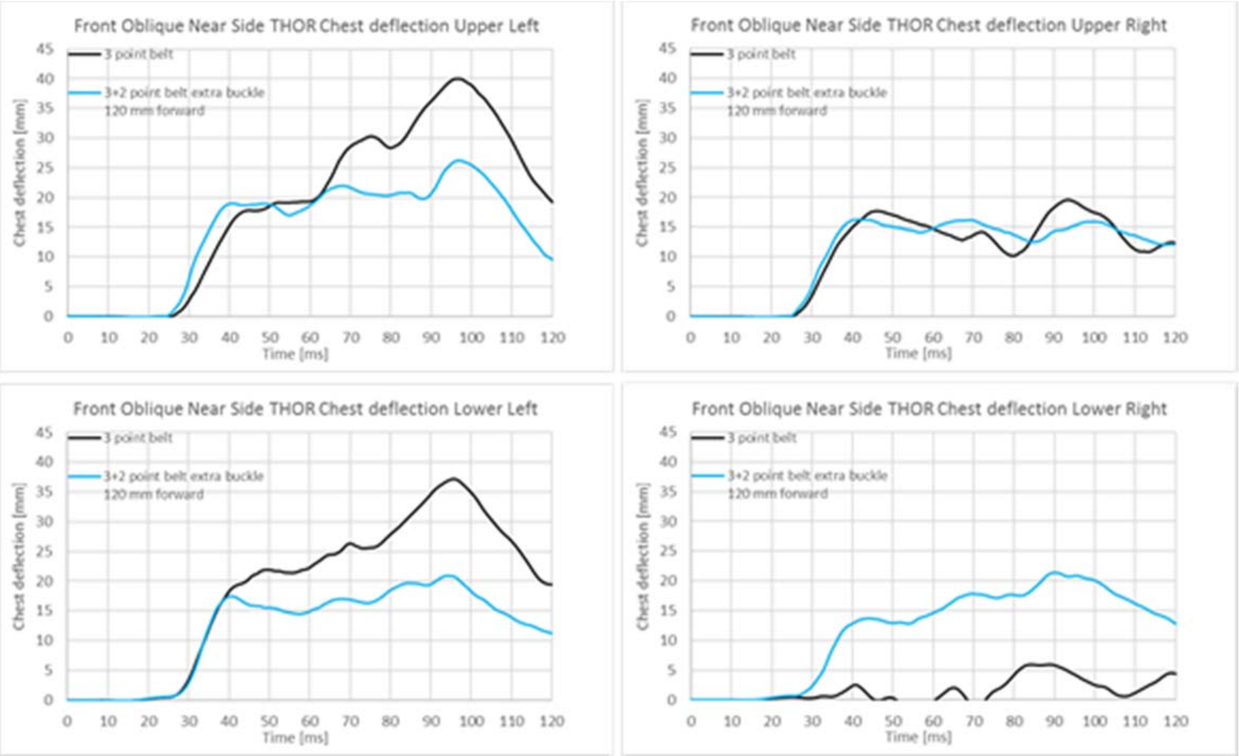


Fig. A15. THOR Frontal Oblique Far side chest deflection.

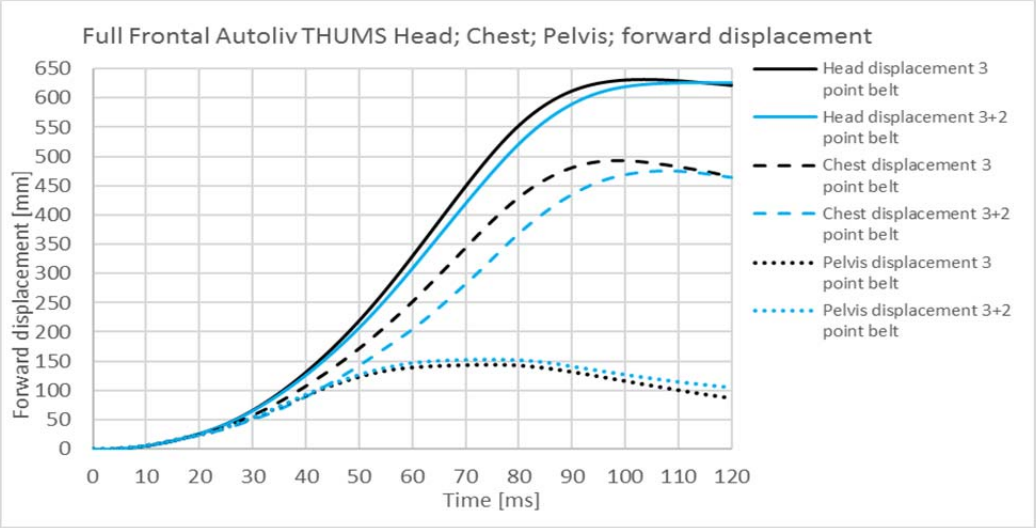
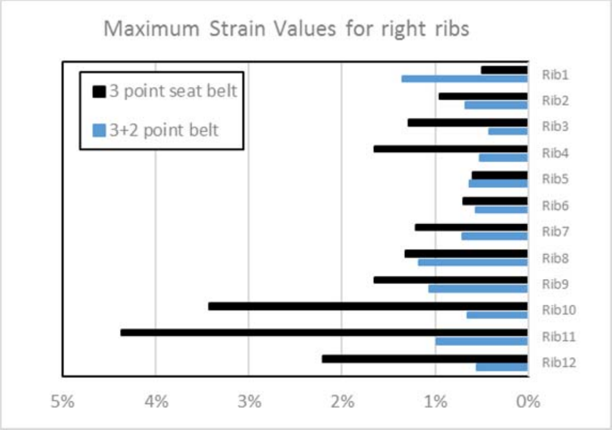


Fig. A16. Autoliv THUMS full frontal forward displacement.



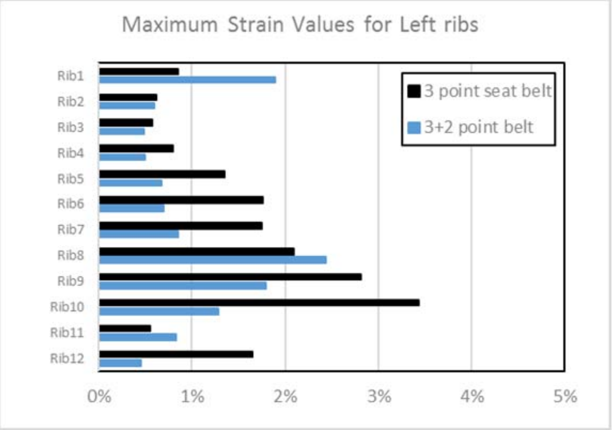
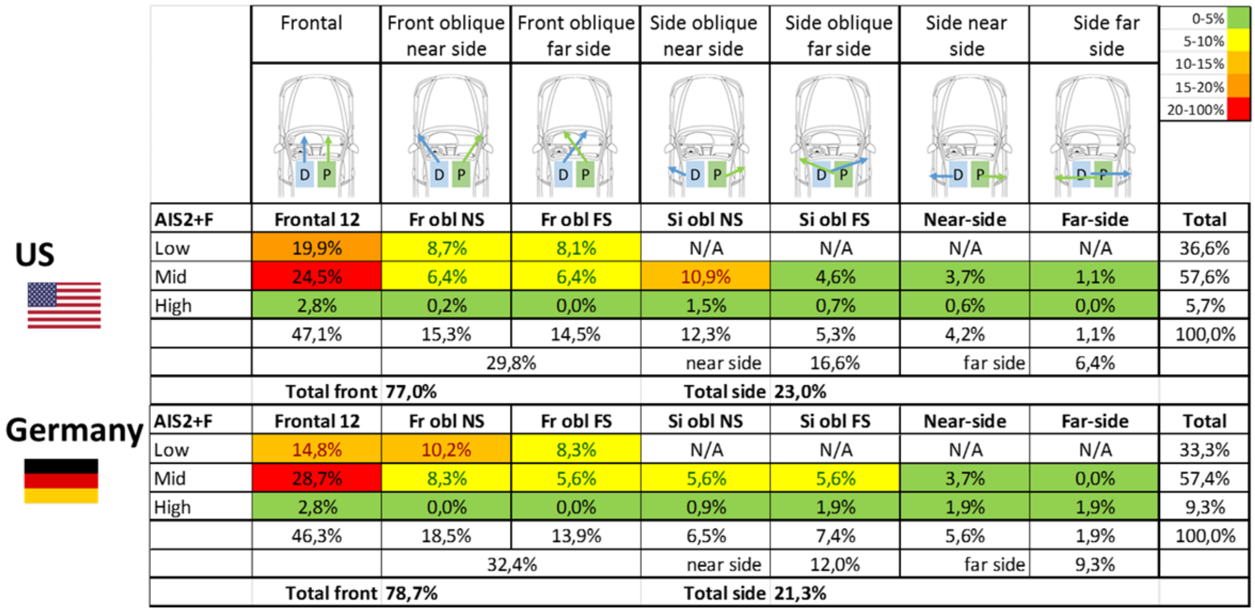


Fig.A17 Right rib strain Autoliv THUMS.

Fig.A18 Left rib strain Autoliv THUMS.

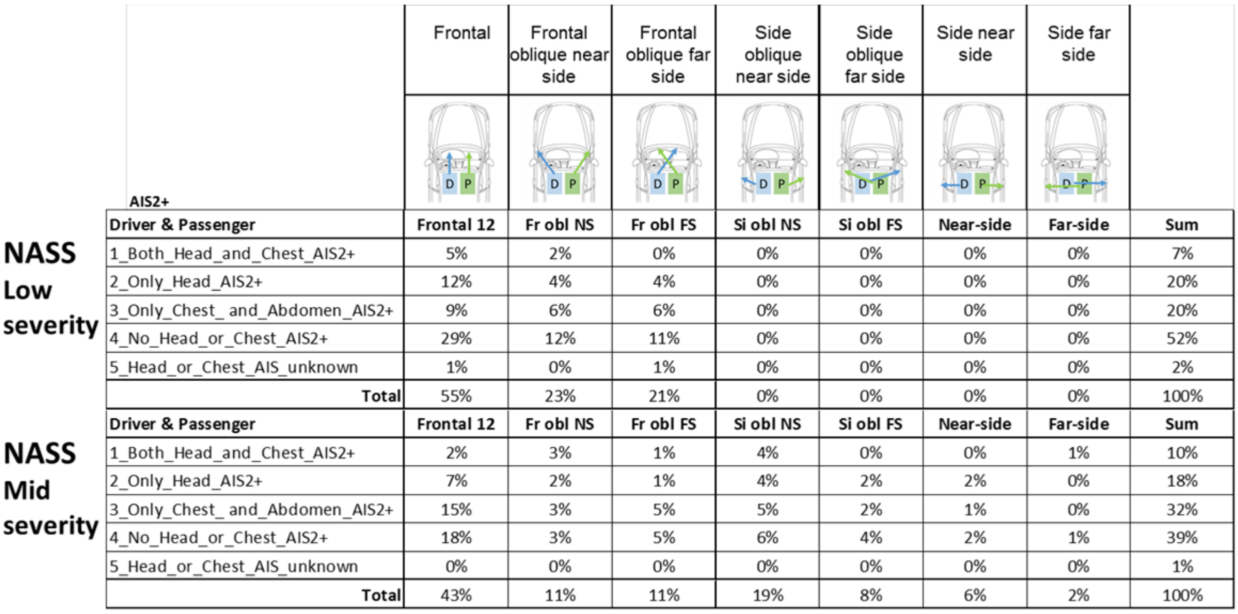
Appendix B Un-weighted crash accident data



		Frontal	Front oblique near side	Front oblique far side	Side oblique near side	Side oblique far side	Side near side	Side far side	
US	**AIS2+F**	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Total**
	Low	19,9%	8,7%	8,1%	N/A	N/A	N/A	N/A	36,6%
	Mid	24,5%	6,4%	6,4%	10,9%	4,6%	3,7%	1,1%	57,6%
	High	2,8%	0,2%	0,0%	1,5%	0,7%	0,6%	0,0%	5,7%
		47,1%	15,3%	14,5%	12,3%	5,3%	4,2%	1,1%	100,0%
			29,8%		near side	16,6%	far side	6,4%	
		Total front	**77,0%**		**Total side**	**23,0%**			
Germany	**AIS2+F**	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Total**
	Low	14,8%	10,2%	8,3%	N/A	N/A	N/A	N/A	33,3%
	Mid	28,7%	8,3%	5,6%	5,6%	5,6%	3,7%	0,0%	57,4%
	High	2,8%	0,0%	0,0%	0,9%	1,9%	1,9%	1,9%	9,3%
		46,3%	18,5%	13,9%	6,5%	7,4%	5,6%	1,9%	100,0%
			32,4%		near side	12,0%	far side	9,3%	
		Total front	**78,7%**		**Total side**	**21,3%**			

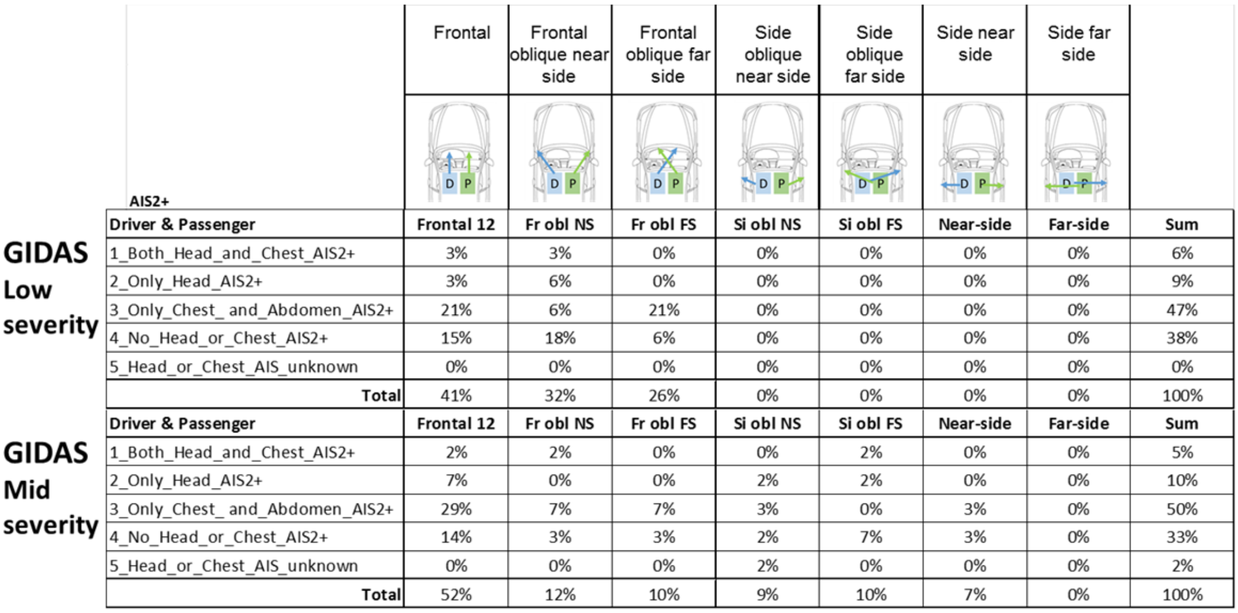
0-5%	🟩
5-10%	🟨
10-15%	🟧
15-20%	🟧
20-100%	🟥

Fig.B1. Un-weighted distribution of the US and German crashes.



	AIS2+	Frontal	Frontal oblique near side	Frontal oblique far side	Side oblique near side	Side oblique far side	Side near side	Side far side	
NASS Low severity	**Driver & Passenger**	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Sum**
	1_Both_Head_and_Chest_AIS2+	5%	2%	0%	0%	0%	0%	0%	7%
	2_Only_Head_AIS2+	12%	4%	4%	0%	0%	0%	0%	20%
	3_Only_Chest_ and_Abdomen_AIS2+	9%	6%	6%	0%	0%	0%	0%	20%
	4_No_Head_or_Chest_AIS2+	29%	12%	11%	0%	0%	0%	0%	52%
	5_Head_or_Chest_AIS_unknown	1%	0%	1%	0%	0%	0%	0%	2%
	Total	55%	23%	21%	0%	0%	0%	0%	100%
NASS Mid severity	**Driver & Passenger**	**Frontal 12**	**Fr obl NS**	**Fr obl FS**	**Si obl NS**	**Si obl FS**	**Near-side**	**Far-side**	**Sum**
	1_Both_Head_and_Chest_AIS2+	2%	3%	1%	4%	0%	0%	1%	10%
	2_Only_Head_AIS2+	7%	2%	1%	4%	2%	2%	0%	18%
	3_Only_Chest_ and_Abdomen_AIS2+	15%	3%	5%	5%	2%	1%	0%	32%
	4_No_Head_or_Chest_AIS2+	18%	3%	5%	6%	4%	2%	1%	39%
	5_Head_or_Chest_AIS_unknown	0%	0%	0%	0%	0%	0%	0%	1%
	Total	43%	11%	11%	19%	8%	6%	2%	100%

Fig. B2. Un-weighted distribution of injured body regions in NASS low- and mid-severity crashes.



		Frontal	Frontal oblique near side	Frontal oblique far side	Side oblique near side	Side oblique far side	Side near side	Side far side	
	AIS2+	D P	D P	D P	D P	D P	D P	D P	
	Driver & Passenger	Frontal 12	Fr obl NS	Fr obl FS	Si obl NS	Si obl FS	Near-side	Far-side	Sum
GIDAS Low severity	1_Both_Head_and_Chest_AIS2+	3%	3%	0%	0%	0%	0%	0%	6%
	2_Only_Head_AIS2+	3%	6%	0%	0%	0%	0%	0%	9%
	3_Only_Chest_ and_Abdomen_AIS2+	21%	6%	21%	0%	0%	0%	0%	47%
	4_No_Head_or_Chest_AIS2+	15%	18%	6%	0%	0%	0%	0%	38%
	5_Head_or_Chest_AIS_unknown	0%	0%	0%	0%	0%	0%	0%	0%
	Total	41%	32%	26%	0%	0%	0%	0%	100%
	Driver & Passenger	Frontal 12	Fr obl NS	Fr obl FS	Si obl NS	Si obl FS	Near-side	Far-side	Sum
GIDAS Mid severity	1_Both_Head_and_Chest_AIS2+	2%	2%	0%	0%	2%	0%	0%	5%
	2_Only_Head_AIS2+	7%	0%	0%	2%	2%	0%	0%	10%
	3_Only_Chest_ and_Abdomen_AIS2+	29%	7%	7%	3%	0%	3%	0%	50%
	4_No_Head_or_Chest_AIS2+	14%	3%	3%	2%	7%	3%	0%	33%
	5_Head_or_Chest_AIS_unknown	0%	0%	0%	2%	0%	0%	0%	2%
	Total	52%	12%	10%	9%	10%	7%	0%	100%

Fig. B3. Un-weighted distribution of injured body regions in GIDAS low- and mid-severity crashes severity.