The need for injury criteria targets to address high exposure, low-severity frontal crashes

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Abstract Due to very high exposure to low-severity crashes, the vast majority of crashes that cause injury are of relatively low severity. Restraint systems that can adapt to the crash severity have a potential to reduce injuries in these high-exposure crashes. Even a small reduction in injury risk is likely to have a substantial practical effect due to the very high exposure to low-severity crashes. In this investigation two different adaptive restraint systems were investigated using contemporary technological constraints and new, proposed injury criteria target values balanced for equal risk of injury for all body regions: 15% injury risk for mid-severity crashes and 2% injury risk for low-severity crashes. It was found that both restraint systems performed better than a state-of-the-art restraint system in meeting the proposed injury criteria targets. Though this should not be considered a proof-of-concept, these results do suggest that it may be feasible to reduce injury occurrence in crashes that are already of very low risk but result in high injury frequency due to very high exposure. Future work should include developing methods to assess the robustness of such systems, across dimensions of crash configuration, occupant, and sensing variability and its uncertainty that are present in the field.

Keywords Adaptive restraint systems, FE simulations, high-exposure frontal crashes, injury criteria targets, low-severity frontal crashes

I. INTRODUCTION

Approximately one million road users were injured in crashes involving cars in the EU during 2018, with car occupants accounting for the largest group (649,016 cases) [1-2]. Even though the majority of fatalities occur in high-severity crashes, the majority of injuries occur at lower crash severity [3-7] because of the high exposure to those crashes. While the risk of injury is in the single digits, the high number of lower severity crashes results in a very high number of injuries [5]. This is consistent with the distribution of crash locality of non-fatally injured car occupants in the EU: 52% of injury-causing crashes occur in urban areas where crash severities tend to be lower, compared to 36% in rural areas, and 12% on motorways where crash severities tend to be higher [1-2].

Current frontal occupant restraint systems are developed and evaluated for a limited crash severity level, with impact velocities ranging from 50 km/h to 64 km/h, and few different barrier conditions (Full Width, Mobile Progressive Deformable Barrier, Offset Deformable Barrier, Small Overlap Barrier), being either Euro NCAP, IIHS, FMVSS 208, UN-ECE R94 or UN-ECE R137. Previous research has found that higher rating in consumer and insurance test programs correlates to reduced injury risk [8-11]. When investigating the historical trend in car occupant fatalities and severely injured, this approach has been successful, resulting in a significant reduction in severely and fatally injured car occupants since the 1970s. However, the reduction has plateaued the last 10 years [12-13], suggesting that additional improvements are needed. Because the frontal impact protection regulations and NCAP test programs provide incentives to optimise the seat belts and airbags for the 50–64 km/h crashes, there is no certainty that the improvements to the occupant restraint systems will translate to better occupant protection in higher or lower severity crashes. Continuing to address single point cases might not be enough to further reduce the number of severely injured and fatal cases. Instead, the situation may require an evaluation at a mix of crash severity levels, occupant sizes and occupant seating positions [4][6-7][14-16].

In recent years, many passenger cars have been equipped with advanced driver assist systems (ADAS), which likely will reduce the number of crashes. However, no combination of ADAS is expected to completely prevent all possible crashes [17-18]. In particular, head-on, intersection and rear-end crashes are predicted to still occur [19-21]. For this reason, many fatal and serious injuries will continue to occur unless further improvements are

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implemented regarding crashworthiness and occupant protection.

Several studies have found that a ΔV of 30–40 km/h is the crash severity range in which most car occupants are injured [4-5][22]. This is not because the injury risk is high but rather because the exposure is high. Reference [5] reported on the injury risk for three different frontal crash severity levels: ΔV of 0–34 km/h, ΔV of 35–59 km/h and ΔV of above 60 km/h. The corresponding AIS2+ risk was 3.7%, 16% and 46% respectively, and the corresponding AIS3+ risks were 0.5%, 5.1% and 27%, respectively. Those values are supported by earlier work by [22], who found AIS3+ risk to be 0.7% and 9.6% for the two crash severity levels ΔV of 0–40 km/h and ΔV of 41–56 km/h. These risks are slightly higher than those reported by [5] but considering the slightly different crash severity ranges and the differences in car model years, the values correspond well. In addition, [5] reported that the majority of the injured occupants in frontal crashes, regardless of AIS level, were injured in the ΔV interval of 0–34 km/h, moreover that the injuries related to all body regions, and that the average age in the low-severity crashes was similar to the average age in the mid-severity crashes. Reference [5] findings indicate that injuries in low-severity crashes are not just pertinent to elderly occupants and chest-related injuries; instead, these are important to be considered for all ages and all body regions.

The objective of this study is to investigate potential injury reduction, trade-offs, and potential challenges for adaptive restraint systems seeking to reduce injury risk in low-severity frontal crashes. Low-severity frontal crash tests have been suggested many times [4][6-7][22] but to the authors' knowledge no details about injury criteria targets for full body evaluations in low-severity frontal crash tests have been proposed. Therefore, new injury criteria target values are proposed balancing for equal risk of injury for all body regions. Using these targets, two examples of adaptive restraint system configurations are designed using finite element (FE) simulations, each using technology constraints present in existing production restraint systems. Both restraint systems are then compared to a modern state-of-the-art restraint system in 30 km/h, 40 km/h and 56 km/h FFRB crash pulses to observe the potential benefit that may be gained by adapting the restraints based on crash pulse (using risk targets appropriate for each crash pulse).

II. METHODS

In this study, new proposed injury criteria target values, balanced for equal risk of injury for all body regions, were defined. Low-severity frontal crashes and mid-severity frontal crashes were given different target values. Those target values were based on injury risk levels in real-world frontal crashes [5]. An earlier validated FE model from [23] was used to design two different adaptive restraint systems (*restraint system A* and *restraint system B*), each with the aim of meeting the proposed targets. *Restraint system A* focused on a mid-severity crash using a 56 km/h FFRB crash pulse and the related injury criteria targets. *Restraint system B* focused on a low-severity crash using a 40 km/h FFRB crash pulse and the related injury criteria targets. Additional simulations were conducted with the performance of each restraint system (the two adaptive restraint systems and the state-of-the-art restraint) in the crash pulses for which they were not designed (e.g. the remaining 30 km/h, 40 km/h and 56 km/h FFRB crash pulses).

Reference Sled Tests

In a previous study [23] repeated frontal sled tests were conducted using a 40 km/h FFRB and a 56 km/h FFRB crash pulse developed by [24] (Fig. 1). THOR-50M was seated in a generic test set-up developed to represent a state-of-the-art driver restraint system of a mid-sized European car. The test set-up consisted of a semi-rigid seat [25-26], a generic floor geometry and foot support; a seatback to support the occupant during preparation for the test; a generic knee bolster (Ethafoam 220 mounted to a rigid plate) and a stroking steering column at a force limit of 5.5 kN and a maximum stroke of 85 mm. The seat belt included a shoulder-belt retractor equipped with a 2 kN pretensioner and a 4 kN load limiter, a wire buckle, a crash-locking tongue, and a 2 kN lap-belt pretensioner. The driver airbag had a 60-litre cushion made of coated fabric with 2 x Ø35 mm vent holes and a pyrotechnical inflator. A hydraulic-type sled catapult manufactured by Mannesmann Rexroth was used in all tests. The sled tests were recorded with six on-board high-speed cameras that recorded the tests at 1000 Hz (see Fig. 2). For details about the test set-up and the instrumentation of theTHOR-50M, see [23].

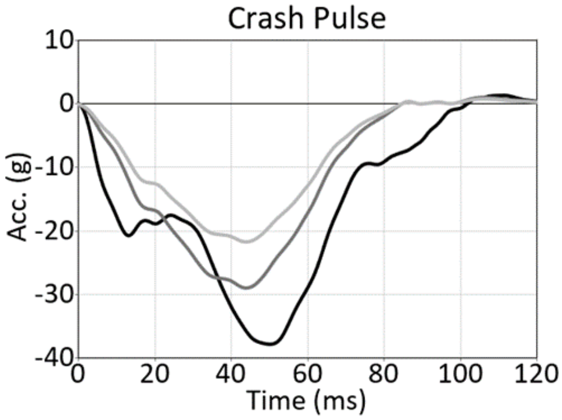

Fig. 1. Black: 56 km/h FFRB crash pulse; grey: 40 km/h FFRB crash pulse; light grey: 30 km/h FFRB crash pulse.

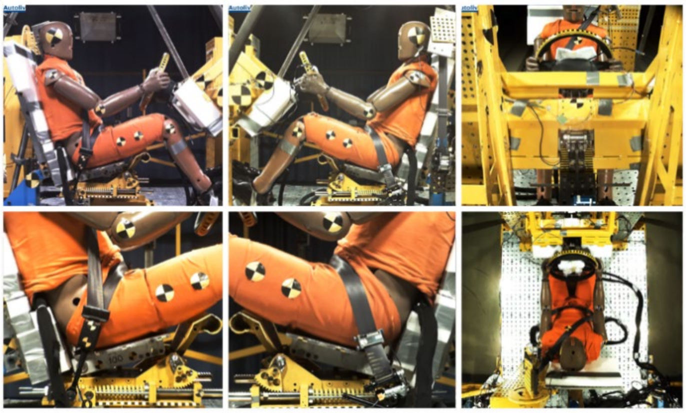

Fig. 2. Film views from sled tests: left and right side overview, a front view, left and right side detailed view of the pelvis, seat and lap belt and a top view.

Frontal Sled FE Model Validation

A frontal sled FE model was developed and validated upon this reference mechanical sled tests. A detailed description of the validation is found in [23]. Differing from [23], a B-pillar belt geometry was used instead of the seat-integrated belt geometry. However, the difference is minor as both seat belt attachments were rigid, consequently only the belt geometries differ. Sled test in the 56 km/h FFRB crash pulse and corresponding simulation is shown in Fig. 3. The model correlated well with the sled tests.

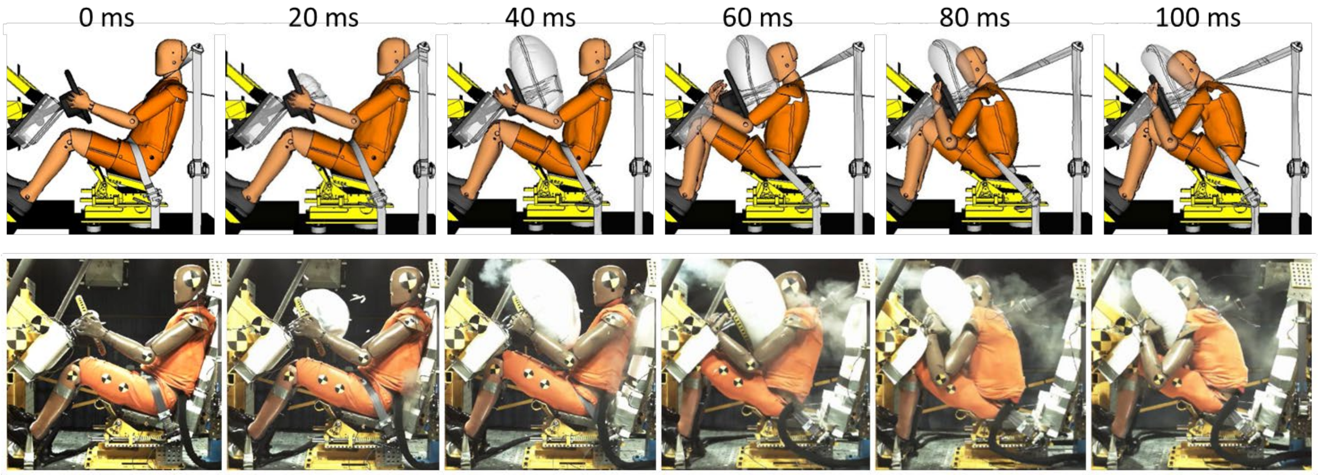

Fig. 3. Simulation (top) and mechanical (bottom) versions of the frontal sled in the 56 km/h FFRB crash pulse.

Proposed Injury Criteria Targets Balanced for Equal Risk of Injury for all Body Regions

Injury criteria target values balanced for equal injury risk for all body regions were created with the purpose of reducing the injury risk in low- and mid-severity crashes. Reference [5] reported that the risk to sustain a maximum abbreviated injury scale (MAIS) 2+ injury in the crash interval 0–34 km/h was about 4%, and in the crash interval 35–59 km/h about 16%, based on analyses from NASS-CDS and CISS. Recently, comparisons between WinSmash-derived ΔV estimates and EDR data have suggested that the ΔVs reported in NASS-CDS/CISS may underestimate true ΔV by an average of 10 km/h [27]. In other words, the 4% risk observed by [5] may in fact applies to collisions with ΔV's up to 44 km/h (34 + 10 km/h). Considering this, and wanting to take a conservative approach, we set the injury target values to 2% risk for an AIS2+ injury in our low-severity simulations (40 km/h and below) and 15% risk for an AIS2+ injury in our mid-severity simulations (56 km/h) for all body regions. While the accuracy of the available injury risk functions at such low risk levels is uncertain and the specific target risk levels are open to debate (e.g. 2% vs 3 or 4% risk), the main goal of these targets was to set conservative values that have a chance of reducing the risk below what is currently present in high-exposure crashes in the field. Furthermore, given the confidence intervals in the field data and the available injury risk functions, this modest decrease in targeted injury risk is really within the margin of error of our field estimates and prediction tools. Hence, the results should not be misconstrued to reflect a precise decrease in risk relative to the current state of the field. Instead, they serve as a starting point to identify targets within the realm of the already very low risk that is present in high-exposure scenarios.

The target values were calculated using the injury risk function defined by [28] (Table I). In addition to the injury criteria targets, like [23], an occupant kinematic criterion was defined: at least 20 mm margin for head-to-steering wheel strikethrough.

TABLE I
THOR-50M TARGET INJURY CRITERIA VALUES PROPOSED FOR LOW-SEVERITY AND MID-SEVERITY CAR CRASHES, BALANCED FOR EQUAL INJURY RISK FOR ALL BODY REGIONS

	Unit	Low-severity targets		Mid-severity targets	
Criteria		Risk	Value	Risk	Value
HIC15 (AIS2)		2%	185	15%	450
BrIC (AIS2)		2%	0.56	15%	0.64
Nij (AIS2)		2%	0.34	15%	0.72
Chest deflection (3+ fracture 40 years)	mm	2%	16	15%	32
Femur compression force (AIS2)	N	2%	5700	15%	7750
Upper Tibia axial force (AIS2)	kN	2%	2.3	15%	4.9
*Lower Tibia axial force (AIS2)**	kN	-	-	15%	4.3
Tibia bending moment (AIS2)	Nm	2%	110	15%	210
Revised Tibia index (AIS2)		2%	0.4	15%	0.79

* Note: this risk curve does not start at 0% risk for 0 load (a known issue when analysing some datasets with simple logistic regression). Instead, this IRF exhibits a 2% risk at 0 N force. As this is likely not realistic, we recommend excluding the Lower Tibia Axial Force from the low-risk evaluations for the time being (until a new IRF can be developed with better confidence in low-risk scenarios).

Design and Simulation of Restraint System A and Restraint System B

In addition to the previously described frontal sled FE model, an adaptive shoulder-belt retractor that can switch down the load limiter force level in the crash [29] and a driver airbag with adaptive vent size were used.

The design process to design and tune restraint systems A and B is visualized in Fig. 4. The FE model was used to design *restraint system A* with the aim of meeting the proposed injury criteria targets of 15% risk for an AIS2+ injury for all body regions for a mid-severity crash using the 56 km/h FFRB crash pulse. The *restraint system A* design parameters were shoulder-belt load limiter levels (LL1 and LL2), time to switch load limiter level, vent size diameters, steering column (SC) force, and maximal steering column (SC) stroke distance. Then, the two parameters, time to switch load limiter level and vent size diameters, were tuned with the aim of meeting the proposed injury criteria targets of 2% risk for an AIS2+ injury for all body regions for a low-severity crash using the 40 km/h FFRB crash pulse. Lastly, a simulation was conducted with a 30 km/h FFRB crash pulse (see Fig. 1) using the restraint settings from the 40 km/h FFRB crash pulse. (The 30 km/h FFRB crash pulse was created by scaling the 40 km/h FFRB crash pulse.)

The FE model was used to design *restraint system B*, this time with the aim of meeting the proposed injury criteria targets of 2% risk for an AIS2+ injury for all body regions for a low-severity crash using the 40 km/h FFRB crash pulse. Again, the restraint system design parameters were the shoulder-belt load limiter levels (LL1 and LL2), time to switch load limiter level, vent size diameters, steering column (SC) force, and maximal steering column (SC) stroke distance. Then, the two parameters, time to switch load limiter level and vent size diameters, were tuned with the aim of meeting the proposed injury criteria targets of 15% risk for an AIS2+ injury for all body regions for a mid-severity crash using the 56 km/h FFRB crash pulse. And again, an additional simulation was conducted with the 30 km/h FFRB crash pulse using the restraint settings from the 40 km/h FFRB crash pulse.

For comparison purposes, simulations were also conducted with the previously described state-of-the-art restraint system for all three FFRB crash pulses.

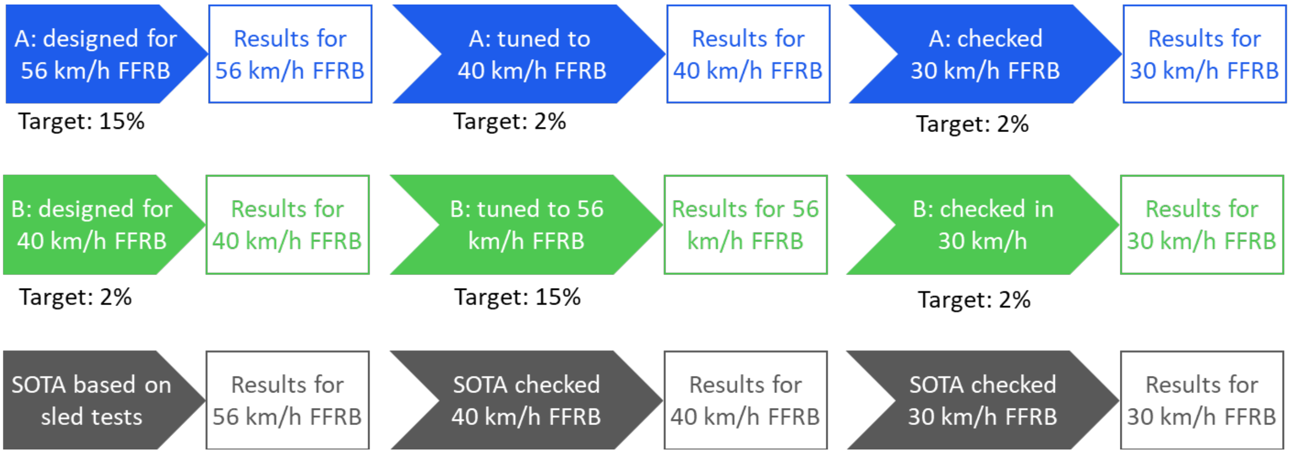

Fig. 4. Simulation process for designing *restraint system A* (blue) and *restraint system B* (green) and simulation of state-of-the-art (SOTA) restraint system (dark grey).

III. RESULTS

The final settings of *restraint system A* and *restraint system B* are described in the first part of this section. The corresponding simulation results and calculated injury risks for the three restraint systems per crash pulse are presented in the following parts.

Final Settings of Restraint System A and Restraint System B

Simulations with random, but physically realistic, settings on all design parameters were conducted for both the 56 km/h and the 40 km/h FFRB crash pulses. These showed that meeting the target criteria values for the chest deflection and the brain injury criterion (BrIC) could be challenging, and that strikethrough of the head-to-steering wheel occurred for some settings. Consequently, *restraint systems A* and *B* were designed and tuned, as described in Fig 4, to meet all proposed injury criteria targets of Table I except the chest deflection. The settings that yielded the lowest chest deflection, but still meeting all proposed injury criteria targets, in each crash velocity were selected. The final settings of the *restraint system A* and the *restraint system B* for the 40 km/h and 56 km/h FFRB crash pulses are found in Table II, together with settings used for the state-of-the-art restraint system.

TABLE II
SETTINGS FOR RESTRAINT SYSTEM A, RESTRAINT SYSTEM B AND STATE-OF-THE-ART RESTRAINT SYSTEM

Restraint system	LL1 [kN]	LL2 [kN]	Switch time [ms]	Vent Ø [mm]	SC force [kN]	SC stroke [mm]
Restraint system A, 56 km/h settings	4.5	2.3	48	2x34	4.8	95
Restraint system A, 40 km/h settings	4.5	2.3	10	2x42	4.8	95
Restraint system B, 56 km/h settings	3.0	-	None	2x32	5.0	95
Restraint system B, 40 km/h settings	3.0	1.7	43	2x39	5.0	95
State-of-the-art settings	4.5	-	None	2x35	5.5	85

Results for 56 km/h FFRB Crash Pulse

Simulation results and the calculated injury risks for the 56 km/h FFRB crash pulses for the three restraint systems are reported in Table III. All three restraint systems met the 15% injury risk targets except for injury risk calculated for chest deflection; its target value of 32 mm was exceeded by 9.9 mm, 5.7 mm and 10.2 mm, for the state-of-the-art restraint system, *restraint system A* and *restraint system B,* respectively (see Fig.5). The remaining head-to-steering wheel strikethrough distance was 84 mm, 43 mm and 66 mm for the state-of-the-art restraint system, *restraint system A* and *restraint system B*, respectively. The shoulder-belt characteristics (force level and retractor pay-out), the steering column stroke displacement, the driver airbag pressure, the head resultant acceleration, the head y-angular velocity (the major contributor for BrIC calculation as x and z angular velocity was small), the upper neck compression/tension force, the upper neck y moment and the maximum resultant chest deflection (right upper Infra-Red Telescoping Rods for the Assessment of Chest Compression, IRTRACC) are presented for each restraint system in Fig 5.

TABLE III

INJURY CRITERIA VALUES AND THE INJURY RISKS FOR THE STATE-OF-THE-ART RESTRAINT SYSTEM, RESTRAINT SYSTEM A AND RESTRAINT SYSTEM B FOR THE 56 KM/H FFRB CRASH PULSE

Restraint system	Unit	State-of-the-art		*Restraint system A*		*Restraint system B*	
Criteria		Value	Risk	Value	Risk	Value	Risk
HIC15 (AIS2)		351	9.7%	206	2.7%	228	3.5%
BrIC (AIS2)		0.61	8.8%	0.63	11.9%	0.64	14.8%
Nij (AIS2)		0.43	3.4%	0.34	2.0%	0.35	2.1%
Chest deflection (3+ fracture 40 years)	mm	41.9	31.4%	37.7	24.0%	42.2	31.9%
Femur compression force (AIS2)	N	2730	0.0%	3180	0.0%	3080	0.0%
Upper Tibia axial force (AIS2)	kN	1.60	1.2%	1.62	1.2%	1.71	1.3%
Lower Tibia axial force (AIS2)	kN	1.90	5.4%	1.90	5.4%	1.90	5.4%
Tibia bending moment (AIS2)	Nm	106	1.7%	106	1.6%	110	1.9%
Revised Tibia index (AIS2)		0.55	5.3%	0.54	5.0%	0.58	6.2%

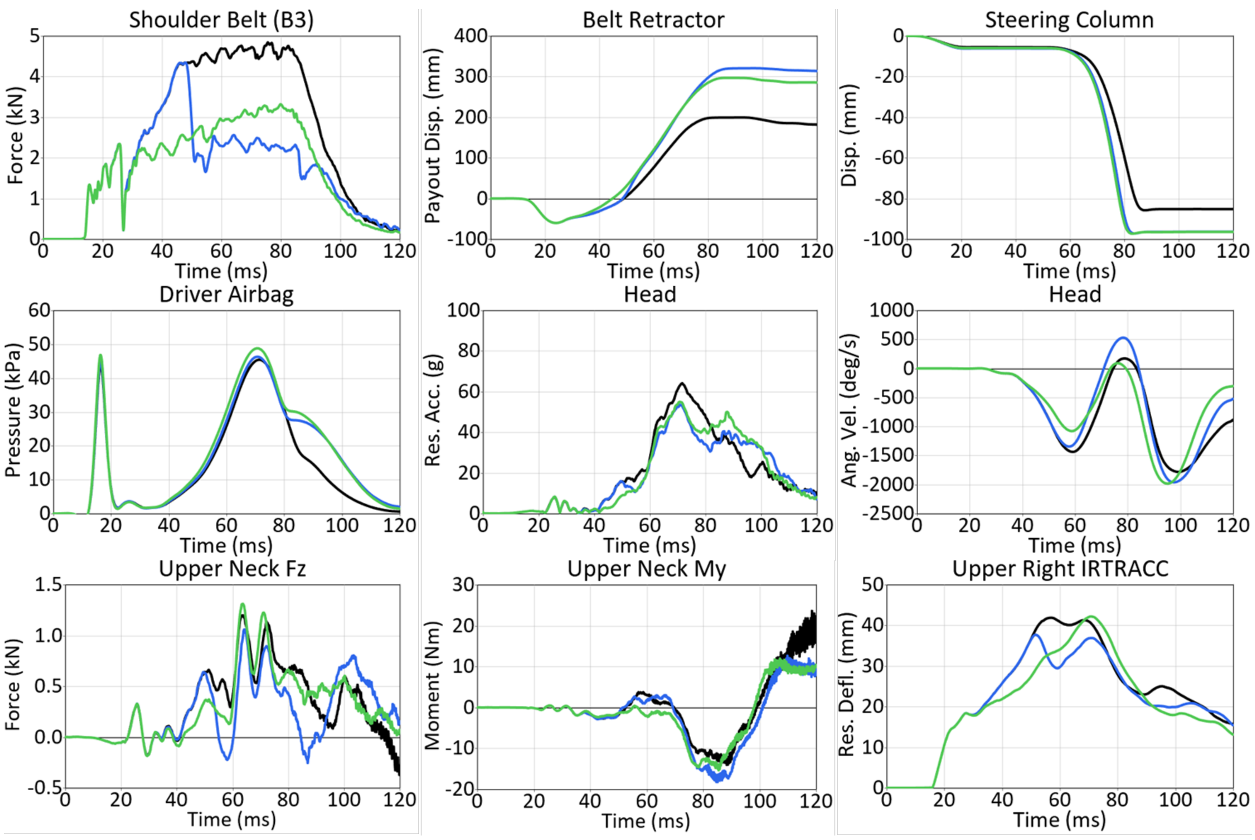

Fig. 5. Results from 56 km/h FFRB crash pulse. For all figures: black = state-of-the art restraint system; blue = *restraint system A*; green = *restraint system B*.

Results for 40 km/h FFRB Crash Pulse

Simulation results and the calculated injury risks for the 40 km/h FFRB crash pulses for the three restraint systems are reported in Table IV. *Restraint system A* and *restraint system B* met the 2% injury risk targets except for injury risk calculated for chest deflection; its target value is 16 mm. However, 16 mm chest deflection was exceeded during pretension of the shoulder-belt retractor for all three restraint systems (see Fig. 6). The remaining head-to-steering wheel strikethrough distance was 120 mm, 28 mm and 42 mm for the state-of-the-art, *restraint system A* and *restraint system B*, respectively. The shoulder-belt characteristics (force level and retractor pay-out), the steering column stroke displacement, the driver airbag pressure, the head resultant acceleration, the head y-angular velocity, the upper neck compression/tension force, the upper neck y moment, and the maximum resultant chest deflection (right upper IRTRACC) are presented for each restraint system in Fig 6.

TABLE IV

INJURY CRITERIA VALUES AND THE INJURY RISKS FOR THE STATE-OF-THE-ART RESTRAINT SYSTEM, RESTRAINT SYSTEM A AND RESTRAINT SYSTEM B FOR THE 40 KM/H FFRB CRASH PULSE

Restraint system	Unit	State-of-the-art		*Restraint system A*		*Restraint system B*	
Criteria		Value	Risk	Value	Risk	Value	Risk
HIC15 (AIS2+)		240	4.0%	118	0.5%	112	0.4%
BrIC (AIS2+)		0.48	0.0%	0.53	0.2%	0.53	0.1%
Nij (AIS2+)		0.25	1.2%	0.29	1.5%	0.29	1.5%
Chest deflection (3+ fracture 40 years)	mm	39.5	27.1%	29.5	12.4%	27.9	10.6%
Femur compression force (AIS2+)	N	1210	0.0%	1430	0.0%	1620	0.0%
Upper Tibia axial force (AIS2+)	kN	1.25	0.9%	1.25	0.9%	1.25	0.9%
Tibia bending moment (AIS2+)	Nm	82	0.7%	84	0.7%	83	0.7%
Revised Tibia index (AIS2+)		0.4	2.0%	0.4	2.0%	0.4	2.0%

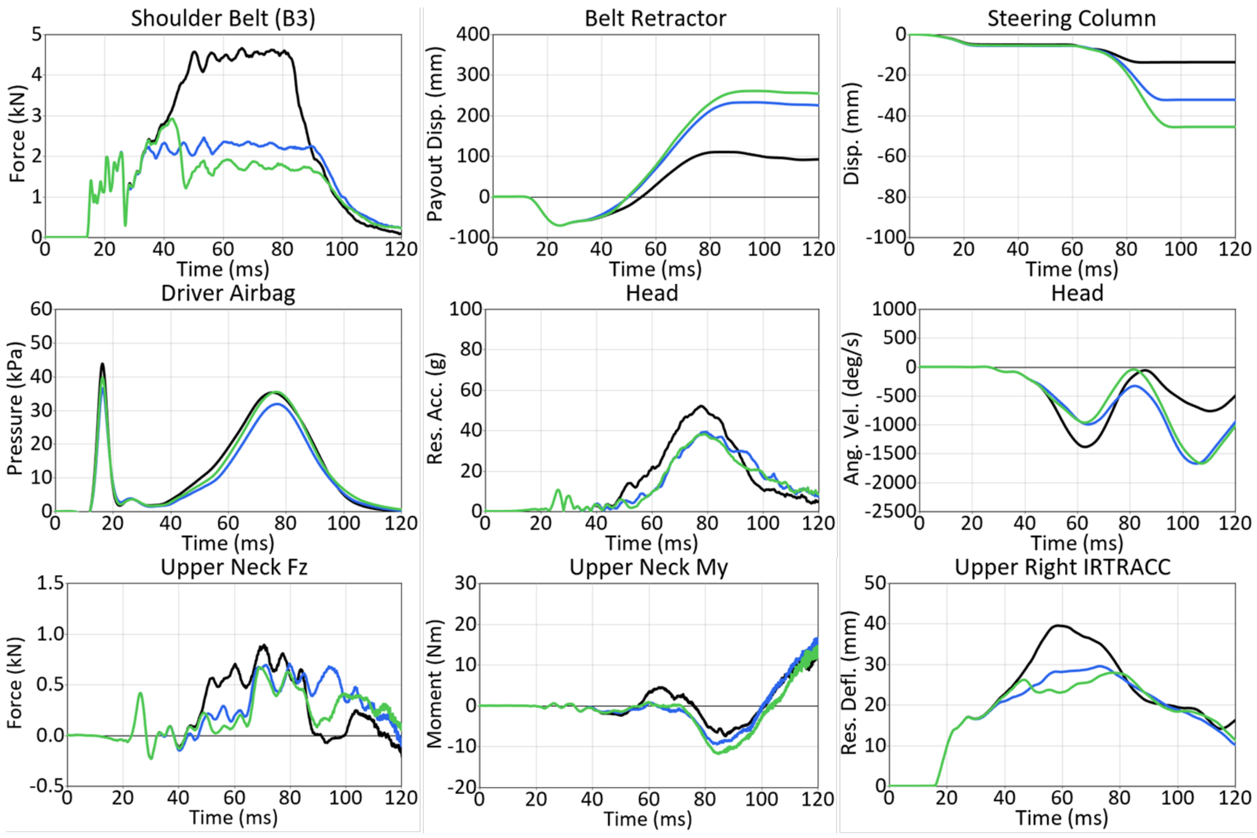

Fig. 6. Results from 40 km/h FFRB crash pulse. For all figures: black = state-of-the art restraint system; blue = *restraint system A*; green = *restraint system B*.

Results for 30 km/h FFRB Crash Pulse

Simulation results and the calculated injury risks for the 30 km/h FFRB crash pulses for the three restraint systems are reported in Table V. In contrast to the 40 km/h FFRB crash pulse simulations, the *restraint system A* and the *restraint system B* were not tuned to fulfil the 2% injury risk targets for the 30 km/h FFRB crash pulse. Instead, the restraint system parameter settings from the 40 km/h FFRB crash pulse were used. As for the 40 km/h FFRB crash pulse simulations, the 16 mm chest deflection target was exceeded during pretension of the shoulder-belt retractor for all three restraint systems (see Fig. 7). The remaining head-to-steering wheel strikethrough distance was 175 mm, 78 mm and 85 mm for the state-of-the-art, *restraint system A* and *restraint system B*, respectively. The shoulder-belt characteristics (force level and retractor pay-out), the steering column stroke displacement, the driver airbag pressure, the head resultant acceleration, the head y-angular velocity, the upper neck compression/tension force, the upper neck y moment, and the maximum resultant chest deflection (right upper IRTRACC) are presented for each restraint system in Fig 7.

TABLE V

INJURY CRITERIA VALUES AND THE INJURY RISKS FOR THE STATE-OF-THE-ART RESTRAINT SYSTEM, RESTRAINT SYSTEM A AND RESTRAINT SYSTEM B FOR THE 30 KM/H FFRB CRASH PULSE

Restraint system	Unit	State-of-the-art		*Restraint system A*		*Restraint system B*	
Criteria		Value	Risk	Value	Risk	Value	Risk
HIC15 (AIS2+)		92	0.2%	41	0.0%	45	0.0%
BrIC (AIS2+)		0.45	0%	0.42	0.0%	0.35	0.0%
Nij (AIS2+)		0.31	1.7%	0.28	1.4%	0.20	0.9%
Chest deflection (3+ fracture 40 years)	mm	36.2	21.6%	25.5	8.2%	23.7	6.7%
Femur compression force (AIS2+)	N	650	0.0%	670	0.0%	700	0.0%
Upper Tibia axial force (AIS2+)	kN	0.99	0.7%	0.99	0.7%	0.99	0.7%
Tibia bending moment (AIS2+)	Nm	64	0.3%	64	0.3%	64	0.3%
Revised Tibia index (AIS2+)		0.35	1.3%	0.35	1.3%	0.35	1.3%

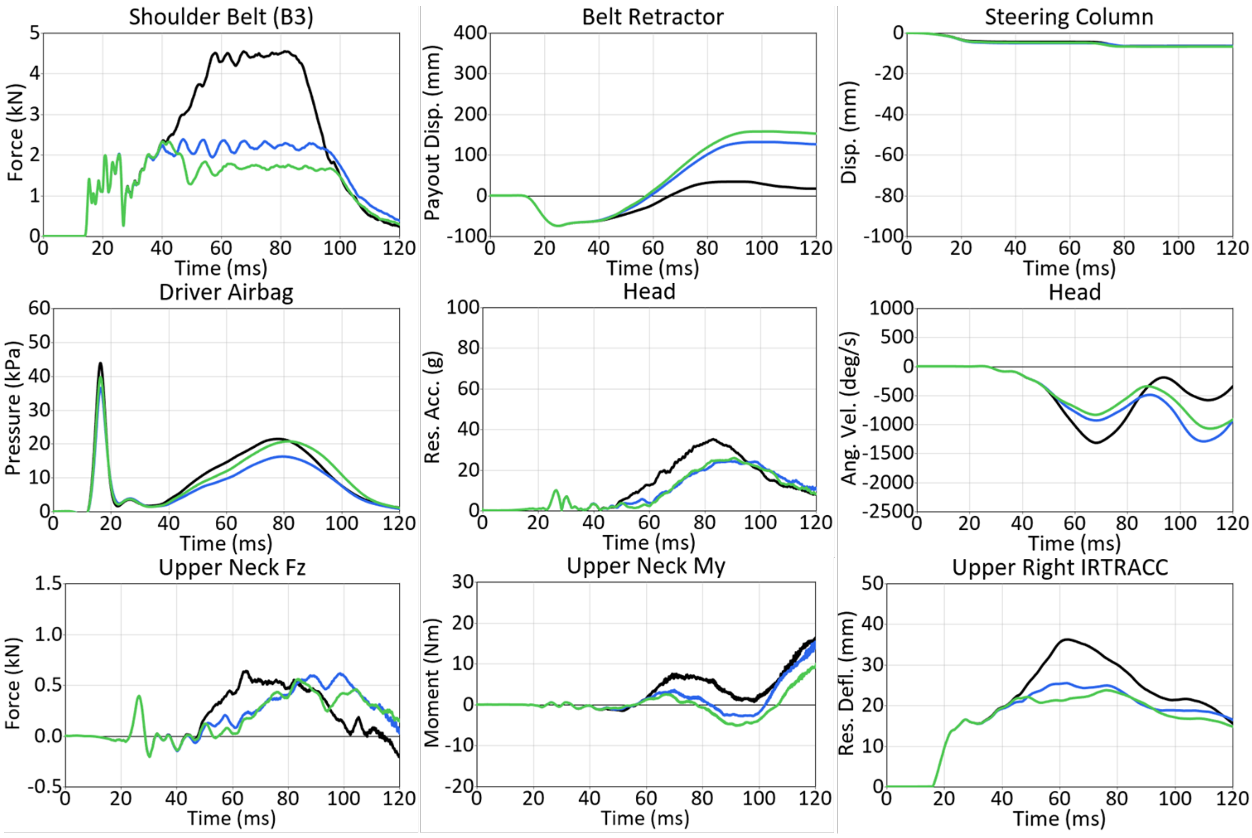

Fig. 7. Results from 30 km/h FFRB crash pulse. For all figures: black = state-of-the art restraint system; blue = *restraint system A*; green = *restraint system B*.

IV. DISCUSSION

Two different adaptive restraint systems were defined by using the new proposed injury criteria target values balanced for equal injury risk of all body regions. *Restraint system A* was designed to mid-severity crashes (56 km/h FFRB crash pulse) and a 15% risk of an AIS2 injury. *Restraint system B* was designed to low-severity crashes (40 km/h FFRB crash pulse) and a 2% risk of an AIS2 injury. During the design phase of the two restraint systems, the two criteria, chest deflection and BrIC, were identified to limit the settings for both restraint systems. The chest deflection is initially built up by the shoulder-belt force, and at a later stage the driver airbag pressure also contributes to the maximum chest deflection. To reduce the chest deflection, the belt force must be low from the start, and the contribution from the airbag should be low enough not to increase the chest deflection. Low contribution from the airbag can be obtained by large-sized venting holes, in combination with a stroking steering column. Thus, it is generally beneficial to couple the anthropomorphic test device (ATD) to the restraint system early in the crash phase, and to reduce the initial velocity of the ATD down to zero over a long distance. In the present study, the available distance, before the head strikes the steering wheel, could not be fully used since large-sized venting holes, soft steering column, and long steering column stroke – in all checked combinations – led to BrIC values exceeding the proposed injury criteria target values. Thus, if BrIC should have been neglected, both *restraint system A* and *restraint system B* could have been designed differently, and a lower chest deflection value could have been achieved.

Despite the conflicting BrIC vs. chest deflection criteria targets, a substantial reduction in rib fracture risk was observed when moving from the state-of-the-art restraint system to an adaptive restraint system designed for targeting a lower risk in the 56 km/h FFRB crash pulse (*restraint system A*). This reduction was preserved when *restraint system A* was tuned for the 40 km/h FFRB crash pulse and checked for the 30 km/h FFRB crash pulse (see Fig. 8). Compared to *restraint system A*, an observable, though subtle, decrease in rib fracture risk was seen in the 40 km/h FFRB crash pulse with *restraint system B*. This decrease was preserved in the 30 km/h FFRB crash pulse. However, when evaluated in the 56 km/h FFRB crash pulse, *restraint system B* resulted in an increased rib fracture risk compared to *restraint system A* (see Fig. 8). This was due to the earlier described conflict between chest deflection and BrIC. The high risk of rib fracture calculated for the state-of-the-art restraint system in both 30 km/h and 40 km/h FFRB crash pulses is mainly related to the shoulder-belt force reached 4.5 kN despite the lower crash pulse although the retractor belt pay-out was short (see Figs 5–6). Except for the rib fracture risk, all three restraint systems resulted in similar risk levels, almost meeting all other injury criteria targets for all three crash pulses.

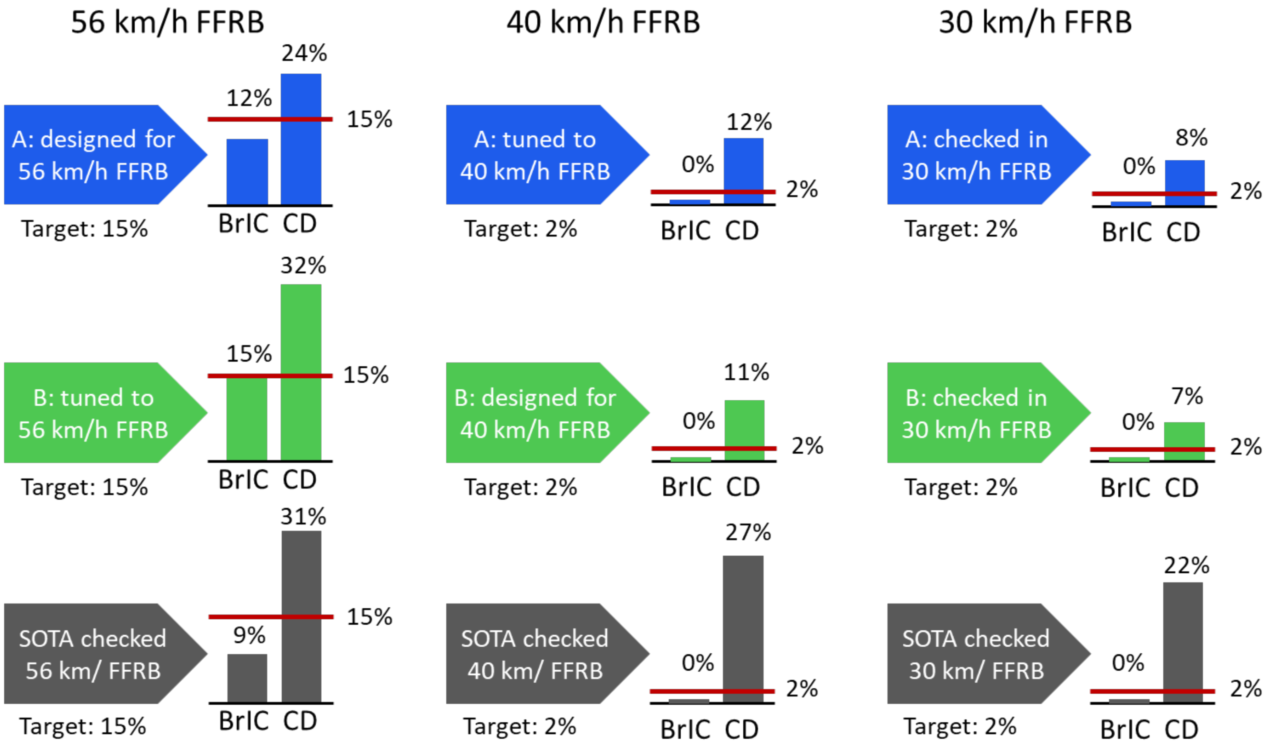

Fig. 8. Injury risks calculated based on BrIC and chest deflection for *restraint system A* (A) = blue, *restraint system B* (B) = green and state-of-the-art (SOTA) = dark grey for all three FFRB crash pulses.

Injury Risk vs. Exposure & Implications in Restraint System Adaptation

The vast majority of crashes occur at relatively low speed. Although the injury risk (per crash) in low-severity crashes is low, the net effect is that, when combined with the very high exposure, most injuries occur in those crashes. For example, in an analysis of frontal impact crashes with belted occupants over a nine-year period (NASS 2010-2015, CISS 2017-2019), [5] found that 72% of the cases that resulted in AIS2+ injury (and 46% of the cases that resulted in AIS3+ injury) occurred with reported ΔVs less than 35 km/h. This is consistent with the large difference in exposure comparing the 0–34 km/h ΔV group to crashes of higher severity. Over the nine-year study span, approximately 3.7 million cases of frontal impact tow-away crashes with belted occupants were estimated to occur in the U.S.A, with ΔVs between 0 and 34 km/h. In comparison, approximately 274,000 such crashes were estimated to occur with ΔVs between 35 and 59 km/h, and only 23,000 were estimated to occur with ΔVs of 60 km/h or above [5].

As a result, the potential implications of changes in restraint performance should be evaluated with consideration to the effects in crash severities of various exposure. In the current study, the results show a relatively large drop in rib fracture risk when moving from the state-of-the-art restraint system to the adaptive restraint system designed for 56 km/h (*restraint system A*), and a much more subtle decrease in rib fracture risk for a low-severity crash when moving from *restraint system A* to the restraint system designed for 40 km/h (*restraint system B*). When crossing with the crash exposure, however, even a modest decrease in risk has the potential to prevent many injuries. For example, if moving from *restraint system A* to *restraint system B* can reduce the risk of thoracic injury by 1.5% in 0–34km/h crashes, this has the potential to eliminate more than 6,000 cases of AIS3+ rib fracture injury in the U.S.A. every year (3.7 million * 1.5% / 9 years of data collection). On the other hand, the *restraint system B* has a higher risk of rib fracture for the mid-severity crashes (Table III), which then will add about 2,400 cases of AIS2+ rib fractures (274,000 * 7.9% / 9 years of data collection). To be clear, we are not advocating one condition at the expense of the other, rather it is important to consider the implications in all crash types.

These results suggest that while substantial decreases in injury counts may be gained through modest decreases in injury risk, our ability to reduce risk may be hampered when constraining to practically realizable contemporary technologies. Specifically, the adaptive components of the restraint system were constrained to the switch time of the shoulder-belt load limiter, and the airbag vent hole size. The load limit levels in the seat belt and steering column remained fixed. Though some modest decreases in risk were achieved in adapting between the mid- and low-severity crashes studied here, these results also demonstrate the challenges in reducing risk when constrained in the choice of features to adapt. Using the framework established here, future work should include investigating the additional risk reduction that may be possible with additional restraint adaptation features, such as a retractor with three load limiter stages, a steering column with adaptive force levels and additional load limiters in the lap belt [30].

Injury Criteria Targets

Due to the very high exposure, most injuries occur in crashes where the per-crash injury risk is already quite low (below 5% risk). Thus, to reduce the injury occurrence further in these high-exposure scenarios, we need low injury risk targets. The target risk used here was 2%, based on attempting to improve the per-crash injury risk below what has been observed in field data of high-exposure crashes that result in most injuries. This 2% value is itself an estimate, however – with the primary goal of seeking to provide some conservative target to try to reduce risk. This study shows that the 2% target is feasible to achieve for most body regions but would be challenging to achieve for the current thoracic injury prediction methods using practical contemporary restraint solutions. For example, the 2% injury risk target of rib fractures corresponds to 16 mm of chest deflection, which was exceeded already during the belt pretensioning phase of the simulations. Given that the 2% level is an intentionally ambitious goal seeking to demonstrate proof-of-concept, reductions short of that goal are still encouraging and are useful for demonstrating that increased risk reduction is possible through restraint adaptation.

These results highlight the need to adapt the injury risk threshold values to the test severity being targeted, to ensure that the assessment scenario will drive down risk below what is already present in the field. However, these results also highlight the need for injury risk functions possessing a high degree of accuracy at very low risk levels. This is especially important for cases where there are trade-offs in risk, as in the trade-off between BrIC and chest deflection observed here. There is substantial uncertainty in all injury risk functions. At very low risk levels, the natural injury risk function (IRF) uncertainty likely dwarfs the fine gradations of risk that we are seeking to predict. Developing and validating an IRF for the low-risk range is extremely challenging – for example, to discern a 2% risk an IRF would need to be built from a data pool that contains 49 cases of non-injury for every 1 case of injury. The vast amount of data needed suggests that this is infeasible through traditional means of IRF fitting (e.g., through tests with post-mortem human surrogates, PMHS). Instead, developing and validating IRFs for low-risk scenarios may require novel means combining traditional PMHS-based data with the addition of large datasets (such as field data or large-scale simulation), potentially using techniques such as Bayesian analysis to develop joint estimates.

Anthropomorphic Test Devices

All these discussions assume that the ATD being used for these evaluations is sensitive to changes in the test severity and restraint characteristics in the correct manner. This may not be the case. One can imagine a scenario where the ATD may be overly stiff, resulting in idealized coupling to the vehicle and nearly zero predicted risk in low-severity crashes. Likewise, one could imagine a more subtle scenario where a model appears biofidelic in a certain scenario, but for whatever reason does not predict the effect of subtle adaptation in restraint characteristics in the correct manner. To be useful as tools for designing and evaluating adaptive restraint systems, occupant models (either physical or computational) must be sensitive to change in the crash and restraint environment in the correct manner. This biofidelity of sensitivity to change is rarely assessed but is critical to establishing the suitability of a model as a restraint design and evaluation tool.

Further work

Earlier studies [6][31-32] have identified that many of the injuries seen in low-severity crashes are induced by the restraint systems, indicating that they are too stiff. It was seen in this investigation that the 4.5 kN load limiter level was reached also in the 30 km/h FFRB crash pulse with the state-of-the-art restraint system. However, in the design of the two adaptive restraint systems for the different crash severity levels and used injury criteria targets, it was found that BrIC limited the possibility to fully use the available distance for forward excursion, i.e. the possibility to design a more compliant restraint system. To fully explore the potential with adaptive restraint systems addressing low-severity frontal crashes it might be meaningful to consider other criteria than those used. Such could potentially be a head excursion criterion similar to what is used in the rear seat [33] or a force distribution criterion for the chest instead of the current deflection criterion. When moving into virtual testing and evaluation, new assessment measures that are not feasible in current physical testing could potentially be introduced. Examples of such measurements could be a contact force measurement or a relative movement of body parts. Implementation of human body models and related tissue-based injury risk functions could potentially also lead to different design of the restraint system.

The injury risk in a frontal crash depends on both severity and impact configuration. It should be noted that a more compliant restraint system may have some drawbacks if activated for the wrong situation. As an example, [27] found that most serious head injuries were sustained in small overlap and oblique crashes. In such scenarios, a low shoulder-belt force, intended to reduce chest deflection, may potentially allow a greater head excursion with an increased risk for a head injury. Another scenario might be if the sensor system misjudges the crash severity level and adjusts the restraint system as if it was a low-severity crash, when in fact it was a mid-severity crash. Such a scenario could cause a strikethrough of the restraint system as a result, potentially increasing the injury risk instead of decreasing it [34]. Therefore, adaptive restraint systems need redundant sensor signals for each information that is used to set the activation logic. Adaptive systems should also be designed recognising the reality that we will never have perfect information on the crash type or occupant characteristics. The control logic should be designed recognizing realistic sources of uncertainty and variability and should be tuned to minimise the potential for adverse effects within the realm of uncertainty that remains after sensing and classification. All this will only be possible through evaluating the robustness of the system, not just in a small number of crash cases with a small number of occupant models, but instead evaluating the system performance across the whole range of crash configurations and occupant states that are expected to occur. This requires shifting from a mentality of point-by-point evaluation (e.g. evaluation in a small number of individual cases) to a mentality of evaluating the continuum of system response across the spectrum of crashes and occupant variability present in the field. While physical testing will still play an important role in validating the predictions of numerical simulations, the desired thorough robustness assessment is likely only feasible through large-scale numerical simulations with advanced data analysis methods designed to characterize the system performance as a response surface spanning realistic dimensions of uncertainty and variability [16][35].

V. CONCLUSIONS

Two adaptive restraint systems were designed using two different approaches. *Restraint system A* was designed for a mid-severity frontal crash (56 km/h FFRB crash pulse) and tuned for a low-severity frontal crash (40 km/h FFRB crash pulse), while *restraint system B* was designed for a low-severity frontal crash (40 km/h FFRB crash pulse) and tuned for a mid-severity frontal crash (56 km/h FFRB crash pulse). It was seen that both restraint systems performed better than a state-of-the-art restraint system, and that each of the two restraint systems result in a lower predicted rib fracture risk for the crash severity that they were each designed for. Trade-offs were also observed between predicted head injury risk (via BrIC) and predicted rib fracture risk (via chest deflection). These two measures were observed to be the most challenging to reduce and functioned as the driving measures for the restraint system changes.

Restraint systems that are made adaptable to the crash severity have a potential to reduce injuries in real-life crashes. Although the injury risk is reduced by a small amount, it is likely to have a substantial practical effect due to the very high exposure to low-severity crashes. However, most of the injury criteria exhibit limited sensitivity in this crash severity range and may not be sufficient to guide the design of adaptive restraint systems at low-severity crashes. This suggests a potential need for supplemental injury criteria targets to be used when designing adaptive restraint systems for low-severity crashes.

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