Initial Evaluation of Underrepresented Occupants in Highly Autonomous Vehicles using VIVA+ Human Body Model

Andrew Harrison, SIMBIO-M 24th September 2024

Content & Overview

- Motivation and Background
- Tool and Process Overview
- Model Preparation
- Simulation Test Matrix
- Results
- Closing remarks

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DLR Urban Modular Vehicle People Mover (UMV PM)

aware2all.eu

The research was conducted in cooperation with

University of Stuttgart
Institute of Engineering and Computational Mechanics

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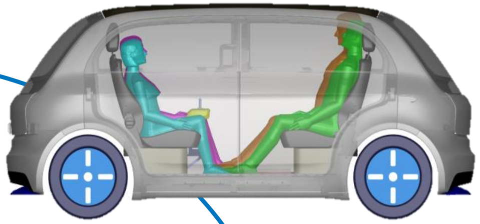
Highly Autonomous Vehicles (HAVs) - Safety Considerations

Mixed Traffic [1]

- → AVs share common roads with conventional vehicles
- → human error
- → unavoidable collisions

Distinct Interior [2]



- → decreased crumple zones
- → flexibility in seating
- → absence of safety structures like knee bolster, footwell

HAVs – Passive Safety Considerations

Diverse Populations [3,4]

- → AVs accesible to wider population groups
- → certain groups still underrepresented
- → female, body fat %, age and mobility

Key Challenges:

- → Human Anthropometry Variability
- → Reduced occupant loadpath of HAV
- → Occupant cabin structures
- → Addressing “Trade-off” of injury regions

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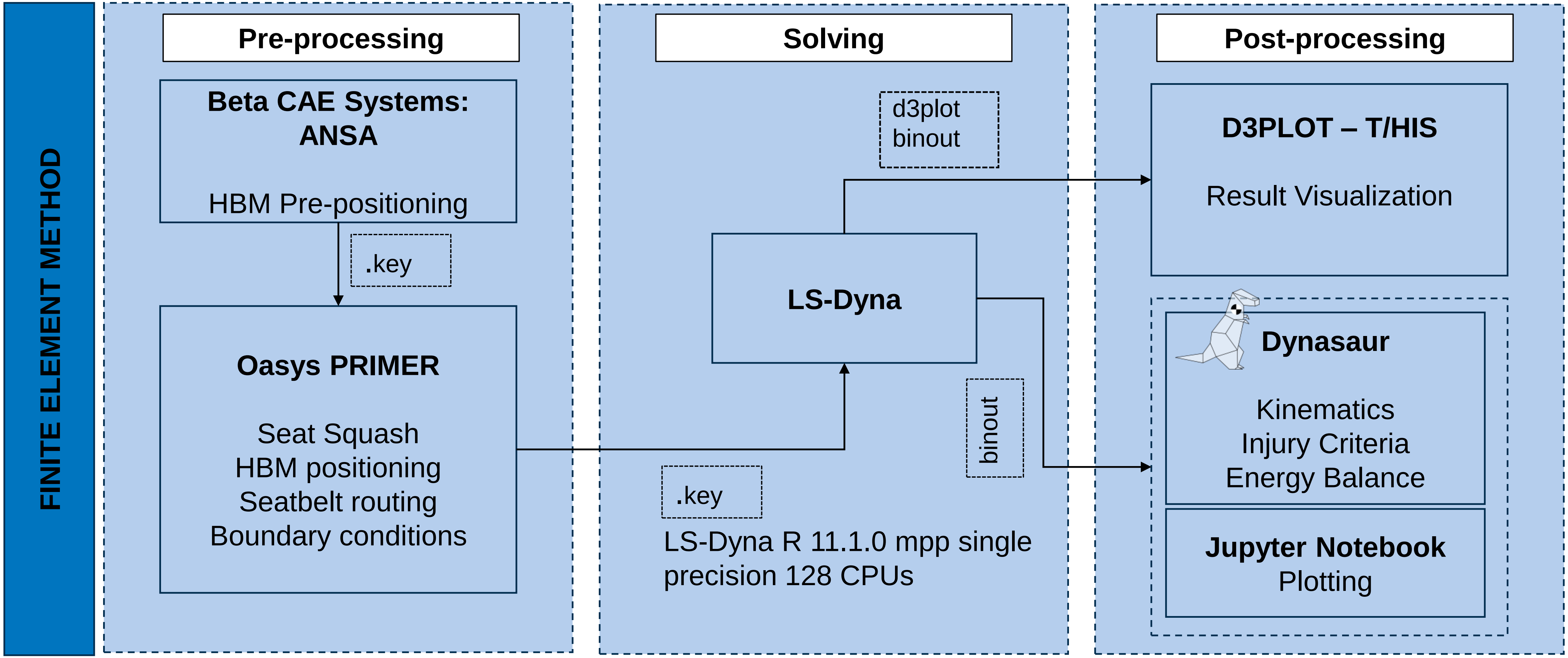
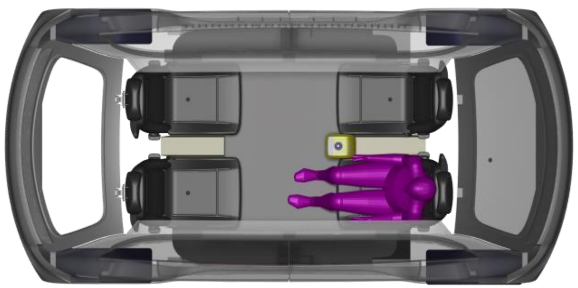
Tool & Process Overview: Workflow

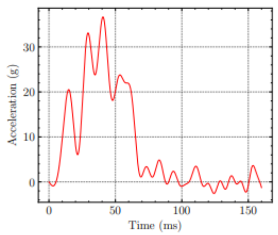


Tool & Process Overview: FE-Models & Input

Simplified sled model



Seat configuration of DLR UMV People Mover

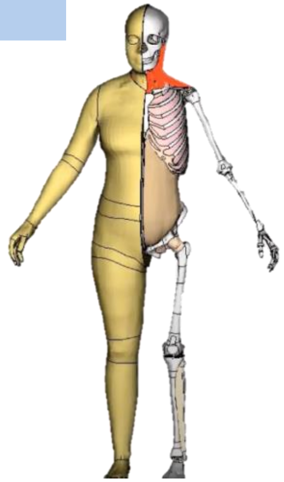


OSCAAR Sled Pulse (Höschele et al. 2022)

Simplified Sled model

- Reduced to a simplified sled with UMV PM seating configuration
- Honda Odyssey second row passenger seat [5]
- Integrated seat belt system
- Two seat back angles: 18° and 45°
- 40km/h Pulse (Höschele et al. 2022)
- Cabin interior interaction not considered

Occupant model

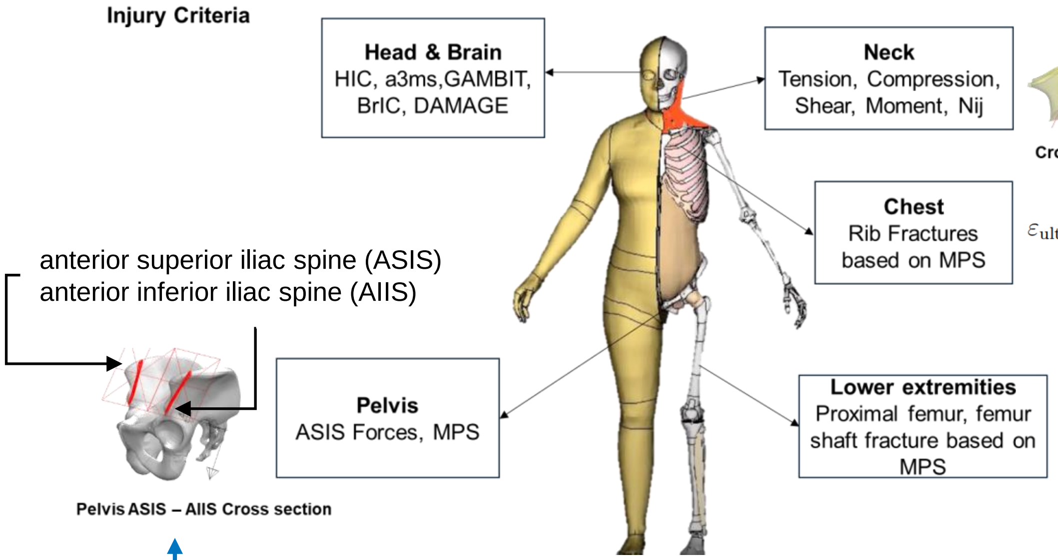


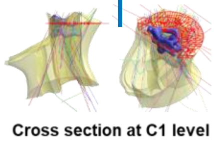
VIVA + 50F model (v1.0.1) [6]

- **50th percentile female model:** Tailored to represent an average female physique
- **Robustness:** superior resilience compared to alternatives
- **Computational efficiency:** simpler internal organs, kinematic joints
- **Rigid and simplified lumbar spine:** Inadequate for strain-based injury analysis.

Model Preparation: HBM metrics and physically disabled occupant

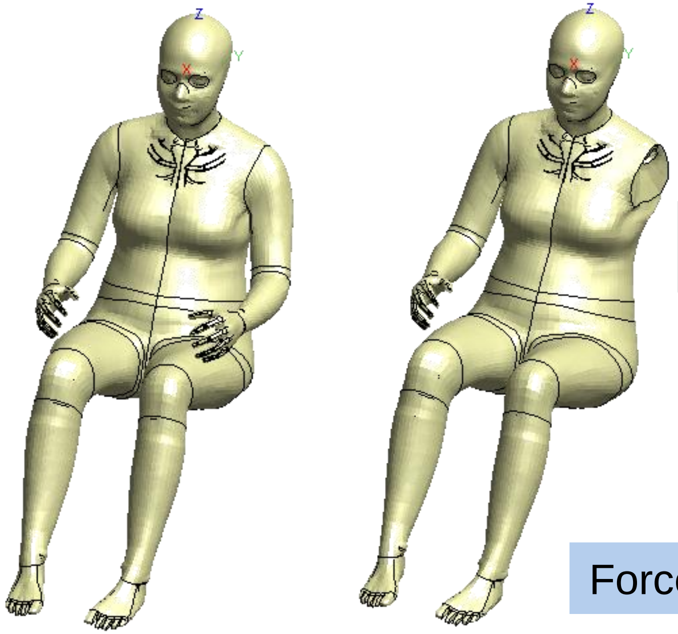
Forces and moments calculation





$$\varepsilon_{\text{ultimate (age)}} = \varepsilon_{\text{ultimate 25}} \times \left(1 - (\text{age} - 25) \times \frac{0.051}{10}\right)$$

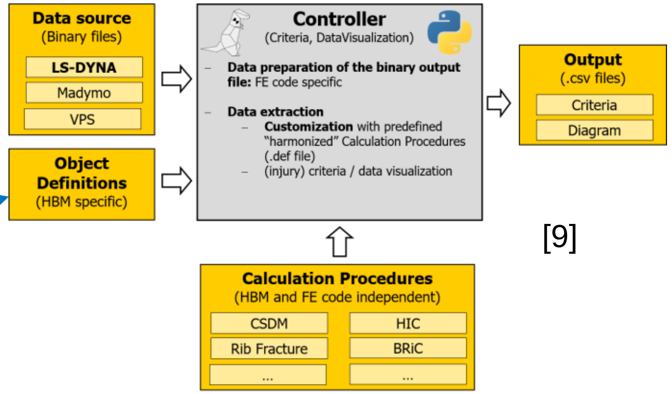
[7,8]



Left: Standard VIVA+ 50F model (**50F**)
(EU H2020 grant agreement number 768960);
Right: Loss of upper-limb VIVA+ 50F model (**50DF**)

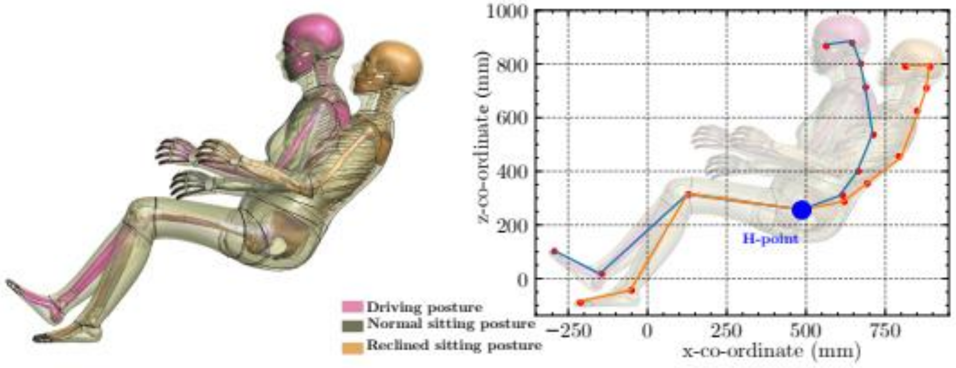
Forces calculation for submarining identifcation

Open-source injury calculation



[9]

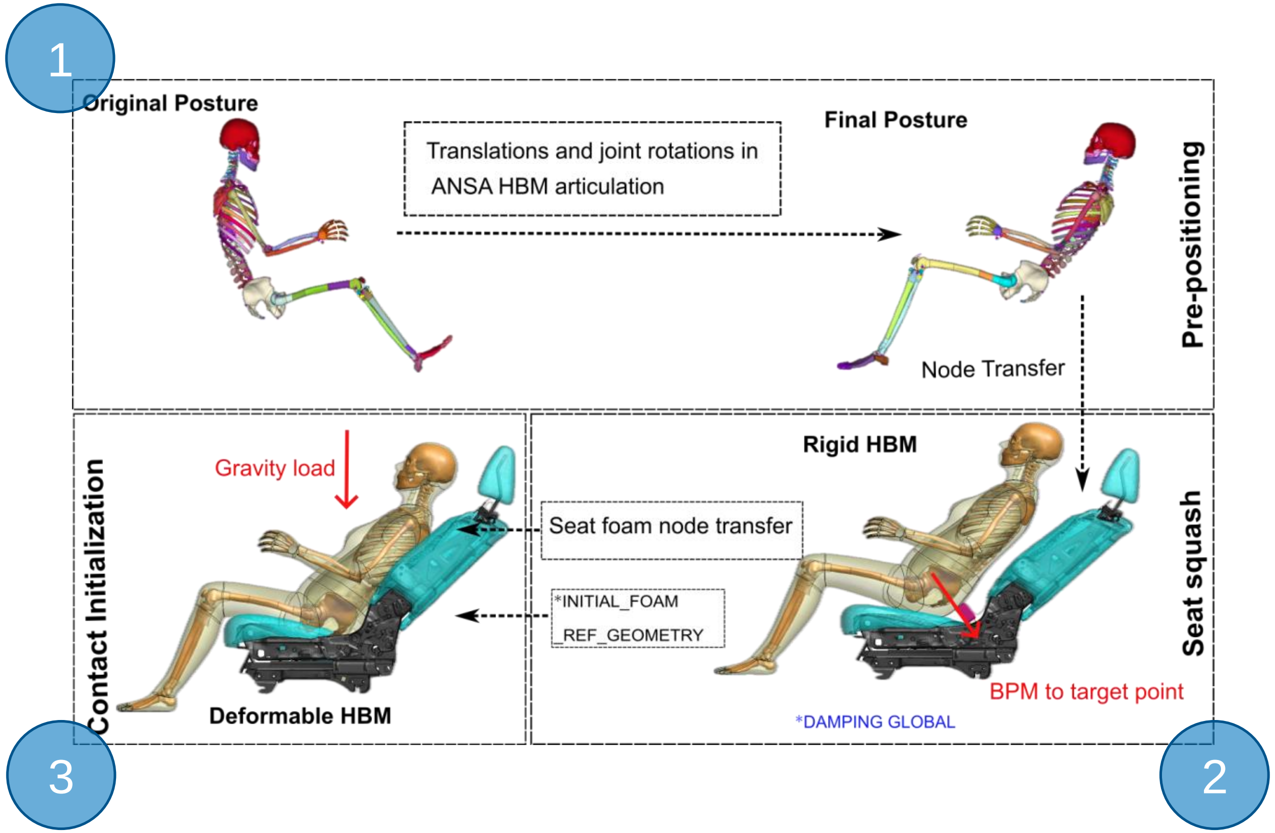
Model Preparation: HBM Posture and positioning



VIVA+ 50F in multiple postures

- **3-stage method:**

1) Pre-processor joint articulation with mesh morphing — *No transient simulation*
2) Rigid HBM Seatsquash — **150ms, 45 minutes*
3) Contact initialisation and convergence — **30ms, 30 minutes*



**2x AMD EPYC 7601, 32 cores, 2.2GHz*

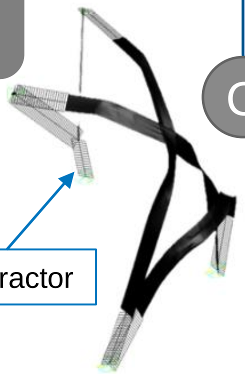
Model Preparation: Seatbelt Restraint System

– 3 seatbelt designs
- **SoA passenger seat-integrated seatbelts (A)**
- **Advanced seat-integrated seatbelts (B,C)**

– ***MAT_B01_SEATBELT** with 0.6mm thin elastic shells for bending stiffness [10,11]

– 1D elements used by retractor and sliprings

*Control and parameters of seabelts **B** & **C** conducted iteratively with combination of literature and simulation results using seatbelt **A***



LL: Load-limiter
PT: Pre-tensioner
CLT: Crash locking tongue

Simulation Test Matrix

full frontal crash pulse

HBM postures	Foot support	Seat belt design	Case ID
50F driving 	✓	A	1
	✓	B	3
50F passenger 	X	A	2 (50F-A)
	X	B	4 (50F-B)
50DF passenger 	X	B	5 (50DF-B)
	X	C	6 (50DF-C)
50F reclined 	X	B	7 (50F-Br)

Due to topic of presentation: Case 1 & 3 will not be presented

A vs. B (50F)

B (50F vs. 50DF)

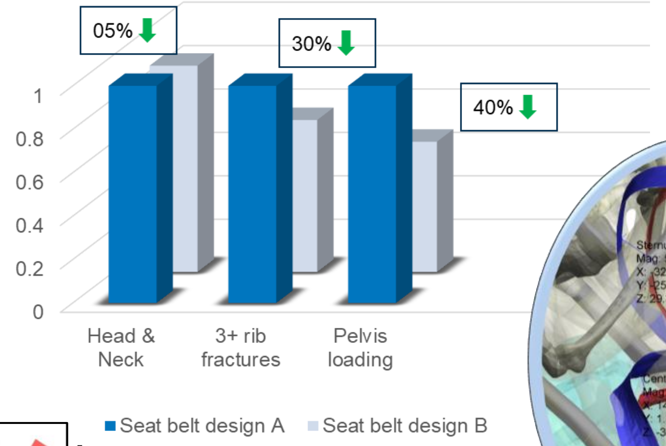
B vs. C (50DF)

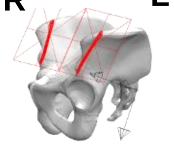
Results: 50F-A (Case 2) vs. 50F-B (Case 4)

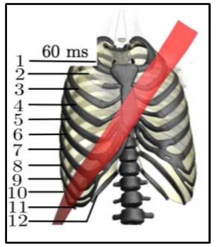
		50F-A (Case 2)	50F-B (Case 4)
Thorax (Probability)	0 fractured ribs L	0	0.35
	0 fractured ribs R	0	0.06
	1+ fractured ribs L	1.00	0.65
	1+ fractured ribs R	1.00	0.94
	2+ fractured ribs L	0.75	0.24
	2+ fractured ribs R	0.96	0.70
	3+ fractured ribs L	0.28	0.05
	3+ fractured ribs R	0.80	0.38
Pelvis	F ASIS L (kN)	2.33	1.40
	F ASIS R (kN)	2.64	1.56

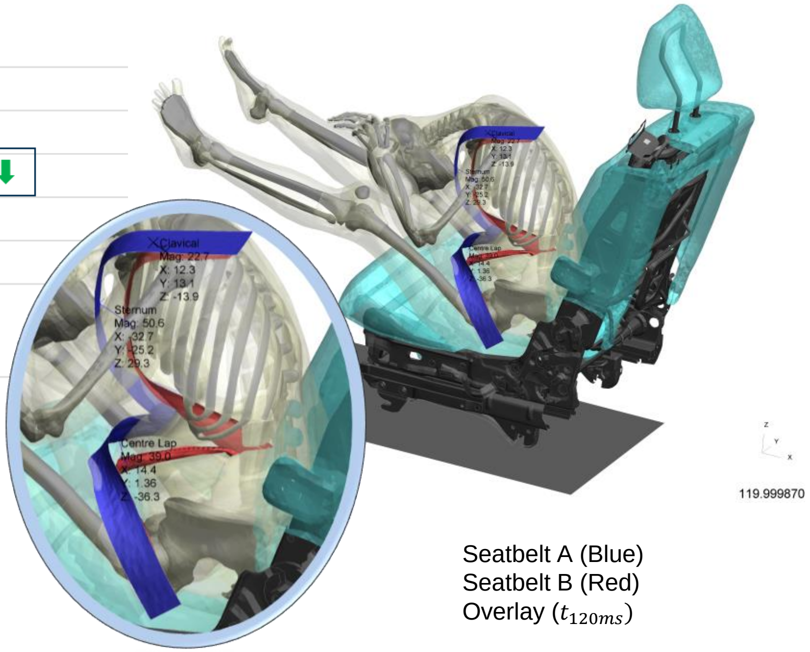
Seatbelt B vs. Seatbelt A (case 4 vs. 2):

- Better retention of occupant (-$20mm_{x,T11\ vertebrae}$, t_{70ms})
- Reduction in 0-3+ rib fracture probability
- Reduced loading and rotation of pelvis
- Leg lift-off present at t_{70ms} in both cases
- General kinematics similar



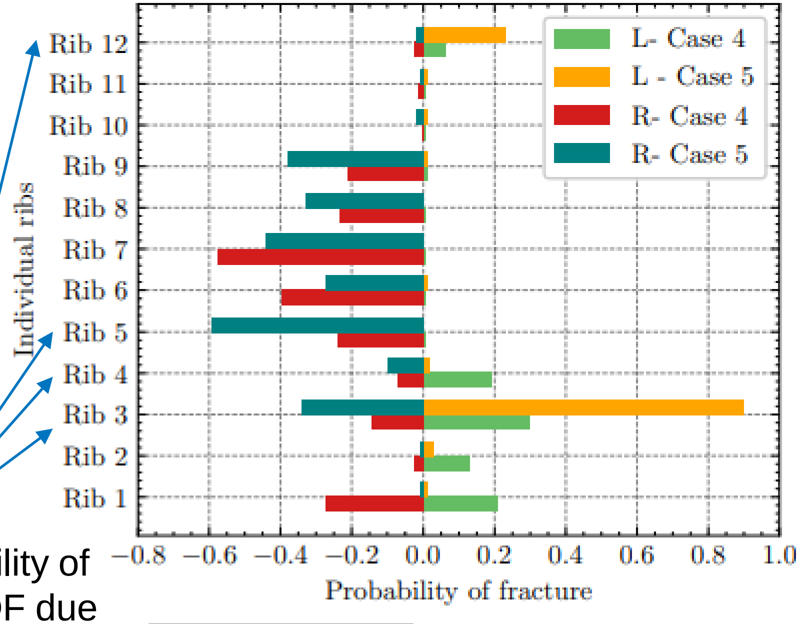




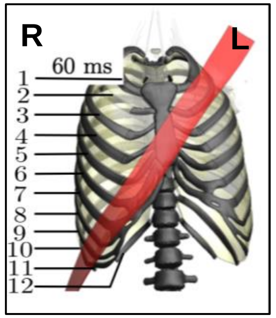


Seatbelt A (Blue)
Seatbelt B (Red)
Overlay (t_{120ms})

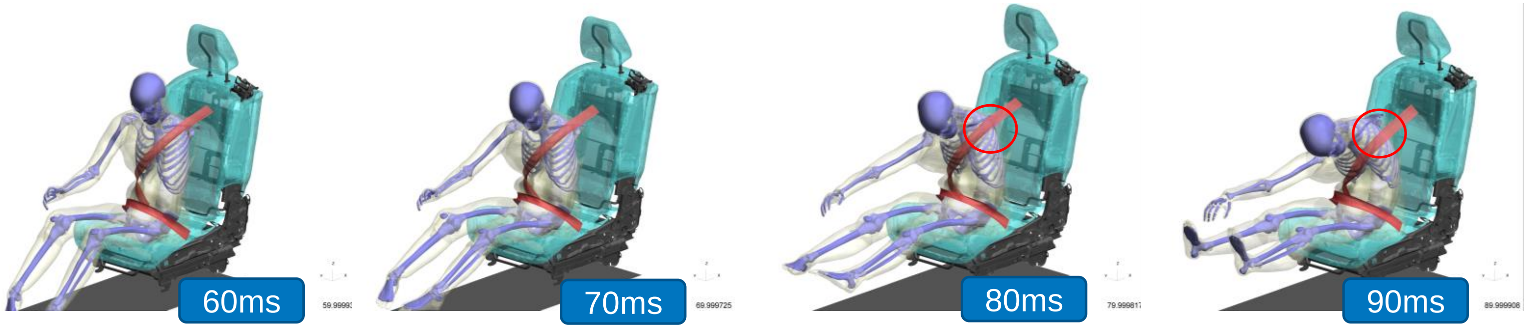
Results: 50F-B (Case 4) vs. 50DF-B (Case 5)



Increased probability of rib fracture to 50DF due to load localisation as a result of seatbelt slippage



		50F-B (Case 4)	50DF-B (Case 5)
Thorax (Probability)	0 fractured ribs L	0.35	0.07
	0 fractured ribs R	0.06	0.04
	1+ fractured ribs L	0.65	0.93
	1+ fractured ribs R	0.94	0.96
	2+ fractured ribs L	0.24	0.27
	2+ fractured ribs R	0.70	0.79
	3+ fractured ribs L	0.05	0.02
	3+ fractured ribs R	0.38	0.49
Pelvis	F ASIS L (kN)	1.40	1.40
	F ASIS R (kN)	1.56	1.59



Case 5, 50DF-B

Results: 50DF-B (Case 5) vs. 50DF-C (Case 6)

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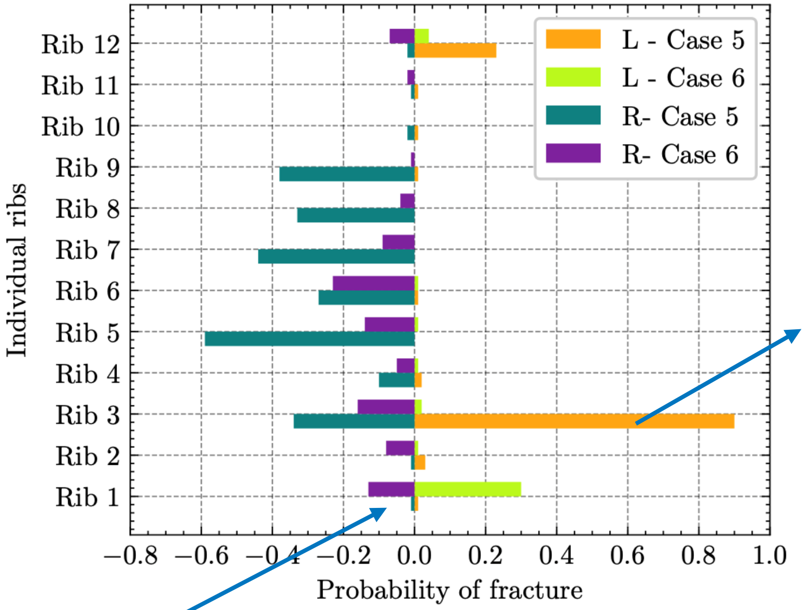
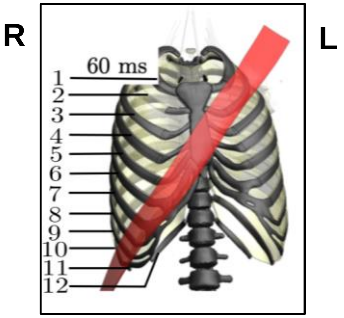
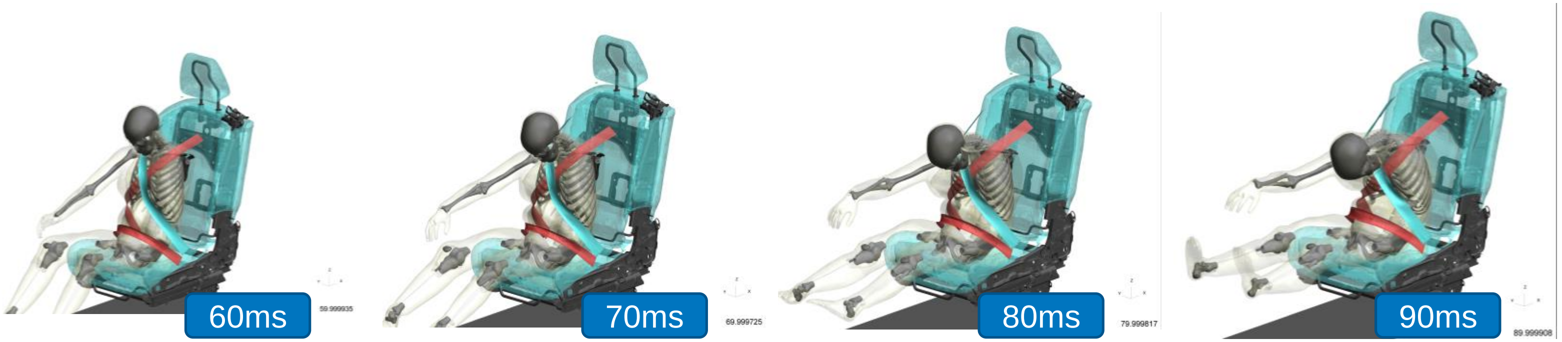


90% probability of 3rd left rib fracture (50DF) of 3-point seatbelt mitigated by 4-point seat belt

4-point seatbelt increases loads to ribs 1



		50DF-B (Case 5)	50DF-C (Case 6)
Thorax (Probability)	0 fractured ribs L	0.07	0.63
	0 fractured ribs R	0.04	0.34
	1+ fractured ribs L	0.93	0.37
	1+ fractured ribs R	0.96	0.66
	2+ fractured ribs L	0.27	0.03
	2+ fractured ribs R	0.79	0.27
	3+ fractured ribs L	0.02	0.00
	3+ fractured ribs R	0.49	0.07
Pelvis	F ASIS L (kN)	1.40	1.43
	F ASIS R (kN)	1.59	1.54

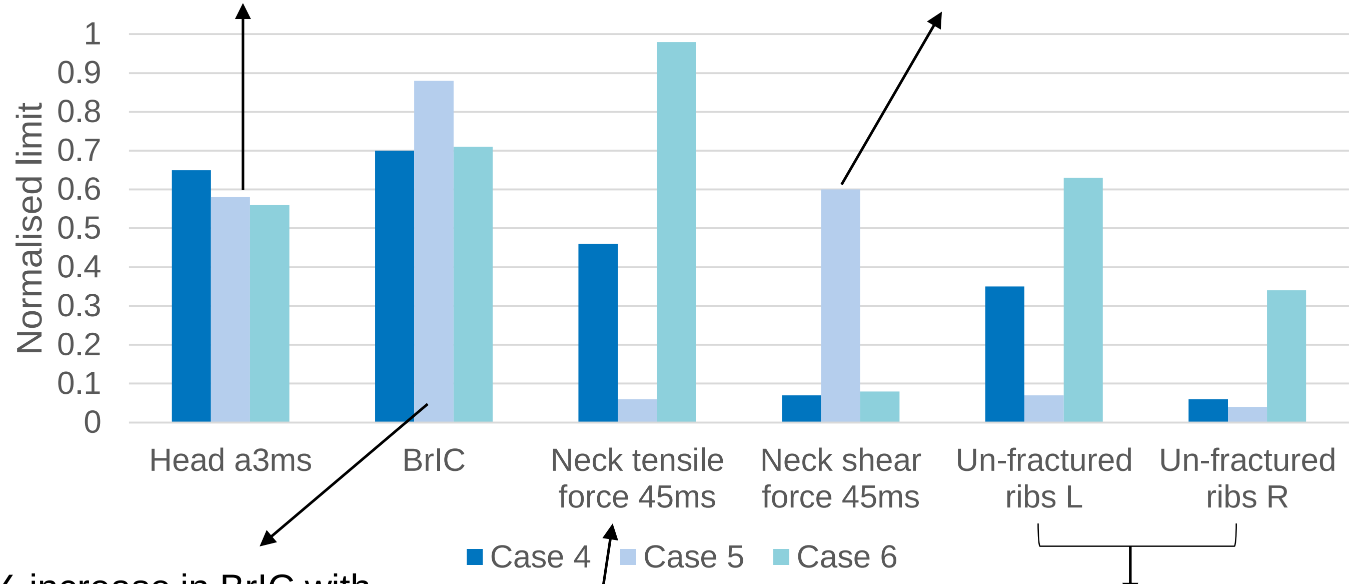


Case 6, 50DF-C

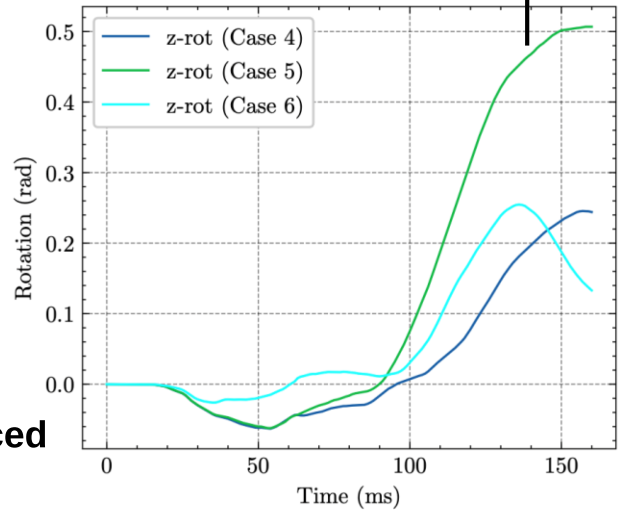
Results: 50F-B (Case 4), 50DF-B (Case 5) and 50DF-C (Case 6)

Minor reductions of linear head accelerations for 50DF to 50F

~**50%** increase in neck shear force for **disabled occupant** with **3-point seatbelt** as a result of head and torso rotation



Pelvis rotates twice as much for **disabled occupant** with **3-point seatbelt.** Insufficient occupant retention



~**18%** increase in BrIC with **disabled occupant** (3-point seatbelt) due to increased head rotation velocity from seatbelt slippage

~$\mathbf{0.98}F_{neck,tensile\ limit}$ with **4-point harness** caused by reduced upper-torso rotation in sagittal plane

~30% reduction in **seat belt B (Advanced 3-point belt) effectiveness** for Disabled Occupant*

~50% increase in **seat belt C (Advanced 4-point belt) effectiveness** for Disabled Occupant*

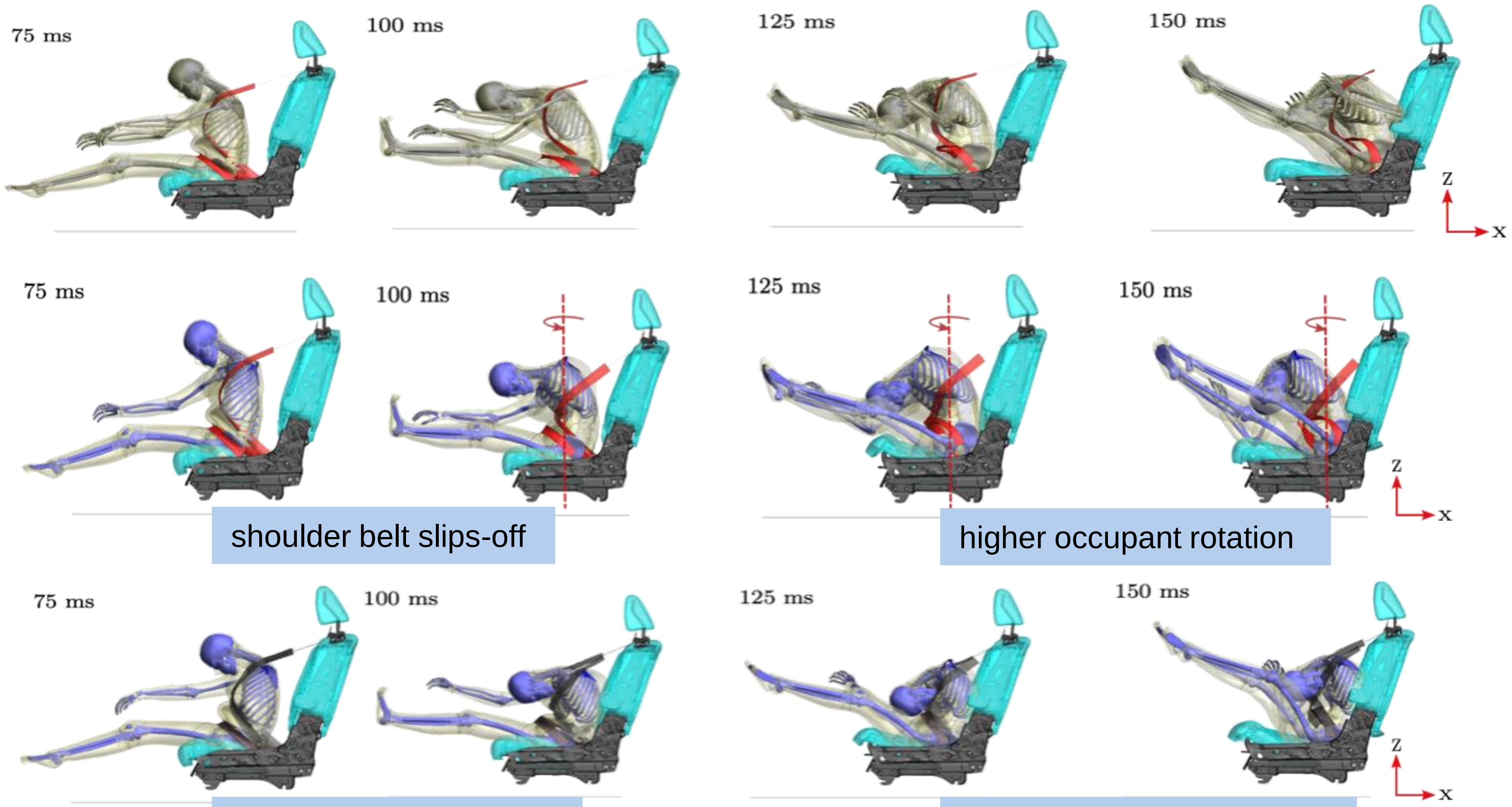
*Based on probability of no rib fractures

Results, Kinematic: 50F-B (Case 4), 50DF-B (Case 5) and 50DF-C (Case 6)

50F-B (Case 4)

50DF-B (Case 5)

50DF-C (Case 6)

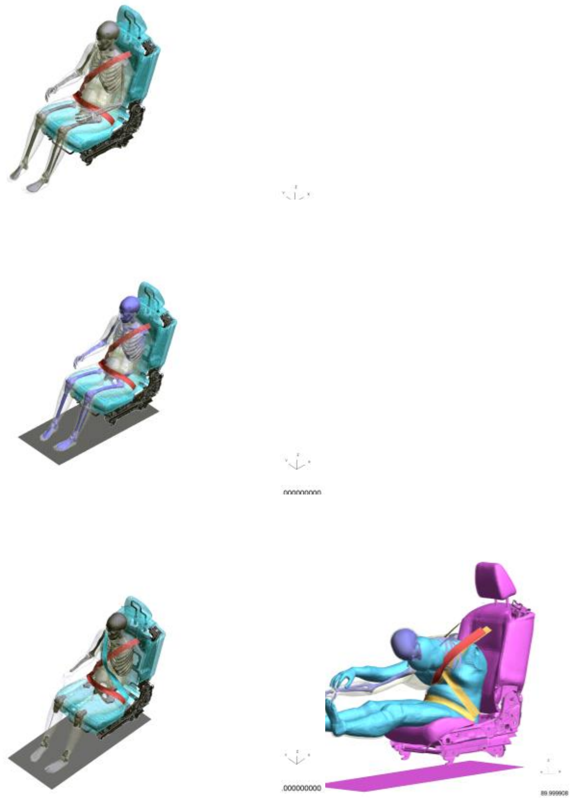


shoulder belt slips-off

higher occupant rotation

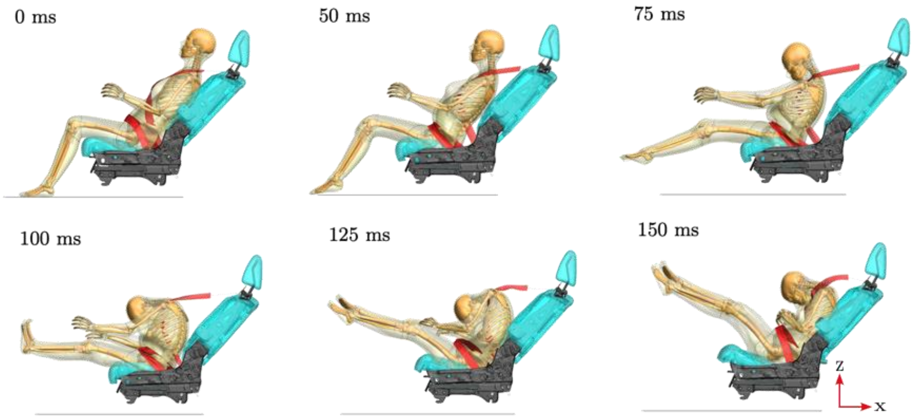
no shoulder belt slip-off

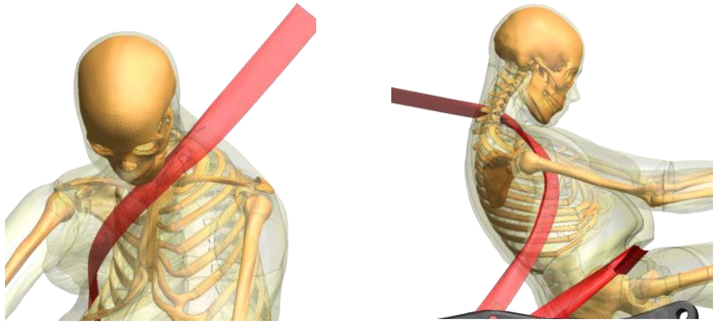
reduced occupant rotation



3-point and 4-point belt-system on 50DF overlay (90ms)

Results: 50F-Br, 45° reclined seatback (Case 7)





Seat belt interaction with the neck

- Large forward excursion with “clothesline” response
  - Sudden loading of ribs and pelvis
- The shoulder belt migrate towards the neck region
  - Increased $F_{x,tension}$ and $M_{y,extension}$ of neck
- Increased risk of Proximal Femur fracture in comparison to other cases with leg “lift-off”

Results: All cases

Severity ⟶ 0.0 | 0.25 | 0.50 | 0.75 | 1.0

Injury Criteria	Cases ⟶	①	②	③	④	⑤	⑥	⑦	Limit
Head	a_{3ms}	0.66	0.75	0.67	0.65	0.58	0.56	0.83	80 g
	HIC(36)	0.38	0.42	0.38	0.38	0.19	0.23	0.58	1000
	GAMBIT	0.22	0.29	0.22	0.21	0.20	0.19	0.27	1
	BrIC (CSDM)	0.72	0.71	0.70	0.70	0.88	0.71	1.04	1
	DAMAGE (AIS 4+)	0.00	0.08	0.00	0.04	0.06	0.00	0.10	1
Neck	$F_{x,tens,1ms}$	0.45	0.5	0.5	0.48	0.13	0.42	0.7	3.3 kN
	$F_{x,tens,45ms}$	0.57	0.53	0.5	0.46	0.06	0.98	1.05	1.1 kN
	$F_{z,comp,1ms}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4 kN
	$F_{zy,shear,1ms}$	0.07	0.08	0.1	0.1	0.1	0.06	0.18	3.1 kN
	$F_{zy,shear,45ms}$	0.13	0.09	0.10	0.07	0.6	0.08	0.02	1.1 kN
	$M_{y,moment,ext}$	0.58	0.7	0.56	0.54	0.42	0.4	15.1	57 kNmm
	$M_{y,moment,flex}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	190 kNmm
	Nij_{max}	0.47	0.54	0.47	0.47	0.2	0.37	6.7	1.0
			(50F-A)		(50F-B)	(50DF-B)	(50DF-C)		

Injury Criteria	Cases ⟶	①	②	③	④	⑤	⑥	⑦	Limit
Chest	0 fract. ribs L	0.0	0.0	0.30	0.35	0.07	0.63	0.0	-
	0 fract. ribs R	0.0	0.0	0.01	0.06	0.04	0.34	0.0	-
	1+ fract. rib L	1.0	1.0	0.7	0.65	0.93	0.37	1.0	1.0
	1+ fract. rib R	1.0	1.0	0.99	0.94	0.96	0.66	1.0	1.0
	2+ fract. ribs L	0.79	0.75	0.28	0.24	0.27	0.03	1.0	1.0
	2+ fract. ribs R	0.99	0.96	0.90	0.70	0.79	0.27	1.0	1.0
	3+ fract. ribs L	0.37	0.28	0.06	0.05	0.02	0.00	0.14	1.0
	3+ fract. ribs R	0.88	0.80	0.66	0.38	0.49	0.07	1.00	1.0
Pelvis	F ASIS L (kN)	2.18	2.33	1.36	1.4	1.4	1.43	1.38	-
	F ASIS R (kN)	2.32	2.64	1.4	1.56	1.59	1.54	1.55	-
	MPS	0.14	0.12	0.11	0.09	0.07	0.07	0.14	-
Femur fract.	Proximal L	0.08	0.74	0.03	0.74	0.74	0.76	0.88	1.0
	Proximal R	0.08	0.61	0.03	0.63	0.58	0.71	0.77	1.0
	Shaft L	0.0	0.02	0.0	0.02	0.0	0.0	0.0	1.0
	Shaft R	0.0	0.01	0.0	0.02	0.0	0.0	0.0	1.0
			(50F-A)		(50F-B)	(50DF-B)	(50DF-C)		

Summary

3-point seatbelt:

- **Current 3-point passenger belt** restraint system **insufficient** for passengers of Highly Autonomous Vehicles. **Greater occupant excursions observed** in comparison to advanced belt systems. **Clotheslining** is observed for **reclined occupants**, extreme loads to neck and thorax.

3-point seatbelt (physically disabled occupant):

- **Seatbelt slippage** of **disabled occupant** caused **increased pelvic, torso and head rotations**, particularly evident in **pelvic rotation** (2x). Approximately **18% increase** of **BrIC** injury risk due to rotational velocity based injury metric.

- 3-point seatbelt **effectiveness reduced by 35%** for **disabled occupant** based on probability of unfractured ribs. **Neck transverse shear loading increased by 60%** for disabled occupant resulting from observed torso and head rotation**.**

4-point seatbelt:

- Significant **reduction in rib fracture probabilities** observed with **4-point harness**, increasing **seatbelt effectiveness by 50%** for **disabled occupants. Neck tensile forces reached threshold at 45ms**, requires mitigative systems to reduce neck loading.

Leg lift-off observed in each case without footrest. **Greater risk** of **occupant-occupant** and **Occupant-Interior** collision due to greater excursion. Effects to lower-extremity injuries requires further study.

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Thank you for your attention!

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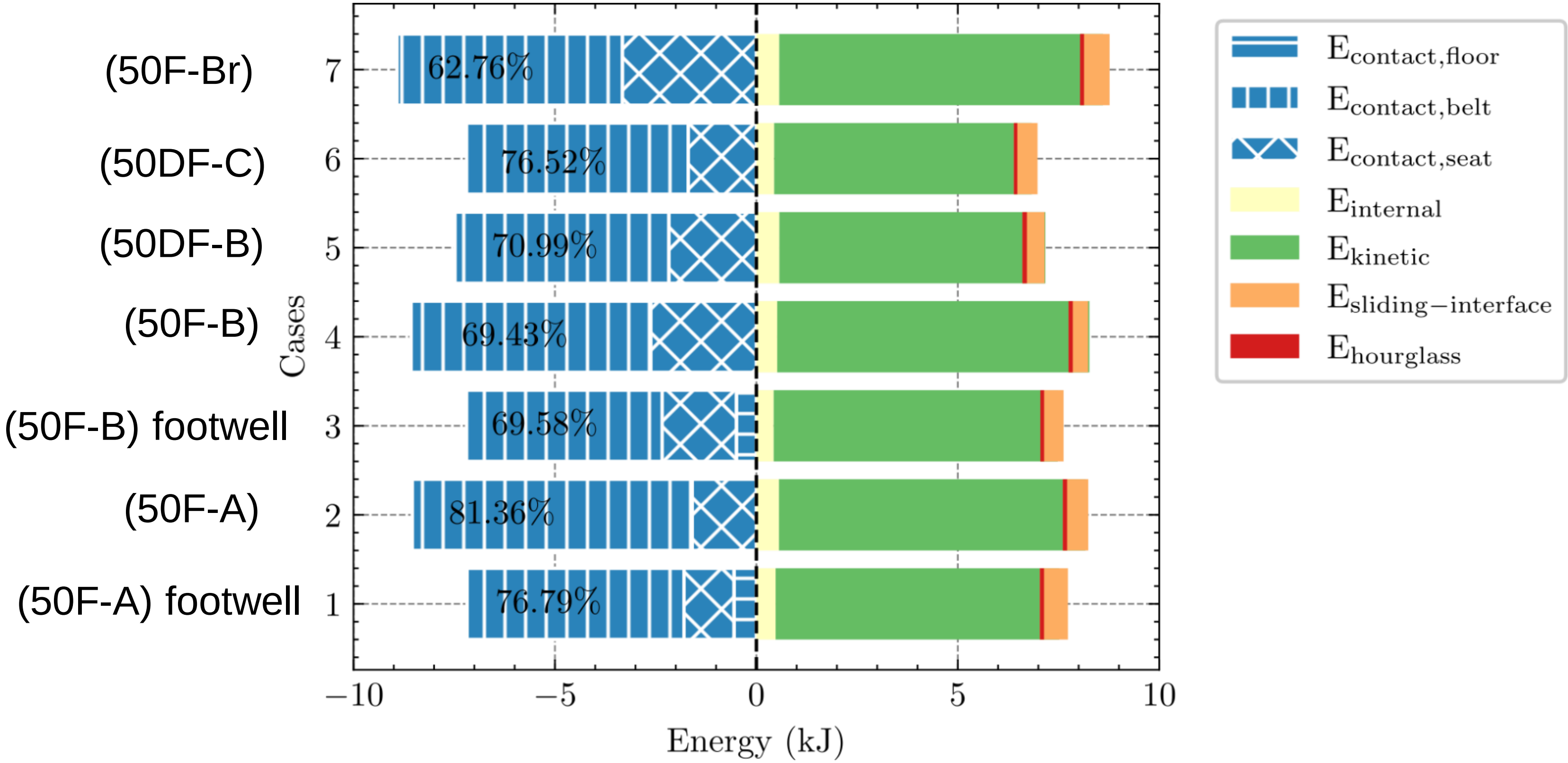
German Aerospace Centre, Institute of Vehicle Concepts

Contact Energy Distribution



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