Priorities in Far-side Protection – What can we learn from field data for the development of virtual testing protocols?

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Abstract The results of this study support the development of procedures for virtual testing with Human Body Models for far-side assessments by having a closer look at the field data.

Datasets from the US (Crash Injury Research and Engineering Network (CIREN) and Crash Investigation Sampling System (CISS)) and Europe (German In-Depth Accident Study (GIDAS) and Central Database for In-Depth Accident Study (CEDATU)) were analysed to identify who is injured in far-side scenarios and how. Parameters of the crash scenarios, the injured persons, and the injury types were analysed. A bias towards females was observed in GIDAS, CISS and CIREN cases, but no significant difference in terms of injury risk was observed.

Thoracic and head injuries were found most often in all analysed datasets. Abdominal injuries were also common. No clear trend in terms of anthropometries was visible in any of the datasets. Average BMIs were comparable between the different datasets, heights and injured body regions. While head injuries were more often related to taller occupants, thoracic injuries were most relevant throughout all height groups.

The results indicate that ideally, a wide range of anthropometries should be considered in the virtual assessments, as no clear trends on the most vulnerable populations were identified in the field data.

Keywords Far-side crashes, field data analysis, occupant protection, virtual testing.

I. INTRODUCTION

As previous studies have shown the relevance of far-side accidents for injuries of vehicle occupants [1]–[3], the assessment of far-side protection was introduced into the European New Car Assessment Programme (Euro NCAP) ratings in 2020 [4].

The current assessment of far-side protection underlies the limitations of the 50th percentile male Worldwide Harmonised Side Impact Dummy (WorldSID) in terms of anthropometry and injury prediction capabilities. Only a 50th percentile male WorldSID is available and limitations in biofidelity and thoracic injury prediction were observed compared to PMHS tests [5]–[7]. To overcome them and to have a more robust evaluation considering more variety in the evaluated scenarios, Euro NCAP has decided to pick this load case as the first pilot study for virtual testing of occupant safety.

Human Body Models (HBMs) have been validated against post-mortem human subject (PMHS) and field data and offer a high level of biofidelity including a human-like interaction with the interior of vehicles [8]–[13]. Furthermore, when using HBMs, one is not limited to standard anthropometries for which crash test dummies are available. They can be also used for more detailed investigations of injury mechanisms and one can distinguish in more detail among different injury types in one body region. As a result, the usage of HBMs in far-side assessments seems promising to aid in overcoming some of the limitations of the WorldSID dummy. In a first step, virtual testing will be done using virtual models of the WorldSID dummy, to make evaluations more robust. In a second step, Human Body Models should be used to enable a more enhanced injury assessment and consideration of human diversity. However, there is more work needed to finally achieve a harmonised, comparable and reliable injury assessment with these complex models.

To define the requirements for the assessment procedure and the HBM itself, field data is an important source to establish priorities.

In previous studies on far-side crashes, variables of focus included delta-v ranges, injured body regions and

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directions of impact. In most of the studies, data from the US National Automotive Sampling System (NASS) was used [2], [14]–[16]. Head and thorax were found as the leading body regions in several studies [2], [4], [14]–[16]. In a recent in-depth study, [17] concussion, rib, and pelvic fractures were identified as injury types that should be the focus of far-side assessments. However, no information on the anthropometry of the involved occupants and related injury patterns is available now.

The aim of this study was to answer the following research questions:

- Which injury types are most relevant in far-side crashes?
- Are there more vulnerable groups in far-side crashes for severe injuries or injuries in specific body regions?
- Which injury patterns and mechanisms can be observed in far-side crashes for different anthropometries?

The results of this study should support the prioritisation of the next steps for virtual testing with HBMs in far-side assessments.

II. METHODS

Datasets from the US - Crash Injury Research and Engineering Network (CIREN) and Crash Investigation Sampling System (CISS) - and Europe - German In-Depth Accident Study (GIDAS) and Central Database for In-Depth Accident Study (CEDATU) - were analysed to identify which occupants in passenger cars are injured in far-side collisions and which injuries are relevant.

The following filter criteria were applied:

- Far-side collision crash was the highest-severity incident
- Principal direction of force (PDOF) 45-135° and 225-310° from a clock face view on the right and left side of the car
- Injured occupant was a belted driver or front-seat passenger and at least 15 years old
- The injury severity was known
- Only the occupant on the non-struck side was considered
- Single and dual occupancy is included
- No filtering regarding the collision partner

Table I provides an overview of the crash data from the respective datasets that were used in this study. Due to differences in how directions of force are reported, the US datasets encompass a slightly smaller PDOF range compared to those from Europe

Injury assessment was based on the Abbreviated Injury Scale (AIS) versions [18]–[19] applicable to each data set, which differed among the studies. For the analysis, the AIS injury severity was transferred into the ISSx injury severity according to [20]. The ISSx is a summation of the exponentials of the AIS severities of the three most severely-injured body regions using exponentials scaled to fit the ISS range from 0 to 75. Two different categories of injury severities were thereby considered: at least moderate injured occupants with ISSx1+ which corresponds to MAIS2+ and severely injured occupants with ISSx2.5+, which corresponds to a minimum ISS of 9, as shown exemplary in Table A-I in the Appendix. For body-region-wise analysis, MAIS was used without recoding from the original AIS version of the databases given in Table I.

TABLE I
DESCRIPTION OF DATASETS USED IN THE STUDY

	CIREN Legacy	CIREN	CISS	GIDAS	CEDATU
Years of recording	2005-2016	2017-2022	2017-2020	2000-2021	2003-2021
Total number of analysed cases	87	29	390	1041	174
PDOF ranges	50°-130° 230°-310°	50°-130° 230°-310°	50°-130° 230°-310°	45°-135° 225-315°	45°-135° 225-315°
AIS code version	1990/98 (39) 2005/08 (48)	2015	2015	2005 upd. 2008	2005 upd. 2008
ISSx1+	86	28	105	30	11
ISSx2.5+	80	18	50	10	5

The Crash Injury Research and Engineering Network (CIREN) is an injury-focused in-depth investigation-based crash data collection programme in the United States. Inclusion criteria prioritise restrained occupants who have suffered clinically significant (generally AIS2+) injuries in newer vehicles (even if more occupants were present in the crash, only consented individuals with significant injuries are included in the database). Due to changes in National Highway Traffic Safety Administration (NHTSA) crash data collection systems in 2016, the CIREN data in this study are presented as two separate groups. The legacy CIREN data, covering data years 2005-2016, were queried from the publicly available SAS (Statistical Analysis Software) dataset. CIREN data from 2017 onward were queried from the internal transactional database. Legacy CIREN injury codes are provided in a mix of 1990 and 2005 versions of the AIS. CIREN cases from 2017 onward include only the 2015 version. The Crash Investigation Sampling System (CISS) is a nationally-representative investigation-based crash data collection programme in the United States. The CISS takes over as the successor to the National Automotive Sampling System Crashworthiness Data System (NASS-CDS). Investigators at the study's primary sampling units collect scene, vehicle, and medical data from sampled crashes. CISS data were queried from crash years 2017 to 2020 and include injury coding based on the 2015 version of the AIS. It does include property damage cases as well.

The German In-Depth Accident Study (GIDAS) is a German in-depth accident database. Approximately 2000 traffic crashes with personal injury are annually recorded by the teams in Hannover and Dresden. Large amounts of information including detailed injury reports are documented, and driving and collision speeds are reconstructed. [21] Version 2021-06 status=4.8 of the database was used for the current study.

The Central Database for In-Depth Accident Study (CEDATU) is an Austrian in-depth database and was established 2004. The crash investigation uses a fully retrospective method using information from court in which police reports, medical reports, witness reports, pictures from scene and vehicles, etc., are collected. The crashes are reconstructed using the accident reconstruction software PC-Crash. All injuries of involved persons are included in the database as well as property damage only cases. [22]

The data is analysed per database, as the datasets use different definitions for some variables that restrict combined analysis. All results are presented in table formats in the Appendix. Odds ratios are calculated between different groups of vehicle occupants. Statistical significance was tested in R using Fisher's Exact Test [fisher.test()] and Chi Square Test [chisq.test()]. Due to the small sample sizes, the US databases were merged for the statistical analyses of anthropometries.

III. RESULTS

The results in this section are presented by dataset. All absolute numbers for the figures presented in this section can be found in the Appendix. The numbers always refer to the number of occupants injured on the non-struck side. As only the front-row was considered, this is equal to the number of cases.

A. Impact Conditions

Figures 1-3 present the principal direction of force (PDOF), collision partner, and delta-v distributions for cases from the respective datasets to give an overview of the analysed crash cases. Based on a breakdown of the US crashes by principal direction of force, most of the moderate to serious-injury crashes occurred with a PDOF of 60-70 degrees (20-30 degrees forward of pure lateral). In GIDAS, more (30%) cases at 120 and 130 degrees PDOF are observed compared to the US and the Austrian datasets (<3%). In the US data sets, delta v was not known in up to 28% (CISS). Up to 50% of the cases were occurring at a delta v < 26 km/h (CISS), depending on the dataset (26% in CIREN Legacy).

The main collision partners in all datasets were cars. A small portion of cases occurred to fixed objects. The newer US cases demonstrated a relatively even distribution of striking vehicles among passenger cars, utility vehicles, and pickup trucks.

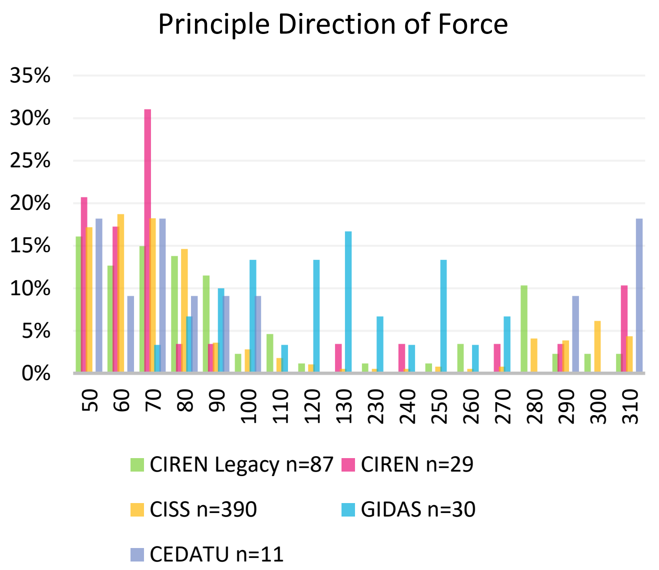

Fig. 1. PDOF distribution of the far-side cases in the different datasets.

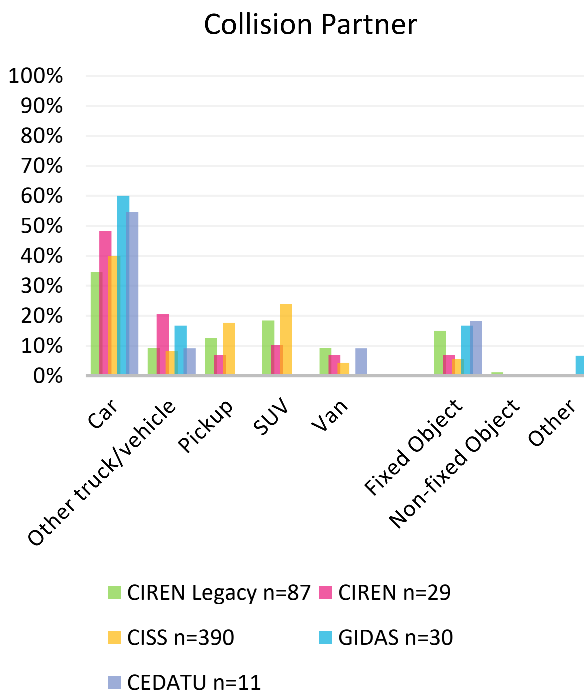

Fig. 2. Share of collision partners in the different datasets.

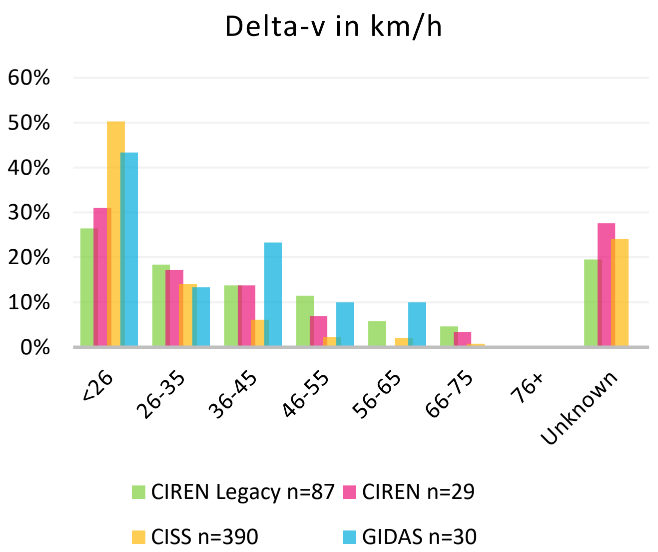

Fig. 3. Delta-v (km/h) distribution from the different data sources.

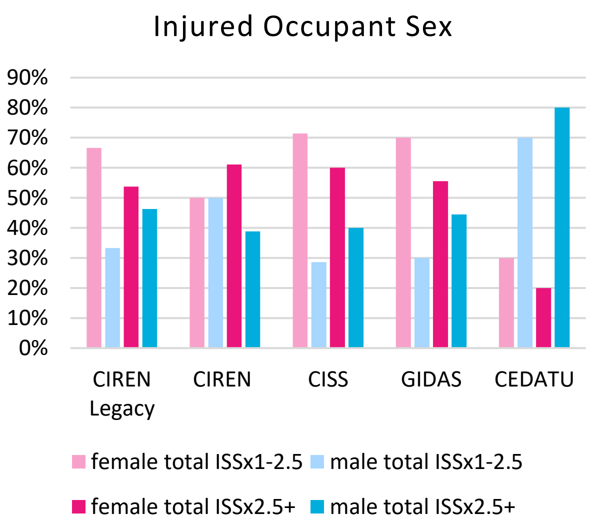

Fig. 4. Share of females and males in the different datasets, injured on the non-struck side.

B. Sex of occupants injured in far-side crashes

As shown in Fig. 4, the majority of injured occupants on the non-struck side in the US and German datasets were female. Only in the CEDATU dataset were more males injured. No significant difference between the ISSx1-2.5 and ISSx2.5+ cases was present in any data source between females and males.

A more detailed analysis of the sex and seating position inside the vehicle as well as the occupancy is shown in Table II. More drivers than passengers sustained injuries in the far-side crashes in all datasets. Females were more often injured as passengers (34% in CISS- 25% in CEDATU for ISSX1+) compared to males (8.3% in CISS -10% in CIREN Legacy for ISSx1+).

Between 32% (CIREN) and 50% (CIREN Legacy) of the ISSx1+ cases happened in scenarios where a second person was present in the front row (dual occupancy). In 51% of CIREN Legacy and 25% CEDATU ISSx1+ cases where females were injured, a second person in the front row was present compared to 8% of CIREN cases and 54% of CEDATU cases where males were injured in dual occupancy cases.

No distinction between driver or occupant was possible for the GIDAS analysis (marked as unk. in the table) in dual occupancy cases. One moderately injured and one severely injured pregnant female was present in the CISS and one in the GIDAS dataset, respectively.

TABLE II
SEX AND OCCUPANCY OF SLIGHTLY AND SEVERELY INJURED OCCUPANTS IN FAR-SIDE CRASHES

# of cases	CIREN Legacy	CIREN	CISS	GIDAS	CEDATU
ISSx1-2.5					
Female driver (single occupancy)	2	1	19	8	2
Female driver (2 persons in front-row)	1	3	9	unk	0
Female passenger	1	1	11	unk.	1
Female dual occupancy total	2	4	20	6	1
Pregnant females	0	0	1	0	0
Male driver (single occupancy)	0	5	11	3	4
Male driver (2 persons in front-row)	1	0	3	unk.	2
Male passenger	1	0	2	unk.	1
Male dual occupancy total	2	0	5	3	3
ISSx2.5+					
Female driver (single occupancy)	21	7	16	1	1
Female driver (2 persons in front-row)	7	0	1	unk	0
Female passenger	15	4	13	unk.	0
Female dual occupancy total	22	4	14	3	0
Pregnant females	0	0	0	1	0
Male driver (single occupancy)	20	6	16	3	1
Male driver (2 persons in front-row)	14	0	1	unk	2
Male passenger	3	1	3	unk.	1
Male dual occupancy total	17	1	4	1	3

C. Age of passengers and drivers in the different datasets on non-struck side

The age distribution of the injured occupants in the different datasets is shown in Fig. 5. Around 20% of the injured persons were older than 75 years (up to 92 years) in all datasets except CEDATU, where no case with occupants older than 75 was found. When focusing on severely injured occupants only, this share slightly increases up to 30% in the US datasets. In the European datasets, the majority of severely injured occupants were younger than 45 years (In GIDAS a 56% and in CEDATU 60%). The mean ages of the injured occupants were similar in all datasets (46.2-54 years). A trend towards younger average ages for males (43-46.1) compared to females (50.5-52.4) was observed in all datasets except in CIREN. More details are provided in Table A-VI in the Appendix.

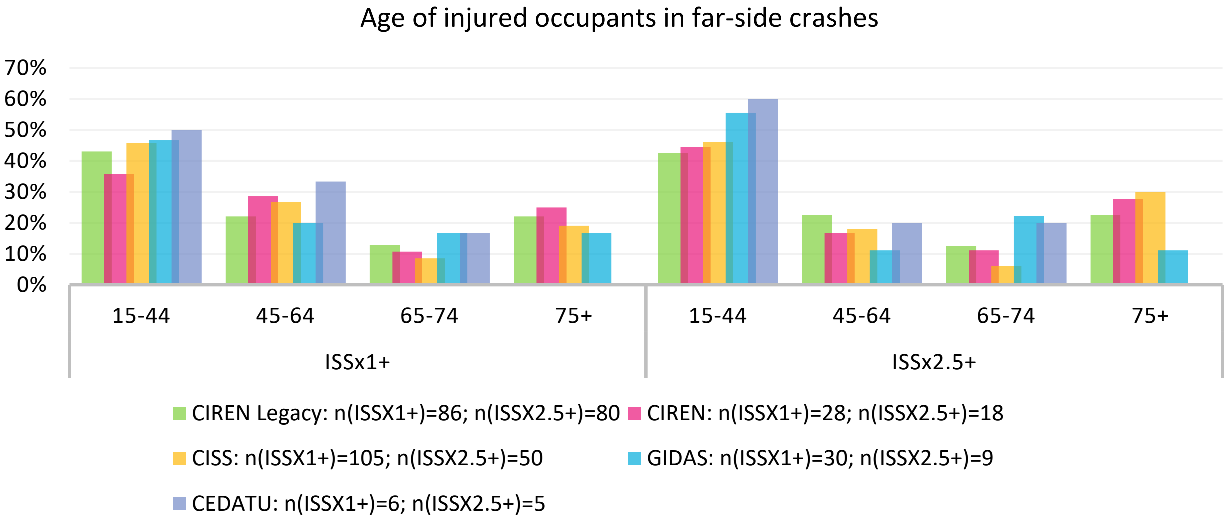

Fig. 5. Share of age groups in different datasets for all ISSx1+ and only the severe ISSx2.5+ cases.

D. Anthropometry of Injured Occupants

As shown in Fig.6, very few cases with occupants shorter than 150 cm or taller than 190 cm were observed. For the severe crashes, no occupant taller than 190 cm was observed in any dataset. In GIDAS, four out of the five severely injured occupants where the height was known were taller than 170 cm. No significant differences were observed when comparing ISSx1-2.5 and ISSx2.5+ cases.

The weight of the severely injured persons in GIDAS ranged from 62 – 90 kg and the height from 155-180 cm. Similar to GIDAS, there were no clear trends among the US crash data. Severely injured occupants ranged between 137-185 cm in CISS and 147-188 cm in CIREN. Occupant mass ranged between 49-160 kg in CISS and 45-159 kg in CIREN for ISSx2.5+ cases.

Body mass indices (BMI) up to 50 were observed in the US datasets, where mean BMIs were between 26 and 29. A single outlier for the BMI (CISS 137 cm; BMI=45, 82 years old) was observed causing the higher average BMI in that group (n=6), but overall no significant differences in BMIs were observed even across the different height ranges of injured occupants and for injuries in different body regions (Fig. 7). More details on the BMI analysis can be found in the Appendix in Table A-VII

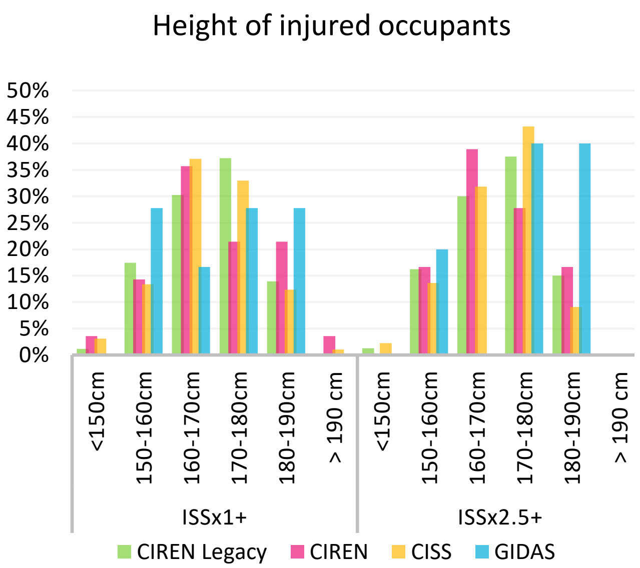

Fig. 6. Height of slightly and severely injured occupants in far-side crashes.

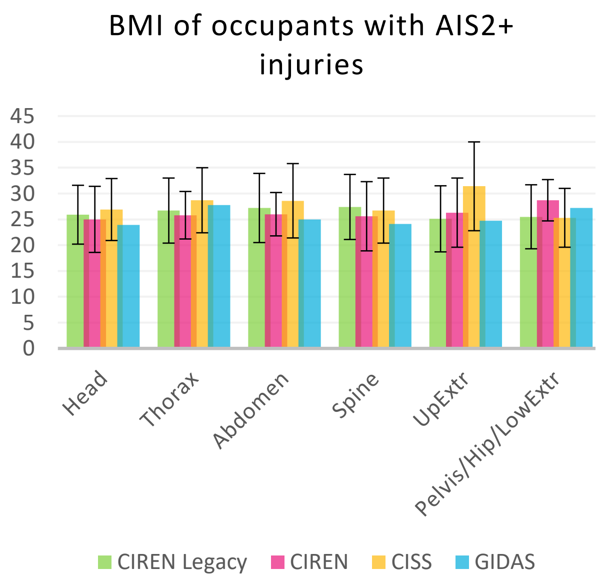

Fig. 7. BMI of injured occupants in far-side crashes with AIS2+ injuries of different body regions.

E. Injuries

The shares of injured body regions among AIS2+ and AIS3+ injuries are shown in Figure 8. Injuries of the thorax are dominant in all datasets, especially when focusing on AIS3+ injuries. Other highly relevant body regions in far-side crashes are head/face/neck, abdomen and spine. Pelvis and hip injuries are observed mainly in the old CIREN and the CEDATU dataset, while smaller shares are observed in the other databases, especially for AIS3+ injuries.

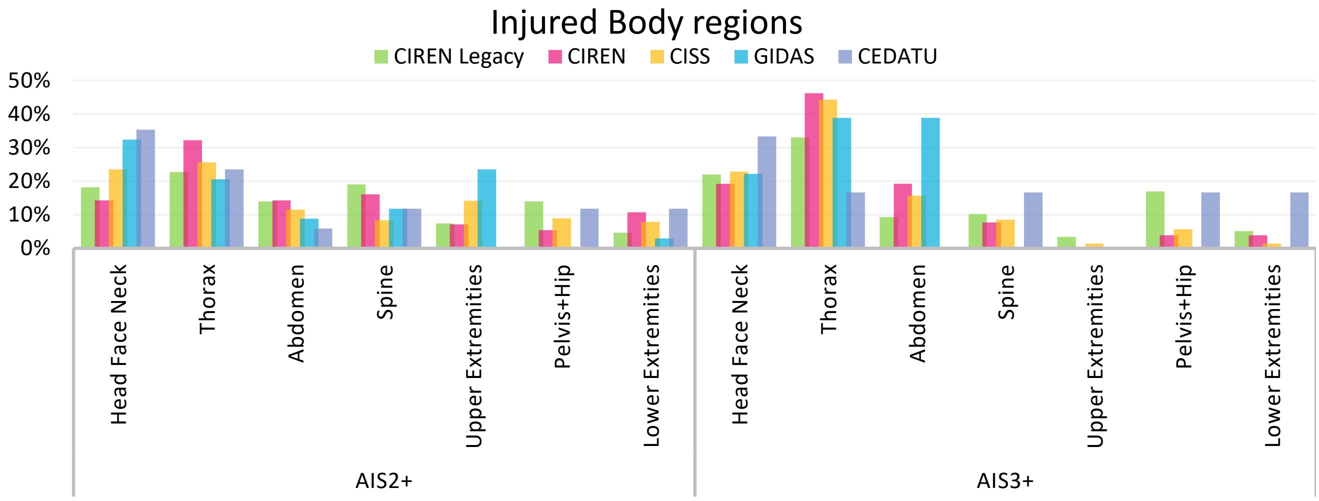

Fig. 8. Share of injured body regions in far-side crashes.

No significant differences between single and dual occupancy were found, although a slight shift towards head injuries was observed in dual occupancy cases, as shown in Table III. The values for AIS3+ injuries are included in the Appendix in Table A-VIII.

TABLE III
INJURED BODY REGIONS FOR AIS2+ INJURIES FOR DIFFERENT OCCUPANCIES

	CIREN Legacy	CIREN	CISS	GIDAS	CEDATU
# of cases					
Head Face Neck	39	8	45	11	6
Single occupancy	22	7	27	6	1
Double occupancy	17	1	18	5	5
Thorax	49	18	49	7	4
Single occup	25	14	34	2	2
Double occup	24	4	15	5	2
Abdomen	30	8	22	3	1
Single occup	18	5	15	1	0
Double occup	12	3	7	2	1
Spine	41	9	16	4	2
Single occup	24	6	13	4	2
Double occup	17	3	3	0	0
Upper Extremities	16	4	27	8	0
Single occup	7	3	15	5	0
Double occup	9	1	12	3	0
Pelvis+Hip	30	3	17	0	2
Single occup	14	3	13	0	0
Double occup	16	0	4	0	2
Lower Extremities	10	6	15	1	2
Single occup	3	4	7	1	0
Double occup	7	2	8	0	2

Statistical analysis of injured body regions (AIS2+) when summarizing all US databases revealed that there is a statistically significant correlation between the probability of injury to specific body regions and occupant height (X-squared = 42.298, p-value = 0.01669). The injured body regions for the different groups of body heights summarised from all datasets are in Fig.9. Higher odds for head and spine injuries are particularly evident among tall occupants (170-180 cm). In contrast, higher odds of abdominal injury among shorter occupants (150-160 cm) were observed. An analysis of the groups at risk for specific injuries is shown in Fig. 10 and in the Tables A-IX – XV in the Appendix.

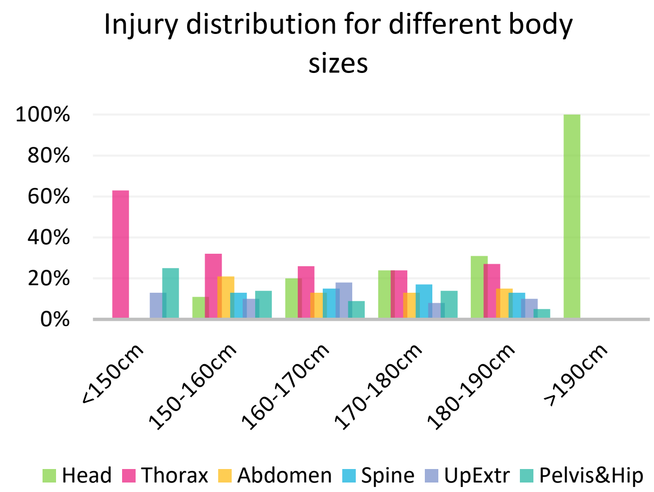

Fig.9. Injured body regions at different body heights in far-side crashes (Summary of all datasets).

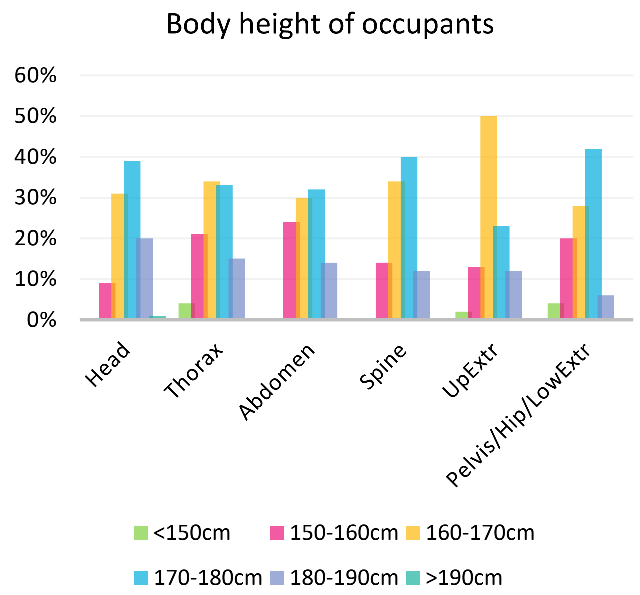

Fig. 10. Body height of occupants with injuries in specific body regions (summary of all datasets).

F. Detailed analysis of factors attributed to injuries in the different body regions

1) Head/Face/Neck

Head/face/neck injuries were observed for occupants with heights between 150 cm up to higher than 190 cm with normal to slight overweight BMIs.

AIS2+ head injuries in CEDATU were crush injury (n=1), subdural haematoma (n=1), subarachnoid haemorrhage (n=1), brain oedema (n=1) and vertebral artery (n=1). In the US datasets, cerebral subarachnoid haemorrhage was most common among CIREN cases (22 in Legacy and 4 in 2017+) while concussion codes were most common in CISS (19). Cerebral subarachnoid haemorrhage was the second-most common injury (17) among CISS cases. The skull base was, overall, the most common site for head/face skeletal injuries (6 Legacy CIREN, 4 CIREN 2017+, 11 CISS) among the US data. Facial fractures, most commonly the orbit and maxilla, occurred less frequently than skull base fractures.

2) Thorax

Thoracic injuries were also present in smaller occupants (25% of the occupants <160 cm). BMI distributions are again comparable to the other body regions. The AIS2+ thoracic injuries in GIDAS were multiple rib fractures (n=9), sternum fractures (n=4), lung contusions (3), pneumothorax (n=2), haematothorax (n=1) and heart contusion (n=1). Among the US cases, multiple rib fractures occurred most frequently (n=29 Legacy CIREN, n=14 CIREN 2017+, and n=39 CISS), while injuries to the lung were second most common (18 Legacy CIREN, 12 CIREN 2017+, and 13 CISS). Thoracic cavity injuries (pneumothorax and haemothorax), when combined, occurred with similar frequency as lung injuries. In CEDATU sample, thorax AIS2+ injuries are lung contusions (n=2), rib fractures (single rib (n=1), multiple ribs (n=1)) and sternum fracture (n=1).

3) Abdomen

Abdominal and spinal injuries were present in occupants with higher BMIs compared to the other body regions (all means >25). Abdominal AIS2+ injuries in CEDATU were kidney laceration (n=1), liver laceration (n=1), and spleen rupture (n=1). Liver (n=13 Legacy CIREN, n=3 CIREN 2017+, and n=11 CISS), spleen (n=13 Legacy CIREN, n=1 CIREN 2017+, and n=3 CISS), and mesentery (n=5 Legacy CIREN, n=3 CIREN 2017+, and n=9 CISS) contusions and lacerations were the most common abdominal injuries in the US datasets. Kidney (n=5) and colon (n=5) injuries were relatively frequent in Legacy CIREN, but less so in the newer datasets (2 each in CISS).

4) Spine

Spinal injuries were sustained in 52% of the cases to occupants taller than 170 cm, but only 12% were taller than 180 cm. BMIs were in the same range as the other body regions.

AIS2+ spine injuries in CEDATU were a cord injury (n=1), fractures of the processus spinosi of the thoracic vertebra without cord involvement (n=3), the cervical vertebra (n=2), fracture of the odontoid (n=1) and pedicle of C2 (n=1). Comparison of AIS2+ spinal injuries in the US data revealed some differences in injury types even accounting for the different AIS versions used (severity for some spinal fractures decreased in newer versions). Lumbar vertebral body fractures were the most common spinal injury in CIREN 2017+ (n=3) and CISS (n=7), but such injuries were not observed in the Legacy CIREN cases. The most common injuries in older CIREN cases were lumbar transverse process fractures (n=60), but such injuries are considered AIS 1 in the 2015 dictionary, used by NHTSA since 2016.

5) Upper extremities

In total, 50% of the occupants sustaining injuries of the upper extremities were between 160 and 170 cm tall The AIS2+ upper extremity injuries in CEDATU were fractures of the clavicle (n=1), humerus (n=2), ulna shaft fractures (n=3) and fractures of the metacarpus (n=1). Within the US datasets, it was again observed that the Legacy CIREN cases demonstrated a different ranking with clavicle fractures being the most common (6), but clavicle injuries were much less common in the CIREN 2017+ (n=0) and CISS (n=5) cases. Forearm humerus fractures were most numerous in CIREN 2017+ (n=6) and CISS (n=21) with humerus fractures in second place (n=3 CIREN 2017+ and n=12 CISS).

Lower extremities

Over all datasets, injuries of the lower extremities and hips occurred slightly more frequently in smaller occupants with overall 52% being smaller than 170 cm. In GIDAS, only three cases with injuries to the lower extremities were present. One of the occupants had a high BMI of 31, leading to the higher BMI (27.2.) compared to other body regions.

In CEDATU, AIS2+ injuries to these body regions were femur fractures (n=2) and proximal tibia fracture (n=1). In the US data, AIS 2+ pelvis and hip fractures were observed in 17% of the Legacy CIREN cases and 5% in the CIREN 2017+ cases. This is also reflected in the number of coded pelvic fractures, which were n=46 for CIREN legacy, n=21 for CISS and n=3 for CIREN. Below-knee injuries, such as tibia and fibula fractures, accounted for most of the remaining AIS 2+ lower extremity injuries (n=13 Legacy CIREN, n=17 CIREN 2017+, and n=10 CISS).

IV. DISCUSSION

The scope of this study was to define a design space for virtual testing, which differs from previous accident analyses.

Interestingly, overall in our dataset more females were injured in far-side crashes than males. No statistically significant difference in terms of the accident severity observed for females and males was found in the current evaluation. For CISS and CEDATU also uninjured and minor injured occupants were additionally analysed. Overall, 26% (n=262) of the female occupants sustained ISSx1+ in CISS compared to 28% (n=118) of the males indicating no significant difference in injury risk. The ratio of females with ISSx1+ was higher for dual occupancy than for males (37% vs. 26%), however also not statistically significant.

In CEDATU, more males (n=114) were included in the total dataset compared to females (n=64) and the share of males with ISSx1+ injuries was higher than for females (9.6% vs. 6.2%), but not significant.

It has to be considered, that the analysis is not normalized for collision speeds or vehicle types.

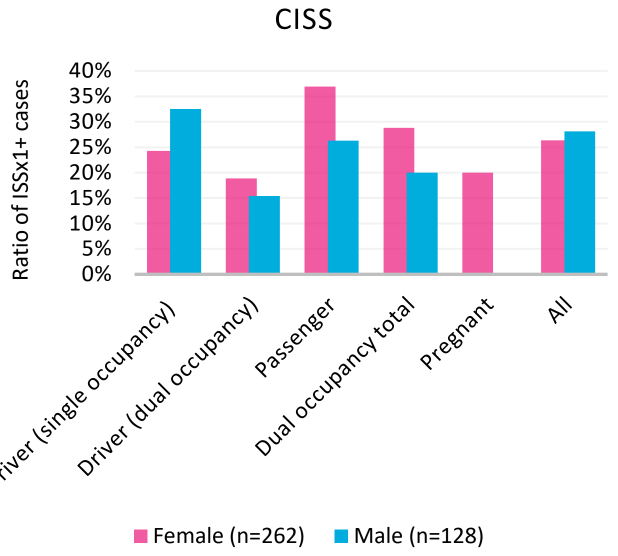

Fig.11. Share of females and males with ISSx1+ injuries for different occupancies and positions inside the car relative to all far-side cases (incl ISSx 0-1) in CISS

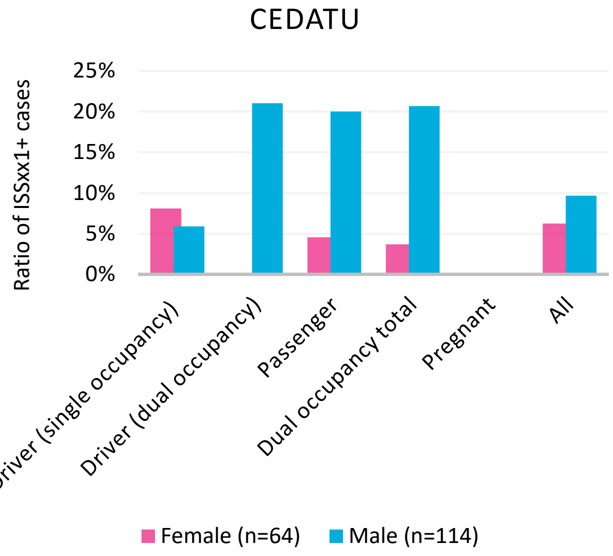

Fig. 12. Share of females and males with ISSx1+ injuries for different occupancies and positions inside the car relative to all far-side cases (incl ISSx 0-1) in CEDATU

In contrast to classic crash test dummy sizes (175 cm / 78 kg; 150 cm / 49kg, 188 cm / 101 kg), several other height / weight combinations were observed in the severely injured occupants. The proportion of higher-mass occupants among the US datasets is notable in contrast to the European cases, with about 10 % of the severe injury cases with occupant mass above 106 kg.

As in previous studies, head and thorax were identified as the leading injured body regions [2], [4], [14]–[16].

We found that with increasing height, the odds for head injuries increases. Thoracic injuries were observed over a wide range of anthropometries, with the majority in CIREN being shorter than 170 cm. As height decreases, the probability of abdominal injuries increases.

The thoracic injury risk might be affected by multiple factors, such as the specific impact characteristics, the restraint system and vehicle environment together with the anthropometry of the vehicle occupant, which might be the reason for the unclear trend observed there.

To gain further insights on the injury sources, the US datasets were analysed, as they feature details on suspected injury causation based on review of available evidence.

Brain injuries and skeletal injuries of the head and face region were commonly attributed to contact to the far-side door and pillar structures, instrument panel, and the other first row occupant. Contact with the collision partner occurred in a small number of cases, even with a deployed curtain airbag in some instances.

Interaction with the belt restraint was by far the most frequent cause of thoracic injuries. The centre console and armrest structure were also frequently implicated, sometimes in concert with the shoulder belt. In cases with higher levels of intrusion from the struck side structures, thoracic injuries were associated with contact to the door. Similar sourcing, with the restraint belt and centre console dominating the involved components, was also observed for abdominal injuries. Spinal injuries, which occurred in the cervical, thoracic, and lumbar regions with relatively similar frequency, were generally attributed to the belt restraint and centre console, though cervical spine injuries involved head contacts to the instrument panel or far-side structures as well.

Upper extremity injuries occurred due to contact with a variety of structures with few standing out as the most prominent - the instrument panel and the far-side structures. The lower extremity injuries were also attributed to a variety of sources, though pelvis and hip fractures were generally associated with the restraint belt and centre console while below-knee fractures were due to the floor and lower instrument panel (knee bolster).

A. Limitations

The current study underlies several limitations, especially due to differences between the different datasets. The definitions were not aligned between the different datasets, e.g., vehicle categories.

Furthermore, the inclusion criteria differ for the different databases. In GIDAS, injuries of all persons (also uninjured) involved in crashes are collected. CISS and CEDATU additionally also contain information about persons involved in crashes with property damage only. In contrast, in CIREN only the information of persons with clinically significant injuries (usually AIS2+) is included.

The shares of different vehicle types are not comparable between European and US data. PDOF is documented in different ways in the databases. In the US databases, it is recorded in 10° increments while it is defined by clock face positions in GIDAS and CEDATU leading to 15° steps.

The BMI and body height analyses were not possible with the CEDATU data and also the GIDAS dataset with known anthropometry was becoming very small. Injury sources described in the previous sections are based on expert's judgment and are therefore subjective.

In our study, we focused on ISSx1+ and ISSx2.5+ accidents. This, however, led to relatively small sample sizes. Although differences were observed in some analyses between different groups, no statistical significance was present except for the relationship between body height and injured body regions where all samples were compared. To increase sample sizes, we have not filtered the data for multiple collisions, but included all cases where the far-side crash was the most severe event and used only injuries related to that event in our analyses. Among the US cases, a rollover event was coded in 12.7% of the Legacy CIREN cases, 7% of CIREN 2017+, and 7% of CISS cases.

B. Outlook

By means of virtual testing, it would be possible to analyse the effect of different BMIs and heights on the injury risk and optimise vehicle safety systems for occupants of varying anthropometries. As it was not possible to identify groups of specific high risk in far-side accidents, virtual testing with anthropometries reflecting the entire population can help provide a robust assessment.

The assessment of rib fractures seems to be of high importance and could be a good starting point for further discussions. Human Body Models could allow for omnidirectional assessment and the effect of different anthropometries and seating positions on the interaction with the centre consoles and centre airbags could be investigated. Although several studies on strain-based assessment of rib fracture risk are available [12], [23] further work is needed to enable a validated standardised assessment comparable among different models in different FE software environments.

V. CONCLUSIONS

The current analysis can be used to guide the anthropometries used in virtual testing, select the most important validation load cases, and develop appropriate evaluation criteria to assess the far-side protection of cars in the future. The results indicate that the assessment of the thorax and head is highly important, but that the pelvic and abdominal regions warrant attention due to the overall anatomical location relative to the primary restraining components. For a more robust assessment, a wide range of anthropometries should be considered in the virtual assessments, as no clear trends on the most vulnerable populations were identified in the field data, except for head injuries where a trend towards larger occupants was observed.

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VIII. APPENDIX

TABLE A-I
EXAMPLES TO SHOW RELATIONSHIP BETWEEN MAIS, AISX, ISS AND ISSX

	MAIS	AISx	MAIS	AISx	MAIS	AISx
Max. body region	2	1.1	2	1.1	3	3.2
2nd highest body region	0	0.0	2	1.1	2	1.1
3rd highest body region	0	0.0	1	0.3	1	0.3
ISS	4		9		14	
ISSx		**1.1**		**2.5**		**4.6**

TABLE A-II
PRINCIPAL DIRECTION OF FORCE (PDOF) IN FAR-SIDE CRASHES (HIGHEST CDC)

PDOF	CIREN Legacy	CIREN	CISS	GIDAS	CEDATU
50	14	6	67	0	2
60	11	5	73	0	1
70	13	9	71	1	2
80	12	1	57	2	1
90	10	1	14	3	1
100	2	0	11	4	1
110	4	0	7	1	0
120	1	0	4	4	0
130	0	1	2	5	0
230	1	0	2	2	0
240	0	1	2	1	0
250	1	0	3	4	0
260	3	0	2	1	0
270	0	1	3	2	0
280	9	0	16	0	0
290	2	1	15	0	1
300	2	0	24	0	0
310	2	3	17	0	2

TABLE A-III
COLLISION PARTNERS IN FAR-SIDE CRASHES

Collision Partner	CIREN Legacy	CIREN	CISS	GIDAS	CEDATU
Car	30	14	156	18	6
Fixed	13	2	22	5	2
Non-fixed	1	0	1	0	0
Other truck/vehicle	8	6	32	5	1
Pickup	11	2	69	0	0
SUV	16	3	93	0	0
Van	8	2	17	0	1
Other	0	0	0	0	1

TABLE A-IV
DELTA V FROM FAR-SIDE CRASHES

Delta V [kph]	CIREN Legacy	CIREN	CISS	GIDAS	CEDATU
<26	23	9	196	13	
26-35	16	5	55	4	
36-45	12	4	24	7	
46-55	10	2	9	3	
56-65	5	0	8	3	
66-75	4	1	3	0	
76+	0	0	1	0	
Unknown	17	8	94	0	
all	87	29	390	30	

TABLE A-V
SEX AND OCCUPANCY OF MINORLY OR UNINJURED OCCUPANTS IN FAR-SIDE CRASHES

	# of cases	CISS	CEDATU
ISSx0-1			
	Female driver (single occupancy)	109	34
	Female driver (2 persons in front-row)	43	5
	Female passenger	41	21
	Female dual occupancy total	84	26
	Pregnant females	4	0
	Male driver (single occupancy)	56	80
	Male driver (2 persons in front-row)	22	15
	Male passenger	14	8
	Male dual occupancy total	36	23

TABLE A-VI
AGE OF OCCUPANTS INJURED IN FAR-SIDE CRASHES

		CIREN Legacy	CIREN	CISS	GIDAS	CEDATU
ISSx1+	# cases	86	28	105	30	6
	Mean Age	49.6	54.0	48.6	47	46.2
	Standard Deviation	24.0	22.3	22.3		13.3
	Median	51	56.5	49	46	43.0
	Min	16	19	15	18	33
	Max	92	91	90	85	68
	Q1	23	30	27		36.5
	Q3	74	72	67		52.5
	15-44	37	10	48	14	3
	45-64	19	8	28	6	2
	65-74	11	3	9	5	1
	75+	19	7	20	5	0
	Mean Age female	52.4	50.4	51.5	52	50.5
	Standard Deviation female	23.1	23.6	21.6	-	24.7
	Mean Age male	46.1	58.8	43.7	43	44.0
	Standard Deviation male	24.9	20.5	22.7	-	8.4
ISSx2.5+	# cases	80	18	50	9	5
	Mean Age	49.6	51.7	52.3	44	39.8
	Standard Deviation	24.2	25.2	23.8		21.7
	Median	52.5	53.5	48		28.0
	Min	16	19	16	21	19
	Max	92	91	90	85	68
	Q1	23	28	34		26
	Q3	74	75	78		58
	15-44	34	8	23	5	3
	45-64	18	3	9	1	1
	65-74	10	2	3	2	1
	75+	18	5	15	1	0
	Mean Age female	52.7	47.2	55.1	54	63.0
	Standard Deviation female	23.2	24.3	23.4	-	7.1
	Mean Age male	46.0	58.9	48.1	32	35.3
	Standard Deviation male	25.1	26.9	24.4	-	22.2

TABLE A-VII
HEIGHT AND BMI OF INJURED OCCUPANTS IN FAR-SIDE CRASHES

		CIREN Legacy	CIREN	CISS	GIDAS
ISSx1+	# cases	86	28	97	18
	<150cm	1	1	3	0
	150-160cm	15	4	13	5
	160-170cm	26	10	36	3
	170-180cm	32	6	32	5
	180-190cm	12	6	12	5
	> 190 cm	0	1	1	0
	Mean BMI of occupant (Min, Max, Std)	26.3 (17;46;6.1)	26.6 (19;50;6.7)	28.9 (16;46;7.1)	26.3 (20;36;4)
	<150cm	25.5	25.0	36.3	.
	150-160cm	26.4	23.0	29.3	27.4
	160-170cm	26.7	24.8	28.6	24.6
	170-180cm	25.8	31.7	28.5	26.5
	180-190cm	26.9	27.0	28.4	23.7
	> 190 cm	.	29,0	28,9	.
ISSx2.5+	*# cases*	80	18	44	5
	<150cm	1	0	1	0
	150-160cm	13	3	6	1
	160-170cm	24	7	14	0
	170-180cm	30	5	19	2
	180-190cm	12	3	4	2
	> 190 cm	0	0	0	0
	Mean BMI of occupant (Min, Max, Std)	26.2 (17;46;6.4)	25.2 (19;38;5.1)	27.6 (19;45;6.7)	25.4 (20;30;3.4)
	<150cm	25.5	.	45.0	.
	150-160cm	26.6	22.7	27.0	25.5
	160-170cm	26.6	25.6	27.6	.
	170-180cm	25.5	28.0	26.6	27.5
	180-190cm	26.9	22.3	29.0	22.2
	> 190 cm	.	.	.	.

TABLE A-VIII
INJURED BODY REGIONS FOR FAR-SIDE OCCUPANTS WITH AIS3+ INJURIES

		CIREN Legacy	CIREN	CISS	GIDAS	CEDATU
Head Face Neck		26	5	16	4	2
	Single occup	14	4	10	3	0
	Double occup	12	1	6	1	2
Thorax		39	12	31	7	1
	Single occup	19	10	21	3	1
	Double occup	20	2	10	4	0
Abdomen		11	5	11	7	0
	Single occup	5	3	9	3	0
	Double occup	6	2	2	4	0
Spine		12	2	6	0	1
	Single occup	8	1	5	0	1
	Double occup	4	1	1	0	0
Upper Extremities		4	0	1	0	
	Single occup	4	0	1	0	
	Double occup	0	0	0	0	
Pelvis+Hip		20	1	4	0	1
	Single occup	7	1	3	0	0
	Double occup	13	0	1	0	1
Lower Extremities		6	1	1	0	1
	Single occup	2	1	0	0	0
	Double occup	4	0	1	0	1

TABLE A-IX
ANTHROPOMETRIES OF OCCUPANTS WITH AIS2+ INJURIES OF THE HEAD INCL. FACE AND NECK

	CIREN Legacy	CIREN	CISS	GIDAS
# cases	39	8	40	6
<150cm	0	0	0	0
150-160cm	3	0	2	3
160-170cm	8	4	16	1
170-180cm	19	2	14	1
180-190cm	9	2	7	1
> 190 cm	0	0	1	0
Mean BMI of occupant (Min; Max; Std)	25.9 (17.0;46.5;5.7)	25.0 (19.0;38.0;6.4)	26.9 (18.0;41.0;6.0)	23.9
<150cm	-	-	-	-
150-160cm	23.3	-	28.0	26.3
160-170cm	27.3	22.5	27.4	20.8
170-180cm	25.5	34.5	25.3	24.2
180-190cm	26.2	20.5	28.4	19.6
> 190 cm	-	-	28.0	-

TABLE A-X
ANTHROPOMETRIES OF OCCUPANTS WITH AIS2+ THORACIC INJURIES

	CIREN Legacy	CIREN	CISS	GIDAS
# cases	49	18	45	8
<150cm	1	1	3	0
150-160cm	9	3	7	4
160-170cm	18	7	12	1
170-180cm	15	2	18	2
180-190cm	6	5	5	1
> 190 cm	0	0	0	0
BMI of occupant (Min, Max, Std)	26.7 (17.7;46.5;6.3)	25.8 (19.0;36.0;4.6)	28.7 (20.0;46.0;6.4)	27.8
<150cm	25.5	25.0	36.3	-
150-160cm	25.3	22.7	26.9	27.4
160-170cm	25.5	25.9	28.3	27.3
170-180cm	27.1	25.5	29.3	27.5
180-190cm	31.2	28.0	25.4	19.6
> 190 cm	-	-	-	-

TABLE A-XI
ANTHROPOMETRIES OF OCCUPANTS WITH AIS 2+ ABDOMINAL INJURIES

	CIREN Legacy	CIREN	CISS	GIDAS
# cases	30	8	22	3
<150cm	0	0	0	0
150-160cm	7	1	6	1
160-170cm	8	6	5	0
170-180cm	12	0	8	0
180-190cm	3	1	3	2
> 190 cm	0	0	0	0
BMI of occupant (Min, Max, Std)	27.2 (17.7;44.1;6.7)	26.0 (22.0;33.0;4.2)	28.6 (20.0;44.0;7.2)	25.0
<150cm	-	-	-	-
150-160cm	27.8	24.0	28.7	25.5
160-170cm	30.6	26.3	32.4	-
170-180cm	26.0	-	26.5	-
180-190cm	21.6	26.0	27.3	24.7
> 190 cm	-	-	-	-

TABLE A-XII
ANTHROPOMETRIES OF OCCUPANTS WITH AIS2+ SPINAL INJURIES

	CIREN Legacy	CIREN	CISS	GIDAS
# cases	41	9	13	2
<150cm	0	0	0	0
150-160cm	6	2	1	0
160-170cm	14	3	4	1
170-180cm	16	3	7	0
180-190cm	5	1	1	1
> 190 cm	0	0	0	0
BMI of occupant (Min, Max, Std)	27.4 (17.7;46.5;6.3)	25.6 (20.0;38.0;6.7)	26.7 (21.0;41.0;6.3)	24.1
<150cm	-	-	-	-
150-160cm	28.0	24.0	24.0	-
160-170cm	26.7	21.7	27.3	23.4
170-180cm	26.6	27.0	27.4	-
180-190cm	31.2	36.0	22.0	24.7
> 190 cm	-	-	-	-

TABLE A-XIII
ANTHROPOMETRIES OF OCCUPANTS WITH AIS2+ INJURED UPPER EXTREMITIES

	CIREN Legacy	CIREN	CISS	GIDAS
# cases	16	4	27	5
<150cm	0	1	0	0
150-160cm	3	1	2	1
160-170cm	8	1	17	0
170-180cm	4	0	7	1
180-190cm	1	1	1	3
> 190 cm	0	0	0	0
BMI of occupant (Min. Max. Std)	25.1 (17.7;44.1;6.4)	26.3 (21.0;36.0;6.7)	31.4 (19.0;46.0;8.6)	24.7
<150cm	-	25.0	-	-
150-160cm	24.2	21.0	31.0	23.4
160-170cm	27.6	23.0	30.7	-
170-180cm	22.4	-	34.9	31.1
180-190cm	18.4	36.0	22.0	23.1
> 190 cm	-	-	-	-

TABLE A-XIV
ANTHROPOMETRIES OF OCCUPANTS WITH AIS2+ INJURIES OF LOWER EXTREMITIES OR HIP

	CIREN Legacy	CIREN	CISS	GIDAS
# cases	30	3	14	3
<150cm	0	0	2	0
150-160cm	7	1	1	1
160-170cm	9	0	4	1
170-180cm	13	1	7	0
180-190cm	1	1	0	1
> 190 cm	0	0	0	0
BMI of occupant (Min, Max, Std)	25.5 (17.7;44.1;6.2)	28.7 (24.0;31.0;4.0)	25.3 (16.0;35.0;5.7)	27.2
<150cm	-	-	32.0	-
150-160cm	26.7	24.0	24.0	25.5
160-170cm	26.4	-	19.8	31.3
170-180cm	24.3	31.0	26.7	-
180-190cm	23.5	31.0	-	24.9
> 190 cm	25.5	-	-	-