Injuries and Physical Long-term Consequences of Pedestrians Due to Collisions with Cars. An Analysis of the In-Depth Data from Germany, United Kingdom and France

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Abstract This study, conducted within the Horizon Europe IMPROVA project, examines the prevalence of injuries that may lead to long-term physical consequences (LTC) in pedestrians struck by the front end of a car. In-depth crash data from Germany (GIDAS), the United Kingdom (RAIDS), and France (VOIESUR) were analysed, focusing on cases involving a single forward-moving vehicle (maximum collision speed 50 km/h) impacting a pedestrian. To evaluate the prevalence of LTC-relevant injuries, those with a predicted Functional Capacity Index (pFCI) < 5 were analysed considering AIS/MAIS severity, body region distributions, and the most frequent AIS-coded injuries. Pedestrians' characteristics (such as sex, age, body size, and body weight), collision configurations, crash parameters, and injury sources were also examined. For LTC-relevant injuries, the most affected body regions were the Lower Extremities, the Upper Extremities, and the Head. Lower-limb fractures were the most common, typically associated with higher pFCI (better state), while pelvic injuries appeared consistently across datasets with high severity and low pFCI (worst state). Head injuries were less frequent but exhibited the highest AIS scores and low pFCI values. Higher impact speeds increased the likelihood of LTC. The study highlights that even AIS2 injuries can lead to LTC, suggesting safety measures should continue prioritising lower limbs and head while also addressing pelvic injury prevention.

Keywords: Car-to-pedestrian collision, Injury severity, Long-term consequences (LTC), Predicted Functional Capacity Index (pFCI), Vulnerable road users.

I. INTRODUCTION

According to the 2025 annual statistical report of the European Road Safety Observatory, among the Member States of the EU in 2023 a total of 900,861 road traffic crashes caused 1.14 million injured people and 20,384 fatalities, 18% of which were pedestrians [1]. These road users are particularly vulnerable, because they generally do not wear any protective clothing or equipment; additionally, if in a collision between a pedestrian and another road user there is any fatality, then 98% of the time it is the pedestrians themselves [2].

Nevertheless, the number of road traffic fatalities in the EU shows a decreasing trend, with 46 fatalities per million inhabitants in 2023, representing a -10% change in respect to 2019 (55 fatalities); Germany, Great Britain, and France also show a decreasing trend, with a -7% [1], -8.8% [3], and -3% [1] change in the same period, respectively. However, reduced fatalities do not necessarily lessen the overall injury burden: although some collisions may be entirely avoided, those that still occur increasingly result in survivors requiring injury recovery. In some cases, these injuries can result in long-term physical consequences, meaning any physical condition or disability that lasts longer than the usual healing period of an injury and that can affect the health status and the quality of life of the survivor. This concept can be extended to other aspects of human well-being and health, identifying therefore different types of LTC, such as psychological, social, or economic LTC.

The Abbreviated Injury Severity (AIS©) scale is a well-known tool used also in injury prevention and mitigation studies. It uses a 7-digits code assigned to each injury, where the numbers before the dot identify the body region and the specific anatomic structure affected as well as the specific nature of the injury and its level, whereas the post-dot digit identifies its severity on a scale from 1 (minor) to 6 (critical) [4]. The predicted Functional Capacity Index (pFCI) is a tool that was developed to predict functional outcomes in trauma survivors 12 months after the injury [5-6] and it has been appended to the AIS© Dictionary [7] as additional parameter for each injury, making it highly suitable for application in conjunction with the AIS scale to characterise the pattern of severity together

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with the physical long-term consequences (LTC) of the injury suffered.

In-depth data collection is a powerful tool for the analysis of collision scenarios and crash-related injuries. The data used for this study comes from the German In-Depth Accident Study (GIDAS) [8], from the Road Accident In-Depth Studies (RAIDS, UK) [9], and from the Vehicle Occupant Infrastructure Road User Safety Study (VOIESUR, France) [10] databases. This work aims to describe relevant parameters and most frequent configurations in collisions between a car and a pedestrian, and to identify those injuries associated with physical LTC – identified based on the pFCI scale – occurring most frequently in this type of crashes. The study has been conducted in the framework of the EU-funded IMPROVA project, aiming to implement mitigation strategies to reduce the occurrence of LTC and serious injuries.

II. METHODS

In-Depth Databases

Since 1999, the German In-Depth Accident Study (**GIDAS**) conducts on-scene investigations of road traffic collisions from a scientific perspective. Approximately 2,000 collisions with personal injuries per year are investigated using a standardized codebook and immediate post-crash data collection (for a total of 47,757 cases up to now). The sampling strategy is regionally based and randomised to provide a representative picture of road traffic collisions in Germany, covering all road user types. Cases are selected independently of liability considerations and include detailed reconstruction and multidisciplinary data, with up to 3,000 collected characteristics for each case. The data collected includes environmental, technical, medical, and psychological information, as well as long-term outcomes. Injuries are documented by AIS 2015.

The UK Road Accident In-Depth Studies (**RAIDS**) programme is the United Kingdom's in-depth road traffic collision data collection initiative, covering crashes investigated from 2013 to 2025. At the time of analysis, the dataset comprised 6,979 collision participants across all road user types, including pedestrians and uninjured individuals. RAIDS applies a targeted sampling strategy, investigating approximately 200 cases per year, with a deliberate focus on more severe collisions and occupants of newer vehicles. The dataset is built from a combination of on-scene (live) investigations and retrospective analyses based on vehicle examinations, police reports, and hospital-provided data. All collisions included involve at least one road user, regardless of injury status, and each case benefits from detailed, fully anonymised injury descriptions provided by participating hospitals. Injuries are coded using AIS 2015.

The sampling design allows the data to be scaled to national representativeness through weighting factors derived from the STATS19 national police-reported collision database. The Vehicle Occupant Infrastructure Road User Safety Study (**VOIESUR**) was a French research project focusing on road accidents that occurred in 2011. It constructed a nationally representative database of approximately 8,500 injury-related crashes derived from in-depth analyses of police reports, including associated medical reports, for accidents involving at least one injured person. The dataset includes all fatal accidents nationwide, all injury accidents in the Rhône region, and a random 5% sample of other injury accidents across metropolitan France. Cases were selected based on police records, and each accident was comprehensively described across three main domains: vehicles, road users (including their injuries), and infrastructure. The sampling design is stratified and supported by weighting factors applied to correct for sampling and reporting biases, ensuring national representativeness. Injury severity was initially coded using AIS 1998 (AIS98) and subsequently harmonized through mapping to AIS 2015.

Data Selection

For this study, the data from the in-depth databases of Germany (GIDAS), UK (RAIDS), and France (VOIESUR) was used. To select the suitable cases, the following filtering criteria have been applied: the vehicles belonged to the M1/N1 categories with first year of registration later than 2005, to include vehicles most likely equipped with the protective measures required (as the European framework directive 2003/102/EC on pedestrians and other vulnerable road users was mandatorily applicable from October 2005). These safety measures concern the front-end geometry of the car, therefore only cases with forward moving vehicles were included in the dataset. To ensure interaction between known collision partners, cases with only two participants (i.e. one vehicle and one pedestrian) and without multiple collisions were included. Only the crash data related to the first (major) collisions and with collision speeds between 0 and 50 km/h of the vehicles was included, because the analysis should also provide robust information on the injury sources with the aim of being able to develop vehicle-specific countermeasures in a subsequent step. Pedestrians lying on the ground at the time of the collision were also excluded. Users of any micro-mobility device were excluded, because they were not the target of the protective measures to propose. Finally, minor severity injuries causing skin abrasions, lacerations, contusions, or avulsions were excluded, as they are very frequent in this type of road traffic collisions and do not have predicted LTC. To exclude the individual 7-digit AIS codes corresponding to these injuries, all of the following exclusion criteria had to be satisfied: severity score equal to 1, first digit 1 to 9 (excluding 6), second digit 1, third digit 0, fourth digit 0, 2, 4, 6, or 8.

Pedestrians' Characteristics, Injuries and Collision Parameters

Variables such as sex, age, body size, body weight – when available in the datasets – have been studied to characterise the sample. The injury data in all three datasets was encoded according to the AIS© 2015 dictionary [7]; therefore, the corresponding severity score, affected body region, injury description, and pFCI value are provided for each individual AIS injury code. The AIS score is a numeric value indicating the severity of the injury and its values span from 1 (minor) to 6 (critical). Serious injuries are generally considered as all injuries having an AIS score of 3 or higher. The use of the AIS scale allows the characterization of each individual injury, but it is also possible to obtain a person-level characterization based on the Maximum AIS value per person (MAIS), which – in case of multiple injuries – corresponds to the highest AIS value for that person. The pFCI scale spans from the value of 1 (worst possible state) to 5 (perfect state). To identify the injuries most frequently occurring in the studied collision type and their correlation with LTC, injuries having a pFCI value comprised between 1 and 4 were all considered as associated with predicted LTC (and will be referred to as LTC-associated injuries). Since the pFCI - like the AIS score - is assigned to individual injuries, a value on person-level for cases with multiple injuries was derived by calculating the minimum pFCI (min pFCI). This value corresponds to the lowest pFCI among all injuries sustained by that person, representing the injury expected to result in the worst health outcome 12 months post-injury.

Collision parameters such as the collision type and the collision speed were investigated to identify the most frequent collision scenarios and to understand if they had an influence on the injury severity or on the occurrence of LTC. Injury sources related to most frequently occurring LTC-associated injuries were also analysed.

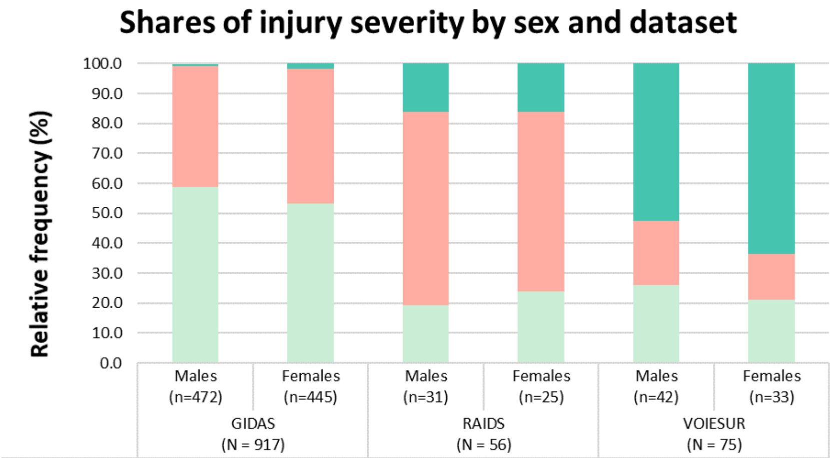
Extended Data Analysis

To provide additional insights on the occurrence of injuries in association with the pedestrians' characteristics, the ratio of killed or severely injured (see group definitions in the appendix) to the total of the pedestrians in the sample (rKSI) and the odds ratios were calculated for the various groups of each characteristic (see Fig. S1 and Table S1 in the Supplementary Material, respectively, for additional information).

III. RESULTS

Datasets

Upon applying the described filtering criteria, the datasets obtained included 917 pedestrians for GIDAS, 56 pedestrians for RAIDS, and 75 pedestrians for VOIESUR. Accordingly, these datasets will hereafter be referred to as the GIDAS sample, the RAIDS sample, and the VOIESUR sample. The plot in Fig. 1 shows the distribution of the data based on the sex group and injury severity for each dataset (see the Appendix for the dataset-specific definition of each injury severity category).



	GIDAS Males (n=472)	GIDAS Females (n=445)	RAIDS Males (n=31)	RAIDS Females (n=25)	VOIESUR Males (n=42)	VOIESUR Females (n=33)
killed	0.6	1.8	16.1	16.0	52.4	63.6
severely injured	40.3	44.9	64.5	60.0	21.4	15.2
slightly injured	58.7	53.3	19.4	24.0	26.2	21.2
not injured	0.2	0.0	0.0	0.0	0.0	0.0

Fig. 1 – Stacked bar plot showing the distribution of injury severity by sex in the three datasets

Pedestrians' Characteristics

Table 1 shows the absolute and relative frequencies for the subgroups of each of the studied pedestrian's characteristics into which each dataset has been split (note that in VOIESUR the data on body size and weight is not available), as well as the shares of the MAIS groups.

TABLE 1
Absolute and relative frequencies for the subgroups of the studied variables in each dataset.

	GIDAS n (%)	**RAIDS** n (%)	**VOIESUR** n (%)
SEX			
Males	472 (51.5%)	31 (55.4%)	42 (56%)
Females	445 (48.5%)	25 (44.6%)	33 (44%)
AGE			
Children (<= 12 years)	199 (21.7%)	7 (12.5%)	11 (14.7%)
Teenagers (13-18 years)	80 (8.7%)	9 (16.1%)	3 (4%)
Mid-Aged Adults (<= 12 years)	459 (50.2%)	24 (42.9%)	22 (29.3%)
Old-Aged Adults (65-74 years)	69 (7.5%)	8 (14.3%)	11 (14.7%)
High-Aged Adults (> 75 years)	108 (11.8%)	8 (14.3%)	28 (37.3%)
BODY SIZE			
<= 125 cm	37 (5.3%)	0	*n/a*
126–165 cm	296 (42.8%)	9 (16.1%)	*n/a*
166–185 cm	319 (46.1%)	9 (16.1%)	*n/a*
> 185 cm	40 (5.8%)	0	*n/a*
Unknown	-	38 (67.9%)	*n/a*
BODY WEIGHT			
< 50 kg	137 (21.0%)	3 (5.4%)	*n/a*
50-65 kg	172 (26.3%)	8 (14.3%)	*n/a*
66-80 kg	188 (28.8%)	9 (16.1%)	*n/a*
81-100 kg	126 (19.3%)	6 (10.7%)	*n/a*
> 100 kg	30 (4.6%)	2 (3.6%)	*n/a*
Unknown	-	28 (50%)	*n/a*
MAIS			
MAIS1	392 (56.6%)	12 (21.4%)	9 (12.0%)
MAIS2	213 (30.8%)	18 (32.1%)	8 (10.7%)
MAIS3	50 (7.2%)	14 (25.0%)	22 (29.3%)
MAIS4	10 (1.4%)	6 (10.7%)	3 (4.0%)
MAIS5	8 (1.2%)	2 (3.6%)	8 (10.7%)
MAIS6	2 (0.3%)	0	0
Unknown	17 (2.5%)	4 (7.1%)	25 (33.3%)

Most Frequent Collision Types

All three databases contain information about the type of collision that occurred. To investigate the typical crash scenarios in collisions between cars and pedestrians, the five most frequent collision configurations from each dataset were identified (see Fig. 2).

In the GIDAS sample, the most frequent collision type is the type 421 which describes a forward moving vehicle driving on a straight road and colliding with a pedestrian who crosses the road from the right-hand side with respect to the trajectory of the vehicle. The matching collision types in the RAIDS sample (type N1, ranked 1st) and in the VOIESUR sample (type 803, ranked 2nd) are also included in their respective most frequent scenarios (note that the moving direction of the pedestrian in the RAIDS N1 collision type is from left to right, which is in agreement with driving on the left in the UK). In the GIDAS sample the collision type 401, where the pedestrian is coming from the left-hand side of the road, is ranked 4th. In the RAIDS dataset, type N2 is ranked 2nd and in the VOIESUR dataset type 804 is ranked 1st. Collision types N1 and N2 (RAIDS) as well as 803 and 804 (VOIESUR), together represent a very large share of all the scenarios included in the datasets (75% and 47%, respectively). In the GIDAS sample, collision types 421 and 222 account for 21%. Collision types 222 and 221, that are ranked 2nd and 3rd, both describe the same scenario where a vehicle is turning left at a crossroad, and the pedestrian crosses from the right-hand side of the road (type 222) or from the left-hand side of the road (type 221). These two scenarios are matched by the N4 and N6 types in RAIDS (ranked 3rd and 4th, respectively), and by the 812 and 813 types in VOIESUR (ranked 3rd and 5th respectively). The remaining scenario in the GIDAS sample (type 451, ranked 5th) describes a collision where a forward moving vehicle hits a pedestrian coming from the right-hand side of the road just before an intersection. The last scenario in the VOIESUR sample is the collision type 814 (ranked 4$^{th)}$, where the pedestrian's crossing takes place after the crossroad, relative to the approaching car. The last collision type in the RAIDS sample (type P1, ranked 5th) describes a collision where the vehicle and the pedestrian are moving to the same direction and the pedestrian stays on the left-hand side of the vehicle.

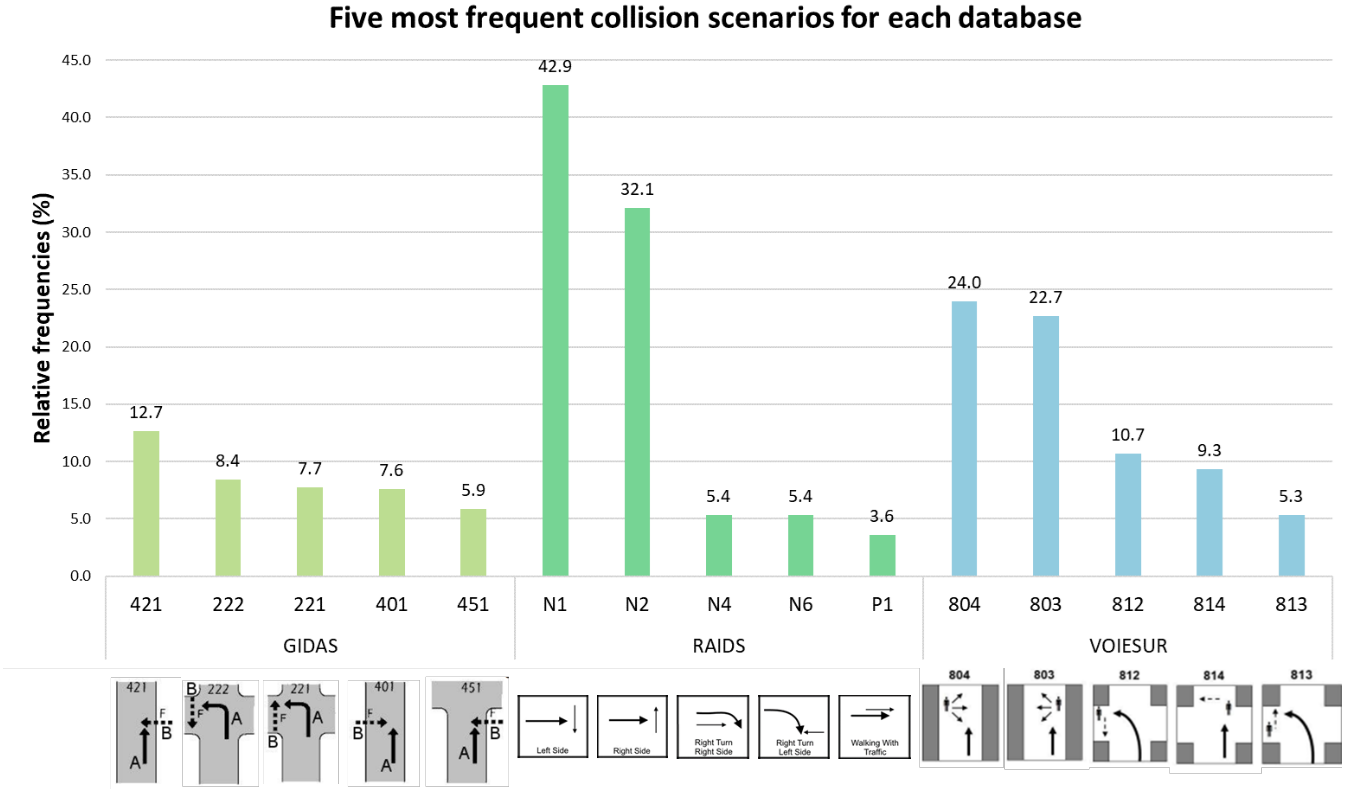


Fig. 2 – Five most frequent collision types included in each dataset (percentages are calculated respect to the total of each dataset). For each collision type, the dataset-specific code is provided, together with the pictogram describing the collision scenario. In the GIDAS pictograms, the participant A is the vehicle and the participant B is the pedestrian (who is also identified by the letter "F", for the German word "Fußgänger"); in the RAIDS pictograms, the big arrows identify the vehicles, the small arrows identify the pedestrians.

Impact Speed

All three databases comprise data on the collision speeds of the vehicles which enables the demonstration of their relationship with the corresponding severity of pedestrians' injuries (see Fig. 3).

The **GIDAS** sample (one unknown and one not injured pedestrians were discarded) shows that the collision speeds median values for those crashes where the pedestrians were severely injured (N=390) is approximately 10 km/h higher than that of the crashes where the pedestrians were slightly injured (N=514). In both cases the speed values spread across the entire range. The situation is different for the group of the killed pedestrians, where the sample size is only 11. It can be seen that the median value is slightly lower than the median value of the severely injured and the range of speed values is narrower compared with the other two groups, most likely because of the big difference in the sample sizes and the abovementioned dataset inclusion criteria. The data from the **RAIDS** sample shows that the collision speeds median values for the crashes where the pedestrians were severely or fatally injured were higher than those of the crashes where pedestrians were slightly injured; additionally, both for the severely injured and for the fatally injures the range of values is wider respect to that of the slightly injured. The data from the **VOIESUR** sample shows that the collision speed median values increase from the slightly injured group, through the severely injured group, to the killed group; in all the three groups, the interval of speed values does not extend across the whole range, and it has approximately the same width in the severely injured and the killed.

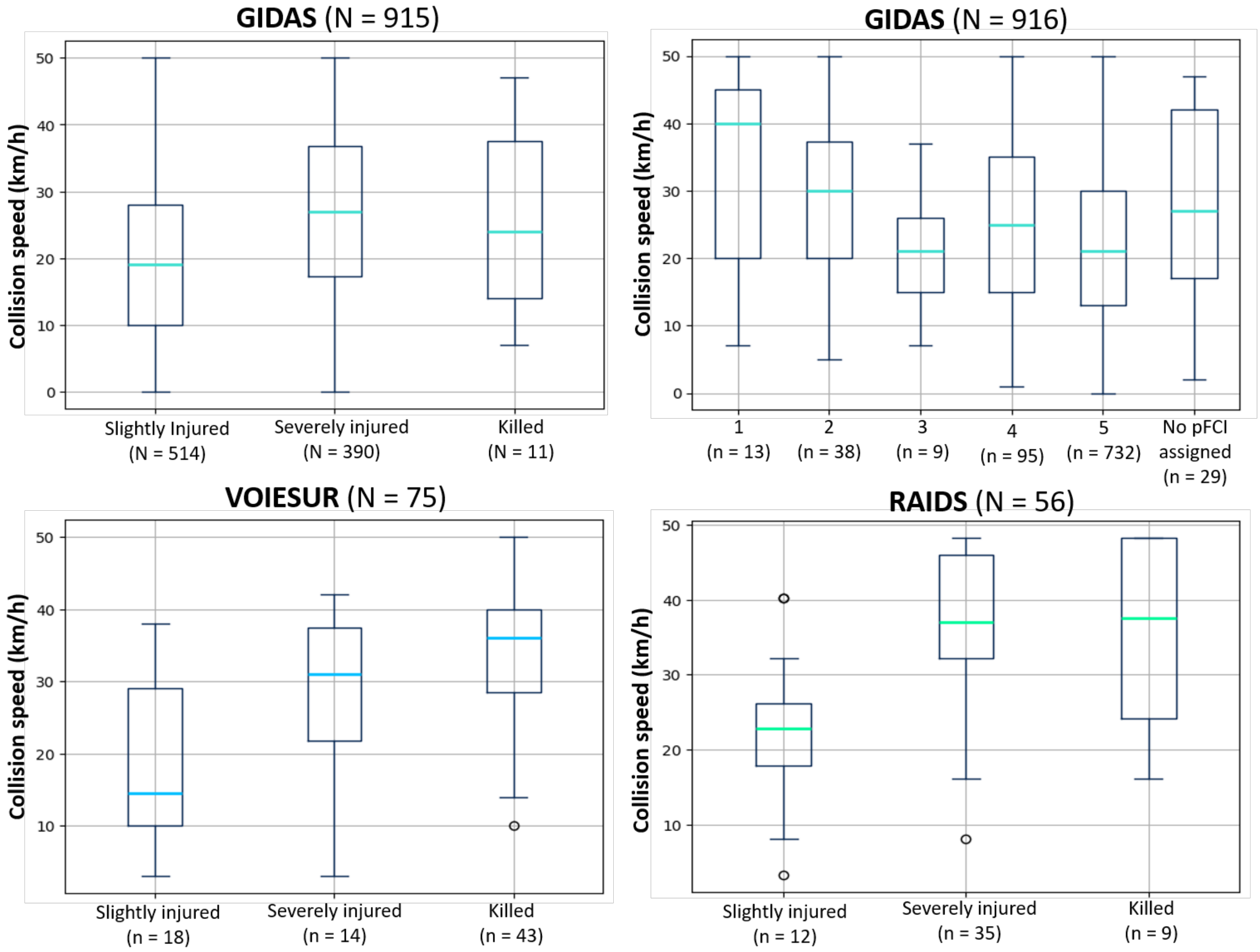


Fig. 3 – Box plots showing the collision speed distribution by overall injury severity for GIDAS (upper plots, RAIDS (lower right plot), and VOIESUR (lower left plot). The plot to the upper right shows the distribution of collision speed by min pFCI value only for GIDAS. Unknown severity/pFCI values and uninjured pedestrians were excluded).

A further distribution of the collision speed by pFCI was analysed only for the **GIDAS** sample, because the sample size of the resulting groups was too small in RAIDS and VOIESUR. It can be seen that the majority (732 out of 916) of pedestrians were assigned pFCI5, predicting a perfect health state 12 months after the crash (i.e. no LTC). In this group, the speeds extend across the whole range and the median is the lowest of all the pFCI groups (approximately 21 km/h) together with the pFCI3 group (predicting a serious state; sample size = 9), where the distribution of speeds is narrower with respect to the other groups, ranging from approximately 8 km/h to approximately 27 km/h. The pFCI4 group (moderate state), which is the second most populated with 95 pedestrians, has a median of approximately 25 km/h and the collision speed values extend across almost the whole range. The pFCI2 group (severe state; 38 pedestrians) has a median of 30 km/h whereas the pFCI1 group (worst state possible; 13 pedestrians) has a median of 40 km/h. In these groups the range of values spans from 6 km/h to 50 km/h (severe state) and from 8 km/h to 50 km/h (worst possible state). Additional box plots showing the distribution only for those cases where a pedestrian suffered at least one injury with pFCI < 5 are shown in Fig. S2.

Injury Severity Distributions

The severity value for each individual injury is encoded in all three datasets together with the affected body region, using the AIS scale. Therefore, it is possible to obtain the distribution at the injury level based on the AIS value and the body region (Fig. 4). For this distribution, only injuries having pFCI < 5 were considered. Additionally, the percentages calculated sum to 100% for each dataset and the values from AIS3 to AIS6 were grouped together in a single AIS3+ group. The body regions External and Other are not shown, because they have no entries in any of the samples. The Supplementary Material contains additional information on the AIS/body region distributions at the injury-level including all pFCI values (Tables S2, S4, S6) and also the MAIS/body region distribution at the person-level, both for all pFCI values (Tables S3, S5, S7) and only pFCI <5 (Fig. S3).

In the **GIDAS** sample, the total number of pFCI < 5 injuries was 269; Fig. 4 (left panel) shows the distribution of the injury shares by AIS score and body region for this dataset. No pedestrian sustained injuries with predicted LTC in any of the following body regions: Neck, Thorax, Abdomen. The vast majority of the injuries with predicted LTC belong to the Lower Extremities and have AIS2 (62%), AIS3 (13%), or AIS1 (4%), followed by the AIS2 injuries in the Upper Extremities (6%), and the AIS3+ injuries to the Head (6%).

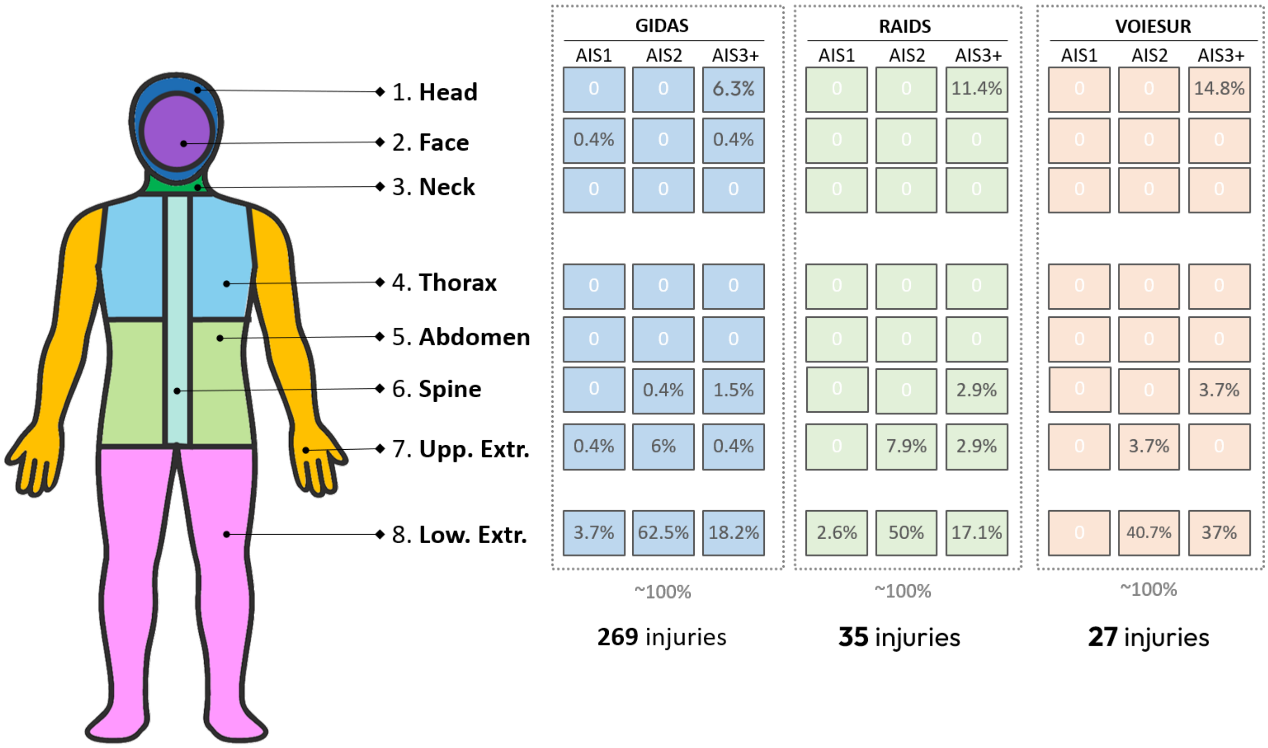


Fig. 4 – Graphical representation of the injury-level distribution in all three datasets based on AIS value and body region affected. Only injuries with pFCI < 5 are included.

In the **RAIDS** sample (central panel of Fig. 4), the total number of pFCI < 5 injuries was 35; mirroring the results from GIDAS, RAIDS has no entry for the body regions Neck, Thorax or Abdomen, indicating that also in this dataset no pedestrian suffered injuries predicted to have LTC in these regions. Also in RAIDS, as seen in GIDAS, the largest share of injuries belongs to the Lower Extremities and have AIS2 (50%), AIS3+ (17%), or AIS1 (3%), followed by the AIS3+ share of the Head (11%) and by the AIS2 share of the Upper Extremities (8%).

In the **VOIESUR** sample, the total number of pFCI < 5 injuries was 27 (right panel of Fig. 4); also in this dataset, the data has no entry for the body regions Face, Neck, Thorax, Abdomen. As seen in GIDAS and RAIDS, the largest shares of the injuries belong to the Lower Extremities and have AIS2 (41%) and AIS3+ (37%), followed by the AIS3+ share in the Head (15%). The remaining minor shares of injuries are given by the AIS3+ injuries to the Spine and the AIS2 injuries in the Upper Extremities (both 4%).

Most Frequent LTC-associated Injuries

Table 2 ranks the most frequent LTC-associated individual injuries (i.e. only injuries assigned to pFCI < 5) in each sample. Only the first 15 injuries were further considered, unless more than one injury was ranked with the same value (in that case all of them were included).

In the **GIDAS** sample a total of 18 individual AIS codes with pFCI < 5 were obtained, accounting for 149 injuries. The regions included are the Lower Extremities (17 out of 18 AIS codes) and the Upper Extremities (1 out of 18 AIS codes in total). All injuries listed are fractures, highlighting the prevalence of this type of injuries in respect to the occurrence of LTC when compared with the most frequent injuries considering all pFCI values, where concussions, strains, sprains, and other types of injuries are common (see Table S8). The AIS score is 2 for all injuries, with the exception of a femur fracture (AIS3) and a pelvic ring fracture (AIS4). Except for the same pelvic ring fracture injury and three distal tibia fractures, all having pFCI2, the remaining injuries have pFCI4.

In the **RAIDS** sample, there were a total of 27 individual AIS codes for injuries having pFCI < 5, representing a total of 35 injuries. Given the small sample size, all AIS codes with pFCI < 5 for this dataset are included in the table. The Lower Extremities region accounts for 19 AIS codes, the Head for four, the Upper Extremities for three, and the Spine for one. All injuries to the Lower and Upper Extremities are fractures, representing therefore also in this dataset the majority of the injuries. The three injuries to the Head and that to the Spine have pFCI1, two Lower Extremity injuries have pFCI2, one Head injury has pFCI3, all the remaining injuries have pFCI4.

In the **VOIESUR** sample, there are a total of 16 individual AIS codes, for a total of 27 injuries. Also in this case, all AIS codes with pFCI < 5 for this dataset are included in the table. The Lower Extremities body region accounts for 11 AIS codes, the Head for three AIS codes, and the Spine and Upper Extremities for one code each. The Head and Spine codes have pFCI1, two Lower Extremities injuries have pFCI2, one Upper Extremities code and all the remaining Lower Extremities codes have pFCI4.

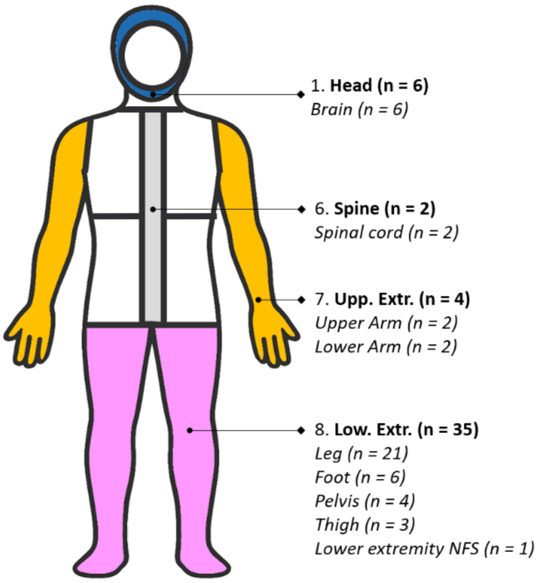
TABLE 2
Most frequent injuries with pFCI < 5. Percentages are rounded up. “AIS Sev.” stands for “AIS Severity”.

AIS Injury Description	n	%	AIS Region	AIS Sev.	pFCI
GIDAS					
Fibula [malleoli] **fracture**, above joint (suprasyndesmotic); isolated shaft, head or neck; Weber C	31	12%	L. Ext.	2	4
Proximal **tibia fracture**, partial articular; Schatzker 1,2,3	13	5%	L. Ext.	2	4
One of four **metatarsal** extra-articular or shaft **fracture**	12	4%	L. Ext.	2	4
Pelvic ring **fracture**, complete disruption of posterior arch and disruption of the pelvic floor	10	4%	L. Ext.	4	2
Distal **tibia fracture**, extra-articular; isolated medial or posterior malleolus	9	3%	L. Ext.	2	4
Fibula [malleoli] **fracture**, through joint (transsyndesmotic); Weber B	6	2%	L. Ext.	2	4
Distal **tibia fracture** NFS [includes isolated medial or posteriori malleolus; pilon fracture]	6	2%	L. Ext.	2	2
Tibia fracture NFS	6	2%	L. Ext.	2	4
Proximal **femur** trochanteric; intertrochanteric **fracture**	6	2%	L. Ext.	3	4
Proximal **humerus fracture**, articular; head or anatomical neck	6	2%	U. Ext.	2	4
Fibula [malleoli] **fracture**, through joint, trimalleolar	6	2%	L. Ext.	2	4
One of four lateral **metatarsal fracture**, partial articular	6	2%	L. Ext.	2	4
Proximal **tibia fracture** NFS	6	2%	L. Ext.	2	4
Open **fibula** [malleoli] **fracture**, above joint (suprasyndesmotic); isolated shaft, head or neck; Weber C	6	2%	L. Ext.	2	4
Distal **tibia fracture**, partial articular	5	2%	L. Ext.	2	2
Tibia shaft **fracture** wedge; “butterfly”; Winquist II or III	5	2%	L. Ext.	2	4
Distal **tibia fracture**, complete articular	5	2%	L. Ext.	2	2
Distal **tibia fracture**, extra-articular; isolated medial or posterior malleolus, open	5	2%	L. Ext.	3	4
RAIDS					
Pelvic ring **fracture** [includes pelvic ring dislocation]; incomplete disruption of posterior arch	3	9%	L. Ext.	3	2
Acetabulum fracture NFS	2	6%	L. Ext.	2	4
One of Four Lateral **Metatarsals fractures**; partial articular	2	6%	L. Ext.	2	4
One of Four Lateral **Metatarsals fractures**; extra-articular or shaft	2	6%	L. Ext.	2	4
Distal **Tibia fracture** NFS [includes isolated medial or posterior malleolus; pilon fracture]	2	6%	L. Ext.	2	2
Fibula [malleoli] **fracture**; above joint (suprasyndesmotic); isolated shaft, head or neck; Weber C	2	6%	L. Ext.	2	4
Proximal **humerus fracture** [includes neck of humerus; articular; head or anatomical neck	2	6%	U. Ext.	2	4
Proximal **Tibia fracture** NFS	1	3%	L. Ext.	2	4
Cerebrum [includes basal ganglia thalamus putamen globus pallidus]; **hematoma** (hemorrhage); subdural; large; massive; extensive; >50cc (>25cc if age <= 10); >1cm thick	1	3%	Head	5	1
Proximal **Femur fracture**; trochanteric; intertrochanteric; open	1	3%	L. Ext.	3	4
Brain stem [includes hypothalamus medulla midbrain pons]; **compression** [includes transtentorial (uncal) or cerebellar tonsillar herniation]	1	3%	Head	5	1
One of Four Lateral **Metatarsals fractures**; complete articular	1	3%	L. Ext.	2	4
Tibia fracture NFS	1	3%	L. Ext.	2	4
Tibia Shaft **fracture**; simple; spiral; oblique; transverse; Winquist I	1	3%	L. Ext.	2	4
Proximal **ulna fracture**, open	1	3%	U. Ext.	3	4
Navicular fracture; extra-articular [includes coronal body split, no joint involvement]	1	3%	L. Ext.	2	4
Cervical: **Spinal cord injury**; incomplete spinal cord injury with preservation of some motor and/or sensory function [includes anterior cord, central cord, lateral or posterior/*Brown-Séquard* syndromes, ASIA Grade B, C or D]; with fracture	1	3%	Spine	4	1
Cerebrum [includes basal ganglia thalamus putamen globus pallidus]; **contusion** [include perilesional edema for size]; multiple at least one on each side; extensive; massive; total volume >50cc (>30cc if age <=10)	1	3%	Head	5	1
Proximal **Femur fracture**; femoral neck	1	3%	L. Ext.	3	4
Tibia fracture; open	1	3%	L. Ext.	3	4
Tibia Shaft **fracture** NFS	1	3%	L. Ext.	2	4
Tibia Shaft **fracture**; complex; comminuted; segmental; Winquist IV	1	3%	L. Ext.	2	4

AIS Injury Description	n	%	AIS Region	AIS Sev.	pFCI
Fibula [malleoli] **fracture**; below ankle joint (infrasyndesmotic); isolated lateral malleolus; Weber A	1	3%	L. Ext.	2	4
Metatarsal fracture NFS	1	3%	L. Ext.	2	4
Proximal **humerus fracture** [includes neck of humerus NFS]	1	3%	U. Ext.	2	4
Phalange **fracture**; **Great Toe** NFS	1	3%	L. Ext.	1	4
Cerebrum [includes basal ganglia thalamus putamen globus pallidus]; **hematoma** (hemorrhage); subdural; small; moderate; <=50cc (<=25cc if age <=10); 0.6-1cm thick	1	3%	Head	4	3
VOIESUR					
Tibia fracture, open	5	19%	L. Ext.	3	4
Fibula fracture, above joint (suprasyndesmotic); isolated shaft, head or neck; Weber C	4	15%	L. Ext.	2	4
Cerebrum, brain **swelling**, severe; absent ventricles or brain stem cisterns	2	7%	Head	5	1
Tibia fracture NFS	2	7%	L. Ext.	2	4
Tibia shaft fracture, open	2	7%	L. Ext.	3	4
Fibula [malleoli] **fracture**, below ankle joint (infrasyndesmotic); isolated lateral malleolus; Weber A	2	7%	L. Ext.	2	4
Cerebrum, **hematoma**, large; massive; extensive; >50cc (>25cc if age <=10); >1cm thick	1	4%	Head	5	1
Cerebrum, **hematoma**, subdural, large; massive; extensive; >50cc (>25cc if age <=10); >1cm thick	1	4%	Head	5	1
Complete **spinal cord injury** motor and sensory complete injury, includes complete spinal cord transection syndrome, [ASIA Grade A], with both fracture and dislocation (with or without disc involvement)	1	4%	Spine	5	1
Ulna fracture NFS	1	4%	U. Ext.	2	4
Degloving, entire extremity	1	4%	L. Ext.	3	4
Proximal **tibia fracture** NFS	1	4%	L. Ext.	2	4
proximal tibia **fracture**, open	1	4%	L. Ext.	3	2
Tibia shaft **fracture** NFS	1	4%	L. Ext.	2	4
Fibula [malleoli] **fracture**, below ankle joint (infrasyndesmotic); isolated lateral malleolus; Weber A, lateral and medial malleoli (bimalleolar)	1	4%	L. Ext.	2	4
Pelvic ring **fracture**, incomplete disruption of posterior arch, blood loss<=20% by volume; moderate pelvic hematoma	1	4%	L. Ext.	4	2

*Table included with permission from AAAM.

Some of the injuries in Table 2 are shared among the three samples (e.g. tibia fracture NFS). Upon combining all the injuries from Table 2 in a single dataset, 47 unique AIS codes accounting for a total of 211 injuries were identified. These 47 AIS codes identify approximately 64% (211 out of 331) of all injuries with pFCI < 5 included in the three samples. Fig. 5 shows how these 47 AIS codes map injuries to anatomic locations based on the AIS body regions (in bold) and the specific body part affected (in italic). It can be observed that 35 out of 47 AIS codes identify Lower Extremities injuries, with a prevalence of injuries to the Leg (i.e., fibula and tibia). Further, the upper table shows the frequency counts based on the type of injury: 38 out of 47 AIS codes identify fractures and six identify traumatic brain injuries (TBIs). The lower table shows instead a crosstabulation between the assigned AIS score and pFCI value, indicating that the majority of the AIS codes (32 out of 47) have pFCI4; all of these injuries – except for one degloving injury – are fractures; only one injury has pFCI3 (a TBI with AIS4); seven injuries have pFCI2 (all fractures; three with AIS2, two with AIS3, and two with AIS4); among the seven AIS codes having pFCI1, there are five TBIs and the two spinal cord injuries.



Injury Type	Counts
Fracture	38
TBI	6
Spinal injury	2
Degloving	1

	pFCI 1	pFCI 2	pFCI 3	pFCI 4	total
AIS1	0	0	0	1	1
AIS2	0	3	0	23	26
AIS3	0	2	0	8	10
AIS4	1	2	1	0	4
AIS5	6	0	0	0	6
tot	7	7	1	32	

Fig. 5 – Graphical representation of the body regions and specific body locations affected by all the injuries listed in Table 2, together with the frequency counts by type of injury and a crosstabulation between the pFCI and the AIS severity.

Injury Sources

As fractures and TBIs were the most common type of injuries among those identified as occurring most frequently in this type of road traffic collision and datasets, a further analysis on the injury sources was conducted to specifically address these two types of injuries only (Table 3). The analysis was conducted exclusively for GIDAS and RAIDS, because VOIESUR does not include this kind of information. As the data for GIDAS shown in Table 2 does not include any injury type other than fractures, the analysis for this database was based only on this injury type. In GIDAS the information on the injury source is encoded in two variables, therefore the data is provided for both of them (when available).

TABLE 3

Injury sources for specific type of injury in GIDAS and RAIDS. For the GIDAS data, only items with a share of equal or higher to 2% are shown. For TBIs only the counts are shown, as the sample size is too small.

GIDAS - Injury sources (fractures)	**%**	**RAIDS – Injury sources (fractures)**	**%**
Front bumper	36.9	Front bumper/vehicle structure below bonnet leading edge (NFS)	22.6
Vehicle front (NFS)	7.4	Bonnet surface (NFS)	9.4
Road surface, even	6.0	Front tyre or wheel	9.4
Fender from front	5.4	Crushed between two surfaces - NFS	9.4
Front wheel	4.0	Bonnet Leading Edge	7.5
Unknown	4.0	Front wing	7.5
Own action, body movement (e.g. Whiplash, tongue bite)	4.0	External object: Carriageway or Footway surface	7.5
Front spoiler below bumper	4.0	external object: Road surface	5.7
Run over	3.4	Front nearside structures (e.g. front wing)	5.7
Sheet metal between C and D pillars	2.7	Bonnet surface with stiff structure beneath	3.8
Front wheel opponent AND road surface, even	2.0	Rear nearside structures (e.g. rear three-quarter panel)	3.8
Front wheel AND run over	2.0	Vehicle Exterior - NFS	3.8
Front fender, lateral direction	2.0	Windscreen (external)	1.9
Bonnet surface	2.0	Central Grille	1.9
		RAIDS – Injury sources (TBIs)	**counts**
-	-	External object: Road surface	2
-	-	Windscreen (external)	2
-	-	External object: Carriageway or Footway surface	1

For RAIDS, the analysis was instead based both on fractures and TBIs. Concerning fractures, it can be observed that the most frequent injury source is the front bumper of the vehicle, accounting for approximately 37% and 27% of the fractures in GIDAS and RAIDS, respectively. Several other frontal parts of the car are involved, such as the unspecific vehicle front (7%), the front fender (5%), the front wheel (4%), and the front spoiler (4%) in GIDAS; in RAIDS, the bonnet surface (9%), the front wheel area (9%), the bonnet leading edge (7%) or the front wing (7%) are listed. The bonnet area appears to occur less frequently as source for this type of injury in GIDAS. The road or footway surface appears to be a frequent cause of injury in both datasets. Regarding TBIs, the sample size in RAIDS is too small to make assumptions on the most frequent injury sources.

IV. DISCUSSION

The objective of this study was to analyse collisions between a vehicle and a pedestrian, to identify the most frequent injuries potentially leading to long-term consequences and collision parameters that might influence their occurrence. In GIDAS, there is some indication that higher collision speeds are associated with higher injury severity and with higher chances of suffering LTC from the injuries sustained that should require further investigation. The collision scenarios represented in the three datasets exhibit a certain degree of homogeneity. The most frequent cases involve a vehicle travelling on a straight path and striking a pedestrian approaching from either the left or right side of the road. In addition, collisions in which a vehicle turns toward the driver's near side and a pedestrian crosses from the left or right are also common in all three datasets. It is reasonable to think that this last type of collisions might on average happen at lower speeds, since vehicles usually reduce their velocity during a curve, thus more detailed analyses are needed to clarify the influence of collision types on injury severity and LTC, in order to prioritise safety protection and LTC mitigation strategies.

The analysis at the injury level indicates that, for maximum collision speeds of 50 km/h and those injuries that are predicted to have LTC 12 months after the trauma (i.e. those injuries having pFCI < 5), certain body regions such as Neck, Thorax, and Abdomen are completely excluded from the distributions, as compared to the distributions including any pFCI value (Tables S2, S4, S6) or to the results from other studies (for example [11]). This suggests that despite commonly occurring in frontal collisions between cars and pedestrians, these injuries are unlikely to result in LTC (according to pFCI). Instead, Lower Extremity injuries were particularly relevant as their share is the largest among all body regions in all datasets. In fact, a comparison between the shares of the pFCI < 5 injuries and all injuries highlights the prevalence of LTC-associated injuries in this body region (approximately 80% instead of 32% in GIDAS, approximately 70% instead of 25% in RAIDS, and approximately 80% instead of 22% in VOIESUR), with the AIS2 injuries being especially relevant. In all three datasets, the Head is the second most affected body region, with only AIS3+ injuries. This is different from what can be described regarding the Lower Extremities, where the share of AIS2 LTC-associated injuries is the highest (although in VOIESUR to a lesser extent than in GIDAS and RAIDS). This has a certain relevance, as AIS2 injuries will not be directly addressed by mitigation strategies to reduce the occurrence of the so-called serious injuries (AIS3+).

In this study, fractures to the Lower Extremities appear to be the most relevant type of injury, especially those to the tibia or to the fibula. These fractures have generally lower AIS severity and higher pFCI values, except for those to the pelvis and some tibia fractures (in both cases with pFCI2). As shown by the analysis on the injury sources from RAIDS and GIDAS, the front bumper appears to be the part of the car that is most frequently involved in this type of injury, suggesting that pedestrian protection strategies addressing this specific part of the vehicle might help reduce the occurrence of LTC from the injuries suffered by the pedestrians in frontal collision with vehicles. A more detailed analysis correlating the front-end geometry of the car and the pedestrians' characteristics could help understand the pattern of injury causation, allowing the proposal of mitigation strategies and specific countermeasures based on less descriptive evidences and correlating the sources of the injuries with LTC-associated injuries.

V. LIMITATIONS

An obvious limitation of this study is given by the different sample sizes of the three datasets, with the one from GIDAS being much larger than those from RAIDS and VOIESUR; the filtering based on the maximum collision speed and the pFCI value further narrowed down the number of injuries. This resulted in largely descriptive results in the case of RAIDS and VOIESUR. A larger base of data could ensure a better comparison between the countries and would allow to obtain relevant figures, for example regarding the evaluation of injury sources for LTC-associated injuries. Additionally, there were differences in parameters availability, which did not always allow to conduct similar analyses on the three datasets. Furthermore, VOIESUR collected data on all road traffic collisions with fatalities and RAIDS focuses on more severe collisions, therefore these different selection criteria resulted in higher overall injury severity levels when compared to GIDAS collecting data also on slightly injured.

There are several limitations to the use of the pFCI as an indicator of LTC. The pFCI was developed based on the FCI developed by Mackenzie et al. (1996) - for each AIS pre-dot code, an expert panel developed a consensus view on the most likely functional state for a person one year after sustaining an injury, and these were clustered into 5 categories from 5 (perfect state) to 1 (the worst possible state). The assessment assumed the injured person was aged 18-65, had proper medical care and rehabilitation, and treated each injury in isolation with no defined approach to estimating the LTC of multiple injuries. Similarly, there is no defined approach to estimating consequences for time frames greater than one year. Furthermore, scales such as RPMI [12] ascribe LTC to soft tissue injuries that are assigned a score of 5 (perfect state) in the pFCI scale, e.g. whiplash. Additionally, predicting the health status 12 months after the injury might not be sufficient to determine if an injury caused long-term consequences, as different functional limitation trajectories exist [13]. Further work to update the pFCI based on the current population is needed, as well as to validate it for persons aged < 18 years and > 65 years.

Other scales that assess the level of impairment and disability exist, such as the abovementioned Risk of Permanent Medical Impairment (RPMI) or the Disability Weights [14]. A combined use of these scales to identify injuries with LTC might increase sensitivity. Further, the topic of LTC is more complex when considering also psychological LTC which cannot be assessed with pFCI. As a consequence of these limitations, it is possible that some injuries causing LTC were not captured by our analysis. Nevertheless, pFCI gives an indication of the likely severity of LTC and is explicitly linked to specific AIS codes typically available in in-depth collision databases, which is useful e.g. for prioritising vehicle design changes targeted at mitigating LTC.

VI. **FURTHER STEPS**

Since 2023, GIDAS collects self-reported data from crash survivors on their physical and psychological health status using follow-up questionnaires two weeks and nine months after the crash. This data could be useful not only to compare the results of the analysis based on the predicted and self-reported health status, but also to study the correlation between physical injuries or crash parameters and psychological LTC. Unfortunately, at the time of the analysis, the GIDAS database did not contain enough data to allow a reliable comparison yet. The IMPROVA project aims to establish a common methodology for LTC data collection, thereby enabling the continuous monitoring of LTC across multiple countries.

VII. CONCLUSIONS

AIS2 injuries to the Lower Extremities, like tibia and fibula fractures, are the prevalent type of injuries that could lead to long-term physical LTC in pedestrians injured in a frontal collision with a car. More severe injuries (AIS3+), like fractures of the Pelvis or traumatic brain injuries are also relevant, although they occur less frequently. Fractures are very often caused by impact against the bumper of the vehicle, as well as against other frontal parts of the vehicle. Higher collision speed appears to be associated with higher chance of suffering from LTC from the injuries.

VIII. ACKNOWLEDGEMENTS

This analysis has been made possible by the German In-Depth Accident Study (GIDAS) dataset, the Road Accident In-Depth Studies (RAIDS) dataset, and the Vehicle Occupant Infrastructure Road User Safety Study (**VOIESUR**) dataset. Born in 1999, **GIDAS** is the result of the cooperation between the Federal Highway and Transport Research Institute (BASt) and the Research Association for Automotive Technology (FAT), to conduct in-depth investigation of traffic collisions from a purely scientific perspective aiming for the collection of about 2,000 for Germany representative collisions with personal injury each year. **RAIDS** is the UK's in-depth collision source capturing detailed data on road vehicle collisions, whose collection began in 2013 and is ongoing. To date, it contains around 2,200 collisions involving over 6,600 individuals. For further detail please contact the Department for Transport via email using RAIDS@dft.gov.uk. **VOIESUR** is a French research project conducted between 2012 and 2015, involving a consortium of four partners: CEESAR, CEREMA, IFSTTAR, and LAB. The dataset includes approximately 8,500 accidents, comprising all fatal accidents nationwide (metropolitan France), all injury accidents in the Rhône area, and a random 5% sample of all other injury accidents across metropolitan France. The project was partially funded by the French National Research Agency (ANR) and the MAIF Foundation.

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X. APPENDIX

Injury severity groups definition

GIDAS (following the official German statistics) and VOIESUR
fatally injured: persons that die within 30 days after the accident
severely injured: persons that become in-patient treated for more than 24 hours in the hospital
slightly injured: all other injured persons

RAIDS (according to the police)
fatally injured: persons that die within 30 days after the accident
slightly injured: whiplash, neck pain, shallow cuts, abrasions, sprains, strains, bruising, and shock
severely injured: all other injured persons

Erratum

Injuries and Physical Long-term Consequences of Pedestrians Due to Collisions with Cars. An Analysis of the In-Depth Data from Germany, United Kingdom and France

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During the preparation of the manuscript, wrong group labels for some age groups have been accidentally inserted in Table 1. The mistake concerns only the labels in the table and not the way in which the data has been grouped. Please, consider this table as a substitute of Table 1 in the text.

TABLE 1
Absolute and relative frequencies for the subgroups of the studied variables in each dataset.

	GIDAS n (%)	**RAIDS** n (%)	**VOIESUR** n (%)
SEX			
Males	472 (51.5%)	31 (55.4%)	42 (56%)
Females	445 (48.5%)	25 (44.6%)	33 (44%)
AGE			
Children (<= 12 years)	199 (21.7%)	7 (12.5%)	11 (14.7%)
Teenagers (13-17 years)	80 (8.7%)	9 (16.1%)	3 (4%)
Mid-Aged Adults (18-64 years)	459 (50.2%)	24 (42.9%)	22 (29.3%)
Old-Aged Adults (65-74 years)	69 (7.5%)	8 (14.3%)	11 (14.7%)
High-Aged Adults (> 74 years)	108 (11.8%)	8 (14.3%)	28 (37.3%)
BODY SIZE			
<= 125 cm	37 (5.3%)	0	*n/a*
126–165 cm	296 (42.8%)	9 (16.1%)	*n/a*
166–185 cm	319 (46.1%)	9 (16.1%)	*n/a*
> 185 cm	40 (5.8%)	0	*n/a*
Unknown	-	38 (67.9%)	*n/a*
BODY WEIGHT			
< 50 kg	137 (21.0%)	3 (5.4%)	*n/a*
50-65 kg	172 (26.3%)	8 (14.3%)	*n/a*
66-80 kg	188 (28.8%)	9 (16.1%)	*n/a*
81-100 kg	126 (19.3%)	6 (10.7%)	*n/a*
> 100 kg	30 (4.6%)	2 (3.6%)	*n/a*
Unknown	-	28 (50%)	*n/a*
MAIS			
MAIS1	392 (56.6%)	12 (21.4%)	9 (12.0%)
MAIS2	213 (30.8%)	18 (32.1%)	8 (10.7%)
MAIS3	50 (7.2%)	14 (25.0%)	22 (29.3%)
MAIS4	10 (1.4%)	6 (10.7%)	3 (4.0%)
MAIS5	8 (1.2%)	2 (3.6%)	8 (10.7%)
MAIS6	2 (0.3%)	0	0
Unknown	17 (2.5%)	4 (7.1%)	25 (33.3%)