Deriving ISO 26262 S-parameters: Unifying Functional Safety Severity with RAPEX HARM

Jonas Krampe, Mirko Junge

Abstract The ISO 26262 injury severity parameter (S-parameter) is taken as a mortality-based measure. But injury severity goes beyond lethality, therefore we included long-term consequences of injuries in the metric. We used AIS2015-coded injuries from the GIDAS (German In-Depth Accident Study) crash database. GIDAS sampled crashes in Greater Dresden and Greater Hannover from 2001 to 2024. To reduce coding ambiguity, we aligned AIS-Identifiers (AIS-IDs) with routine medical coding and documentation for lethality (AIS codes) and for long-term consequences (pFCI, predicted Functional Capacity Index). This reduced the number of codeable injuries from 2,006 to 345 for lethality, and 453 for long-term focus, respectively. The RAPEX HARM (Rapid Exchange of Information System-Hazard and Risk Assessment Methodology) injury severity metric combines lethality and long-term consequences. We mapped it to the ISO 26262 S-metric to calculate the new S-parameters: the H-parameters. Thus, the H-parameters incorporate acute injury severity and long-term consequences.

For belted, front-row occupants in vehicles introduced to the market in 2001 or later, our new mapping affects the severity ratings. Specifically, there are increases for frontal collisions in the 50–70 km/h and 70–100 km/h traffic domains, from S0.5 and S1.5 to H1 and H2, respectively. Furthermore, the rating for near-side collisions in the 70–100 km/h traffic domain increases from S1.5 to H2.

Keywords ISO 26262 S-parameters, ASIL (automotive safety integrity level), RAPEX HARM, Long-term Consequences (LTC), Functional Capacity Index (FCI).

I. INTRODUCTION

Functional safety for electric and electronic systems in vehicles was formalised in ISO 26262 [1]. Each possible failure must be rated for exposure (frequency or duration of occurrence), controllability of the situation if the failure occurs, and injury severity if the situation cannot be avoided or mitigated. This paper focuses on measuring injury severity. Annex B of the ISO standard defines injury severity, or the S-parameter, using the Abbreviated Injury Scale (AIS). It uses the AIS code (AIS-CD) linked to the individual injury descriptors (AIS-IDs) in the AIS codebook [2]. The AIS code is highly correlated with lethality [3]. Our aim was to broaden the definition of injury severity to include long-term consequences (LTCs). These are specified by the predicted Functional Capacity Index (pFCI) values linked to the AIS-IDs in the AIS2015 codebook. We combined measures of lethality and LTCs, as described in the Rapid Exchange of Information System (RAPEX). RAPEX is used to detect unsafe consumer products [4]. A data-driven method to establish S-parameter for frontal and side-crashes was developed in [5]. These results were for AIS98 and are updated to AIS2015 in [3]. This paper builds on the methodology in [5] and incorporates acute as well as long-term consequences as proposed in [6]. [5] established S-parameter grouped by traffic domain and not on more technical severity metrics like energy equivalent speed. Grouping by traffic domain eases the assessment of advanced driver assistance systems (ADAS).

To address the misalignment between medical diagnoses and the specification of individual injury descriptors (AIS-IDs) in the AIS codebook, we introduced an aggregation step [3][6]. This aggregation, performed separately for each metric (AIS-CD and pFCI), aimed to reduce ambiguity before carrying forward to subsequent analyses [6].

The injury severity aggregation at the patient level followed the New Injury Severity Score (NISS). We used the three most severely rated injuries, per AIS-CD and per pFCI [6]. These triples were mapped to the RAPEX Hazard and Risk Assessment Methodology (HARM) levels. We used the higher of the two ratings. The ISO 26262 Annex B defines the S-parameter as the 90th percentile of the injury severity distribution [1]. We estimated H-parameters as the 90th percentile, with one-sided 95% statistical confidence. H-parameters were tabulated for front-row occupants in frontal, near-side, far-side, and rear-end crashes.

We also provided sets of tables for crashes that resulted from (semi-)autonomous vehicles' failure to react to

M. Junge (e-mail: mirko.junge@volkswagen.de) is a Senior Researcher at Group Innovation, Volkswagen AG, Germany. J. Krampe is a post-doc at the Technical University Braunschweig, Germany.

an impending crash, where there was no pre-crash braking. We called these automobiles 'vehicle under investigation' (VUI). The VUI hit the crash-opponent, the 'crash involved automobile' (CIA), on average at a much higher speed. As a result, the frontal crash for the VUI was more severe. The side-impact crashes into CIA vehicles by a VUI were also more severe [3][5]. We have provided an extra set of tables for these scenarios.

II. METHODS

GIDAS Database

Crash data from the German In-Depth Accident Study (GIDAS) [7] provided the crash scenarios and the medical information for this investigation. The GIDAS dataset aims to be a 50% sample of real-world crash situations. These involve at least one injured participant in the Greater Dresden and Greater Hannover areas. The sample size is about 1,000 crashes per metropolitan region per year. We used crashes from 2001 to 2024 involving front-row occupants in cars and SUVs involved in vehicle-to-vehicle or vehicle-to-object crashes. There were no restrictions on the type of the impacting vehicle or object. Our focus was on belted, front-row occupants in modern vehicles. By modern, we mean vehicles with a market introduction in 2001 or later, i.e. those designed with the Euro NCAP 64 km/h offset deformable barrier (ODB) [8-10] and the first iteration of UN-ECE R94 [11-12] tests in mind. Note that the S-Parameters are 90th percentiles which are estimated with 95% statistical confidence. Hence, too small sample sizes would result in unrealistically conservative S-parameters. Thus, these sample sizes restrictions prevent us from narrowing the definition of modern vehicles to a more recent year of market introduction.

Information on unbelted crash participants and occupants in older vehicles is provided in the Appendix AI & AII.

AIS 2015 Codebook

The 2015 edition of the Abbreviated Injury Scale (AIS) was the basis of this investigation [2]. It provides a complete list of codeable individual injuries, each with a unique identifier (AIS-ID). An AIS Code (AIS-CD) is attached to each AIS-ID to describe the lethality of the individual injury. A predicted functional capacity index (pFCI) code provides an estimate of expected long-term impairment and is also attached to each AIS-ID.

To better align AIS-IDs with medical coding and clinicians' diagnostic procedures, some AIS-IDs were reduced to the general 'not further specified' (NFS) AIS-ID already included in the AIS codebook. When this aggregation was too broad, new AIS-IDs were created by clustering existing AIS-IDs in the codebook [3]. This AIS-ID aggregation was performed independently for both AIS-CD and pFCI [6]. It is provided as an Excel file in the supplementary material.

RAPEX HARM

RAPEX is a mandatory method introduced by the European Commission for detecting unsafe consumer products [4]. The European Union introduced it to protect consumers from health hazards and technical defects in faulty products. Similar to a functional safety evaluation, a RAPEX assessment requires information on injuries caused by product defects. The Hazard and Risk Assessment Methodology (HARM) is a risk-assessment tool that ranks injury severity on a 4-level scale. HARM separately assesses injury severity as lethality and LTCs. The most severe rating is assigned to the case [4].

ISO 26262

Functional safety assessment, as defined in ISO 26262 (an automotive safety standard), uses injury severity to describe the consequences of system failures that cannot be prevented. The standard does not specify how to measure injury severity. Annex B of ISO 26262 implicitly references the AIS classification system, particularly the maximum AIS-CD (MAIS), the highest injury severity level assigned to any injury a person sustains. Annex B also uses distribution information, such as the 90th percentile of injury severity levels, to reduce the influence of rare or extreme crashes in the database [1].

Injury severity is more than the risk of lethality, which can be measured using AIS-CD values [3]. Long-term consequences also contribute significantly to the burden of injury. The pFCI estimate linked to each AIS-ID in the AIS 2015 Codebook [2], combined with the RAPEX HARM aggregation algorithm, allows for a more complete injury assessment. This approach incorporates both lethality and LTCs into the evaluation of injury severity for ISO 26262.

Crash Configuration

The principal direction of force (PDOF), which describes the main direction from which external forces act on a vehicle during a crash, is represented on a clock-face to identify the crash configuration. For the driver's side: frontal collisions correspond to PDOF at 11, 12, and 1 o'clock; near-side at 8, 9, and 10 o'clock; far-side at 2, 3, and 4 o'clock; and rear-end at 5, 6, and 7 o'clock. For the passenger side, the definitions for near-side and far-side are interchanged.

Traffic Domains

Traffic domains are defined by speed limits in km/h: 0–15, 15–30, 30–50, 50–70, 70–100, 100+. The lower bounds are inclusive. We excluded 'Autobahn' (Interstates) because of its inherently different structure such as single direction of traffic, non-homogenous speed limits, work zones, and sample size.

The outset speed (v_0) is defined as the speed of the vehicle before the vehicle's driver reacts to the conflict situation leading to the crash. A crash is included in a traffic domain if v_0 is at least 90% of the traffic domain's lower speed limit. This approach, unlike prior evaluations that used 100% [3][5], accounts for the mandatory overestimation of speed by vehicle speedometers. Furthermore, this approach recruits more cases at the edge of the traffic domain, resulting in much narrower confidence intervals for the 90th percentile estimators.

Abbreviated Injury Scale

The AIS coding separates a patient's injuries into individual entities (AIS-IDs) and assesses their severity separately. The segregation process and codeable injuries are detailed in the AIS codebook, which specifies two assessment schemes [2]: the Abbreviated Injury Scale (AIS-CD) emphasises the acute injury, i.e. threat to life; the pFCI evaluates long-term impairment if the injury is survived.

Aggregating individual injury assessments is required to evaluate a patient's overall injury severity. This ensures a comprehensive patient-level summary that incorporates the full range and severity of their injuries, rather than considering them in isolation. Injuries from traffic crashes are primarily the result of blunt force trauma [13]. Therefore, this evaluation focuses on such injuries, with less emphasis on penetrating and blast-related injuries.

AIS-ID Aggregation

The AIS2015 codebook identifies more than 2,000 individual injuries, each with a unique 6-digit AIS-ID. While the codebooks provide comprehensive coding rules, AIS-IDs do not align well with medical diagnoses or treatment regimens. This is because it differs from the coding used by medical doctors and others involved in the treatment of trauma patients [14-15]. The following AIS-ID Aggregation was developed by the authors and cross-checked by five trauma surgeons.

AIS-Code

The AIS-CDs range from 1 (minor) to 6 (maximal), and 9 for 'unknown' [2]. Uninjured body regions are usually coded as 0 (uninjured).

AIS-CDs 0–6 are highly correlated with lethality [3].

AIS-ID Aggregation for the AIS-Code

In a recent study [3] we aggregated AIS-IDs to address two issues: first, AIS-ID coding does not align well with medical diagnoses [14-15]; second, coders sometimes subjectively adjust severity ratings [15-16]. Aggregation addresses these issues by creating patient-level summaries based on medically meaningful groupings and reducing the impact of subjective coder decisions on severity ratings. The aggregation approach is primarily applied at the organ system level, while differentiation between open and closed fractures is maintained. The AIS-IDs are mainly aggregated to the 'not further specified' (NFS) level (Level 1) which also addressed coding quality problems.[6] The effect of this AIS-ID aggregation on AIS-CD distribution is shown in Table I [6].

AIS1 Skin Injuries

Most AIS1 skin injuries are self-reported and not documented in medical records because they are not reimbursable. Additionally, skin injuries are captured more completely in post-mortem text which may result in bias towards subjects of a specific severity level. Relying on self-reported injuries results in bias, such as over-reporting by people who think they can claim compensation for pain and suffering. AIS1 skin injuries also outnumber other AIS1 injuries, especially those in the distal parts of the extremities. For this reason, we removed AIS1 skin injuries from the evaluation, including AIS1 penetrating injuries.

TABLE I
NUMBER OF CODEABLE AIS-IDS FOR THE DIFFERENT AIS-CD AND FCI-CD LEVELS

	CD							9			Σ
	0	1	2	3	4	5	6	1	2	3	
AIS 2015		455	721	449	176	127	35	22	5	16	2006
AIS 2015 Level 1	17	82	117	54	12	11	8	24	6	14	345
FCI 2015		1361	194	124	135	150			42		2006
FCI 2015 Level 1		310	75	62	83	92			42		664

Note: the AIS-CD 0 are purged superficial skin injuries, downcoded from AIS-CD 1. The AIS-CD 9 column states the minimal AIS-CD required to sustain the described injury.

FCI-Code (FCI-CD)

For every individual injury in the AIS2015 codebook, i.e. every AIS2015-ID, a pFCI value coding the functional limitation following a non-fatal outcome is given. The pFCI was determined iteratively by a panel of experts [17] for the AIS 90 update 98 [18]. The number of codeable AIS-IDs was extended from about 1,300 to over 2,000 in the AIS2015 codebook to better account for the pFCI [2].

The pFCI was recoded to the Functional Capacity Index code (FCI-CD) for easier use and better alignment with the AIS-CD metric. In this scheme, FCI-CD 1 represents the 'perfect state' and FCI-CD 5 the 'worst possible state': for determined pFCI values (1 to 5)

$$\text{FCI-CD} = 6 - \text{pFCI}.$$

Note that the pFCI 9, 'unknown severity', stays at FCI-CD 9. The FCI-CD assesses the LTCs of an individual injury. The recoding considerably eases the formulation of FCI aggregation to the person level (see below).

We recoded the 10 non-descript upper and lower extremity injuries, arm and leg fracture from pFCI 5 (perfect state) to FCI-CD 9 (unknown severity). Our expert panel agreed with our assessment that their long-term outcomes are indeterminate. Table II provides more details. In all other cases, the original pFCI scores of the AIS 2015 codebook were used.

TABLE II
RECODED NON-DESCRIPT SKELETAL INJURIES TO THE UPPER AND LOWER EXTREMITIES TO FCI 9 [2]

AIS2015				Injury description
ID	AIS-CD	pFCI	FCI-CD	
751800	2	5	9	arm fracture, NFS
751801	2	5	9	open
751900	2	5	9	forearm fracture, NFS
751901	2	5	9	open
752000	2	5	9	hand fracture, NFS
752001	2	5	9	open
852002	2	5	9	leg fracture, NFS
852003	2(3*)	5	9	open
852004	2	5	9	foot fracture, NFS
852005	2	5	9	open

Note: * the injury coding systematic would dictate AIS-CD 3, as all open fractures of long bones of the leg are coded as AIS-CD 3.

AIS-ID Aggregation for the FCI-Code

Aggregating AIS-IDs by lethality improved the quality of AIS-CDs [3]. However, it masked any long-term injury signal in the data. Therefore, we developed an AIS-ID aggregation specifically for FCI evaluation. This method clusters AIS-IDs by ease of impairment diagnosis, independent of lethality. AIS-IDs for AIS-CDs can be deduced from emergency protocols and hospital discharge letters. Functional impairments are best coded from physical examination records [19]; cartilage damage, a precursor to arthritis, is well documented in radiological reports [20].

This aggregation method groups AIS-IDs by clearly diagnosable functional impacts, such as motor loss or impairments like deafness and blindness, as well as by injuries likely to cause future impairment (e.g. joint and bone injuries involving cartilage). The logic is to cluster by diagnosable impairment, regardless of lethality. We call this the AIS-ID Level 1 FCI aggregation, reducing over 2,000 AIS-IDs to 453 (see Tables I and III). Figure 1 shows the overlap and discrepancies of mapping AIS 2015 IDs to level 1 IDs for AIS-CD and to level 1 IDS for FCI.

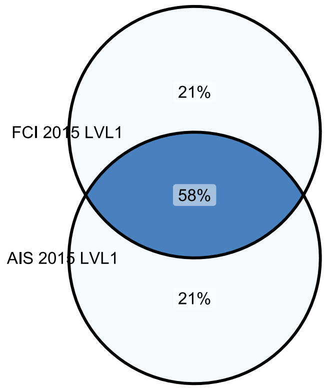

FIGURE 1 Venn-diagram of AIS2015 ID to AIS2015 LVL1 and AIS2015 ID to FCI 2015 LVL1 mappings.

Person Level Aggregation

Historically, the AIS-CD was aggregated to the patient level using the maximum AIS-CD (MAIS). In Krampe *et al*. [3] we introduced an alternative aggregation with sorted injury-severity triples, modelled on the NISS [21].

TABLE III

AIS-IDS: CORRELATION OF AIS-CDS AND FCI-CDS AT LEVEL 1 [6]

		AIS 2015-CD Level 1							9			Σ
		0	1	2	3	4	5	6	1	2	3	
FCI-CD Level 1	1	148	366	564	319	24	7		2			1430
	2	1	52	88	43							184
	3	2	35	49	21							107
	4	1	19	41	52	6	2					121
	5		2	20	86	3	19	9				139
	9								25	6	14	45
	Σ	152	474	762	521	33	28	9	27	6	14	2026

Note: 20 new AIS-IDs were introduced to better differentiate between AIS and FCI in Level 1 aggregation, increasing the number of AIS-IDs from 2,006 to 2,026.

AIS9 Code: minimum AIS

Some AIS-IDs code for injuries that have not been fully diagnosed, e.g. AIS-ID 220099 vascular injury to the face. Although a more detailed diagnosis would have been possible, it was not performed or documented. The AIS-codebook assigns an AIS-code 9 (‘unknown severity’) to these AIS-IDs. For each of these AIS-IDs, the minimum AIS (mAIS) code needed to inflict such an injury was determined. The mAIS ranges from AIS-CD1–3. We used this mAIS code, along with the patient's other AIS codes, to calculate the sorted mAIS-CD triple. If the resulting triple fell into the highest H-scale cluster (S2.5, S3.0), see Table IV, the case was included in the evaluation [3].

AIS9 Code: non-survivable injury

Each AIS-ID coding was scanned for a non-survivable injury or an injury that, by description, was not survivable, e.g. AIS-ID 511000 'torso transection,' or AIS-ID 100999 'died of head injuries'. All patients with a non-survivable AIS9 coding were assigned a HARM 4 rating, the most severe rating possible (see below).

Note that this is a conservative estimate, i.e. a possible overestimation of the HARM level as some of the deceased may have been HARM 3, and a departure from the probabilistic AIS scale. Its sole purpose was to recruit more AIS9 cases for the evaluation.

TABLE IV
CODE-TRIPLE TO HARM CONVERSION FOR SORTED AIS-CD AND FCI-CD TRIPLES,
I.E. X IS LESS OR EQUAL TO THE SEVERITY TO ITS LEFT. NISS [21] VALUES FOR REFERENCE ONLY

HARM	H-Scale	S-Scale	AIS-CD and FCI-CD Triple	NISS
1	0	S0.0, S0.5	0/0/0, 1/x/x	0–3
2	1	S1.0, S1.5	2/0/0, 2/1/x, 2/2/0, 2/2/1	4–9
3	2	S2.0	2/2/2, 3/0/0, 3/1/x	9–12
4	3	S2.5, S3.0	3/2/x, 3/3/x, 4+/x/x	13+

FCI

FCI-Code Aggregation

Selecting only the maximum FCI per patient would oversimplify long-term impairment assessment, as shown with the MAIS approach regarding lethality. Evaluating the three most severe injuries gives a more complete and valid measure of overall severity.[21] We used the sorted-triple-based AIS-CD aggregation metric for FCI codes (see Tab. IV).

FCI 9 Code

FCI-CD aggregation was not possible in patients with even a single FCI 9 code because, unlike the AIS-CD, a reliable minimum FCI value could not be derived. However, to ensure the most severe outcomes were captured, a liberal aggregation approach was implemented for the person-level HARM assessment: if the injury aggregation process involved FCI 9 codes (which were temporarily treated as FCI 1 codes for this check) and the patient's most severe injury outcome was still determined to be HARM 4 (most severe, life-threatening) based on the overall result, then an aggregated HARM value, see below, was successfully derived. For the remaining FCI 9 cases, only the AIS-CD was used in the final HARM determination.

Assignment of Triplets to HARM levels

Assignment Method

While AIS-IDs are injury descriptors at the individual injury level, the HARM levels describe injury severity at the person level. The chosen aggregation mirrors the NISS aggregation: the most severely rated injuries for each measure are grouped into AIS-CD and FCI-CD triples [21]. These sorted triples were mapped to the S-scale, as detailed in Krampe *et al.* [3]. Furthermore, the sorted triples were assigned to the HARM levels via a direct HARM-to-AIS/FCI triple match, using the functional description in the RAPEX documentation from the European Commission [4]. See Table IV for the mapping.

The HARM level is calculated independently for AIS-CD and FCI-CD, therefore lethality and LTCs are assessed separately. The assigned HARM level reflects the most severe outcome from either AIS-CD or FCI-CD.

TABLE V
HARM TO INJURY SEVERITY MAPPING AS SUGGESTED BY THE EUROPEAN COMMISSION [4]

	Severity Description	
HARM Level	Health / Safety Harm	Other Harm
1 (minor)	Harm or consequence that, after basic treatment (first aid, normally not by a doctor), does not substantially hamper functioning or cause excessive pain; usually, the consequences are completely reversible.	Negative effects are usually completely reversible within the short term without specialist intervention.
2 (moderate)	Harm or consequence for which a visit to the hospital may be necessary, but in general, hospitalisation is not required. Functioning may be affected for a limited period, not more than 6 months, and recovery is likely to be more or less complete.	Negative effect, reversible within a certain period; specialist intervention is required.
3 (severe)	Harm or consequence that normally requires hospitalisation and will affect functioning for more than 6 months or lead to a permanent loss of function.	Significant negative effect; significant effort required to reverse by specialist intervention; irreversible without this intervention and effort.
4 (life-threatening)	Harm or consequence that is or could be fatal, including brain death; consequences that affect reproduction or offspring; severe loss of limbs and/or function, leading to more than approximately 10% of disability.	Large negative effect, irreversible in several aspects, whether or not acute.

Specific Assignment to HARM levels

There are four HARM severity levels in RAPEX, beginning with HARM 1 (minor) to HARM 4 (life-threatening) (see Table V). At the HARM 1 level, all injuries are easily treatable and do not necessarily need the attention of a medical doctor and the consequences of the injury are (almost) entirely reversible. This description aligns with S0, S0.5, and the respective FCI-CD triple.

A medical doctor must evaluate HARM 2 level (moderate) injuries, though hospitalisation is usually not required. This description aligns with AIS-CD2 injuries. Therefore, S1 and S1.5 align with HARM 2; however, patients with three or more AIS-CD2 injuries typically require hospital care and are thus categorised as HARM 3. The long-term impairment at HARM 2 should be 'reversible within a certain period', matching the corresponding FCI-CD triples.

At the HARM 4 level, the injuries start to be life-threatening, corresponding to AIS-CD3 injuries, when combined with at least another moderate (AIS-CD2) or more severe injury. Thus, the S2.5 and S3 injury severities are coded as HARM 4. Regarding long-term impairment, HARM 4 requires a 'large negative effect' that is 'irreversible in several aspects', aligning with FCI-CD 3 (serious state) when in combination with at least an FCI-CD 2 (moderate state) as well as FCI-CD 4 (severe state) and FCI-CD 5 (worst possible state).

HARM 3 bridges the gap between HARM 2 and 4: S2 and the corresponding FCI-CD triples. The injury severity triples for AIS-CD and FCI-CD are each matched to the HARM scale, according to Table IV.

HARM and ISO 26262

HARM 4 (life-threatening) matches to ISO 26262 S3(life-threatening, survival uncertain); HARM 3 (severe) to S2 (severe, survival probable); HARM 2 (moderate) to S1 (light and moderate); HARM 1(minor and no negative effect) to S0 ('no' injuries). Putting this together and mapping the HARM-scale (1–4) to the ISO 26262 S-scale (0–3), we can simply subtract 1 from the HARM-scale, yielding the H-scale (see Table IV). Thus, we can compute a H-value for each AIS2015-coded person in the database.

The sought-after H-parameters are the 90th percentiles on the H-scale for a given traffic domain. We estimate these percentiles with 95% statistical significance [3][5].

VUI/CIA vehicle differentiation

The system failure under investigation can affect the collision speed. More precisely, the failure can result in the VUI failing to react to an impending collision, e.g. no pre-crash braking. If the system failure results in a lack of pre-crash braking, the collision speed ($v_{collision}$) must be adjusted to the outset speed (v_0), i.e. the distribution of collision speed for a given traffic domain must be replaced by the distribution of outset speed for the domain. After adjusting the speed distributions, the H-parameters are calculated as previously described.

Note: Energy equivalent speed (EES) is a good proxy for injury severity. However, the systems assessed by ISO 26262 are defined for traffic domains. Hence, it is helpful to derive tables in traffic domains and not in EES. Within traffic domains and frontal crashes, ego speed is a proxy for ego EES and for side and rear-end crashes opponent's speeds is a proxy for ego EES. Thus, for frontal crashes, the ego velocity is assumed to be the injury severity-determining metric for occupants in the ego vehicle. Furthermore, in side and rear-end crashes, the opponent's speed is used as the metric for driving injury severity in the ego vehicle.

III. RESULTS

H- and S-parameter Tables

Table VI shows the HARM-based H-parameters alongside the lethality-based S-parameters. The table is stratified by the four crash configurations and six traffic domains for belted front-row occupants in vehicles with market introduction in 2001 or later, based on the current GIDAS dataset. The S-parameters have been included for direct comparison with the H-parameters, as they are computed from the same dataset using the same assumptions. To obtain integer S-parameters as used in ISO 26262, the given S-parameters must be truncated, not rounded, e.g. S1.5→S1 as detailed in [3].

To better understand the real-world crash data, we provide statistical measures of technical crash severity and case counts in Table AIII in the Appendix. We provided the mean and the 90% quantile for outset velocity (v_0), collision velocity ($v_{collision}$), and Δv for each of the four crash configurations and six traffic domains.

TABLE VI

BELTED, FRONT-ROW OCCUPANTS; VEHICLE MARKET INTRODUCTION 2001 OR LATER, STRATIFIED BY TRAFFIC DOMAIN AND CRASH CONFIGURATION

	Traffic Domain [km/h]					
	0–15	15–30	30–50	50–70	70–100	100+
frontal	H0	H0	H0	H1	H2	H3
near-side	H0	H0	H0	H1	H2	H3
far-side	H0	H0	H0	H0	H1	H3
rear-end	H0	H0	H0	H0	H0	H1
frontal	S0.5	S0.5	S0.5	**S0.5**	**S1.5**	S3.0
near-side	S0.5	S0.5	S0.5	S1.0	**S1.5**	S3.0
far-side	S0.5	S0.5	S0.5	S0.5	S1.0	S3.0
rear-end	S0.5	S0.5	S0.5	S0.5	S0.5	S1.5
S-parameters published in [3]						
frontal	S0.5	S0.5	S0.5	S0.5	S1.5	S3.0
near-side	S0.5	S0.5	S0.5	S1.0	**S2.0**	S3.0
far-side	S0.5	S0.5	S0.5	S0.5	S1.0	S3.0
rear-end	S0.5	S0.5	S0.5	S0.5	**S1.0*S2.5**	**S1.0*S1.0**

Note: H- and first S-parameter block computed from the current dataset, last S-parameter block from a previous publication [3]. The asterisk (∗) denote cells with insufficient elements, and the S-scale value following indicates the highest injury severity in that cell. Changes between parameter blocks are set in bold.

Note: H- and S-scale 90th percentiles estimated with 95% statistical certainty. To obtain integer S-parameters as used in ISO 26262, the given S-parameters must be truncated, not rounded, as detailed in [3].

H- and S-parameter Tables for VUI/CIA Vehicles

Recall that for VUI in frontal collisions, the injury severity is determined by the VUI collision speed, which by definition is not reduced from the outset speed ($v_{collision} = v_0$). In near-side, far-side, and rear-end collisions with VUI vehicles, the bullet vehicle's collision speed determines injury severity, enabling onset speed reduction via pre-crash braking. Note that these assumptions are reversed for the CIA vehicle: frontal crashes include possible pre-crash braking, whereas for near-side, far-side, and rear-end crashes, the bullet vehicle is the VUI, a vehicle without pre-crash braking, and thus the collision speed equals the outset speed. The results are tabulated in Table VII. For cases where the bullet vehicle is not a VUI, use the values from Table VI.

Parameters for Unbelted Occupants and Older Vehicles

H- and S-parameters for belted, front-row occupants in vehicles with a market introduction before 1998 are shown in Tables A1 and A2 in the Appendix, along with the parameters for unbelted front-row occupants.

IV. DISCUSSION

On the Process

Substantial medical recoding was done in order to improve the objectivity of the coding. We looked into the level of detail that can be coded from the medical documentation provided to coders. As previously published, we used different AIS-ID aggregations for AIS-CD and FCI-CD evaluations [6]. This split was introduced to better focus on acute injury and LCT. A combination of both aggregations (AIS-ID for AIS-CD and AIS-ID for FCI-CD) in one table would lead to an unnatural split in AIS-IDs coding for AIS-CD and in AIS-IDs coding for FCI-CD to take care of the other metrics' consistency, making the AIS coding process and the proofreading of the aggregation tables much more difficult, see Figure 1.

The HARM metric treats AIS-CD and FCI-CD as equally important for the rating. For some parties, like insurance companies, this might not be a satisfactory aggregation function. For simplicity, we stuck with the European Commission's definition, though it can be modified if necessary.

The scale transformations of pFCI to FCI-CD and HARM to S-parameter are, though uncommon, simple renaming exercises of ordinal scales, with no effect on the underlying data nor the underlying dependencies.

The computation of the 'parameters' was mainly unchanged from previously published results, though we used the current, updated GIDAS database, i.e. new crashes and recodings from quality improvement efforts. We increased the cut-off to modern vehicles introduced to the market, from 1998 or later to 2001 or later. We also relaxed the representative outset speed in traffic domains from the speed limit and faster, to 90% of the speed limit and faster, to account for speedometer speed overestimation. The later measure significantly increased the sample size in the two high-speed traffic domains, enabling the parameters to be computed for each cell.

H- and S-parameter Tables

The inclusion of LTCs in the injury severity assessment results in some increases in injury severity parameters. Note that, by design, including long-term injuries alongside the lethality rating can only increase the injury severity parameters, never decrease them.

Specifically, for belted, front-row occupants in vehicles introduced to the market in 2001 or later, our new mapping affects severity ratings (see Table VI). There are increases for frontal collisions in the 50–70 km/h and 70–100 km/h traffic domains, from S0.5 and S1.5 to H1 and H2, respectively. These increases are probably due to the higher LTCs ratings for extremity injuries, especially lower extremity injuries, compared to their lethality (AIS-CD) assessments. Note that these ratings are also higher than those in previously published S-parameter tables (see Table VI).

Furthermore, the rating for near-side collisions in the 70–100 km/h traffic domain increased from S1.5 to H2. Even though curtain airbags provide very good protection against head/face/neck injuries in pole-side crashes [22-23], their frequency has decreased relative to T-bone vehicle-to-vehicle crashes since electronic stability control (ESC) was built into nearly every new vehicle [24-25]. Note that the previously published S-parameter agrees with the new H-parameter value, indicating the conservative nature of the previous S-parameter estimation and its smaller sample size. Recall that the injury severity parameters are the 90th percentiles estimated with 95% statistical significance, i.e. they are estimates of distribution parameters, not specific injury severities of an individual, and therefore dependent on sample size.

It should be noted that all cells in the result tables are calculated independently of one another. Thus, the increase in injury severity rating across the traffic domains is data-driven and not a modelling result. That the increase in injury severity rating across the traffic domains, a fundamental assumption in crash research, holds for the estimated 90th percentile is a sanity check of the underlying data and a hint of a sufficient sample size for each cell.

VUI/CIA H-parameters and S-parameters

When assessing an advanced driver assistance system (ADAS) according to ISO 26262, some system failures affect the collision speed. These failures usually eliminate all pre-crash braking, i.e. the collision speed equals the outset speed (v_0). To assess the functional safety of these systems, the VUI section of the tables must be used. For vehicles into which these failed vehicles crash, the 'crash involved automobile' (CIA) section of the table must be used.

Comparing H- and S-parameters in the VUI section of the table shows an increase in injury severity only in the 70–100 km/h traffic domain for frontal and near-side crashes from S2.5 to H3 and S1.5 to H2, respectively. It should be noted that the increase for frontal collisions to H3 is also above the previously published assessment of S2.5 [3].

The increased sample size enabled a statistically sound evaluation of the parameters for rear-end crashes in the 70–100 km/h and 100+ km/h traffic domains.

For the CIA vehicles, the H-parameters show an increase for frontal collisions in the 50–70 km/h and 70–100 km/h traffic domains, S0.5 to H1 and S1.5 to H2, respectively. It should be noted that frontal crashes in the 70–100 km/h traffic domain are rated at H2, while the previously published S-parameter was S1.5 [3]. Furthermore, the side and rear-end collision assessment for the highest two traffic domains was severely hampered by the sample size.

For the 70–100 km/h traffic domain, the H-parameters are down from S3 to H2 and H1 for near-side and far-side collisions, respectively. The only absolute reduction in injury severity rating is found for far-side crashes in the 50–70 km/h traffic domain: H0 instead of the S1.0 previously published [3]. This is due to the previously mentioned increase in sample size resulting in S0.5 for the current data set, see Table VII. The injury severity parameters for far-side collisions in the 100+ km/h traffic domain and for rear-end collisions in the highest two traffic domains could be computed for the first time.

Final Thoughts

The inclusion of LTCs in the S-parameter computation did not change the result for the low-speed traffic domains. At first glance, this might seem surprising. Still, the H- and S-parameters are statistical measures that focus on the ratio of uninjured to injured, not on the absolute number of cases. Furthermore, there is significant undersampling in the low-speed traffic domains, up to about a factor of 5 [26-27] The GIDAS sampling criterion is a crash with an injured person [7]. Some injuries with LTCs might seem so insignificant that they are overlooked at the crash site, thereby eliminating the crash from the sample.

At least the finer granularity of the S-parameter shows an S0.5 for the low-speed traffic domains, not a straight S0.0, though this detail gets blurred in the H-parameters.

The most influential change from the inclusion of LTCs in the S-parameter calculation is in frontal crashes. In the 50–70 km/h and 70–100 km/h traffic domains, injury severity increases from S0.5 and S1.5 to H1 and H2, respectively. Note that the 50–70 km/h traffic domain is the 'city domain' and nearly half of all collisions are frontal [28-29]. Furthermore, frontal collisions in the 70–100 km/h traffic domain are just above the crash-test speeds for frontal collisions. Elevating the injury severity assessment to H2 by including long-term injuries highlights a safety potential that has not yet been fully utilised.

Thus, including LTCs in the S-parameter calculation affects injury severity assessment.

TABLE VII

BELTED, FRONT-ROW OCCUPANTS; VEHICLE MARKET INTRODUCTION 2001 OR LATER, STRATIFIED BY TRAFFIC DOMAIN AND CRASH CONFIGURATION FOR VUI AND CIA VEHICLES

Vehicle under Investigation (VUI)						
VUI	Traffic Domain [km/h]					
collision	0–15	15–30	30–50	50–70	70–100	100+
frontal	H0	H0	H0	H1	H3	H3
near-side	H0	H0	H0	H1	H2	H3
far-side	H0	H0	H0	H0	H1	H3
rear-end	H0	H0	H0	H0	H0	H1
frontal	S0.5	S0.5	S0.5	S1.0	**S2.5**	S3.0
near-side	S0.5	S0.5	S0.5	S1.0	**S1.5**	S3.0
far-side	S0.5	S0.5	S0.5	S0.5	S1.0	S3.0
rear-end	S0.5	S0.5	S0.5	S0.5	S0.5	S1.5
VUI S-parameter published in [3]						
frontal	S0.5	S0.5	S0.5	S1.0	S2.5	S3.0
near-side	S0.5	S0.5	S0.5	S1.0	**S2.0**	S3.0
far-side	S0.5	S0.5	S0.5	S0.5	S1.0	S3.0
rear-end	S0.5	S0.5	S0.5	S0.5	**S1.0**[*S2.5]	**S1.0**[*S1.0]
Crash Involved Automobile (CIA)						
CIA	Traffic Domain [km/h]					
collision	0–15	15–30	30–50	50–70	70–100	100+
frontal	H0	H0	H0	H1	H2	H3
near-side	H0	H0	H1	H1	H2	H3
far-side	H0	H0	H0	H0	H1	H3
rear-end	H0	H0	H0	H0	H1	H2
frontal	S0.5	S0.5	S0.5	**S0.5**	**S1.5**	S3.0
near-side	S0.5	S0.5	S1.0	S1.0	S2.0	S3.0
far-side	S0.5	S0.5	S0.5	S0.5	S1.0	S3.0
rear-end	S0.5	S0.5	S0.5	S0.5	S1.0	S2.0
CIA S-parameters published in [3]						
frontal	S0.5	S0.5	S0.5	**S1.0**	S1.5	S3.0
near-side	S0.5	S0.5	S1.0	S1.0	**S3.0**	S3.0
far-side	S0.5	S0.5	S0.5	**S1.0**	**S3.0**	
rear-end	S0.5	S0.5	S0.5	S0.5	**S1.0**[*S2.5]	**S1.0**[*S1.0]

Note: H- and first S-parameter block computed from the current dataset, last S-parameter block from a previous publication [3]. The asterisk (∗) denote cells with insufficient elements, and the S-scale value following indicates the highest injury severity in that cell. Changes between parameter blocks are set in bold.

Note: H- and S-scale 90th percentiles estimated with 95% statistical certainty using bootstrap[5]. To obtain integer S-parameters as used in ISO 26262, the given S-parameters must be truncated, not rounded, as detailed in [3].

Limitations

The available crash data source limits the current evaluation. The work could include more crash configurations, such as subdividing frontal impacts, as suggested by Brumbelow [30], or differentiating vehicle side impacts from pole crashes. A different approach would be to cluster by crash type [31] rather than by crash configuration, shifting the focus from the crash to the pre-crash situation.

The vehicle age, type, and the masses of the colliding vehicles could be included in a future analysis. An additional 'Autobahn' traffic domain for one-way, high-speed traffic could lead to new insights. As this traffic domain is not homogeneous, it must be stratified by speed limits and work zones. Currently, this domain is under-represented in the crash data at hand. Furthermore, this study should be replicated for other geographic regions.

The current sample size hinders stratification by age or sex and thus the projection of results to different driver populations, or even the ageing population. Low occupancy of the front-row passenger seat and second-row passenger seats hinders the separate evaluation of these positions.

Future Work

A detailed investigation into methods for decomposing crash situations into crash configurations additionally their reaggregation could be warranted. And looking into future mobility concepts, such as quads, pods, Kei cars, and even the future M0-class of micro vehicles, could yield new insights. Avenues for further research are also studies to provide insights into the correlation between pFCI and long-term consequences.

In addition, the process of including LTCs in ISO 26262 S-parameter calculations could be extended to the injury assessment of VRUs. VRUs are especially prone to extremity injuries which usually are not lethal but result in severe LTC.

VI. References

[1] Fritzsche, E. (ed.) (2018) ISO/FDIS 26262, Road vehicles - Functional safety. DIN-Normenausschuss Automobiltechnik.

[2] Gillich, P. (ed.) (2015) The Abbreviated Injury Scale 2015 Revision. Barrington, IL: Association for the Advancement of Automotive Medicine.

[3] Krampe, J. and Junge, M. (2025) Injury Severity for Hazard & Risk Analyses. *Proceedings of the IRCOBI Conference*, 2025, Vilnius, Lithuania.

[4] European Commission (2024) "C(2024) 6023 final – Supplementing Regulation (EU) 2023/988," tech. rep., European Commission, 2024.

[5] Krampe, J. and Junge, M. (2020) Injury Severity for Hazard & Risk Analyses: Calculation of ISO 26262 S-parameter Values from Real-World Crash Data. *Accident Analysis & Prevention*, **136**: pp. 105321.

[6] Krampe, J. and Junge, M. (2026) RAPEX HARM from AIS2015 Coded Injuries. medRxiv 2026.03.04.26346267; doi:10.64898/2026.03.04.26346267.

[7] Otte, D., Krettek, C., Brunner, H., Zwipp, H. (2003) Scientific approach and methodology of a new in-depth investigation study in Germany so called GIDAS. Enhanced Safety Vehicles (ESV), Nagano, Japan, p. 204.

[8] Lowne, R. W. (1996) EEVC working group 11 report on the validation of the EEVC frontal impact test procedure. Enhanced Safety Vehicles (ESV), Melbourne, Australia, no. 96-S3-O-28, pp. 1–13.

[9] van Ratingen, M., Williams, A., *et al*. (2016) The European new car assessment programme: a historical review. *Chinese Journal of Traumatology*, **19**(2): pp. 63–69.

[10] Euro NCAP (2018)Offset Deformable Barrier Frontal Impact Testing Protocol, Version 7.1.3. tech. rep., European New Car Assessment Programme (Euro NCAP).

[11] Edwards, M. and the APROSYS SP1.2 consortium (2009) Development of a high deceleration full width frontal impact test for Europe. Enhanced Safety Vehicles (ESV), Stuttgart, Germany, pp. 09–0105.

[12] European Union (1996) Directive 96/79/EC of the European Parliament and of the Council of 16 December 1996 on the protection of occupants of motor vehicles in the event of a frontal impact and amending Directive 70/156/EEC. tech. rep., European Union.

[13] Simon, L. V., Lopez, R. A., King, K. C. (eds.) (2023) *Blunt Force Trauma*. *StatPearls Publishing*, 2023. https://www.statpearls.uk/point-of-care/18413 accessed 27.04.2026.

[14] Ringdal, K. G., Skaga, N. O., *et al*. (2013) Abbreviated injury scale: Not a reliable basis for summation of injury severity in trauma facilities? *Injury*, **44**(5): pp. 691–699.

[15] Isles, S., McBride, P., *et al*. (2023) Accuracy of injury coding in a trauma registry. *Trauma*, **25**(1): pp. 35–40.

[16] Twiss, E., Krijnen, P., Schipper, I. (2021) Accuracy and reliability of injury coding in the national Dutch Trauma Registry. *International Journal for Quality in Health Care*, **33**(1): pp. 1–8.

[17] MacKenzie, E. J., Damiano, A., Miller, T., Luchter, S. (1996) The Development of the Functional Capacity Index. *The Journal of Trauma*, **41**(5): pp. 799–807.
[18] Gennarelli, T. A. (ed.) (1998) The Abbreviated Injury Scale 1990 - Update 98. Barrington, IL: Association for the Advancement of Automotive Medicine.
[19] Bates, B. (1991) Guide to Physical Examination and History Taking. *Lippincott, Williams and Wilkins*, 5 ed., Baltimore, USA.
[20] Piccolo, C. L., Mallio, C. A., Vaccarino, F., Grasso, R. F., Zobel, B. B. (2023) Imaging of knee osteoarthritis: a review of multimodal diagnostic approach. *Quantitative Imaging in Medicine and Surgery*, **13**(11): pp. 7582–7595.
[21] Osler, T., Baker, S. P., Long, W. (1997) A modification of the injury severity score that both improves accuracy and simplifies scoring. *The Journal of Trauma*, **43**(6): pp. 922–926.
[22] Griffin, R., Huisingh, C., McGwin, G., Reiff, D. (2012) Association between side-impact airbag deployment and risk of injury: A matched cohort study using the CIREN and the NASS-CDS. *The Journal of Trauma*, **73**(4): pp. 914–918.
[23] Gaylor, L., Junge, M., Abanteriba, S. (2019) Effectiveness of vehicle passive safety systems in lateral fixed-object collisions. *International Journal of Vehicle Safety*, **10**(3): pp. 195–211.
[24] Eis, V., Otte, D., Schäfer, R. (2009) Characteristics of Passenger Car Side to Pole Impacts - Analysis of German and UK in-depth data using different approaches. Enhanced Safety Vehicles (ESV), Stuttgart, Germany, pp. 60–73.
[25] Viano, D. C., Parenteau, C. S., Teoh, E. R. (2024) Effect of esc on tree and pole impacts with focus on rear impacts. *Heliyon*, **10**(18): p. e37591.
[26] Andricevic, N., Junge, M., Krampe, J. (2018) Injury risk functions for frontal oblique collisions. *Traffic Injury Prevention*, **19**(5): pp. 518–522.
[27] Lubbe, N., Jeppsson, H., Sternlund, S., Morando, A. (2024) Injury risk curves to guide safe speed limits on Swedish roads using German crash data supplemented with estimated non-injury crashes. *Accident Analysis & Prevention*, **202**: p. 107586.
[28] Otte, D., Sferco, R., *et al.* (2009) Assessment of injury severity of near-side occupants in pole impacts to side of passenger cars in European traffic accidents. Enhanced Safety Vehicles (ESV), Stuttgart, Germany, p. 243.
[29] Östling, M., Jeppsson, H., Forman, J. (2024) Injury observations in high-exposure, low-severity frontal car crashes - a GIDAS investigation. *Proceedings of the IRCOBI Conference*, pp. 981–1002, 2024, Stockholm, Sweden.
[30] Brumbelow, M. L. (2019) Front crash injury risks for restrained drivers in good-rated vehicles by age, impact configuration, and EDR-based delta v. *Proceedings of the IRCOBI Conference*, pp. 561–575, 2019, Florence, Italy.
[31] Ortlepp, J. and Butterwegge, P. (eds.) (2016) Unfalltypen-Katalog - Leitfaden zur Bestimmung des Unfalltyps. Gesamtverband der deutschen Versicherungswirtschaft e.V.

VII. APPENDIX

TABLE AI

FRONT-ROW OCCUPANTS, STRATIFIED BY TRAFFIC DOMAIN AND CRASH CONFIGURATION FOR VUI VEHICLES

Vehicle under Investigation (VUI)						
VUI (H-parameter)	Traffic Domain [km/h]					
collision	0–15	15–30	30–50	50–70	70–100	100+
belted, front-row occupants in vehicles VMY before 1998						
frontal	H0	H0	H0	H1	H2	H3
near-side	H0	H0	H1	H1	H3	H3
far-side	H0	H0	H0	H0	H1	H3
rear-end	H0	H0	H0	H0	H0	H1
unbelted, front-row occupants						
frontal	H0	H1	H1	H2	H3	H3
near-side	H0	H0	H0	H1	H3	H3
far-side	H0	H0	H0	H1	H3	H3
rear-end	H0	H0	H0	H0	H1	H3
VUI (S-parameter)	Traffic Domain [km/h]					
collision	0–15	15–30	30–50	50–70	70–100	100+
belted, front-row occupants in vehicles VMY before 1998						
frontal	S0.5	S0.5	S0.5	S1.0	S2.0	S3.0
near-side	S0.5	S0.5	S1.0	S1.0	**S2.5**	S3.0
far-side	S0.5	S0.5	S0.5	S0.5	S3.0	**S2.5**
rear-end	S0.5	S0.5	S0.5	S0.5	S0.5	S1.0
unbelted, front-row occupants						
frontal	S0.5	S1.0	S1.0	S2.0	S3.0	S3.0
near-side	S0.5	S0.5	S0.5	S1.0	**S2.5**	S3.0
far-side	S0.5	S0.5	S0.5	S1.0	S3.0	S3.0
rear-end	S0.5	S0.5	S0.5	S0.5	S1.0	**S2.5**

Note: H- and first S-parameter block computed from the current dataset, last S-parameter block from a previous publication [3]. The asterisk (∗) denote cells with insufficient elements, and the S-scale value following indicates the highest injury severity in that cell. Changes between parameter blocks are set in bold.

Note: H- and S-scale 90th percentiles estimated with 95% statistical certainty. To obtain integer S-parameters as used in ISO 26262, the given S-parameters must be truncated, not rounded, as detailed in [3].

TABLE AII

FRONT-ROW OCCUPANTS, STRATIFIED BY TRAFFIC DOMAIN AND CRASH CONFIGURATION FOR CIA VEHICLES

Crash Involved Automobile (CIA)						
CIA (H-parameter)	Traffic Domain [km/h]					
collision	0–15	15–30	30–50	50–70	70-–	100+
belted, front-row occupants in vehicles VMY before 1998						
frontal	H0	H0	H0	H1	H1	H3
near-side	H0	H0	H1	H1	H3	H3
far-side	H0	H0	H0	H0	H3	H3
rear-end	H0	H0	H0	H0	H1	H1
unbelted, front-row occupants						
frontal	H0	H0	H0	H1	H3	H3
near-side	H0	H0	H1	H2	H3	H3
far-side	H0	H0	H0	H2	H3	H3
rear-end	H0	H0	H0	H1	H3	H3
CIA (S-parameter)	Traffic Domain [km/h]					
collision	0–15	15–30	30–50	50–70	70–100	100+
belted, front-row occupants in vehicles VMY before 1998						
frontal	S0.5	S0.5	S0.5	S1.0	S1.5	S3.0
near-side	S0.5	S0.5	S1.0	S1.5	S3.0	S3.0
far-side	S0.5	S0.5	S0.5	S0.5	**S2.5**	S2.5
rear-end	S0.5	S0.5	S0.5	S0.5	S1.0	S1.0
unbelted, front-row occupants						
frontal	S0.0	S0.5	S0.5	S1.0	**S2.5**	S3.0
near-side	S0.5	S0.5	S1.0	S2.0	S3.0	S3.0
far-side	S0.5	S0.5	S1.0	S2.0	S3.0	S3.0
rear-end	S0.5	S0.5	S0.5	S1.0	**S2.5**	**S2.5**

Note: H- and first S-parameter block computed from the current dataset, last S-parameter block from a previous publication [3]. The asterisk (∗) denote cells with insufficient elements, and the S-scale value following indicates the highest injury severity in that cell. Changes between parameter blocks are set in bold.
Note: H- and S-scale 90th percentiles estimated with 95% statistical certainty. To obtain integer S-parameters as used in ISO 26262, the given S-parameters must be truncated, not rounded, as detailed in [3].

TABLE AIII
NUMBER OF CASES (N) AND DISTRIBUTION PARAMETERS FOR TECHNICAL CRASH SEVERITIES FOR BELTED, FRONT-ROW OCCUPANTS IN CURRENT (MARKET INTRODUCTION 2001 OR LATER) (VUI)

	speed limit (vehicles at or above 90% above speed limit) mean (90th percentile) [km/h]											
	0–15		15–30		30–50		50–70		70–100		100 +	
frontal collision												
$v_{collision}$	32	(57)	38	(60)	46	(66)	58	(80)	78	(98)	103	(119)
Δv	15	(33)	17	(36)	21	(41)	26	(53)	34	(67)	36	(70)
v_0	39	(70)	45	(70)	53	(77)	64	(90)	83	(104)	108	(129)
n	6242		5038		3471		1573		429		73	
near-side collision												
$v_{collision}$	32	(58)	36	(60)	42	(66)	49	(71)	64	(89)	83	(109)
Δv	9	(23)	10	(24)	12	(25)	13	(28)	15	(35)	16	(36)
v_0	37	(68)	43	(70)	52	(75)	60	(81)	80	(102)	105	(120)
n	1752		1464		1091		714		226		52	
far-side collision												
$v_{collision}$	29	(54)	33	(58)	41	(64)	49	(70)	63	(85)	80	(103)
Δv	8	(22)	9	(24)	12	(27)	15	(29)	16	(35)	18	(36)
v_0	33	(64)	41	(67)	51	(73)	60	(80)	79	(100)	105	(123)
n	1706		1341		907		562		180		38	
rear-end collision												
$v_{collision}$	26	(48)	30	(50)	32	(51)	38	(58)	55	(85)	77	(116)
Δv	11	(22)	13	(24)	14	(25)	15	(27)	19	(33)	14	(25)
v_0	36	(62)	46	(68)	50	(70)	57	(74)	80	(100)	105	(133)
n	2704		1892		1664		1094		242		57	

TABLE AIV
NUMBER OF CASES (N) AND DISTRIBUTION PARAMETERS FOR TECHNICAL CRASH SEVERITIES FOR BELTED, FRONT-ROW OCCUPANTS IN OLD CLUNKERS (MARKET INTRODUCTION 1998 OR EARLIER) (VUI)

	speed limit (vehicles at or above 90% above speed limit) mean (90th percentile) [km/h]											
	0–15		15–30		30–50		50–70		70–100		100 +	
frontal collision												
$v_{collision}$	35	(62)	39	(65)	47	(70)	61	(84)	79	(99)	101	(120)
Δv	16	(37)	18	(39)	21	(43)	26	(52)	30	(61)	31	(63)
v_0	45	(76)	49	(80)	57	(85)	70	(98)	87	(114)	110	(132)
n	8622		7380		5156		2399		840		171	
near-side collision												
$v_{collision}$	38	(67)	41	(69)	45	(72)	52	(79)	65	(92)	78	(105)
Δv	13	(30)	14	(31)	15	(33)	18	(37)	21	(43)	23	(53)
v_0	46	(84)	51	(86)	57	(90)	66	(97)	85	(110)	105	(126)
n	2165		1938		1631		1140		494		168	
far-side collision												
$v_{collision}$	36	(65)	39	(67)	45	(71)	52	(77)	64	(90)	78	(106)
Δv	12	(29)	13	(30)	16	(33)	18	(37)	20	(44)	25	(53)
v_0	43	(80)	49	(84)	57	(88)	65	(94)	84	(107)	105	(123)
n	2068		1789		1416		992		419		130	
rear-end collision												
$v_{collision}$	27	(50)	33	(55)	36	(56)	40	(65)	57	(90)	81	(130)
Δv	13	(25)	15	(27)	16	(28)	18	(30)	22	(38)	23	(40)
v_0	33	(65)	48	(73)	52	(75)	60	(80)	82	(110)	109	(136)
n	2704		1865		1624		1090		304		76	

TABLE AV
NUMBER OF CASES (N) AND DISTRIBUTION PARAMETERS FOR TECHNICAL CRASH SEVERITIES FOR UNBELTED, FRONT-ROW OCCUPANTS (VUI)

	speed limit (vehicles at or above 90% above speed limit) mean (90th percentile) [km/h]					
	0–15	15–30	30–50	50-–0	70–100	100 +
frontal collision						
$v_{collision}$	31 (56)	37 (60)	46 (70)	61 (85)	81 (104)	107 (126)
Δv	14 (35)	16 (38)	21 (44)	28 (54)	35 (72)	34 (76)
v_0	41 (71)	47 (75)	56 (85)	70 (100)	91 (118)	112 (130)
n	3347	2726	1740	742	245	60
near-side collision						
$v_{collision}$	31 (57)	34 (58)	41 (63)	49 (70)	60 (82)	78 (110)
Δv	8 (22)	9 (23)	12 (26)	14 (30)	19 (39)	27 (75)
v_0	37 (70)	43 (71)	52 (76)	63 (88)	81 (109)	108 (123)
n	972	827	582	350	136	31
far-side collision						
$v_{collision}$	27 (51)	31 (54)	41 (67)	49 (77)	62 (100)	81 (108)
Δv	7 (21)	8 (23)	12 (30)	15 (36)	17 (40)	20 (48)
v_0	32 (64)	38 (70)	52 (80)	63 (90)	82 (107)	106 (125)
n	935	761	444	267	100	29
rear-end collision						
$v_{collision}$	23 (44)	28 (47)	30 (50)	34 (55)	49 (70)	80 (102)
Δv	10 (21)	12 (23)	13 (23)	14 (24)	20 (32)	30 (67)
v_0	31 (60)	45 (65)	49 (65)	56 (70)	76 (97)	104 (115)
n	1419	965	832	536	105	14

TABLE AVI

NUMBER OF CASES (N) AND DISTRIBUTION PARAMETERS FOR TECHNICAL CRASH SEVERITIES FOR BELTED, FRONT-ROW OCCUPANTS IN CURRENT (MARKET INTRODUCTION 2001 OR LATER) ADAS-EQUIPPED VEHICLES (CIA)

	speed limit (vehicles at or above 90% above speed limit) mean (90th percentile) [km/h]					
	0–15	15–30	30-–0	50–70	70–100	100 +
frontal collision						
$v_{collision}$	32 (57)	36 (60)	40 (62)	46 (69)	62 (87)	80 (108)
Δv	15 (33)	17 (36)	19 (38)	22 (43)	30 (58)	35 (67)
v_0	39 (70)	46 (70)	51 (73)	59 (80)	79 (100)	103 (120)
n	6242	5144	4373	2890	848	177
near-side collision						
$v_{collision}$	32 (58)	37 (61)	47 (69)	59 (80)	78 (98)	102 (117)
Δv	9 (23)	10 (24)	13 (27)	14 (29)	14 (34)	12 (24)
v_0	37 (68)	43 (70)	52 (77)	63 (90)	83 (112)	103 (125)
n	1752	1421	927	454	130	25
far-side collision						
$v_{collision}$	29 (54)	35 (60)	46 (65)	58 (78)	77 (95)	100 (114)
Δv	8 (22)	10 (24)	14 (28)	15 (31)	15 (36)	19 (44)
v_0	33 (64)	40 (67)	51 (75)	62 (89)	82 (111)	105 (120)
n	1706	1280	771	364	98	15
rear-end collision						
$v_{collision}$	26 (48)	33 (50)	43 (60)	58 (80)	82 (110)	110 (131)
Δv	11 (22)	14 (25)	17 (28)	20 (32)	19 (34)	13 (22)
v_0	36 (62)	43 (69)	52 (72)	65 (95)	93 (127)	115 (137)
n	2471	1815	1028	347	82	21

TABLE AVII

NUMBER OF CASES (N) AND DISTRIBUTION PARAMETERS FOR TECHNICAL CRASH SEVERITIES FOR BELTED, FRONT-ROW OCCUPANTS IN OLD CLUNKERS (MARKET INTRODUCTION 1998 OR EARLIER) (CIA)

	speed limit (vehicles at or above 90% above speed limit) mean (90th percentile) [km/h]					
	0–15	15–30	30–50	50–70	70–100	100 +
frontal collision						
$v_{collision}$	35 (62)	37 (64)	41 (67)	47 (74)	61 (90)	81 (108)
Δv	16 (37)	17 (39)	19 (40)	22 (45)	28 (55)	30 (61)
v_0	45 (76)	49 (79)	54 (80)	63 (88)	81 (102)	104 (123)
n	8622	7744	6555	4468	1705	421
near-side collision						
$v_{collision}$	38 (67)	42 (70)	49 (75)	62 (85)	80 (100)	102 (120)
Δv	13 (30)	14 (31)	17 (35)	19 (40)	20 (44)	15 (40)
v_0	46 (84)	50 (86)	59 (90)	70 (100)	89 (120)	112 (132)
n	2165	1914	1424	760	272	63
far-side collision						
$v_{collision}$	36 (65)	41 (67)	49 (74)	61 (84)	79 (100)	105 (126)
Δv	12 (29)	14 (31)	17 (34)	20 (39)	23 (46)	24 (47)
v_0	43 (80)	49 (85)	58 (90)	69 (100)	87 (111)	113 (136)
n	2068	1734	1250	675	229	46
rear-end collision						
$v_{collision}$	27 (50)	34 (53)	44 (64)	61 (86)	84 (120)	111 (138)
Δv	13 (25)	16 (26)	19 (30)	23 (35)	26 (49)	22 (46)
v_0	33 (65)	40 (70)	51 (80)	68 (99)	89 (120)	112 (140)
n	2704	2047	1175	405	123	37

TABLE AVIII
NUMBER OF CASES (N) AND DISTRIBUTION PARAMETERS FOR TECHNICAL CRASH SEVERITIES FOR UNBELTED, FRONT-ROW OCCUPANTS (CIA)

	speed limit (vehicles at or above 90% above speed limit) mean (90th percentile) [km/h]											
	0–15		15–30		30–50		50–70		70–100		100 +	
frontal collision												
$v_{collision}$	31	(56)	35	(60)	38	(63)	44	(71)	61	(91)	82	(107)
Δv	14	(35)	16	(37)	18	(39)	21	(46)	31	(58)	32	(67)
v_0	41	(71)	47	(75)	53	(80)	61	(88)	82	(108)	106	(120)
n	3347		2837		2364		1571		525		153	
near-side collision												
$v_{collision}$	31	(57)	35	(59)	46	(65)	59	(78)	78	(103)	106	(115)
Δv	8	(22)	9	(23)	13	(29)	16	(34)	20	(44)	29	(90)
v_0	37	(70)	42	(71)	54	(80)	67	(94)	82	(120)	117	(125)
n	972		805		485		216		64		11	
far-side collision												
$v_{collision}$	27	(51)	33	(55)	46	(70)	61	(82)	81	(103)	103	(110)
Δv	7	(21)	8	(23)	14	(33)	18	(38)	16	(39)	13	(22)
v_0	32	(64)	38	(70)	53	(80)	68	(102)	89	(115)	113	(132)
n	935		714		373		156		53		14	
rear-end collision												
$v_{collision}$	23	(44)	30	(47)	40	(56)	56	(70)	79	(96)	98	(110)
Δv	10	(21)	13	(23)	16	(25)	21	(31)	26	(43)	23	(42)
v_0	31	(60)	40	(64)	49	(70)	61	(90)	84	(105)	106	(114)
n	1419		981		492		136		23		6	

VIII. Glossary of Key Terms

AIS (Abbreviated Injury Scale)
The standard anatomical injury severity scoring system (AIS 2015 edition) was used in this paper. It provides two main metrics for each injury:

- **AIS-CD** (AIS Code): A 1–6 scale (plus 9 = unknown) primarily measuring threat to life (lethality).
- **AIS-ID** (AIS Identifier): Unique 6-digit code for each specific individual injury descriptor.

AIS-ID Aggregation (Level 1)
A medically motivated clustering/aggregation of the original >2,000 AIS-IDs into fewer, more robust categories (345 for lethality/AIS-CD and 453 for long-term consequences/FCI). Performed separately for AIS-CD and pFCI to reduce coding ambiguity and align better with routine medical documentation.

CIA (Crash Involved Automobile)
Normal vehicle involved in a crash, i.e. pre-crash braking or evasive manoeuvres may occur. Can collide with either CIA or VUI vehicle (see contrast with VUI).

FCI / pFCI (Functional Capacity Index / predicted Functional Capacity Index)
A measure of expected long-term functional impairment (disability) if the patient survives the injury. Each AIS-ID in the AIS 2015 codebook has an associated pFCI value.
FCI-CD: Recoded version of pFCI (1 = perfect state → 5 = worst possible state; 9 = unknown) for easier aggregation and alignment with AIS-CD.

GIDAS (German In-Depth Accident Study)
The real-world crash database used in the study (crashes from Greater Dresden and Greater Hannover, 2001–2024).

HARM (Hazard and Risk Assessment Methodology)
The RAPEX injury severity metric (4-level scale: HARM 1 = minor to HARM 4 = life-threatening). It separately evaluates lethality (in our case via AIS-CD) and long-term consequences (in our case via FCI-CD), then takes the **higher (more severe)** ratings for the overall person-level severity.

HARM-to-S/H Mapping (simplified from Table IV):

- HARM 1 → H0 / S0 (minor)
- HARM 2 → H1 / S1 (moderate)
- HARM 3 → H2 / S2 (severe)
- HARM 4 → H3 / S3 (life-threatening)

H-parameter (H-scale)
The new injury severity parameter is proposed in the paper. It is the **90th percentile** of the HARM-derived severity distribution (mapped to a 0–3 scale, where H0 ≈ S0, H1 ≈ S1, H2 ≈ S2, H3 ≈ S3). It unifies acute lethality and long-term consequences (LTCs).

H-scale
The 0–3 severity scale obtained by subtracting 1 from the HARM scale (HARM 1–4 → H-scale 0–3). Used to compute H-parameters (see above).

ISO 26262 S-parameter (S-scale)
The current functional safety severity parameter is defined in ISO 26262 Annex B. It is primarily based on lethality (MAIS / AIS-CD) and corresponds to the **90th percentile** of the injury severity distribution in a given scenario (typically expressed as integer values, here expanded to .0 or .5 granularity, e.g., S0.5, S1.5, S2.5, S3.0). Truncated (not rounded) to integer values for ASIL evaluations.

LTC (Long-term Consequences)
Permanent or long-lasting functional impairments resulting from survived injuries, quantified via pFCI / FCI-CD.

MAIS (Maximum Abbreviated Injury Scale)
Traditional person-level aggregation: the single highest AIS-CD of any injury sustained by the patient. Replaced in this paper by a more comprehensive AIS-CD triple-based aggregation.

NISS (New Injury Severity Score)
A person-level injury severity score that sums the squares of the three highest AIS scores (used here as inspiration for the sorted triple approach).

PDOF (Principal Direction of Force)
The main direction of impact force on the vehicle, represented on a clock-face (used to define frontal, near-side, far-side, and rear-end crash configurations).

RAPEX
Rapid Exchange of Information System – EU system for rapid alert and risk assessment of unsafe consumer products. This paper adapts the HARM methodology for road vehicle functional safety.

S-parameter
See **ISO 26262 S-parameter** above.

Traffic Domain
Speed-based scenario categories used for grouping crashes and deriving parameters: 0–15, 15–30, 30–50, 50–70, 70–100, 100+ km/h; the lower bound is inclusive. A crash is assigned to a domain if the outset speed (v_0) is at least 90% of the lower bound of the domain.

VUI (Vehicle Under Investigation)
The vehicle whose (semi-)autonomous system failure is being assessed under ISO 26262. In VUI scenarios, pre-crash braking of the VUI vehicle is assumed absent, so collision speed equals outset speed (v_0).

90th Percentile (with 95% statistical significance)
The primary statistical measure used to derive both S-parameters and H-parameters. It represents a conservative yet robust estimate of injury severity in a traffic domain, reducing the influence of rare extreme cases. It is estimated one-sided with 95% statistical significance.