Injury Severity for Hazard and Risk Analyses: Calculation of ISO 26262 S-parameter Values from Real-World Crash Data

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Abstract ISO 26262 hazard and risk analyses require a robust injury severity assessment of system-failure-related crashes. We chose a data-driven approach and used a crash database focused on current vehicles. Medical progress was accounted for by recoding the individual injuries to the current Abbreviated Injury Scale (AIS 2015) from the original medical documentation. Coding ambiguity was reduced by aligning AIS 2015 codebook details to the precision of the medical diagnoses used to treat the patients. A procedure closely related to the New Injury Severity Score (NISS) was used to aggregate the individual injury severities to the person level. The use of robust cut-off points resulted in a seven-level injury severity scale (S-scale).

We used six traffic domains to differentiate between the crash severities.

The crash configurations were segmented into frontal, near-side, far-side, and rear-end impacts. Historically, ISO 26262 uses the 90th percentile of the injury severity measure, which we estimated with 95% right-hand-side statistical certainty. We used the S-scale as the injury severity measure.

The results are presented in two S-parameter tables. One for vehicles driven by unassisted drivers, i.e., those who can react to the impending crash, and one for Advanced Driver Assistance Systems (ADAS) assisted drivers with a system malfunction where neither the driver nor the ADAS system reacts, i.e., no avoidance manoeuvre whether steering or braking is initiated.

The results are compared previous evaluations and the literature in general.

Keywords ISO 26262, S-scale, S-parameter, injury severity, injury aggregation.

I. INTRODUCTION

Functional safety is a qualitative analysis in the early stages of advanced driver assistance systems (ADAS) development. Its primary goals are to avoid unreasonable injury risk in case of electrical and/or electronic system malfunction and estimate the quality with which system sub-functionalities have to be developed. The primary building blocks are exposure (E), i.e., the frequency or duration of a situation where system failure would lead to consequences; controllability (C), i.e., the ease with which the driver can handle the system malfunction; and severity (S), i.e., the injury severity sustained by any involved party if the driver cannot handle the situation. All three variables, (E), (C), and (S), contribute equally to the Automotive Safety Integrity Level (ASIL). The ISO26262 has introduced a structured methodology for functional safety assessment in road vehicles. (For more details, refer to part 3 of [1].)

While there is consensus on how to define the exposure [2] and to verify the controllability in controlled tests [3], the situation for injury severity assessment is more complex. The S-parameter assesses the injury severity when a driver did not handle the situation and crashed [1]. The S-parameter estimates the 90th percentile of the injury distribution of the crash configuration, i.e. it represents the injury severity that is not exceeded in 90% of the crashes in a given scenario, providing a robust measure of injury severity.

There is some information in the S-parameter table in Annex B of the ISO 26262 standard, which details impact direction but doesn't go into specific values for the technical crash severity [1, part 3, Table B.1] The 'Verband der Automobilindustrie' (engl. 'German Association of the Automotive Industry,') compiled a more detailed catalogue along the same lines, but it was never published. The Society of Automotive Engineers (SAE) 'recommended practice' also features an S-parameter table [4]. It stratifies injury severity by delta-v ranges. Delta-v (Δv) describes the absolute value of velocity change during a collision; it is correlated to the closing speed and to the mass ratio of the colliding objects, making delta-v values ideal for crash severity assessment but hard to estimate and interpret for non-experts.

In previous work, we developed the first data-driven approach using real-world crash data for statistical S-

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parameter estimation [5-6]. Our primary goal was to develop a statistically sound, data-driven method for the correlation between a crash scenario and the S-parameter that can be used by non-crash investigators in hazard and risk assessments.

This paper updates the S-Parameter tables of [5] by using the latest GIDAS dataset and the updated AIS 2015 injury severity coding and aligning the codable individual injury detail to the granularity of the medical information. An aggregation function to the patient level was developed for these more robust individual injury codes, which highly correlates with mortality; seven instead of the previous four, statistically separate injury severity levels are defined, focusing on the lower injury severities. The 90th percentiles of these injury severity levels are estimated with right-hand-sided 95% statistical confidence. All these steps, i.e., making the AIS coding more robust, the aggregation function to the patient level, and the construction of the S-scale, can be used independently in other evaluations using AIS-coded injuries for more stable results than conventional injury severity aggregation, e.g., MAIS, ISS.

II. METHODS

We continue to rely on car crash data from the German In-Depth Accident Survey (GIDAS) [7] for our current S-parameter estimation, and we are still using traffic domains to cluster crash severity instead of Δv or EES. By introducing a 'shared zone' (0–15 km/h) for low-speed crashes, we expanded the traffic domain stratification to six: shared zones, residential streets, city roads, arterial thoroughfares, rural roads, and intercity highways. The crashes are divided by crash configuration, i.e. front, near-side, far-side, and rear-end collisions. We updated the injury severity assessment from AIS 90/98 coding [8] to AIS 2015 [9] using the original medical documentation, thereby updating the medical evaluation 30 years into the future, i.e. translating 1980s treatment into the treatment current in the 2010s [10]. We also evaluated the AIS coding quality of old and new cases and aggregated the AIS injury descriptors where we found overly specific details or a high risk of upcoding by the crash investigator teams. When we examined self-reported injuries, we found an underreporting of skin injuries in some cohorts, leading us to exclude skin injuries from the evaluation. Finally, we paid special attention to individual injury aggregation at the person level, relying on a NISS-like aggregation and using cut-off points on that scale to derive the S-scale on which the S-parameters are based.

The S-parameters were evaluated individually in all traffic domains for each crash configuration. Thus, the S-parameter derived for a specific crash configuration in a traffic domain gives the injury severity, which is most likely not exceeded in such a crash. Note that the S-parameters describe only the upper bound of the risk and are not a predictor for the injury outcome.

For the analysis, we differentiated between the ADAS-equipped vehicle (AEV) with a system failure and the car involved in the crash due to an ADAS-failure in the opposing vehicle (CIA). We assume that the AEV does not change its closing speed, i.e. the collision speed is equal to the closing speed, whereas the CIA has the ability to react to the erratic behaviour of the AEV as it would to any other vehicle. The S-parameters were calculated for AEV and CIA to a 95% confidence level. The results are given by crash configuration, i.e. frontal, near-side, far-side, and rear-end.

Note that the estimation uncertainty for the S-parameters is in the domain of the injury severity itself. In contrast, injury risk functions connect some technical severity to a fixed level of injury severity. Thus, using injury risk functions to derive S-parameters with a confidence interval is challenging. That is why a novel approach was developed.

Data

The August 2024 GIDAS image, with crashes from 1999 to 2023, was used for this analysis [7]. The data were stratified in multiple ways.

With the introduction of Euro NCAP, the requirements for self-protection of vehicles have increased [11-12]. Therefore, based on the first year of market introduction, i.e. the year of homologation, the dataset was divided into vehicles designed with the Euro NCAP in mind (POST) and those too old to do so (PRE). To define the POST group, 1998 and later was used for all crash configurations. Our focus was on belted front-row occupants of passenger cars, multi-purpose vehicles, and light-duty vehicles involved in vehicle-to-vehicle or vehicle-to-object crashes. There were no restrictions on the type of the impacting vehicle or object. In multiple-collision crashes the most severe collision was taken to be representative of the crash.

Crash Configuration

We considered three crash configurations: frontal, side, and rear-end collisions. The vehicle deformation index (VDI1) defines the crash configurations using the principle direction of force (PDOF) [13]. The frontal collisions are those with a deformation from 11 to 1 o'clock. Side collisions are characterised by a VDI1 of 8 to 10 o'clock or 2 to 4 o'clock. Due to their different injury mechanics [14] and associated risks [15], the side collisions are divided into far-side and near-side. Collisions are said to be rear-end if VDI1 ranges from 5 to 7 o'clock.

AIS 2015

The GIDAS database codes individual injuries based on medical diagnosis by a medical doctor. These medical diagnoses were the basis for recoding all individual injuries according to the Abbreviated Injury Scale 2015 (AIS 2015) codebook [9-10].

AIS 2015-Identifier Aggregation

AIS coding is error-prone [16]; the medical diagnoses for patient treatment do not align well with the AIS-Identifiers (AIS-IDs) used for injury descriptions. Medical doctors use scores incorporating injuries and physiological parameters for patient treatment. They are not that interested in the injury severity right after the crash but in the current state of the patient and the trend. Thus, much of the AIS coding in trauma databases is only done because it is mandatory; the AIS coding is not needed for the patient's medical diagnosis or treatment. To address this coding quality problem, we aggregated the AIS-IDs to the 'not further specified' (NFS) level (Level 1), as specified in the AIS codebook, thereby addressing both the level of medical diagnostics and the level of coding expertise. To consider higher level of detail, we also introduced Level 2 and Level 3. At Level 2, all named nerves, vessels, and bones in the AIS 2015 codebook are treated separately, and open and closed fractures are differentiated. At Level 3, there is a differentiation between 'contusion', 'laceration', and 'avulsion'. Furthermore, Level 3 codings assume that modifiers are assigned accurately, e.g., '>20% blood loss by volume'. For systematic reasons, some new aggregated AIS-IDs had to be added. Most significant is the separation of minor heart injuries (contusion, some lacerations) from injuries that cause functional destruction of the heart, e.g. transmural perforation of the heart muscle or avulsion. The resulting 2015 individual AIS-IDs are aggregated to 322 and 550 AIS-IDs at Levels 1 and 2, respectively. Level 1 AIS-ID aggregation will be used throughout this paper.

Special treatment for AIS1 skin injuries

Real-world road-traffic crash research relies on self-reporting slight injuries, i.e. AIS1 injuries, as most such injuries are not treated or medical professionals do not document their treatment as they are not reimbursable. Haematomas and superficial lacerations are underreported by people who caused a crash and overreported by those who think they can claim compensation. Therefore, we disregarded all AIS1 skin and scalp haematomas, lacerations, and skin perforations in the evaluation, i.e. all AIS1 codes for skin injuries at Level 1 AIS-ID aggregation are set to AIS0.

Special treatment of AIS9 injuries

Injuries associated with an AIS9 code are those without a complete medical diagnostic procedure but with a known injury to the body region, e.g. injuries to the head NFS, vascular injury in the abdomen NFS, vertebrae injury NFS. The AIS9 codes for the 'unknown' injury severity hinder injury severity aggregation of the 'normal' AIS codes, ranging from 'minor' (AIS1) to 'maximum' (AIS6). To at least partially address this problem, a lower limit on the injury severity scale was assigned to each of the AIS9 injury IDs. These limits represent the minimal AIS severity with which the injury could occur. These minimal AIS codes range from AIS1 to AIS3.

Note that these minimal AIS codes need special attention in injury severity aggregation and must be treated separately from other AIS codes (see below).

AIS-Code-Triples

The maximum AIS code (MAIS) is widely used to aggregate injury severity to the person level [9]. The MAIS works well on a single organ, component, or body region level. But its major shortcoming, the underestimation of injury severity when multiple injuries are present in different body regions, has been known for decades [17]. The three most severe AIS-coded injuries (AIS-triples) have been used in the New Injury Severity Score (NISS) to describe the severity of the injury at the person level [18]. We followed the idea of the NISS but replaced the quadratic AIS scale transformation with an exponential one while keeping the range, emphasising the more severe injuries over lesser ones and making the transformation bijective [19]. To elaborate, let AIS_i be the AIS code of injury $i = 1, \dots, n$, where n refers to the n injuries a person sustained. Then, the AISx is defined as:

$$\mathrm{AISx}_i = \begin{cases} 25 * \dfrac{\exp(AIS_i) - 1}{\exp(5) - 1}, AIS_i \in \{1,2,3,4,5\} \\ 75, AIS_i = 6 \end{cases}$$

Additionally, let $\mathrm{AISx}_{[i]}$ be in decreasing order such that $\mathrm{AISx}_{[1]}$ refers to the most severe injury. Then,

$$NISSx = \min\left(75, \sum_{i=1}^{\min(n,3)} AISx_{[i]}\right)$$

where the outer minimum keeps the NISSx in the range of 0 to 75.

For injured persons with an AIS9-coded injury, the NISSx is computed by substituting the AIS9 code with the assigned minimal AIS. If the resulting value is in the highest *S*-scale bin under investigation, i.e. usually S3.0, the case can be included in the investigation.

Injury Severity Scale (S-Scale)

To use the NISSx injury severity aggregation function as an injury severity scale, we defined cut-off points closely resembling those used on the ISS and NISS, i.e. 16, 9 and 4 [20-21] (see Table I). Furthermore, we tried to position cut-off points so they would not separate AIS0 and AIS1 injuries into different groups. This was impossible for the S0.5 cut-off, which was calculated using the special treatment for skin injuries. All cut-offs were calculated using Level 1 aggregated AIS-IDs.

The following six cut-off points have been defined on the NISSx injury severity score, leading to the seven-item *S*-scale.

The lower end of the AIS-triple to S-scale mapping is given in Table II.

TABLE I

NISSX CUT-OFF POINTS FOR INJURY DATA WITHOUT AIS1 SKIN INJURIES, INDEPENDENT OF THE AIS-ID AGGREGATION LEVEL, IF ANY

S3.0: NISSx >= 5.5, life-threatening injuries (survival uncertain)
S2.5: NISSx >= 4.0, life-threatening injuries (survival probable)
S2.0: NISSx >= 2.5, severe injuries
S1.5: NISSx >= 2.0, moderate injuries
S1.0: NISSx >= 1.0, light injuries (≈ MAIS2+)
S0.5: NISSx >= 0.25, minor injuries
S0.0: NISSx < 0.25, 'no' injuries

This defines the following function mapping the NISSx-score ([0,75]) to the *S*-scale ({0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0}):

$$\tilde{S}(x): [0,75] \to \{0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0\}, \tilde{S}(x) = \begin{cases} 0.0, x \in [0.0, 0.25) \\ 0.5, x \in [0.25, 1.0) \\ 1.0, x \in [1.0, 2.0) \\ 1.5, x \in [2.0, 2.5) \\ 2.0, x \in [2.5, 4.0) \\ 2.5, x \in [4.0, 5.5) \\ 3.0, x \geq 5.5 \end{cases}$$

It is assumed here that the S-scale is ordered. Thus, the least severe injuries are coded 0.0 and the most severe injuries 3.0. If we denote 'less severe injury' using '<', the relationship 0.0 < 0.5 < 1.0 < 1.5 < 2.0 < 2.5 < 3.0 holds for the S-scale.

TABLE II
AIS-TRIPLE VS. S-SCALE TOTAL ENUMERATION OF THE LOWER VALUE AIS-TRIPLES ORDERED BY NISSX-VALUES

AIS-triple	NISS	NISSx	S-scale	
⋮	⋮	⋮	⋮	
4/0/0	16	9.09	S3.0	
3/3/2	22	7.56	S3.0	
3/3/1	19	6.76	S3.0	
3/3/0	18	6.47	S3.0	≈ multiply injured
3/2/2	17	5.40	S2.5	
3/2/1	14	4.61	S2.5	
3/2/0	13	4.32	S2.5	
3/1/1	11	3.82	S2.0	
3/1/0	10	3.53	S2.0	
2/2/2	12	3.25	S2.0	
3/0/0	9	3.24	S2.0	≈ MAIS3+
2/2/1	9	2.46	S1.5	
2/2/0	8	2.17	S1.5	
2/1/1	6	1.67	S1.0	
2/1/0	5	1.37	S1.0	
2/0/0	4	1.08	S1.0	= MAIS2+
1/1/1	3	0.87	S0.5	
1/1/0	2	0.58	S0.5	
1/0/0	1	0.29	S0.5	
0/0/0	0	0.00	S0.0	

S-Parameter

In the spirit of the ISO 26262 standard, we did not use the cut-offs for the S-scale as absolute values but looked at the distribution of all crashes and used the 90th percentiles as cut-offs [1, part 3, B.2]. That is, the S-parameters are probabilistic injury severity measures, i.e. the 90th percentiles, based on the S-scale injury levels, estimated with 95% certainty, i.e. the right-hand-side (RHS) of a one-sided 95%-confidence interval for the 90th percentiles is used as S-parameter. This approach hinders undershooting S-parameters for small sample size. The S-parameters take the values of S0.0, S0.5, S1.0, S1.5, S2.0, S2.5, and S3.0.

For a situation to be classified as S2.0, 90% of all crash occupants suffer injuries that do not exceed the 2.0 level (in S-scale), and at least 10% suffer injuries at or above 2.0 level. To be more specific, let us assume we have the following injury distribution for some crash configuration: {0.0 : 5%; 0.5 : 15%; 1.0 : 40%; 1.5 : 16%; 2.0 : 15%; 2.5 : 7%; 3.0 : 2%}. Then, the S-parameter for this crash configuration would be S2.0. Thus, the S-parameter itself is not an appropriate measure to predict the injury outcome of a given crash configuration. The S-parameter is a risk measure that quantifies the injury severity level, which would likely not be exceeded in a given crash configuration.

We follow the methodology of [5] to estimate the S-parameters, see [5, Section 2], for a rigorous description of the involved assumptions and the estimation method. We additionally estimate S-parameters for rear-end. This crash type is estimated analogously as side crashes.

The ISO 26262 defines only four levels of injury severity, ranging from 0 for an uninjured occupant to 3 for the most severe injury level [1, part 3, 6.4.3]. The seven-level S-parameters used in this paper can be converted to the four-level scale by using the most significant digit only. Thus, the four-level S-parameters take the values S0, S1, S2, and S3.

Traffic Domain Classification

Consider the situation of a vehicle driving in a particular traffic domain (TD) (i.e. shared zone, residential street, city road, ...) with a domain-specific speed limit (SL). The traffic domains are defined using a partition of half-open intervals of the SL of the road the vehicles are driving on. This results in the following traffic domains (in km/h): shared zone (0-14 km/h), residential streets (15-29 km/h), city roads (30-49 km/h), arterial thoroughfares (50-69 km/h), rural roads (70-99 km/h), and intercity highways (100+ km/h).

Since the traffic domain 'Bundesdeutsche Autobahn' (German Autobahn) differs significantly from the other traffic domains, this domain is not considered in the current analysis.

Note that the traffic domains are defined only via the speed limits.

S-parameters for Advanced Driving-Assistance Systems Failures

Advanced Driver-Assistance Systems (ADAS) help the driver to safely manoeuvre a vehicle [22]. The S-parameters are calculated to assess the injury severity in cases of ADAS failure. We assume ADAS failures occur at typical driving speeds and the analysis excludes stationary and stop-and-go traffic. To analyse specific scenarios (e.g., stop-and-go), the traffic domain can be adjusted (e.g., to 'residential streets'), but requires careful consideration.

ADAS failures can lead to uncontrolled vehicle behaviour, delaying pre-crash actions. We define S-parameters for vehicles with no pre-crash response (AEV) and those with typical driver responses (CIA). In the estimation of the S-parameter, no pre-crash response is taken into account by assuming that the AEV's collision velocity is as high as its closing velocity [5, Section 2.2.5]. Crash opponents may react to AEV behaviour. Our S-parameter calculations account for these reactions: the frontal CIA and the side and rear-end AEV S-parameters include the pre-crash reaction.

III. RESULTS

S-Scale vs. Lethality

The lethality of S-scale values for the raw AIS-coding and the AIS-ID aggregation Levels 1, 2, and 3 are visualised in Fig. 1. The numerical results are given in Table AI in the Appendix.

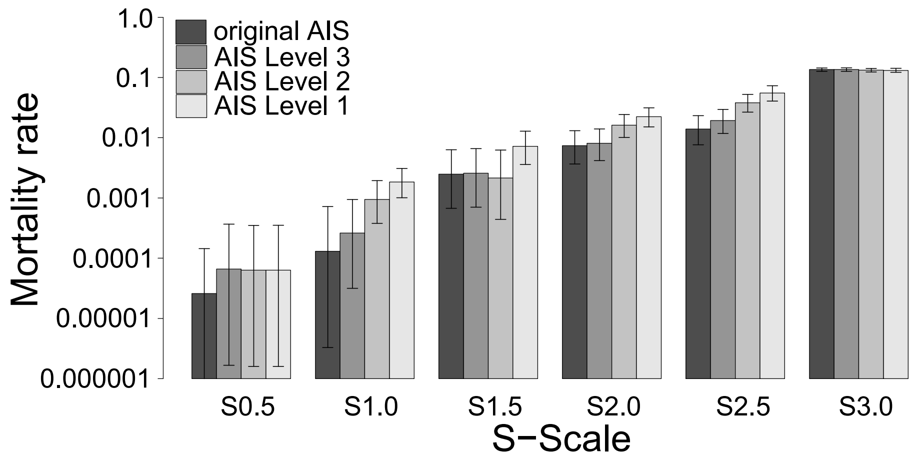

Fig. *1* S-Scale vs. Lethality: influence of AIS-ID aggregation on the lethality of the S-scale expressions: non-aggregated AIS-IDs and Level 1, 2, and 3 aggregation for GIDAS AIS coding.

S-Parameter Tables

Tables III and IV show the data-driven S-parameters for each of the four crash configurations and six traffic domains based on the GIDAS dataset. Only S-parameters based on at least 10 observations are shown. Cells left empty should be treated as S3.

To better understand the real-world crash data, we printed statistical measures of technical crash severity and case counts in Tables AII (AEV) and AVI (CIA) in the Appendix. We provide the mean and the 90% quantile for closing velocity (V0), collision velocity (VC), and delta-v (Δv) for each of the four crash configurations and six traffic domains. Note that we assume that an ADAS failure result in no pre-crash reaction. Thus, there is no reduction in the ego collision velocity for AEV vehicles, while for CIA vehicles in frontal collisions, there is a possible pre-crash ego velocity reduction. For side and rear-end collisions of AEV vehicles, the CIA can react and there is a possible pre-crash reduction of the impact velocity. In contrast, for side and rear-end collisions of CIA vehicles, due to the ADAS malfunction the AEV does not react and there is no reduction in impact velocity. Thus, in the rows of the AEV table for side and rear-end collisions, a CIA vehicle crashes into the AEV vehicle, i.e., a vehicle that can reduce its crash velocity. Vice versa, in the row of the CIA table for side and rear-end collisions, the opposing vehicle is an AEV, which does not mitigate its speed. For reference, we provide the S-scale 90th percentiles for belted occupants in pre-Euro NCAP vehicles, post-2006 vehicles, and unbelted front-row occupants in the Appendix.

TABLE III
BELTED OCCUPANTS IN POST-1998 AEV VEHICLES

[km/h]	0–14	15–29	30–49	50–69	70–99	100+
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	S0.5*$^{S2.5}$	S1.0*$^{S1.0}$

Note: *S-scale 90th percentiles estimated with 95% RHS statistical certainty for belted front-row occupants in ADAS-equipped vehicles stratified by traffic domain and crash configuration. For ISO 26262 S-parameters, use the non-rounded integer values.*
For cells in which the injury severity samples are not covering the whole S0 to S3 range, the maximum S-parameter value found in the samples for the cell is given following the asterisk (*); the S-parameters in such cells should be used with care.

TABLE IV
BELTED OCCUPANTS IN POST-1998 CIA VEHICLES

[km/h]	0–14	15–29	30–49	50–69	70–99	100+
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: *S-scale 90th percentiles estimated with 95% RHS statistical certainty for belted front-row occupants in crash 'partners' of the ADAS-equipped vehicles (CIA) stratified by traffic domain and crash configuration. For ISO 26262 S-parameters, use the non-rounded integer values.*
For cells in which the injury severity samples are not covering the whole S0 to S3 range, the maximum S-parameter value found in the samples for the cell is given following the asterisk (*); the S-parameters in such cells should be used with care. Cells with insufficient data were left empty and should be treated as S3.

IV. DISCUSSION

We wanted to compute crash data-driven S-parameters for ISO 26262 hazard and risk evaluations that non-expert crash researchers could use to evaluate crash injury severity. Therefore, we reduced the stratification of the crash configurations to a minimum, differentiating only between frontal, near-side, far-side, and rear-end collisions.

We also wanted to account for the increased passive safety standards in later years, especially the increased side-protection introduced with the Euro NCAP 2006 protocol [24]. Though the results for the lower speed traffic domains with their higher crash frequencies gave plausible results, the statistical uncertainty for the 90th percentiles for the high-speed domains was too wide to show an improvement (see Tables AIV and AVIII). Especially in the 70-90km/h traffic domain, the evaluations show several statistical artefacts due to the low case count and the rigid statistical requirements: For frontal collisions of AEV and CIA vehicles, the model year 2006 or later the right-hand-side 95% confidence interval of the 90% percentile is larger than those 98 or later. The AEV vehicles show the same behaviour for far-side crashes in the same traffic domain.

Due to the sample size, the statistical estimates for the S-parameters calculated for pre-1998 vehicles are more stable than for the other groups: The S-parameters for rear-end collision for the 70-99km/h traffic domain are stable for AEV and CIA vehicles. Furthermore, the S-parameter for the far-side crashes of CIA vehicles is lower despite the non-availability of curtain airbags.

Under the assumption of an ever-improving passive safety, the S-parameter tables for current AEV and CIA could be constructed using the minimum S-value from each of the three AEV and CIA tables, respectively. We continue to use 1998 as the homologation cut-off year for our evaluations.

Comparison with previously published S-parameter tables

The Examples given in ISO 26262 Annex

The ISO 26262 only asks for a four-level injury severity scale based on patient survival, without specifying any details. Annex B of the ISO 26262 touches on a non-descript AIS injury coding and introduces the 90th percentiles for an aggregated AIS code. As there are only qualitative crash speeds, e.g. very low speed, low speed, and medium speed, that cannot be directly compared to our data-driven results, a comparison is difficult, though none of the examples conflicts with our results. The note under the table that the informative examples must be considered on a case-by-case basis should be taken seriously [1].

By clustering crashes by traffic domain, we shift the focus from individual crashes to crash-speed distributions and their corresponding injury severity distribution. These injury severity distributions are the basis for constructing the S-scale and, thus, the S-parameters needed for the ISO 26262 evaluation. Our albeit coarse collision configuration stratification includes all vehicle crashes, not just some hand-picked examples.

SAE J2980: Considerations for ISO 26262 ASIL Hazard Classification

The SAE 'recommended practice' S-parameter table in Appendix B uses delta-v ranges to specify technical crash severity [4]. Note that delta-v (Δv) is not the difference in closing velocities of the vehicles but the absolute value of velocity change during a collision [25-26]. It is calculated post-crash during crash reconstruction. The results have a high level of uncertainty (5–10%), are underestimated for newer, stiffer vehicles [27], and are unreliable for new crash configurations [28]. In-crash delta-v measurements stored in event data-recorders (EDR) might improve the situation in the future [29-30]. Furthermore, delta-v is correlated to the closing speed but also depends on the mass ratio of the colliding objects, making delta-v values hard to estimate and interpret.

The wide delta-v ranges for the minimum and maximum for each injury severity level (20–30 km/h delta-v) hinder the practical use of the table, as does the overly wide delta-v range for each injury severity (40–45 km/h). Furthermore, the given delta-v ranges do not align well with the crash test results. For example, a modern vehicle's 64 km/h offset deformable barrier (ODB) crash test [31] has a less than 10% MAIS3+ injury severity risk, translating to an S1 and not an S3 (Table B1 in [4]).

Comparison to the 2020 Krampe/Junge paper

The injury severity assessment in the previously published data-driven S-parameter table [5] was based on the AIS 98 [8], a minor update of the AIS 1990 codebook [32] regarding the AIS-identifier codes. Even though injury severity evaluation using the AIS 90/98 was valued for its consistency and stable results, the assessment is based on the medical treatment of the 1980s. Using the AIS 2015 codebook [9] in the evaluation updates the medical treatment to the current standards. Using the original medical diagnoses instead of the AIS 98-identifier coding as a starting point for the AIS 2015 coding assesses the injuries as if they were treated to current standards [10].

The robustness of the injury severity coding was improved by aggregation of the individual injuries, i.e. the Level 1 coding, and an improved algorithm for the aggregation to the person level, i.e. NISS-like aggregation instead of MAIS [18]. This improved aggregation led directly to the seven-level S-scale, i.e. a scale with finer granularity, especially at the lower injury severity end, eliminating S0 from the S-parameter tables. The lowest 90th percentile in any traffic domain and any crash configuration is now S0.5. Assuming that one in 10 crashes results in relevant injuries, even in the low-speed traffic domains, seems much more reasonable than everybody always escaping unscathed. It should be noted that the S0.5, instead of an S0, makes it abundantly clear that there is no such thing as a low-speed S0 to get rid of an ASIL-level, i.e. reducing the E4, C3 ASIL-A to just a 'quality management' (QM) measure.

The S-parameter for the 30−50 km/h domain is increased from S0 to S1 for the near-side impact of a vehicle that does mitigate its impact speed (CIA). In the AEV vehicle's 70−100 km/h traffic domain, the side impact assessment was switched between near- and far-side to S2 and S1, respectively, thus rating near-side crashes as more dangerous than far-side ones, in line with the literature [14]. In the previous publication, the near-side collision was rated S1 and S3 for near-side collision with and without curtain airbag protection, respectively. The current evaluation does not stratify for curtain airbags as they are quasi-mandatory with the introduction of the 2006 Euro NCAP side pole crash test [24]. Restricting the vehicle homologation year to 2006 or later to stratify for vehicles equipped with curtain airbags elevates the S-parameter to S3 (see Table VIII), but this could be a side-effect of the consequential reduction of the number of crashes in the cell to just 50.

The previous 0−30 km/h traffic domain was separated into a 0−15 km/h ‘shared zone’ and a 15−30 km/h ‘residential road’ to ease the evaluation of crashes in low-speed zones and parking scenarios.

V. Limitations

The available crash data source limits the current evaluation. The work could include more crash configurations, such as sub-dividing frontal impacts, as suggested by Brumbelow [30], or differentiating side impacts from pole crashes. A different approach would be the clustering by crash type [33] instead of crash configuration, shifting the focus from crash to pre-crash. Furthermore, the vehicle 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 underrepresented in the crash data.

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

VI. Future Work

A detailed investigation into methods for decomposing crash situations into crash configurations and their re-aggregation could be warranted. And looking into future mobility concepts like quads, pods, and Kei cars could result in new insights.

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VIII. Appendix

A. AIS-ID Aggregation

TABLE AI
S-SCALE VS. LETHALITY

AIS-ID Level	S-scale	Count	Deceased	Mortality Rate	95% CI lower	95% CI upper
AIS Level 1	S0.5	15808	1	6.33E-05	1.60E-06	3.52E-04
AIS Level 1	S1.0	7590	14	1.84E-03	1.01E-03	3.09E-03
AIS Level 1	S1.5	1523	11	7.22E-03	3.61E-03	1.29E-02
AIS Level 1	S2.0	1389	31	2.23E-02	1.52E-02	3.15E-02
AIS Level 1	S2.5	814	45	5.53E-02	4.06E-02	7.33E-02
AIS Level 1	S3.0	5509	723	1.31E-01	1.22E-01	1.40E-01
AIS Level 2	S0.5	15838	1	6.31E-05	1.60E-06	3.52E-04
AIS Level 2	S1.0	7413	7	9.44E-04	3.80E-04	1.94E-03
AIS Level 2	S1.5	1401	3	2.14E-03	4.42E-04	6.24E-03
AIS Level 2	S2.0	1362	22	1.62E-02	1.01E-02	2.44E-02
AIS Level 2	S2.5	920	35	3.80E-02	2.66E-02	5.25E-02
AIS Level 2	S3.0	5699	757	1.33E-01	1.24E-01	1.42E-01
AIS Level 3	S0.5	15128	1	6.61E-05	1.67E-06	3.68E-04
AIS Level 3	S1.0	7646	2	2.62E-04	3.17E-05	9.45E-04
AIS Level 3	S1.5	1550	4	2.58E-03	7.04E-04	6.59E-03
AIS Level 3	S2.0	1487	12	8.07E-03	4.18E-03	1.41E-02
AIS Level 3	S2.5	1035	20	1.93E-02	1.18E-02	2.97E-02
AIS Level 3	S3.0	5787	786	1.36E-01	1.27E-01	1.45E-01
original AIS	S0.5	38503	1	2.60E-05	6.58E-07	1.45E-04
original AIS	S1.0	7689	1	1.30E-04	3.29E-06	7.24E-04
original AIS	S1.5	1612	4	2.48E-03	6.76E-04	6.34E-03
original AIS	S2.0	1493	11	7.37E-03	3.68E-03	1.31E-02
original AIS	S2.5	1005	14	1.39E-02	7.64E-03	2.33E-02
original AIS	S3.0	5849	794	1.36E-01	1.27E-01	1.45E-01

Note: *influence of AIS-ID aggregation on the lethality of the S-scale expressions: non-aggregated AIS-IDs and Level 1, 2, and 3 aggregation for GIDAS AIS coding. Note that at Level 1, all six S-scale levels have a statistically significant difference in lethality.*

B. AEV (ADAS-equipped vehicle)

TABLE AII
NUMBER OF CASES (N) AND DISTRIBUTION PARAMETERS FOR THE TECHNICAL CRASH SEVERITIES OF BELTED FRONT-ROW OCCUPANTS IN CURRENT ADAS -EQUIPPED VEHICLES (AEV): MEAN AND 90% QUANTILE IN BRACKETS, BOTH IN KM/H

	[*km/h*]	0–14	15–29	30–49	50–69	70–99	100+
frontal	*V*0	39 (70)	45 (70)	54 (79)	70 (96)	89 (111)	113 (130)
	VC	32 (57)	38 (60)	47 (68)	64 (84)	85 (105)	111 (130)
	Δv	15 (34)	17 (36)	21 (42)	28 (55)	34 (67)	40 (98)
	n	7533	5984	3844	1359	349	60
far-side	*V*0	34 (65)	41 (68)	52 (74)	64 (86)	84 (101)	113 (129)
	VC	29 (55)	34 (60)	42 (65)	52 (75)	67 (89)	86 (110)
	Δv	8 (23)	9 (24)	13 (28)	16 (31)	18 (40)	19 (50)
	n	2042	1617	1079	552	158	25
near-side	*V*0	38 (70)	44 (70)	53 (77)	64 (89)	85 (110)	113 (130)
	VC	32 (60)	36 (61)	43 (67)	52 (77)	67 (94)	93 (114)
	Δv	9 (23)	10 (24)	13 (26)	14 (30)	17 (40)	17 (52)
	n	2148	1794	1321	718	217	37
rear-end	*V*0	36 (63)	46 (70)	51 (70)	61 (80)	84 (100)	115 (137)
	VC	26 (49)	31 (50)	33 (54)	41 (64)	58 (90)	87 (126)
	Δv	12 (23)	13 (24)	14 (26)	16 (28)	19 (34)	15 (28)
	n	3027	2314	1984	997	236	36

Note: *crash parameters: VC (collision velocity; ego vehicle for frontal, opponent's vehicle for rest), Δv (change of velocity), V0 (travelling velocity; ego vehicle for frontal, opponent's vehicle for rest).*

TABLE AIII
OCCUPANTS IN POST-1998 VEHICLES, NO BELT USE AEV

[*km/h*]	0–14	15–29	30–49	50–69	70–99	100+
frontal	S0.5	S1.0	S1.0	S2.5	S3.0	
near-side	S0.5	S0.5	S1.0	S1.5	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*$^{S2.0}$	

Note: *S-scale 90th percentiles estimated with 95% RHS statistical certainty for unbelted front-row occupants in ADAS-equipped vehicles with a homologation after 1998, stratified by traffic domain and crash configuration. For ISO 26262 S-parameters, use the non-rounded integer values.*
For cells in which the injury severity samples are not covering the whole S0 to S3 range, the maximum S-parameter value found in the samples for the cell is given following the asterisk (*); the S-parameters in such cells should be used with care. Cells with insufficient data were left empty and should be treated as S3.

TABLE AIV
OCCUPANTS IN POST-2006 VEHICLES, BELT USE AEV

[*km/h*]	0–14	15–29	30–49	50–69	70–99	100+
frontal	S0.5	S0.5	S0.5	S1.0	S3.0	
near-side	S0.5	S0.5	S0.5	S1.0	S2.0	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*$^{S1.5}$	S1.0*$^{S1.0}$

Note: *S-scale 90th percentiles estimated with 95% RHS statistical certainty for belted front-row occupants in ADAS-equipped vehicles with a homologation after 2006, stratified by traffic domain and crash configuration. For ISO 26262 S-parameters, use the non-rounded integer values.*
For cells in which the injury severity samples are not covering the whole S0 to S3 range, the maximum S-parameter value found in the samples for the cell is given following the asterisk (*); the S-parameters in such cells should be used with care. Cells with insufficient data were left empty and should be treated as S3.

TABLE AV
OCCUPANTS IN PRE-1998 VEHICLES, BELT USE AEV

[*km/h*]	0–14	15–29	30–49	50–69	70–99	100+
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	S1.0	S1.5	S2.5
rear-end	S0.5	S0.5	S0.5	S0.5	S0.5	S1.0

Note: *S-scale 90th percentiles estimated with 95% RHS statistical certainty for belted front-row occupants in ADAS-equipped vehicles with a homologation before 1998, stratified by traffic domain and crash configuration. For ISO 26262 S-parameters, use the non-rounded integer values.*

C. CIA (Car involved in the crash due to an ADAS-failure in the opposing vehicle)

TABLE AVI

NUMBER OF CASES (N) AND DISTRIBUTION PARAMETERS FOR THE TECHNICAL CRASH SEVERITIES OF BELTED FRONT-ROW OCCUPANTS IN CRASH PARTNER VEHICLE (CIA): MEAN AND 90% QUANTILE IN BRACKETS, BOTH IN KM/H.

CIA							
	[*km/h*]	0–14	15–29	30–49	50–69	70–99	100+
frontal	*V* 0	39 (70)	46 (70)	52 (75)	63 (85)	84 (101)	110 (130)
	VC	32 (57)	36 (60)	40 (64)	49 (74)	66 (93)	89 (117)
	Δv	15 (34)	17 (36)	19 (38)	23 (46)	31 (60)	37 (75)
	n	7533	6206	5111	2654	774	125
far-side	*V* 0	34 (65)	41 (70)	53 (77)	68 (92)	87 (116)	118 (134)
	VC	29 (55)	36 (60)	47 (68)	63 (81)	81 (97)	107 (116)
	Δv	8 (23)	10 (25)	14 (29)	17 (34)	17 (38)	17 (37)
	n	2042	1533	894	319	84	8
near-side	*V* 0	38 (70)	44 (70)	54 (80)	69 (96)	88 (114)	114 (136)
	VC	32 (60)	38 (62)	48 (70)	64 (84)	83 (103)	110 (123)
	Δv	9 (23)	11 (24)	14 (28)	15 (32)	15 (36)	15 (42)
	n	2148	1718	1086	422	116	16
rear-end	*V* 0	36 (63)	43 (70)	54 (77)	72 (99)	94 (127)	119 (142)
	VC	26 (49)	34 (51)	44 (60)	64 (87)	87 (114)	118 (135)
	Δv	12 (23)	14 (25)	18 (28)	22 (34)	20 (38)	17 (27)
	n	3027	2198	1170	299	83	17

Note: *crash parameters: VC (collision velocity; ego vehicle for frontal, opponent's vehicle for rest), Δv (change of velocity), V0 (travelling velocity; ego vehicle for frontal, opponent's vehicle for rest).*

TABLE AVII
OCCUPANTS IN POST-1998 VEHICLES, NO BELT USE CIA

[*km/h*]	0–14	15–29	30–49	50–69	70–99	100+
frontal	S0.5	S0.5	S0.5	S1.0	S3.0	
near-side	S0.5	S0.5	S1.0	S2.0	S3.0	
far-side	S0.5	S0.5	S1.0	S2.5	S3.0	
rear-end	S0.5	S0.5	S0.5	S1.0	S2.0*[S2.0]	

Note: *S-scale 90th percentiles estimated with 95% RHS statistical certainty for unbelted front-row occupants in crash 'partners' of the ADAS-equipped vehicles (CIA) with a homologation after 1998, stratified by traffic domain and crash configuration. For ISO 26262 S-parameters, use the non-rounded integer values.*
For cells in which the injury severity samples are not covering the whole S0 to S3 range, the maximum S-parameter value found in the samples for the cell is given following the asterisk (*); the S-parameters in such cells should be used with care. Cells with insufficient data were left empty and should be treated as S3.

TABLE AVIII
OCCUPANTS IN POST-2006 VEHICLES, BELT USE CIA

[*km/h*]	0–14	15–29	30–49	50–69	70–99	100+
frontal	S0.5	S0.5	S0.5	S1.0	S2.5	S3.0
near-side	S0.5	S0.5	S1.0	S1.0	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*[S1.5]	

Note: *S-scale 90th percentiles estimated with 95% RHS statistical certainty for belted front-row occupants in crash 'partners' of the ADAS-equipped vehicles (CIA) with a homologation after 2006, stratified by traffic domain and crash configuration. For ISO 26262 S-parameters, use the non-rounded integer values.*
For cells in which the injury severity samples are not covering the whole S0 to S3 range, the maximum S-parameter value found in the samples for the cell is given following the asterisk (*); the S-parameters in such cells should be used with care. Cells with insufficient data were left empty and should be treated as S3.

TABLE AIX
OCCUPANTS IN PRE-1998 VEHICLES, BELT USE CIA

[*km/h*]	0–14	15–29	30–49	50–69	70–99	100+
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	S1.0	S2.5	S3.0
rear-end	S0.5	S0.5	S0.5	S0.5	S1.0	S0.5

Note: *S-scale 90th percentiles estimated with 95% RHS statistical certainty for belted front-row occupants in crash 'partners' of the ADAS-equipped vehicles (CIA) with a homologation before 1998, stratified by traffic domain and crash configuration. For ISO 26262 S-parameters, use the non-rounded integer values.*