Development of a combined Injury Criteria for the comparative Evaluation of Long-term Injury Outcome and Mortality Risk assessed in Car-to-Pedestrian Accidents

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Abstract In order to assess the relevance of certain traffic accident types, collisions or injury patterns, the abbreviated injury scale and its maximum value, known as MAIS, is a well-established evaluation measurement in the field of accident research and vehicle safety. Despite all of its benefits, however, it lacks the ability to compare or combine severe injuries with respect to either mortality or long-term impairment. With vehicle safety specifically and traffic safety in general improving, an evaluation method to assess non-fatal injuries as well as fatal injuries has become necessary. This paper proposes a combined evaluation method based on the AIS 2005 rev. 08 code and period life tables. The method is generically formulated and in the context of this paper applied to GIDAS data and German period life tables. Its usefulness is proven in an example analysis involving car-to-pedestrian frontal collisions from GIDAS. The method shows a certain significance for the lower extremities due to their long-term impairment characteristics, while the head is still proven to be the most relevant body part in this area of action. For the lower extremities, the most important injury type is the fracture of bony structures in the lower leg.

Keywords Accident Data Analysis, Abbreviated Injury Scale, Injury Assessment, Injury Evaluation, Pedestrian Accidents.

I. INTRODUCTION

Over the last decade, the number of killed and severely injured (KSI) pedestrians in Germany was reduced by over 15% [1-2]. Many different countermeasures have been introduced, ranging from infrastructure to road safety education to passive as well as active safety systems and improvement of the rescue chain. Abbreviated Injury Scale (AIS) injury scores are frequently used to evaluate injury outcome because they take the mortality risk of an injury into account. This metric is best suited for injuries that pose a threat to survival (e.g. the head and thorax), however injuries with minor risk to life but long-term impairment are underrated by this approach. This applies to body regions such as the upper and lower extremities, with the latter currently being the focus of consumer metrics for passive safety countermeasures.

In order to assess the effectiveness of such countermeasures, it is necessary to evaluate the long-term injury outcomes of pedestrians in addition to the mortality risk. Therefore, the aim of this study is to develop a combined measure that allows injury risk and long-term injury outcome to be directly compared. The method developed is then used to assess the relevance of all injuries, with a focus on lower extremity injuries in car-to-pedestrian frontal collisions using the GIDAS (German In-Depth Accident Study) database. The lower extremity body region is then further investigated for relevant injury types.

II. METHODS

This section describes, first, the evaluation method. Then, the steps taken to filter and isolate car-to-pedestrian accidents from GIDAS in order to assess the relevance for the different AIS body regions with respect to pedestrian injuries is explained.

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Evaluation Method

The objective of this study is to identify a methodology that would allow long-term impairment to be quantified and directly compared with short-term effects. Furthermore, the methodology is combined with a newly developed predictor for fatality risk by body region and was applied to a specific field of interest. This comparison can be done quantitatively only if both types of effect have the same units (i.e. years, euro, etc.). This methodology performs a Quality Adjusted Life Years (QALY) [3-4] type calculation using the Functional Capacity Index (FCI) [5-6] as the health metric, multiplied by the predicted remaining life years for a person [7]. This measure, Life Years Lost to Injury (LLI_{FCI}), has the units of years and it can be directly compared with the number of years of life lost when a person is killed in a crash (LLI_{Fatal}).

For the assessment of long-term injury outcome as well as mortality risk, measurements for each aspect are needed. The latter is described in general by the AIS, which is also used for the proposed method, in its 2005 version with 2008 revision [8], referred to here as AIS08. As the AIS08 is widely accepted in the field of accident research, it is included in most in-depth accident databases. For the assessment of long-term consequences w.r.t. impairment, the Functional Capacity Index 100, as described by [7] is used, referred to here as FCI_{100}. It evaluates the impairment in 10 functional dimensions, d (eating, excretory function, sexual function, ambulation, hand and arm function, bending and lifting, visual function, auditory function, speech and cognitive function) [7] one year after being injured. It is based on the AIS08 coding and thus also applicable for many in-depth accident databases.

To combine both aspects, the proposed method uses the approach of measuring lost life years via a QALY calculation [7]. The main idea is that at the time of sustaining an injury (t_0), the respective person has statistically y_{rem} remaining life years, which are completely lost in the case of death or partly lost due in the case of reduced life quality (Q) caused by long-term impairment. The QALY can be computed using the following equation:

$$QALY = \int_{t_0}^{t_0+y_{rem}} Q(t)\, dt \tag{1}$$

with $Q(t) \in [0,1] \in \mathbb{R}$. In the context of this paper, $Q(t)$ for $t \geq t_0$ is assumed to be constant, so (1) simplifies to:

$$QALY = y_{rem}\, Q \tag{2}$$

Please note that death can be considered as $Q = 0$, thus $QALY$ can be used for impairment as well as mortality. $Q(t)$ for $t < t_0$, due to lack of better knowledge, is assumed to be equal to 1, so reduction of Q is considered to reduce the $QALY$ to full extent. The life years lost (LL) can then be computed by:

$$LL = y_{rem} - QALY = y_{rem}(1 - Q) \tag{3}$$

The y_{rem} can be computed by using period life tables, with age, gender and year of accident as parameters. In this paper, the period life tables of Germany from 2015 [9-10] are used, so the latter parameter is skipped.

For impairment, the FCI_{100} is used to compute Q by interpreting its value as life quality in percentage as in [7]. As the FCI_{100} only evaluates single injuries, a measurement combining multiple injuries w.r.t. impairment is needed. For an entire injury pattern of a single person, this measurement has been developed by [7] and is called Whole-Body FCI (WBFCI). Based on the WBFCI the multi-injury FCI ($MIFCI$) is proposed and computed by applying the computation formula of the FCI_{100} using the minimum of each FCI dimension for all considered injuries in an injury pattern I:

$$MIFCI(I) = 40 \cdot \prod_{d=1}^{10} \left(\frac{\min_{i \in I}\left(FCI_{100,d}^{i}\right) - 60}{40} + 60 \right) \tag{4}$$

$FCI_{100,d}^{i} \in [60,100] \in \mathbb{R}$ here denotes the FCI_{100} value for impairment dimension d of injury i. Within the context of this paper, an injury pattern is defined as a set of AIS08 codes, as shown in Table I.

TABLE I
EXAMPLE COMPUTATION FOR THE MIFCI

AIS08 CODE	$FCI_{100,1}$	$FCI_{100,2}$	$FCI_{100,3}$	$FCI_{100,4}$	$FCI_{100,5}$	$FCI_{100,6}$	$FCI_{100,7}$	$FCI_{100,8}$	$FCI_{100,9}$	$FCI_{100,10}$
121499.3	100	100	100	80	73.1	92.7	100	100	90	78
711002.4	100	100	88.9	100	73.1	92.7	100	100	100	100
856174.5	100	79.9	88.9	85	100	92.7	100	100	100	100
873089.1	100	100	88.9	80	100	92.7	100	100	100	100
320211.4	86	79.9	88.9	80	76.9	86	91	97	79	78
310806.3	100	100	100	100	100	100	100	100	100	100
MIFCI	86	79.9	88.9	80	73.1	86	91	97	79	78

In the context of this paper, the MIFCI is primarily used for the whole body and then referred to as $WBFCI$, or for a single AIS body region r. In the latter case it is denoted as $MIFCI_r$. Q is finally defined as follows:

$$Q := \begin{cases} 0 & if\ person\ died \\ \dfrac{WBFCI}{100} & if\ person\ survived \end{cases} \tag{5}$$

With knowledge of the fatality probability $p(I_{WB})$ of the whole-body injury pattern I_{WB}, one can compute the expected value for Q by:

$$E(Q) = p(I_{WB}) \cdot 0 + (1 - p(I_{WB}))\frac{WBFCI}{100} = (1 - p(I_{WB}))\frac{WBFCI}{100} \tag{6}$$

and thus the expected value for the life years lost for a given y_{rem}:

$$E(LL) = y_{rem}\big(1 - E(Q)\big) = y_{rem}\left(1 - \big(1 - p(I_{WB})\big)\frac{WBFCI}{100}\right)$$

$$= \underbrace{p(I_{WB})\, y_{rem}}_{LL_D} + \underbrace{\big(1 - p(I_{WB})\big)\left(1 - \frac{WBFCI}{100}\right) y_{rem}}_{LL_I} \tag{7}$$

The expected life years lost can be divided into the expected life years lost due to death (LL_D) and life years lost due to impairment (LL_I), as shown in Equation (7) where $\big(1 - p(I_{WB})\big)$ is the chance of survival and $\left(1 - \frac{WBFCI}{100}\right)$ is the grade of impairment.

In the following, the fatality risk function $p(I_{WB})$ is derived. The derivation is based on GIDAS, Status Dec. 2018. For the regression, all persons with known survival state (03_PERSDAT.PVERL is known) and only injuries with known severity (05_VERL.AIS08 for all injuries of the person is not 9) are taken into account. Furthermore, persons coded as dead (03_PERSDAT.PVERL = 5) where the death is not caused by the injuries are excluded. The resulting dataset consists of 82,789 persons, comprising 44,471 injured and 529 fatalities.

The following assumptions have been made:

1. No injuries should result in no fatality risk: $p(\emptyset) := 0$.
2. The risk is between 0 and 100%: $0 \leq p(I) \leq 1$.
3. p should be monotonically increasing with the severity of I.
4. Injury mortality is comparable between injuries of the same AIS severity.

For the measurement of an injury severity pattern, this paper proposes the use of the NISSx, as developed by [11]. It is based on the AIS severity and the main idea of the New Injury Severity Score (NISS) is defined as:

$$NISSx(I) := \begin{cases} 0 & if\ I = \emptyset \\ 75 & if\ I\ contains\ at\ least\ one\ AIS\ 6\ injury \\ \sum_{l=1}^{\min(3,|I|)} AISx_l & otherwise \end{cases} \quad (8)$$

where $AISx_1$, $AISx_2$, $AISx_3$ denote the $AISx$ values of the three most severe injuries of I, if existing. The $AISx$ is a nonlinear transformation of the AIS severity aimed at linearising the relation between the AIS severity and mortality:

$$AISx(AIS) := 25\frac{e^{AIS} - 1}{e^5 - 1} \quad (9)$$

With this transformation, the mortality risk of a single injury [8] becomes nearly linear:

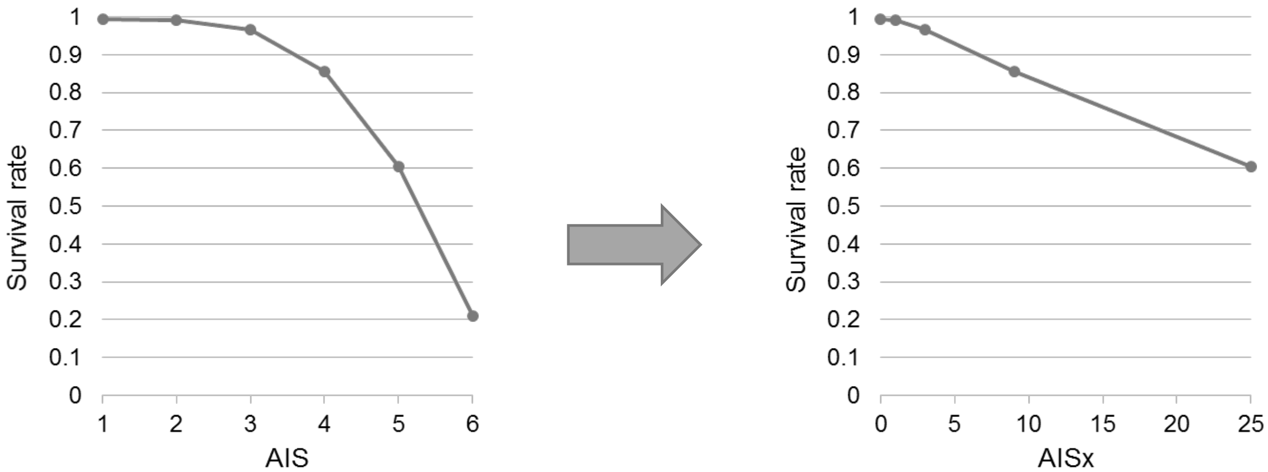

Fig. 1. Comparison of AIS and AISx severity w.r.t. mortality risk.

The NISSx has been chosen as a predictor feature by the authors because, compared to the NISS, it has two very advantageous properties. First, it is a bijective mapping from the triplet of AIS values to a real value – in contrast to the NISS, which is surjective. Consequently, different triplet map to the same value, e.g. (4,3,0) and (5,0,0). Secondly, w.r.t. to mean fatality rates, the NISSx shows a much stronger tendency to be monotonically increasing, which is quite beneficial in finding a suitable predictor model and much more comprehensible than a non-monotonic correlation. Furthermore, this property is beneficial to meet the requirement of assumption 3.

Now, using the NISSx as an independent variable, a suitable regression model has to be found. After comparing different model functions, such as logistic, cosine, polynomial, exponential, etc. a piecewise linear approach with three linear parts showed the best data fit. Additionally, a feed-forward neural network regressor (FF-NN) has been trained with the data. The resulting regression was very similar to the piecewise linear function, despite the FF-NN being a non-linear and much more complex model. Hence, the simpler model has been chosen.

For the fitting, Python 3.6 was used with scipy 1.1.0. and sklearn 0.19.1. The model parameterisation has been performed using the Ordinary Least Squares (OLS) method.

The resulting model parameters are as follows:

TABLE II
COMPUTED MODEL PARAMETERS

End of 1st part [NISSx]	5.09887299
End of 2nd part [NISSx]	14.8734728
Slope of 1st part [1 / NISSx]	0.00081308
Slope of 2nd part [1 / NISSx]	0.02779069
Slope of 3rd part [1 / NISSx]	0.01140048

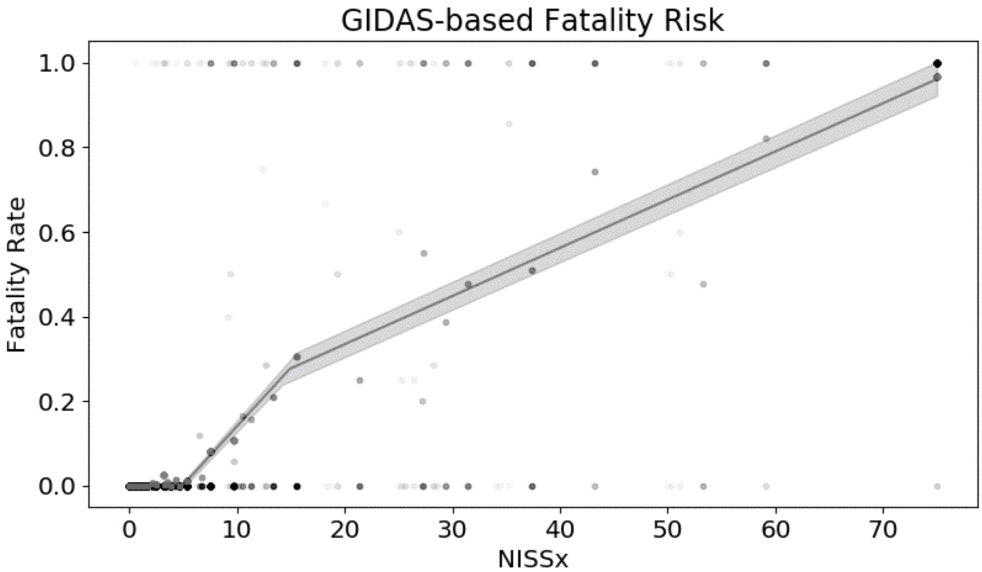

Fig. 2. The developed piecewise mortality risk function consists of three linear parts. The dots at 0 (=survival) and 1 (=fatal) indicate the observations in the dataset. The other data points show the mean rate of fatality for each NISSx value. The darker the dots, the more observations are present in the dataset. The grey band shows the 95% confidence band w.r.t. the parameter optimisation based on the covariance matrix of the optimisation process and a student-t distribution for the model error.

For the assessment of the relevance of the lower extremities, the next step is to determine the contribution of each AIS body region to the life years lost due to death (LL_D) and impairment (LL_I). It is proposed to calculate the contributions to LL_D and LL_I by the weighted proportion of fatality risk and impairment severity, respectively.

As $p(I)$ was derived solely on the basis of injury severity, it can also be applied to single body regions and their respective injury patterns (I_r). Assuming only body region r was injured, $p(I_r)$ computes the fatality risk. This can be done for each body region individually. The so computed $p(I_r)$ enables comparison of the contribution to the overall fatality risk. Weighted by the $p(I_r)$, the attributable life years lost due to death of body region r (called $LL_{D,r}$) can be computed as follows:

$$LL_{D,r} \coloneqq \frac{p(I_r)}{\sum_{a=0}^{9} p(I_a)} LL_D \tag{10}$$

Similarly, the attributable life years lost due to impairment of body region r (called $LL_{I,r}$) can be computed by the respective impairment:

$$LL_{I,r} \coloneqq \frac{100 - MIFCI(I_r)}{\sum_{a=0}^{9}\left(100 - MIFCI(I_a)\right)} LL_I \tag{11}$$

The life years lost of a body region (LL_r) are therefore:

$$LL_r \coloneqq LL_{D,r} + LL_{I,r} \tag{12}$$

Please note that the following equations hold, due to the design of the $LL_{D,r}$ and $LL_{I,r}$:

$$LL_D = \sum_{r=0}^{9} LL_{D,r} \tag{13}$$

$$LL_I = \sum_{r=0}^{9} LL_{I,r}$$

$$LL = \sum_{r=0}^{9} LL_r$$

Equation (13) shows that the proposed method to divide the overall life years lost to the single body regions maintains the total amount of life years lost.

Summary

In this section, a method was developed that allows the assessment of mortality risk and impairment of injury patterns on a common basis, i.e. the life years lost (LL). It is based on AIS08 coding. Furthermore, a method to derive the contribution of each AIS body region to the LL has been proposed. This allows comparison between body regions w.r.t. to mortality and impairment in a combined measurement. The computation of the LL fatality risk function based on the NISSx has been derived based on GIDAS data.

Dataset

For the comparison of the proposed evaluation method, the relevance of the individual AIS body regions in frontal accidents between pedestrians and cars has been chosen as an example, using GIDAS. Subject to the comparison are the pedestrians and their injury patterns.

Only fully reconstructed and coded cases were chosen (01_UMWELT.STATUS = 4) and only accident years starting from 2000 (01_UMWELT.JAHR > 1999) were taken into account. To ensure that the analysis reproduces relevant numbers that are representative for the case of a modern car colliding with a pedestrian, those cases were excluded in which the pedestrian had a secondary collision with another vehicle, the car had another collision prior to that with the pedestrian, a second car was involved or the cars had a model year introduction prior to 2000. Frontal collisions were defined by the involved car plane (i.e. frontal, 20_REKO.VDI2=1) and a forward moving direction (27_STRASSE.RICHT = 3). Furthermore, cases containing injuries with unknown injury severity and thus unsure diagnosis were excluded (05_VERL.AIS08 != 9). To ensure a body pose comparable to a typical pedestrian accident, only cases without involvement of sport equipment (SPORT = 2) or equipment maintaining an upright standing/walking position (GEHHILFE in 2, 3, 4, 5 or 6) have been taken into account. These filter steps resulted in 497 cases, including only four cases without any injuries. All injuries are taken into account, independent of coded injury cause (e.g. vehicle parts, ground impact).

TABLE III

ACCIDENT DATA FILTER STEPS

Data filter (GIDAS), Dataset Dec. 2018	**Number of persons**
All pedestrians in fully reconstructed accidents starting with year 2000 (ARTTEIL=6) & (STATUS=4) & (JAHR ≥2000)	4,576
1st collision of the pedestrian is with passenger car (FART=3, FZART≤26 OR 36 OR 60 OR 61 OR 62, FZGKLASS < 15)	3,151
Passenger car year of market introduction ≥ 2000	1,022
Pedestrian has no further collisions with 2-track vehicle	990
Only one passenger car involved in the accident	977
Only collisions in which the 1st collision of the passenger car is with a pedestrian	975
Only frontal collisions of passenger car (VDI2=1) & (RICHT = 3)	575
Only injured pedestrians with known MAIS08 (MAIS08 ≠ 9)	551
Only pedestrians with “pedestrian-like” pose (SPORT=2) & (GEHHILFE is in [2,3,4,5,6])	497

III. RESULTS

As a first step, the maximum AIS severity was calculated for each pedestrian and body region. Then the percentage of pedestrians that suffered an AISX+ injury in each body region w.r.t. all pedestrians in the subset was computed. Fig. 3 shows these shares for AIS2+, AIS3+ and AIS4+ injuries.

In terms of AIS2+ injuries, the highest relevance can be shown for the lower extremities, the head, the upper extremities and the thorax in descending order. This is not surprising as the lower extremities are prone to be contacted by the car, and injuries to the head often result in a higher injury severity. With higher injury severity, the relevance shifts towards head and thorax, with the importance of the upper and lower extremities decreasing. For AIS3+ injuries, the relevance of head, lower extremities and thorax is nearly equal. For AIS4+ injuries, the highest relevance is found in the head region. Based on the selected severity limit, very different conclusions can be drawn.

As AIS2 injuries pose a significantly lower threat to life compared to injuries with a higher severity, AIS3+ or AIS4+ shares seem to provide a better basis for an evaluation. On the other hand, AIS3+ or AIS4+ shares might understate the importance of the lower extremities, as many of the possible injuries located there result in long-term impairment. Thus, the proposed method is used to generate a combined assessment for both effects, i.e. fatal and long-term impairment outcomes.

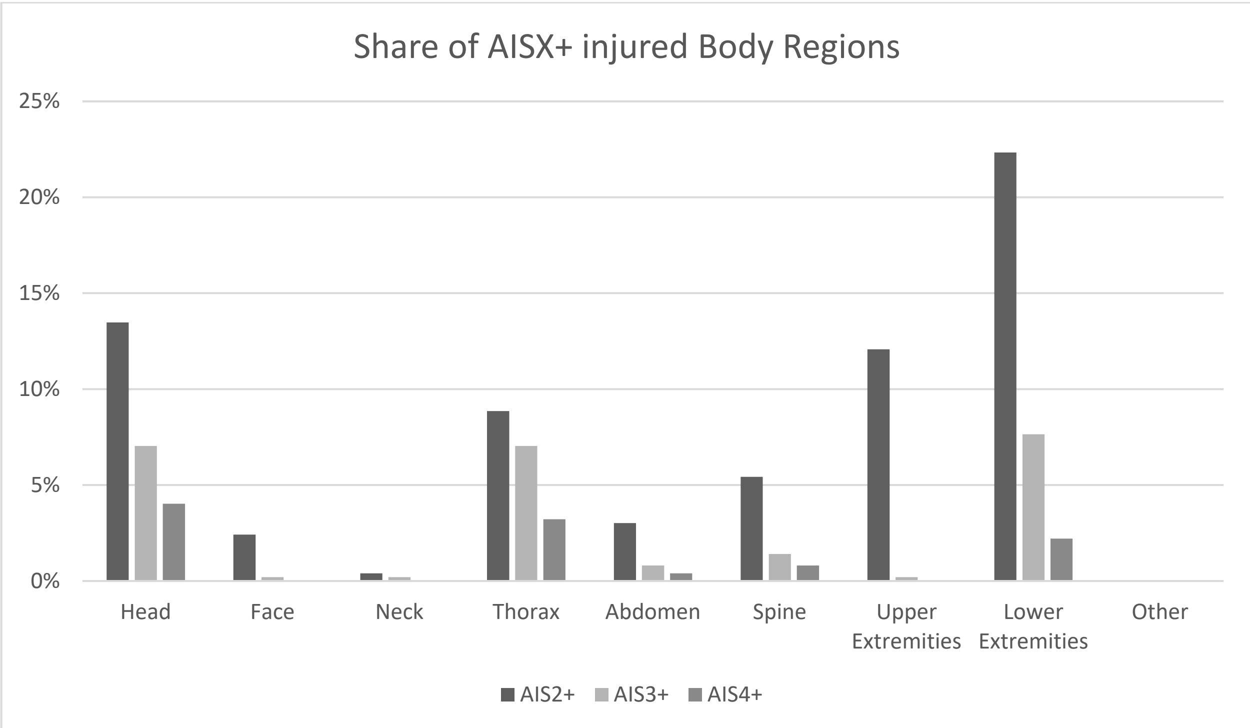

Fig. 3. The share of pedestrians with at least one AISX+ injury in the specified body region. For example, 22.3% of all pedestrians suffered at least one AIS2+ injury in the lower extremities.

For each pedestrian the expected life years lost due to injury and due to death are computed and weighted between the injured body regions following the method developed in section II. The $LL_{D,r}$ and $LL_{I,r}$ values for each body region are summed up to gain the LL_r over all pedestrians w.r.t. each body region in relation to all life years lost.

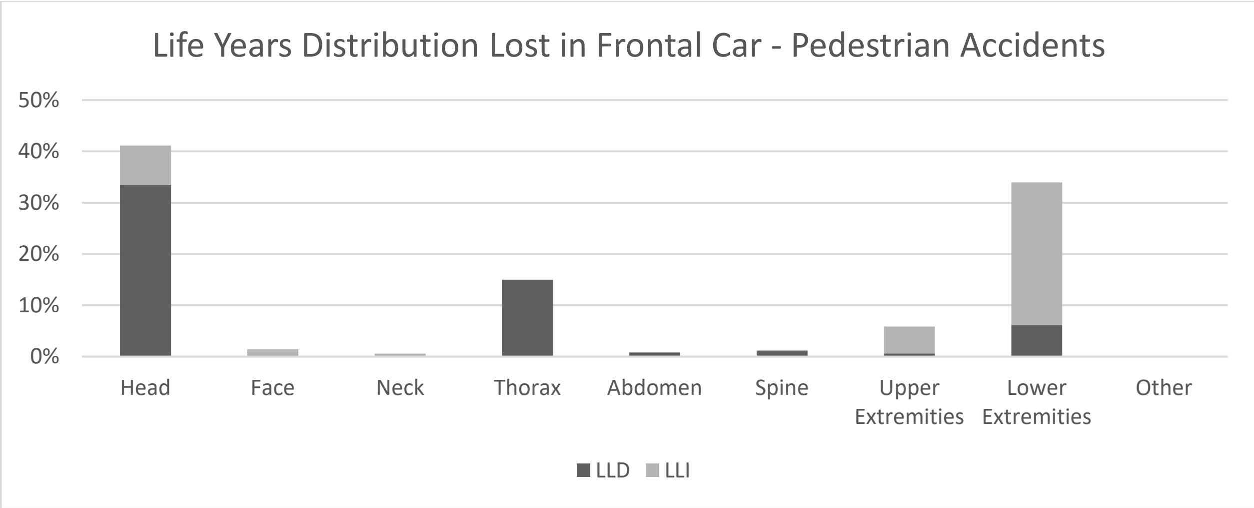

Fig. 4. Distribution of all life years lost w.r.t. AIS body region. For example, 41.1% of all life years lost are caused by injuries to the head, with 33.4% due to mortality and 7.7% due to long-term impairment.

The results show a different pattern compared to the AIS-based analysis, with a comparatively high relevance for the lower extremities. The life years lost accounted to the AIS region 8 (lower extremities) are mainly caused by long-term impairment. The $LL_{I,8}$ accounts for 27.8% of all LL, while the $LL_{D,8}$ at 6.2% is much lower, summing up to 33.9%. The third most important body region is the thorax, which only shows significant importance in mortality risk (15%). This is also caused by the fact that most injuries in the thorax region do not have long-term impairment effects, according to the FCI scale. Finally, the most relevant region is the head, with a relevance of 41.1%, with 33.4% to mortality and 7.7% to long-term impairment, respectively. Therefore, the fatal outcome of the head body region alone is nearly as important as the overall outcome for the lower extremities.

As consumer organisations focus more and more on lower extremity injuries, an analysis of lower extremity injuries caused by primary contact with the car in collisions at speeds below 45 km/h is performed. To allow for a certain inaccuracy in the collision velocity data, all cases with a collision speed up to 47 km/h are included in the analysis (20_REKO.VK <= 47). This reduces the previous dataset to 434 pedestrians, including one case with a car standing still. In 45 cases the collision speed exceeds 47 km/h, and 18 cases have unknown velocity data. The injuries in the lower extremity body region are divided into several groups and the attributable life years lost are computed analogously to equations (10) and (11). Figure 5 shows the results.

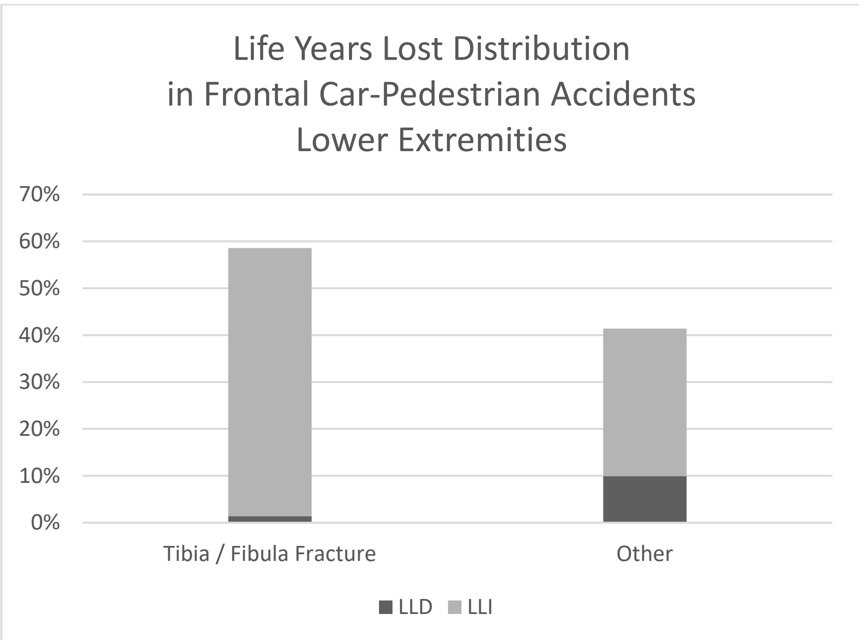

Fig. 5. Distribution of life years lost attributable to the lower extremities comparing tibia and fibula fractures with all other occurring injuries.

From the results it can be seen that the relevance w.r.t. life years lost within AIS region 8 (lower extremities) is dominated by fractures in the lower leg, meaning fibula and tibia. All other occurring injuries result in less life years lost, although the share w.r.t. mortality of the tibia and fibula is comparably low.

IV. DISCUSSION

The proposed method adds a combined approach for the assessment of injuries with fatal or long-term impairment consequences to the field of accident research and traffic safety. It is based on existing scoring systems and measurements like the AIS08, the FCI and the QALY. The assessment is measured in the units of life years lost and thus allows a direct comparison between mortality and long-term impairment.

With the AIS08 being a widely used and accepted injury rating system, the proposed method is suitable for most accident databases. Due to the use of an AIS-based mortality risk function as an estimator for fatal injury outcome, the method can be used on arbitrary injury patterns, i.e. in particular subsets of injury patterns, but also on purely virtual patterns. In summary, the long-term injury outcome can be derived for the whole body as well as per body region or any other injury pattern subset.

The computation method for the attributable life years lost enables comparison of subsets of injury patterns, although it should be noted that this method is a pragmatic approach that has not yet been validated. As the computation of the LL_I is based mainly on the WBFCI, it inherits its strengths and limitations. It measures the impairment state one year after sustaining an injury [12]. However, if the long-term consequences of an injury change after this point in time for better or worse, this change will not be measured by the LL_I. Another characteristic of the proposed method is its dependency on the life span of the persons who are to be evaluated. On the one hand, this could lead to over- or underrating because of different life spans. On the other hand, this effect incorporates the impact of age to injury reception.

V. CONCLUSIONS

This paper and the evaluation method it proposes present, for the first time, a comparison between long-term injury outcome and mortality risk for pedestrians in collisions with passenger cars. The proposed method allows injuries with a different severity basis, i.e. mortality and long-term impairment, to be compared using the same units of measurement.

Using the proposed method, it is evident that injuries of the lower extremities have a certain relevance that is mainly caused by fracture injuries of the lower leg. Despite the particular consideration of long-term injury outcome, the relevance of head injuries still outnumbers that of the lower extremities.

Therefore, rating schemes should represent this overall distribution in order to optimise real-world effectiveness of passive safety systems. Moreover, active and passive countermeasures must be evaluated on the same basis in order to promote those countermeasures with the highest overall effectiveness.

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