Injury Severity Modeling: Scales, Incidence, Hospitalization Rate, Mortality Risk, Economic Costs, and Best Practice Recommendations

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Abstract

Injury severity assessment and modeling present several challenges for injury and safety investigators. Three of the most common and widely applicable injury severity scales are reviewed: hospitalized/non-hospitalized dichotomy; Abbreviated Injury Scale (AIS); and Injury Severity Score (ISS). Data related to these scales are summarized (incidence, hospitalization rate, mortality risk, and economic costs). Various types of cost data are included, encompassing medical and productivity costs, quality-of-life costs, and willingness-to-pay estimates. A clustering algorithm (k-means) is used to group ranges of severity levels (AIS/ISS) using these various data features. Operations research, machine learning, econometrics, and statistical classification methods are used to assess the range of possible AIS levels at each ISS value, to develop a probabilistic AIS-ISS map to allocate shares across these AIS levels (ordinal logistic regression, naïve Bayes classifier), and to map AIS-based injury costs onto the ISS scale. The method can be applied to any quantity (not just costs), facilitating better comparisons between the scales and the pooling of mixed AIS/ISS data in meta-analyses. Bounding analysis reveals each ISS value corresponds to one or a small number of AIS levels. For each scale (AIS/ISS), the cluster assignments are reasonably stable across data features. And when viewed over the entire ISS range, the mapped AIS costs are remarkably linear. Throughout, modeling considerations are discussed and best practice recommendations offered.

Keywords: injury severity; Abbreviated Injury Scale (AIS); Injury Severity Score (ISS); economic costs; logistic regression; naïve Bayes classifier; k-means clustering

I. Introduction

1.1. Primary contributions

The main contributions of this article are

1. Reviews three simple and widely applicable off-the-shelf injury severity scales, brings together data for these scales (incidence, hospitalization rate, mortality risk, and economic costs), and uses a clustering algorithm to group ranges of severity values using these data features.
2. Uses operations research, machine learning, econometrics, and statistical classification methods to transfer injury costs based on the AIS (Section III) onto the ISS scale (Section IV), using a probabilistic map. This method can be applied to any quantity (not just costs), facilitating better comparisons between the scales and the pooling of mixed AIS/ISS data in meta-analyses.
3. Discusses relevant modeling considerations and offers best practice recommendations.

1.2. Scope

Several important things to note regarding this article are

1. The focus is safety analyses and related economic studies, and not clinical or other settings.
2. Only the *severity of injury* dimension is examined. All other factors are exogenous.
3. The data are for nonfatal injuries (unless otherwise noted), and are central or expected values.
4. Literature reviews encompassed all works written in English, examining injuries overall (not narrow subsets), and in U.S. populations. Motor vehicle accident injuries are included.

1.3. Injury modeling challenges

Injury modeling presents several challenges. Compared to fatalities, nonfatal injuries are more prevalent, present along a spectrum of severity, and are multidimensional in their effects (particularly related to disability, impairment, pain and suffering, and reduced quality-of-life) [1,2,3]. While death is not entirely unidimensional or monolithic, it is less variable in its presentation and effects.[2]

1.4. Injury cost types

Three basic types of cost data are used [4-11]

1. *Cost of injury*. Costs that are relatively easy to quantify in monetary terms (e.g., medical expenditures, reduced wages); can include market and household productivity; excludes more intangible costs (e.g., pain and suffering); generally regarded as lower bound cost value.
2. *Quality-of-life.* Quality-related costs or disutility, often translated into monetary terms, although the link between the quality measure and true economic value may be tenuous or uncertain.
3. *Willingness-to-pay*. Value that society actually places on injury risk reductions, considering all of the trade-offs involved, as evidenced by behavior in economic markets (*revealed preference*).

A common quality measure is the *quality-adjusted life year* (QALY), assessing the trade-offs between longevity and time in various injury/health states.[3] While useful for making comparisons, many authors caution against assigning monetary values to QALYs, as linking it to economic value and behavior in markets can be tenuous (because QALYs or similar goods are not traded in markets) [4,6,7,9,10,12].

1.5. Injury severity scales

Numerous injury severity scales have been developed [13-16]. A review by Mehmood *et al*. [17] identified 57 such scales. The following sections discuss three of the most common and broadly applicable scales. Only data expressed in terms of these scales are presented, and only where the data are articulated for each level of the scale (not ranges or summary measures such as mean or median).

II. Hospitalized/non-hospitalized

A simple yet powerful injury severity stratification is these two mutually exclusive categories [5,18,19]

1. *Non-hospitalized*. Treated and released (e.g., at scene, hospital ED, outpatient, doctor's office); can also include injuries that were not so severe that the person sought formal treatment.
2. *Hospitalized*. Inpatient hospitalization, where the person survives at least until discharge.

Hospitalized injuries are further characterized by *length of stay* (LOS), which can be a reasonable surrogate for injury severity [20]. After the Boston Marathon bombing (2013), LOS was used to allocate funds to victims, with compensation increasing in LOS [21]. Data on cost per hospital inpatient day by U.S. state are available from [22], and data on average LOS and cost per stay from [23].

Incidence and cost data for hospitalized/non-hospitalized injuries are summarized in Table 1. While the Finkelstein *et al*. [18] study size is larger, the WISQARS [19] data are more recent. However, WISQARS may represent a more severely injured population (based on hospitalization rate). Regardless, the costs in Table 1 are similar across sources. And while useful, the hospitalized/non-hospitalized bifurcation can be somewhat of a blunt instrument, often unable to adequately differentiate the many gradations of injury. Some more specialized instruments are discussed in Sections III and IV.

[2] For example, the timing of death is variable (e.g., immediate, in hospital, reduced life expectancy).

[3] Similar measures include the disability-adjusted life year (DALY), health-adjusted life year (HALY), and value per statistical life year (VSLY), but these are not discussed in this article.

Table 1. Hospitalized/Non-Hospitalized Injuries - Incidence and Economic Costs

Injury Severity	Incidence		Cost (2023$)	
	Finkelstein *et al.* [18]	WISQARS [19]	Finkelstein *et al.* [18] + QoL [19]	WISQARS [19]
Non-hospitalized	96.3%	84.5%	$85,300	$88,000
Hospitalized	3.7%	15.5%	$247,000	$235,000

QoL = quality-of-life. Incidence of nonfatal injuries. Cost per injury incident. Consumer Price Index (CPI) for adjustments. Costs given to three significant digits. Mortality rate zero for both groups. WISQARS - 26,480,000 injuries (2023), medical and productivity costs and monetized QALYs (Section 1.4), using methods of [10,24]. Finkelstein *et al*. - 49,978,023 injuries (2000), medical and productivity costs, supplemented using WISQARS QoL costs (for better comparisons). Additional data available in [5], but are more dated (1985).

III. Abbreviated Injury Scale

3.1. Definition

The *Abbreviated Injury Scale* (AIS) ranges from 1 to 6 (integer-valued). Based on expert deliberation and consensus, the AIS was developed by the Association for the Advancement of Automotive Medicine (AAAM), as a systematic and standardized way of characterizing injuries from motor vehicle accidents. The AIS is useable across many different types of injuries and is often regarded as a good compromise between clinical detail and ease of practical application [1,14,15,25]. The methods of AIS scoring are periodically revised and expanded, most recently with the 2015 version [26]. In cases of multiple injuries, the *maximum AIS* (MAIS) is the most severe injury (i.e., highest AIS) anywhere in the body.

The MAIS levels are perhaps best understood using the example injuries in Willis & LaTourrette [27] (Table 2). Injury investigators often treat the most severe level, MAIS 6, as equivalent to fatalities [2,11,27,28,29], although some MAIS 6 are survivable in some circumstances [1,15,28,30-35]. However, theoretical justification does exist for considering MAIS 6 as being the same as fatalities (Section VII).

Table 2. Maximum Abbreviated Injury Scale (MAIS) Levels

Injury Severity		Example Injuries	General Prognosis
MAIS 1	Minor	Abrasion; laceration; contusion	Treated and released
MAIS 2	Moderate	Simple broken bone; loss of consciousness; serious strain/sprain	Follow-up required; weeks to months to heal
MAIS 3	Serious	Complicated fracture; concussion; minor crush injury	Substantial follow-up needed; some minor disability likely
MAIS 4	Severe	Heart laceration; loss of limb; crushed extremities	Hospitalization; substantial short-term and moderate long-term disability
MAIS 5	Critical	Spinal cord syndrome; crush syndrome with kidney failure; massive head injury	Extended hospitalization; significant long-term disability
MAIS 6	Maximum	Decapitation; massive injury to head, brain stem, or heart; 2nd or 3rd degree burns to ≥90% of body surface area	Usually (though not invariably) fatal (see Table 3)

Sources: AAAM [26]; MAIS 1-5 from [27]; MAIS 6 examples from [31,34,35].

3.2. Applicability

The fundamental goal of the AIS is to divide the vast, diverse, complex, and multifaceted landscape of injuries into a small number of manageable levels – to facilitate categorization, analysis, research, discussion, and communication. In this way, the AIS is similar to many other scales, such as the

- Enhanced Fujita scale (tornadoes)
- Saffir-Simpson scale (hurricanes)
- Modified Mercalli Intensity (earthquakes)
- Volcanic Explosivity Index (volcanic eruptions)
- International Nuclear and Radiological Event Scale (radiation/nuclear events)
- Air Quality Index (air pollution)
- Carnegie Classification (higher education)
- Insurance Institute for Highway Safety crash ratings (vehicle safety)

One of the most commonly used severity scales in injury research, the AIS has been used to characterize a wide array of injuries occurring in diverse settings, including: transportation accidents (its original purpose) [2,11,29,36], tornados [37], earthquakes [38], hurricanes [39], gunshot injuries [40], terrorist attacks [27,41,42], and war [43].

3.3. Limitations

Rigorous AIS scoring requires specialized knowledge and training. However, if injury descriptions are available, AIS scores can often be estimated with sufficient precision for use in many applications. Semi-structured approaches are also available, such as [35]. The AIS was developed to describe injuries from motor vehicle accidents, or mainly blunt trauma (push/pull or impact) type injuries. Caution should therefore be exercised when applying it to penetrating injuries (e.g., gunshot wounds) [13,16,40,44], disease/illness (e.g., cancer, COVID), or psychological afflictions (e.g., PTSD). The MAIS also discards all injury information other than the most severe, and may not capture the full landscape of injury [3].

3.4. Incidence, hospitalization, mortality, and costs

Incidence, hospitalization rate, and mortality risk data by MAIS level are summarized in Table 3. These studies all differ in their data, methods, manner of AIS coding, etc., and exhibit some variability. For example, the study populations in [1,28,30] consist of persons treated at hospital trauma centers, and may represent more severely injured populations than those in [11,18]. The mortality data can be used to remove deaths from mixed (fatal/nonfatal) data, or to adjust injury-only incidences to gauge the total persons impacted. Cost data by MAIS level are summarized in Table 4, encompassing a mix of cost types in Section 1.4. The MAIS costs are also plotted in Figure 1, showing their generally exponential nature. Note that the Graham *et al*. [29] costs are not always monotonic in the MAIS (specifically, MAIS 4).

Table 3. Maximum Abbreviated Injury Scale (MAIS) - Incidence, Hospitalization, and Mortality

Injury Severity	Incidence			Hosp. Rate	Mortality Risk		
	Copes *et al*. [30]	Finkel-stein *et al*. [18]	Blincoe *et al*. [11]	Blincoe *et al*. [11]	Copes *et al*. [30]	Gennarelli *et al*. [28]	Gennarelli & Wodzin [1]
MAIS 1	12.4%	76.6%	86.0%	0.007	0.002	0.007	0.007
MAIS 2	34.9%	20.7%	9.5%	0.233	0.002	0.017	0.008
MAIS 3	35.6%	1.9%	3.1%	0.815	0.053	0.054	0.035
MAIS 4	13.0%	0.3%	0.4%	1	0.224	0.202	0.146
MAIS 5	3.9%	0.1%	0.2%	1	0.459	0.453	0.396
MAIS 6	0.1%	0.3%	0.8%	1	0.893	0.873	0.790

Incidence and hospitalization for nonfatal injuries. Mortality risk uses pooled fatal/nonfatal data.
Blincoe *et al*. - 4,470,023 injuries, 36,500 deaths (2019); motor vehicle accidents (reported and estimated non-reported); MAIS 6 is fatal; MAIS 6 hospitalization rate inferred.
Finkelstein *et al*. - approx. 43,100,000 injuries (2000); excludes unknown MAIS (approx. 6,950,000).
Copes *et al*. - 85,820 injuries, 8,381 deaths (1982-1988).
Gennarelli & Wodzin - 181,707 fatal/nonfatal ("past several years"); all persons had only a single injury.
Gennarelli *et al*. - 174,160 fatal/nonfatal (1982-1989).
Schellenberg *et al*. [34] additionally find a MAIS 6 mortality risk of 0.746 (19,247 fatal/nonfatal, 2007-2017).
Additional data available in [45] (motor vehicle accidents), but the study size is smaller (1,840 injuries, 247 deaths), the data are more dated (1968-1969), and MAIS 6 was not used, and also in [46], but the study size is smaller (5,333 injuries, 201 deaths) and all persons had only a single injury.

Table 4. Maximum Abbreviated Injury Scale (MAIS) - Economic Costs

Injury Severity	ISS Bounds		Cost (2023$)			
	Min.	Max.	Graham *et al*. [29,47]	Finkelstein *et al*. [18] + QoL [11]	DOT [2,47]	Blincoe *et al*. [11]
MAIS 1	1	3	$0	$52,700	$39,600	$59,000
MAIS 2	4	12	$1,450,000	$490,000	$620,000	$551,000
MAIS 3	9	27	$2,110,000	$2,130,000	$1,390,000	$2,410,000
MAIS 4	16	48	$924,000	$3,590,000	$3,510,000	$4,270,000
MAIS 5	25	75	$10,700,000	$6,130,000	$7,830,000	$7,170,000
MAIS 6	75	75	$13,200,000	$11,200,000	$13,200,000	$11,800,000

CoI = cost of injury. DOT = U.S. Department of Transportation. ISS = Injury Severity Score. QoL = quality-of-life. VSL = value of statistical life. WTP = willingness-to-pay. Cost per injury incident. Costs given to three significant digits. Consumer Price Index (CPI) for adjustments. ISS bounds from Section 4.5.
DOT VSL [47] - WTP measure; $13.2 million (2023$); based on wage-risk studies (analyzing wages paid to workers to perform riskier employment); applied to Graham *et al*. and DOT injury fractions.
Finkelstein *et al*. - hybrid CoI/QoL measure; medical and productivity costs, supplemented using QoL costs from Blincoe *et al*. (for better comparisons); excludes unknown MAIS (approx. 6,950,000).
Blincoe *et al*. - hybrid CoI/QoL measure; motor vehicle accidents (2019); medical, EMS, productivity, workplace, insurance, and legal costs, and monetized QALYs (Section 1.4); MAIS 6 estimated as weighted average of MAIS 5 (25%) and deaths (75%), on the basis that MAIS 6 resemble fatalities 75% of the time [34].
DOT - hybrid QoL/WTP measure; quality-adjusted portion of remaining life lost (0.003, 0.047, 0.105, 0.266, 0.593, 1), similar to QALY (Section 1.4), applied to DOT VSL; MAIS 6 is fatal.
Graham *et al*. - hybrid QoL/WTP measure; disutility fractions (0, 0.11, 0.16, 0.07, 0.81, 1), based on the *Functional Capacity Index* [48]; applied to DOT VSL; MAIS 1 excluded (on the basis they are relatively minor); MAIS 6 is fatal.

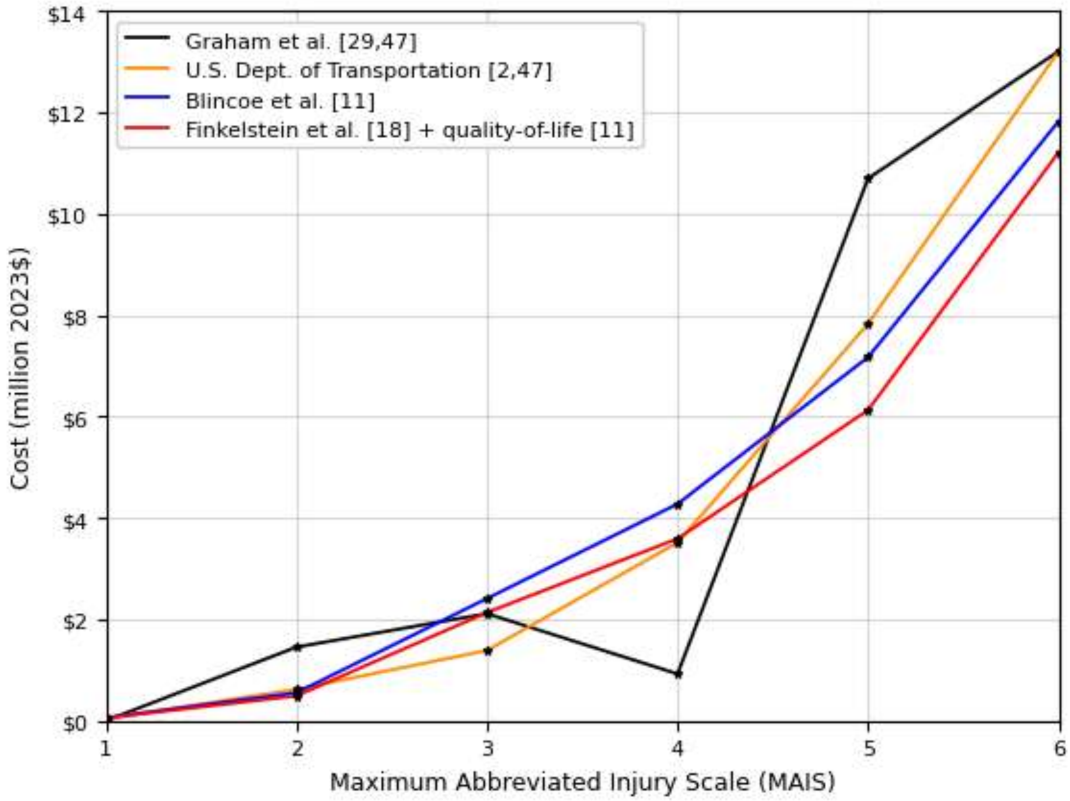

Figure 1. Maximum Abbreviated Injury Scale (MAIS) - Economic Costs

IV. Injury Severity Score

4.1. Definition

A more information-rich alternative to the MAIS (Section III), especially useful in cases of multiple injuries, is the *Injury Severity Score* (ISS) [45].[4] First, the most severe (highest AIS) injury in each of six body regions is noted. The ISS value is then the sum of squares of the three highest of these AIS values, each representing an injury in a different body region, or

$$ISS = (AIS_1)^2 + (AIS_2)^2 + (AIS_3)^2 \quad (1)$$

The ISS ranges from 1 (single AIS 1) to 75 (trio of AIS 5, or any number of AIS 6), taking on 44 possible values (with varying distance between adjacent ISS values). The developers of the ISS cite its linearity (as it relates to mortality risk) as one of its benefits relative to the MAIS. The ISS is used most often to control for injury severity or patient mix in injury and trauma studies, and to correlate it to various outcomes of interest [14,16,31,32,44,49,50,51]. The ISS has proven quite useful to injury researchers: *Google Scholar* reveals nearly 11,700 citations of the original ISS article (May 2025) (see also [50]).

[4] Other related measures include the ICD-9 Injury Severity Score (ICISS), New Injury Severity Score (NISS), and Trauma and Injury Severity Score (TRISS), but these are not discussed in this article.

4.2. Limitations

The ISS is based on the AIS (Equation 1), and so it inherits many of the AIS limitations (Section 3.3). Similar to the MAIS, the ISS discards all but the most severe injury in each body region, and considers only the three most severely injured body regions. This may bias it in cases of many injuries clustered in a single body region. Similarly, the ISS sometimes overlooks more severe injuries in favor of less severe ones occurring in a different body region [52]. However, this could also be a benefit of the ISS, or that it takes a more “wholistic” approach, rather than “overfitting” to injuries in a single body region. Kilgo *et al*. [50] find that when the body regions assumption is relaxed, and the three most severe injuries are used, regardless of where in the body they occur, the result is equal to the ISS in 56% of cases.

4.3. Statistical perspective

The ISS has three parameters (Equation 1) whereas the MAIS has only one.[5] From a statistical standpoint, justifying the inclusion of these additional model parameters requires that the model fit improve. This is incorporated in statistics like the *Akaike information criterion* (AIC) [53] and *Bayesian information criterion* (BIC) [54], which penalize models that have more parameters (while rewarding models that have better fits to the data). Whether or not sufficiently improved model fit is achieved (as assessed using AIC, BIC, or other statistics) will depend on the particular nature and structure of the data and model, but should be considered when making MAIS/ISS comparisons.

4.4. Incidence and mortality

Incidence and mortality risk data by ISS value are summarized in Table 5. Note that the study size in [50] is considerably larger and the data are more recent than that in [44]. Mortality is not always monotonic in the ISS, in part because different AIS triplets with the same ISS value (Equation 1) can have very different mortality rates [31,32,44,50]. The sample sizes also vary enormously, potentially contributing to variability at less-populated ISS values. The majority of persons exist at only three ISS values (1, 4, 9).

[5] Even in the case that one or two of the ISS component AIS values are zero-valued, there remain three parameters, as the zeros nevertheless contain statistical information.

Table 5. Injury Severity Score (ISS) - Incidence and Mortality

ISS	Incidence		Mortality Risk		ISS (cont.)	Incidence (cont.)		Mortality Risk (cont.)	
	Copes *et al*. [44]	Kilgo *et al*. [50]	Copes *et al*. [44]	Kilgo *et al*. [50]		Copes *et al*. [44]	Kilgo *et al*. [50]	Copes *et al*. [44]	Kilgo *et al*. [50]
1	13.28%	14.69%	0.003	0.007	**26**	0.83%	0.78%	0.237	0.276
2	1.49%	3.09%	0.000	0.003	**27**	0.39%	0.50%	0.191	0.144
3	0.11%	0.40%	0.000	0.006	**29**	1.18%	1.11%	0.226	0.175
4	18.79%	19.64%	0.003	0.006	**30**	0.14%	0.20%	0.208	0.318
5	8.85%	8.25%	0.005	0.004	**32**	0.16%	0.06%	0.290	0.288
6	0.83%	1.26%	0.000	0.004	**33**	0.17%	0.18%	0.324	0.292
8	3.57%	2.17%	0.008	0.008	**34**	0.85%	0.66%	0.331	0.300
9	19.80%	20.84%	0.025	0.023	**35**	0.11%	0.15%	0.407	0.387
10	6.60%	5.62%	0.020	0.020	**36**	0.10%	0.13%	0.440	0.192
11	0.37%	0.75%	0.000	0.012	**38**	0.21%	0.30%	0.356	0.376
12	0.80%	0.71%	0.000	0.009	**41**	0.27%	0.20%	0.449	0.393
13	3.65%	2.89%	0.029	0.025	**42**	0.02%	0.04%	0.727	0.498
14	2.33%	2.66%	0.024	0.020	**43**	0.11%	0.19%	0.385	0.413
16	3.91%	2.41%	0.146	0.128	**45**	0.07%	0.09%	0.583	0.478
17	3.03%	3.01%	0.104	0.047	**48**	0%	0.02%	1.000	0.462
18	1.11%	1.11%	0.088	0.074	**50**	0.12%	0.15%	0.564	0.546
19	0.64%	0.79%	0.063	0.052	**51**	0.01%	0.01%	0.667	0.694
20	1.14%	0.68%	0.141	0.087	**54**	0.01%	0.02%	0.800	0.611
21	0.72%	0.68%	0.123	0.063	**57**	0%	0.03%	1.000	0.602
22	1.13%	1.42%	0.087	0.055	**59**	0.01%	0.02%	0.667	0.694
24	0.59%	0.51%	0.099	0.074	**66**	0%	0.01%	1.000	0.773
25	2.46%	1.48%	0.382	0.438	**75**	0.03%	0.08%	0.926	0.812

Incidence of nonfatal injuries. Mortality risk uses pooled fatal/nonfatal data. Copes *et al*. - 13,925 injuries, 951 deaths (1982-1985). Kilgo *et al*. - 342,319 injuries, 19,057 deaths (1994-2002).

4.5. MAIS-ISS feasible region

The ISS is based on the AIS (Equation 1), and this relationship allows the MAIS to be linked (mapped) to the ISS, either perfectly or within a small range. At each MAIS, the ISS value is bounded between

$$ISS_{min} = (MAIS)^2 \quad (2)$$

$$ISS_{max} = 3 \cdot (MAIS)^2 \quad (3)$$

reflecting the AIS triplets (MAIS, 0, 0) and (MAIS, MAIS, MAIS), respectively, and where MAIS 6 is assigned ISS = 75 (Section 4.1). This forms a “feasible region” within the MAIS-ISS space (Figure 2), containing 76 total possible MAIS-ISS combinations (not to be confused with the maximum ISS = 75). The MAIS bounds are summarized in Table 6, which align with the information in [44], but are more extensive, showing the full range of possible MAIS levels at each ISS value (rather than heuristics).

The feasible region (Figure 2) exhibits a cantilever-like structure, with adjacent MAIS levels overlapping one another vertically, and several MAIS “shelfs” (horizontal). Around a third (15/44, 34%) of ISS values link to a single MAIS level; the majority (26/44, 59%) of ISS values link to two possible MAIS levels; and three midrange ISS values (25, 26, 27) exhibit the most variability, linking to three possible MAIS levels (3, 4, 5). MAIS levels 2-5 begin at ISS = (4, 9, 16, 25), and MAIS levels 1-4 cease at ISS = (3, 12, 27, 48).

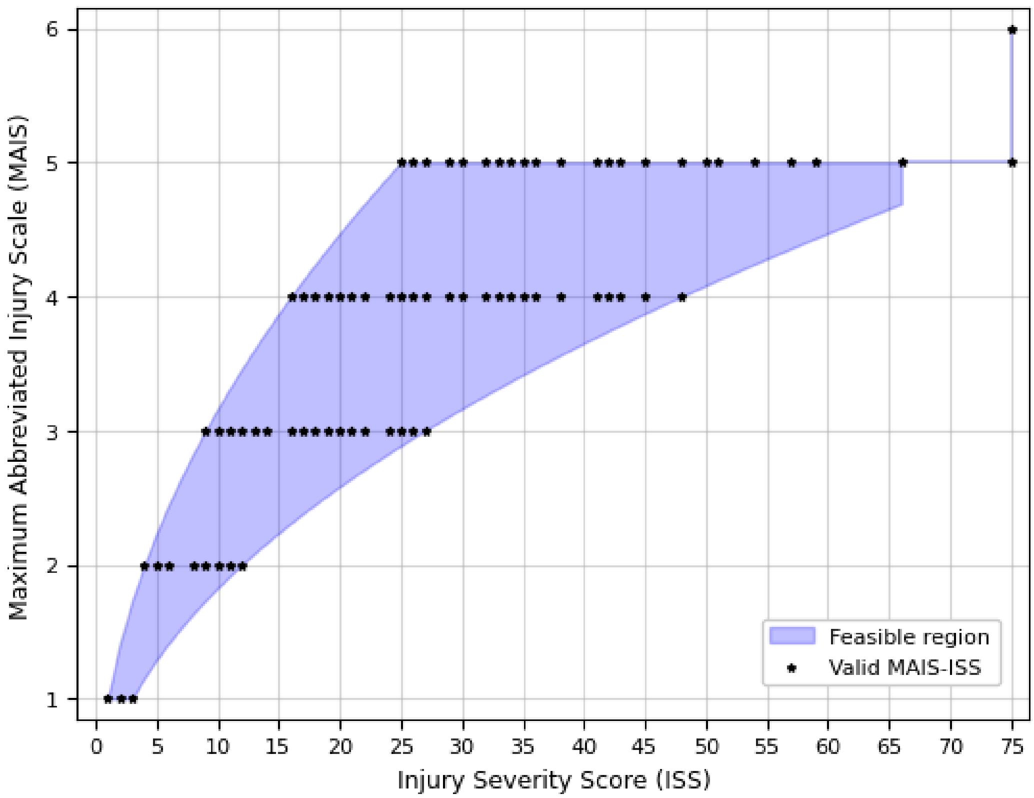

Figure 2. MAIS-ISS Feasible Region

4.6. MAIS-ISS probabilistic map

Nearly two thirds of ISS values (29/44, 66%) link to multiple possible MAIS levels (Section 4.5). This raises the issue of how the various levels should be weighted or combined at each ISS value. While a simple average could be taken, a more sophisticated approach is using machine learning and statistical classification methods to allocate shares (probabilities) across MAIS levels. This is done using the Python programming language [55].[6] Two classifiers are examined: *ordinal logistic regression* (OLR);[7] and the *Gaussian naïve Bayes* classifier (GNB).[8] Both of these are *supervised learning* algorithms, meaning that the class memberships (MAIS) are a model input (rather than being determined by the model).

OLR is an extension of simple linear regression that is used to model a multilevel discrete/categorical quantity (rather than a continuous linear relationship), and where there is a natural order (monotonicity) to the levels.[9] It uses the logistic function (s-curve) to assign probabilities across categories. However, OLR can be limited because of its "proportional odds" assumption, or that the slopes are the same across all of the levels (MAIS), with the categories being differentiated only through their intercepts.

[6] The code and input data are available at https://github.com/nathaniel-heatwole/Injury_costs.

[7] *OrderedModel()* function, statsmodels library.

[8] *GaussianNB()* function, scikit-learn library.

[9] More rigorously, this means: increases or decreases in the value of a predictor variable are expected to always promote membership in either a higher or lower level (depending on the sign of the coefficient).

GNBs are grounded in Bayes theorem and Bayesian inference. They assume the class membership probabilities are proportional to the probability density function (PDF) of the normal distribution (hence, Gaussian), which is computed for each independent variable (ISS) and at each level of the dependent variable (MAIS) (using sample means and standard deviations). These PDFs are then multiplied together (i.e., independent), then multiplied by the empirical class membership portions in the input data, and the probabilities then normalized to sum to one. GNBs can be limited because they assume all of the predictors act independently to influence the dependent variable (hence, "naïve"), but this is less applicable in the case of a lone predictor variable (ISS).

The *training data* (input) for the models are all valid MAIS-ISS pairs, and the *test data* are all valid ISS values. The predictions of the two classifiers differ somewhat (for those ISS values that link to multiple possible MAIS levels). For this application, there is no particular reason to favor one of these classifiers over the other, and so the outputs were averaged together. Both classifiers assign non-zero probabilities to all MAIS levels at each ISS value (because the logistic function and normal distribution both span the entire x-axis). To ensure the predictions remain in-range (Figure 2), the probabilities corresponding to all impossible MAIS-ISS combinations were recoded to zero, and the remaining probabilities then renormalized to sum to one (at each ISS value).

The maximum ISS = 75 can result either from the AIS triplet (5, 5, 5) or from any number of MAIS 6 (Section 4.1). Collectively, the studies of [31,32,33] identified 1,460 survivors with ISS = 75 who had MAIS 6, versus only seven persons with MAIS 5. As such, ISS = 75 is essentially MAIS 6, and is modeled accordingly (and excluded from the training data).

The final MAIS shares are given in Table 6.[10] These shares allow any quantity developed for one scale (incidence, hospitalization, LOS, ICU admission, mortality, disability, costs, etc.) to be transferred (mapped) to the other scale. This facilitates better comparisons between the scales and the pooling of mixed MAIS/ISS data in meta-analyses. Table 6 also provides the average MAIS at each ISS value (using the shares), providing a direct link between the scales.

[10] These shares, while probabilistic in form, assess how the various MAIS levels at each ISS value should be combined to arrive at "best estimate" values. Variation about these central values will nevertheless exist.

Table 6. Injury Severity Score (ISS) - Maximum Abbreviated Injury Scale (MAIS) Shares

ISS	MAIS		Shares					
	Bounds	Average	MAIS 1	MAIS 2	MAIS 3	MAIS 4	MAIS 5	MAIS 6
1	(1)	1.00	100%	-	-	-	-	-
2	(1)	1.00	100%	-	-	-	-	-
3	(1)	1.00	100%	-	-	-	-	-
4	(2)	2.00	-	100%	-	-	-	-
5	(2)	2.00	-	100%	-	-	-	-
6	(2)	2.00	-	100%	-	-	-	-
8	(2)	2.00	-	100%	-	-	-	-
9	(2, 3)	2.37	-	62.8%	37.2%	-	-	-
10	(2, 3)	2.44	-	56.0%	44.0%	-	-	-
11	(2, 3)	2.53	-	47.2%	52.8%	-	-	-
12	(2, 3)	2.63	-	36.9%	63.1%	-	-	-
13	(3)	3.00	-	-	100%	-	-	-
14	(3)	3.00	-	-	100%	-	-	-
16	(3, 4)	3.25	-	-	75.0%	25.0%	-	-
17	(3, 4)	3.28	-	-	72.2%	27.8%	-	-
18	(3, 4)	3.31	-	-	68.9%	31.1%	-	-
19	(3, 4)	3.35	-	-	65.2%	34.8%	-	-
20	(3, 4)	3.39	-	-	61.0%	39.0%	-	-
21	(3, 4)	3.44	-	-	56.4%	43.6%	-	-
22	(3, 4)	3.49	-	-	51.4%	48.6%	-	-
24	(3, 4)	3.59	-	-	40.7%	59.3%	-	-
25	(3, 4, 5)	3.82	-	-	30.6%	56.7%	12.7%	-
26	(3, 4, 5)	3.89	-	-	25.4%	59.8%	14.8%	-
27	(3, 4, 5)	3.97	-	-	20.6%	62.2%	17.2%	-
29	(4, 5)	4.26	-	-	-	74.2%	25.8%	-
30	(4, 5)	4.28	-	-	-	71.7%	28.3%	-
32	(4, 5)	4.34	-	-	-	65.8%	34.2%	-
33	(4, 5)	4.38	-	-	-	62.5%	37.5%	-
34	(4, 5)	4.41	-	-	-	58.9%	41.1%	-
35	(4, 5)	4.45	-	-	-	55.2%	44.8%	-
36	(4, 5)	4.49	-	-	-	51.3%	48.7%	-
38	(4, 5)	4.57	-	-	-	43.4%	56.6%	-
41	(4, 5)	4.68	-	-	-	32.3%	67.7%	-
42	(4, 5)	4.71	-	-	-	28.9%	71.1%	-
43	(4, 5)	4.74	-	-	-	25.7%	74.3%	-
45	(4, 5)	4.80	-	-	-	20.1%	79.9%	-
48	(4, 5)	4.87	-	-	-	13.5%	86.5%	-
50	(5)	5.00	-	-	-	-	100%	-
51	(5)	5.00	-	-	-	-	100%	-
54	(5)	5.00	-	-	-	-	100%	-
57	(5)	5.00	-	-	-	-	100%	-
59	(5)	5.00	-	-	-	-	100%	-
66	(5)	5.00	-	-	-	-	100%	-
75	(5, 6)	6.00	-	-	-	-	-	100%

MAIS bounds from Section 4.5. Average MAIS determined by applying shares to integer MAIS values (1-6). Dashes represent zero values. ISS = 75 shares discussed in Section 4.6.

4.7. Economic costs

Reviews of the literature did not reveal any cost values that are specific to the ISS scale. However, the probabilistic map (Section 4.6) allows cost data (or any quantity) developed for the MAIS to be transferred to the ISS scale. These ISS injury costs, formed by combining the MAIS costs (Table 4) and MAIS shares at each ISS value (Table 6), are plotted in Figure 3.

When viewed over the entire ISS range, the mapped MAIS costs exhibit considerable linearity. This is because costs increase faster-than-linearly in the MAIS (Figure 1), and the MAIS-ISS feasible region increases slower-than-linearly in the ISS (Figure 2), and these factors are offsetting. Recall also that the original ISS study cites its linearity as a benefit relative to the MAIS (Section 4.1). The ISS cost curves inherited the MAIS-ISS feasible region "shelfs" (Figure 2), where the ISS value is increasing but costs (MAIS) are not (most notably, ISS = 50-66). The ISS costs are always non-decreasing, except for one segment of the Graham *et al*. [29] cost curve (ISS = 16-24), stemming from the non-monotonicity of those underlying injury values (Figure 1). Beginning in the midrange ISS values (ISS ≥ 36), the Graham *et al*. costs are strictly greater than or equal to the other costs.

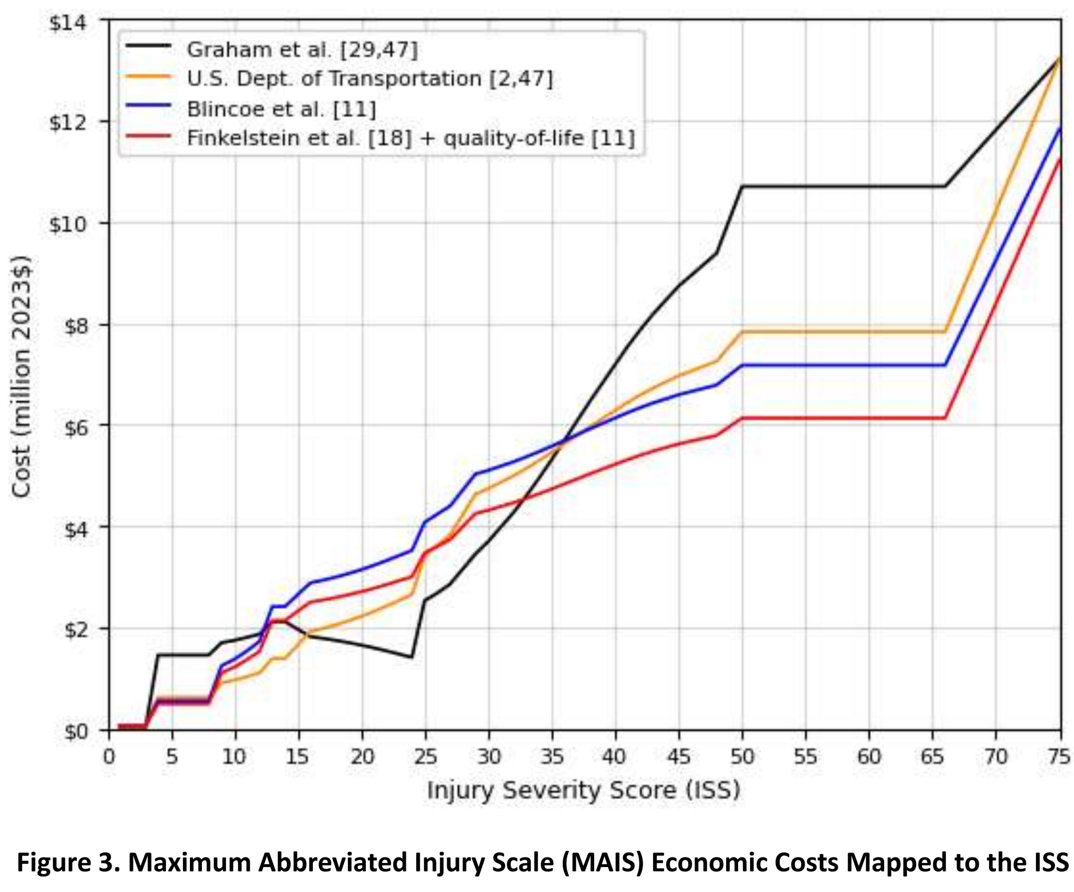

Figure 3. Maximum Abbreviated Injury Scale (MAIS) Economic Costs Mapped to the ISS

V. Clustered injury values

Alternatives to the hospitalized/non-hospitalized dichotomy (Section II) include the more information-rich MAIS (Section III) and ISS (Section IV). However, it is also possible to go in the other direction, by "condensing" ranges of severity values (MAIS/ISS), grouping them according to various data features. This is done using *k-means clustering*, again using Python [55].[11]

In contrast to OLR and GNB (Section 4.6), k-means is an *unsupervised learning* method, meaning that the class memberships (MAIS/ISS ranges) are an output from the model (rather than an input). Observations are assigned to the cluster with the nearest centroid (hence, "means"), minimizing variance about the cluster centroids, and maximizing within-cluster homogeneity.

The lone model hyperparameter, *k*, is the total number of clusters to fit. For MAIS, two clusters are used, and for ISS, two, three, and four clusters are examined. Various data features are used to generate the clusters: incidence, hospitalization, mortality, and costs. Although mortality risk relates to likelihood of *death*, rather than severity of *injury*, it may nevertheless correlate with severity (or dimensions of it).

The cluster assignments are summarized in Table 7. For each severity scale, the results are reasonably consistent across data features. For the MAIS clusters (two total), MAIS 1 is never left in isolation, always being combined with either MAIS (2, 3, 4). For the ISS, with two clusters, the results are the same across all data features (threshold at ISS = 31). With three ISS clusters, depending on the particular feature used to form them, the first cluster ends at ISS = 18-22, and the second cluster ends at ISS = 38-45. Finally, when using four ISS clusters, the first cluster ceases at ISS = 13-16, the second cluster ceases at ISS = 27-33, and the third cluster ceases at ISS = 45-51.

A threshold of ISS = 15 is often used to classify major trauma or serious injury [56]. This is where MAIS 4 emerges (Figure 2), and where all injuries require hospitalization (Table 3). This is also where mortality risk departs from being flush with the ISS-axis (Table 5). The four-level ISS clustering routines all selected essentially this same threshold as the first cluster (note that ISS = 15 itself cannot occur). The National Trauma Data Bank [57] uses a fourfold ISS categorization: 1-8 (minor); 9-15 (moderate); 16-24 (severe); and 25-75 (very severe). However, none of the four-level ISS cluster categorizations align particularly well with these categories. Of course, the threshold that is most useful in clinical settings may be quite different from that selected by a mathematical clustering algorithm.

[11] *KMeans()* function, scikit-learn library.

Table 7. Maximum Abbreviated Injury Scale (MAIS) and Injury Severity Score (ISS) Clusters

Clustering Input			Cluster Assignments (ranges of severity values)			
Severity Scale	**Feature Type**	**Source**	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**
MAIS (k = 2)	Incidence	Copes *et al*. [30]	1-4	5-6	-	-
		Finkelstein *et al*. [18]	1-4	5-6	-	-
		Blincoe *et al*. [11]	1-3	4-6	-	-
	Hospitalization rate	Blincoe *et al*. [11]	1-3	4-6	-	-
	Mortality risk	Copes *et al*. [30]	1-3	4-6	-	-
		Gennarelli *et al*. [28]	1-3	4-6	-	-
		Gennarelli & Wodzin [1]	1-4	5-6	-	-
	Economic costs	Graham *et al*. [29,47]	1-3	4-6	-	-
		Finkelstein *et al*. [18] + QoL [11]	1-2	3-6	-	-
		DOT [2,47]	1-4	5-6	-	-
		Blincoe *et al*. [11]	1-3	4-6	-	-
ISS (k = 2)	Incidence	Copes *et al.* [44]	1-30	32-75	-	-
		Kilgo *et al*. [50]	1-30	32-75	-	-
	Mortality risk	Copes *et al.* [44]	1-30	32-75	-	-
		Kilgo *et al*. [50]	1-30	32-75	-	-
	Economic costs	Graham *et al*. [29,47]	1-30	32-75	-	-
		Finkelstein *et al*. [18] + QoL [11]	1-30	32-75	-	-
		DOT [2,47]	1-30	32-75	-	-
		Blincoe *et al*. [11]	1-30	32-75	-	-
ISS (k = 3)	Incidence	Copes *et al.* [44]	1-18	19-38	41-75	-
		Kilgo *et al*. [50]	1-18	19-38	41-75	-
	Mortality risk	Copes *et al.* [44]	1-22	24-45	48-75	-
		Kilgo *et al*. [50]	1-18	19-38	41-75	-
	Economic costs	Graham *et al*. [29,47]	1-18	19-38	41-75	-
		Finkelstein *et al*. [18] + QoL [11]	1-21	22-43	45-75	-
		DOT [2,47]	1-18	19-38	41-75	-
		Blincoe *et al*. [11]	1-18	19-38	41-75	-
ISS (k = 4)	Incidence	Copes *et al.* [44]	1-14	16-30	32-50	51-75
		Kilgo *et al*. [50]	1-14	16-30	32-48	50-75
	Mortality risk	Copes *et al.* [44]	1-16	17-33	34-51	54-75
		Kilgo *et al*. [50]	1-14	16-30	32-45	48-75
	Economic costs	Graham *et al*. [29,47]	1-14	16-30	32-51	54-75
		Finkelstein *et al*. [18] + QoL [11]	1-14	16-27	29-45	48-75
		DOT [2,47]	1-14	16-30	32-50	51-75
		Blincoe *et al*. [11]	1-13	14-27	29-45	48-75

QoL = quality-of-life. K-means clusters (k total). Ranges are inclusive. Dashes represent not applicable. Incidence and hospitalization for nonfatal injuries. Mortality risk uses pooled fatal/nonfatal data. Cost per injury incident.

VI. "Snapshot" injury values

A primary goal of this article is to stratify injury values by severity (Section 1.2). However, it can also be informative and useful to have some injury values handy that are severity-neutral.

The average injury costs – formed by combining the incidence and cost data in various ways – can serve this purpose, which are summarized in Table 8. The hospitalized/non-hospitalized costs are considerably below those for the MAIS/ISS. Among the MAIS/ISS costs, the study populations in [30,44,50] consist of persons treated at hospital trauma centers, and therefore may represent more severely injured populations than those in [11,18], which may be more representative of injuries generally. The ISS values in Table 8 (average ISS = 9.0 or 9.5) correspond to about MAIS = 2.4 (Table 6), which is much better aligned with [30] (average MAIS = 2.6) than [11,18] (average MAIS = 1.2 or 1.3).

When valuing injuries that are of generally unknown severity, Chatterjee & Abkowitz [42] suggest averaging the MAIS injury values. However, given the generally exponentially nature of the MAIS costs (Figure 1), the *geometric mean* (non-zero values only) may be a better choice, so as to put greater emphasis on lower values (rather than more catastrophic injuries).

Table 8. Average Injury Costs (Product of Incidence and Costs)

Injury Severity			Cost (2023$)				
Scale	**Incidence**	Avg.	Graham *et al*. [29,47]	Finkelstein *et al*. [18] + QoL [11,19]	DOT [2,47]	Blincoe *et al*. [11]	WISQARS [19]
HOS/ NH	Finkelstein *et al*. [18]	3.7%	-	$91,400	-	-	$93,500
	WISQARS [19]	15.5%	-	$110,000	-	-	$111,000
MAIS	Copes *et al*. [30]	2.6	$1,810,000	$1,650,000	$1,490,000	$1,900,000	-
	Finkelstein *et al*. [18]	1.3	$402,000	$240,000	$252,000	$268,000	-
	Blincoe *et al*. [11]	1.2	$332,000	$275,000	$271,000	$304,000	-
ISS	Copes *et al*. [44]	9.5	$1,560,000	$1,230,000	$1,120,000	$1,410,000	-
	Kilgo *et al*. [50]	9.0	$1,510,000	$1,160,000	$1,070,000	$1,320,000	-

HOS/NH = hospitalized/non-hospitalized. ISS = Injury Severity Score. MAIS = maximum Abbreviated Injury Scale. QoL = quality-of-life. Incidence of nonfatal injuries. Cost per injury incident. Costs given to three significant digits. Consumer Price Index (CPI) for adjustments. HOS/NH average severity is percent hospitalized. Dashes represent not applicable. Copes *et al*. [44] data aggregated over ages groups and injury types. Finkelstein *et al*. medical and productivity costs supplemented using QoL costs from WISQARS (HOS/NH) or Blincoe *et al*. (MAIS/ISS) (for better comparisons).

VII. Variability and bounding

Throughout, the injury values presented are average or expected values, and do not capture the enormous variation that exists about these central values. Some of the dimensions along which injury values can vary may include [5,15,18,19]: injury characteristics (mechanism/cause, body region, poly-injury), individual affected (age, sex, co-morbidities, pre-existing conditions), and treatment characteristics (promptness, quality, availability/cost). Uncertainty analysis is therefore an important aspect of injury and safety analyses and related risk management and policy considerations [2,6,10,58]. However, it can sometimes yield counterintuitive and paradoxical results.

The MAIS-ISS feasible region (Figure 2) bounds the range of possible MAIS levels at each ISS value. However, variation will nevertheless remain *within* MAIS levels. From literature reviews, DOT [2] recommends parametric variation of 40% about the central or base injury values. This can sometimes cause the value of injury to exceed that of fatalities (base value). This is not necessarily nonsensical.

While death is the cessation of physical functioning and the loss of all future life years, it also squelches pain and suffering and the costs of treatment. Miller *et al*. [5] suggest three categories of injuries – quadriplegia, severe head trauma, and catastrophic burns – cause comparable or greater losses than death. The worst fate possible, they posit, is severe burns, with a loss almost 40% greater than death (1982 treatment capabilities). This also provides a rationale for considering MAIS 6 as being the same as fatalities (Section 3.1), because while some MAIS 6 are survivable, others may entail costs exceeding those of fatalities.

Conversely, and paradoxically, at the other extreme, there may be justification for considering some injuries as having zero or even *negative* cost (i.e., benefits). In a study of severe burn survivors, Pindus *et al*. [59] found that some of the participants rated their quality-of-life as *improved* (relative to before the injury). Some of the positive impacts cited by the participants include returning to school, increased family closeness, improved health behaviors, enhanced sensitivity to disabled persons, and greater appreciation of life.

VIII. Summary

This article reviews, summarizes, and extends some of the most common and broadly applicable injury severity scales. It brings together various ancillary data related to these scales (incidence, hospitalization, mortality, and costs), and clusters ranges of severity values using these various data features. Throughout, modeling considerations are discussed and best practice recommendations offered.

It also presents a new methodology for probabilistically mapping any quantity based on one of the scales (MAIS/ISS) onto the other, which is demonstrated by mapping MAIS-based economic costs onto the ISS. This greatly improves the comparability of the scales and facilitates the pooling of mixed MAIS/ISS data in meta-analyses. Previously, such comparisons had to be made informally (e.g., using heuristics), or data for the two scales analyzed separately, or data for one of the scales discarded. The MAIS and ISS scales can now be compared reasonably directly (using the data in Table 6).

The methods could be refined for use in any particular application area, by using data that are more specific to the injuries or populations of interest. Rich application-specific data could also allow for rigorous handling of uncertainty and the quantifying of probability distributions for various injury outcomes. The MAIS shares (Table 6) too could be improved, by using empirical data on the true prevalence of different MAIS levels at each ISS value (rather than statistical classification methods).

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