Derivation of a Harm Metric to Assess Total Occupant Injury – Application to a Crash Pulse Optimisation Study

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In order to optimise a design, it is necessary to first develop a performance measure of the system. This performance measure is often termed the cost or objective function for the design, and is expressed in such a way that the design is considered optimal when the cost function is a minimum.

Traditionally, occupant injury has been measured using injury criteria for different body regions. These criteria have allowed designers to attain a reasonable method of assessing the injury to different parts of the body. However, a numerical optimisation procedure ultimately requires a single number to minimise, and therefore a method is required to measure total body injury.

This paper describes a harm formulation which was derived for application to a crash pulse optimisation study. The harm metric was developed to assess injury severity from occupant responses simulated in MADYMO. In recent years the concept of harm has gained attention as a method of quantifying road trauma in terms of dollar cost, and much work has been done to gather the statistics required for its implementation. Optimisation for minimum harm is based on the premise that the best design is the one which minimises the total costs associated with road trauma. The harm formulation used was in the general form:

$$\text{Harm} = \sum_{\text{all injuries considered}} \left(\text{probability of injury} \times \text{cost of injury}\right) \qquad [1]$$

This paper provides an explanation of how the harm metric was developed from current statistical data, and implemented in an optimisation process. The performance of the harm metric and its perceived strengths and weaknesses are discussed. It is argued that the harm metric has questionable value as a measure of absolute cost, but may nonetheless be useful as an optimisation cost function, where relative values are more important than absolute values.

NOTATION

Harm	societal cost associated with a crash	($AUD)
HIC	Head Injury Criterion (HIC 36ms)	(-)
N_{ij}	Neck Injury Criterion	(-)
CTI	Combined Thoracic Index	(-)
Femur Load	Femur Load Criterion	(N)
IAF	injury assessment functions	
AIS	Abbreviated Injury Scale	

INTRODUCTION

In order to optimise a design, it is first necessary to develop a performance measure of the system. This performance measure is termed the *cost* or *objective* function for the design, and is expressed in such a way that the design is considered optimal when the cost function is a minimum.

Traditionally, occupant injury has been measured using injury criteria for different body regions. These criteria have allowed designers to attain a reasonable method of assessing the injury to different parts of the body. However, considering the broader goal of optimisation of an automobile for maximum overall safety, a measure of safety effectiveness is required which satisfactorily balances a range of crash variables, including:

- Injury to different regions of the body;
- Different vehicle collision speeds;
- Different occupant physiologies and gender;
- Different types of collision.

A realistic and cost-effective design cannot perfectly satisfy every crash variable, and therefore any solution will involve a trade-off between the many different requirements identified. In any case, the final design should approximately reflect the relative priority of each variable, whilst simultaneously meeting any minimum requirements mandated by law.

This paper describes a harm formulation derived for application to a crash pulse optimisation study. Optimisation for minimum harm is based on the premise that the best design is the one which minimises the costs associated with road trauma. A harm metric was developed to assess injury severity from occupant responses simulated in MADYMO (refer to Figure 1). Harm is a metric for estimating the costs associated with road trauma, involving both a frequency and unit cost component [1]. In recent years the concept of harm has gained attention as a method of quantifying road trauma in terms of dollar cost, and much work has been done to gather the statistics required for its implementation. Researchers in different countries have attempted to estimate the economic costs of automotive injuries [2-5], in an attempt to provide an objective measure of the effectiveness of different safety solutions.

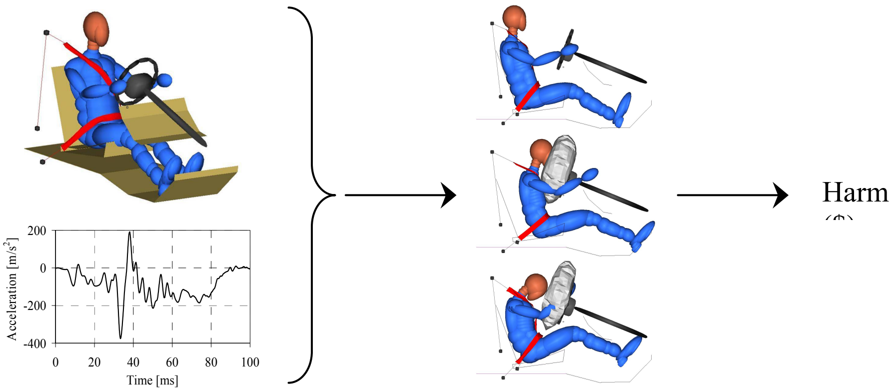


Figure 1. Application of harm metric to crash pulse optimisation study.

THEORY

General Harm Model

In this analysis, harm was defined as the expected societal cost associated with a given crash pulse and subsequent occupant injuries. The general harm model used is outlined below:

$$\text{Harm} = \sum_{\text{all injuries considered}} \left(\text{probability of injury} \times \text{cost of injury}\right) \qquad [2]$$

A representative range of injuries was considered:

- Head injury;
- Neck injury;
- Chest injury;
- Lower extremities injury.

A measure of injury severity and corresponding expected cost was required for each body region considered. The technique to determine these variables is discussed below.

Measurement of Injury Severity

In order to assess crash severity, a meaningful relationship must be established between the forces and motions measured in the dummy (via crash test or computer simulation), and the injury consequences for a living human [6]. Injury criteria have been derived which attempt to relate dummy load and kinematic responses to actual injuries suffered. The following injury criteria were used in this analysis:

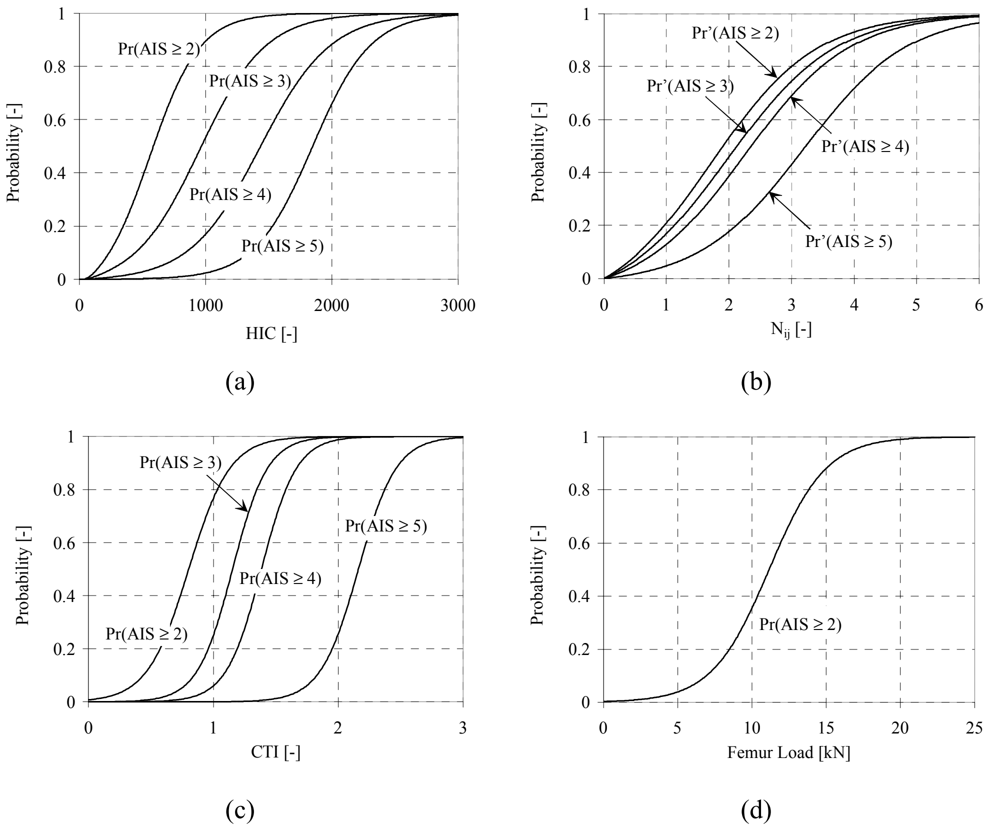
- Head region - Head Injury Criterion (HIC 36ms)
- Neck region - Neck Injury Criterion (N_{ij})
- Chest region - Combined Thoracic Index (CTI) Criterion
- Lower extremities region - Femur Load Criterion

Injury assessment functions (IAFs) are employed in an attempt to relate measured injury criteria to the expected probability of a given level of injury severity in a human [4]. Injury severity in a human is generally measured using the Abbreviated Injury Scale (AIS) [7], which classifies injuries on a threat-to-life six-point scale [1, 4] as follows:

AIS 1: Minor
AIS 2: Moderate
AIS 3: Severe (not life threatening)
AIS 4: Serious (life threatening, survival probable)
AIS 5: Critical (survival uncertain)
AIS 6: Maximum (potentially non-survivable)

Accurate IAFs are not readily available for automobile accidents in Australia. IAFs worldwide that have been developed are based on incomplete statistical data and significant assumptions [4]. However, they provide a useful preliminary basis for predicting the severity of injury to different body regions. The IAFs used in this analysis are summarised in Figure 2 below. Curves were sourced from NHTSA data, which were derived from United States transport accident statistics [6, 8]. It is noted that curves were not available for all injury levels.

Equations for the curves shown in Figure 2 may be sourced from references [6, 8]. It is noted that the N_{ij} IAFs have been modified – original N_{ij} IAFs had non-zero injury risk at $N_{ij} = 0$, and for some values of N_{ij} , $\Pr(\text{AIS} \geq 3) > \Pr(\text{AIS} \geq 2)$, even though $\Pr(\text{AIS} \geq 2)$ is inclusive of $\Pr(\text{AIS} \geq 3)$. These inconsistencies were removed for the modified N_{ij} curves shown below:



(a) (b)

(c) (d)

Figure 2. IAF curves. (a) Head injury [8]. (b) Neck injury [6]. (c) Chest injury [6]. (d) Leg injury [6].

Each IAF curve in Figure 2 gives the probability of injury above a certain AIS level, inclusive of all lower AIS levels. Except for the lower extremity region, these probabilities were converted to discrete AIS probabilities, with the following conservative assumed formulation:

$$\mathrm{Pr(AIS\ 3)} = \mathrm{Pr}(2 \leq \mathrm{AIS} < 3) = \mathrm{Pr(AIS} \geq 2) - \mathrm{Pr(AIS} \geq 3) \quad [3]$$

$$\mathrm{Pr(AIS\ 4)} = \mathrm{Pr}(3 \leq \mathrm{AIS} < 4) = \mathrm{Pr(AIS} \geq 3) - \mathrm{Pr(AIS} \geq 4) \quad [4]$$

$$\mathrm{Pr(AIS\ 5)} = \mathrm{Pr}(4 \leq \mathrm{AIS} < 5) = \mathrm{Pr(AIS} \geq 4) - \mathrm{Pr(AIS} \geq 5) \quad [5]$$

$$\mathrm{Pr(AIS\ 6)} = \mathrm{Pr(AIS} \geq 5) \quad [6]$$

Average Cost per Injury

Injury cost data was sourced from MUARC [1]. Table 1 below shows the average cost per injury as a function of AIS injury level, for each of the body regions considered. It is noted that these statistics originate from data collected in 1988-1990 [1].

	Injury Severity					
Body Region	Minor (AIS = 1)	Moderate (AIS = 2)	Serious (AIS = 3)	Severe (AIS = 4)	Critical (AIS = 5)	Maximum (AIS = 6)
Head	2.1	9.8	40.3	92.9	328.2	332.3
Neck	2.1	9.8	40.3	53.2	108.9	332.3
Chest	1.5	8.3	23.2	37.7	54.7	332.3
Lower Extremity	1.5	14.4	43.3	64	108.9	332.3

Table 1. Average cost per injury (1991 $Au ‘000’s) [1]

Table 1 was used to determine the cost corresponding to each discrete AIS injury level ($\text{AIS} = 3$ to $\text{AIS} = 6$). For the lower extremity (LE) region, an AIS injury probability range was used ($\text{AIS} \geq 2$), and therefore a corresponding weighted cost was calculated as follows:

$$\text{cost}(\text{AIS} \geq 2)_{\text{LE}} = \frac{\sum_{i=2}^{6} (7-i)\left[\text{cost}\left(\text{AIS } i\right)\right]_{\text{LE}}}{\sum_{i=1}^{5} i} \qquad [7]$$

Injury Cost by Body Region

Harm was calculated for each body region (BR) using the following formula:

$$\text{Harm}\left(\text{BR}\right) = \sum_{i=m}^{n} \left[\Pr\left(\text{AIS } i\right)\right]_{\text{BR}} \times \left[\text{cost}\left(\text{AIS } i\right)\right]_{\text{BR}} \qquad [8]$$

The variables m and n define the range, $\left[m,n\right]$, of AIS injury levels considered. For each body region (excluding the lower extremities), the available statistical data resulted in the range of AIS injury levels being limited to $\left[3,6\right]$. Equation [8] was applied to each specific body region, noting that the lower extremity region was formulated for a single probability range only:

$$\text{Harm}\left(\text{Head}\right) = \sum_{i=3}^{6} \left\{\left[\Pr\left(\text{AIS } i\right)\right]_{\text{Head}} \times \left[\text{cost}\left(\text{AIS } i\right)\right]\right\}_{\text{Head}} \qquad [9]$$

$$\text{Harm}\left(\text{Chest}\right) = \sum_{i=3}^{6} \left\{\left[\Pr\left(\text{AIS } i\right)\right]_{\text{Chest}} \times \left[\text{cost}\left(\text{AIS } i\right)\right]\right\}_{\text{Chest}} \qquad [10]$$

$$\text{Harm}\left(\text{Neck}\right) = \sum_{i=3}^{6} \left\{\left[\Pr\left(\text{AIS } i\right)\right]_{\text{Neck}} \times \left[\text{cost}\left(\text{AIS } i\right)\right]\right\}_{\text{Neck}} \qquad [11]$$

$$\text{Harm}\left(\text{L.E.}\right) = \text{cost}(\text{AIS} \geq 2)_{\text{L.E.}} \times \Pr(\text{AIS} \geq 2)_{\text{L.E.}} \qquad [12]$$

Total Occupant Harm

Total occupant harm is calculated by summing the harm for each body region:

$$\text{Harm (\$)} = \text{Harm}\left(\text{Head}\right) + \text{Harm}\left(\text{Neck}\right) + \text{Harm}\left(\text{Chest}\right) + \text{Harm}\left(\text{L.E.}\right) \qquad [13]$$

Equation [13] provides the total harm, requiring only the statistical information provided in this section, together with calculated injury criteria from the MADYMO simulation. It is noted that this formulation does not include all possible injuries – for example spinal injuries, puncture wounds etc.. However, it does consider a broad range of serious injuries. It is expected that a design configuration which simultaneously reduces injury to head, neck, chest and leg regions, will also result in low injury to other critical body regions.

Harm Weighting by Collision Velocity

Collisions do not simply occur at a single speed, but across a whole range of impact velocities. Figure 3 illustrates the percentage frequency of frontal collisions as a function of impact velocity for Australian roads [3]:

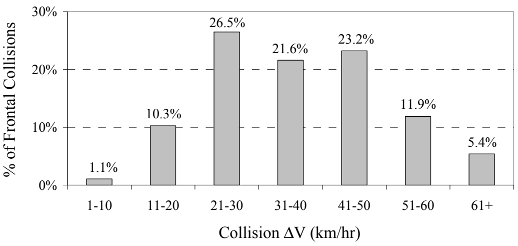


Figure 3. Percentage frequency of collisions as a function of impact velocity [3]

If a vehicle is to provide safety across a range of impact speeds, then the performance of the vehicle may be measured in terms of which configuration minimises total harm across all speeds considered. Using this approach it becomes necessary to weight the harm calculated at a given speed with the likelihood that a crash will occur at that speed.

A weighted harm metric was developed for a crash pulse optimisation study which considered total occupant harm across three impact speeds – 28 km/hr, 48 km/hr and 56 km/hr [9]. These three impact velocities fall into three velocity ranges from Figure 3:

Impact velocity (km/hr)	Relevant ΔV (km/hr)	Proportion of crashes (%)
28	21-30	26.5
48	41-50	23.2
56	51-60	11.9
		Total = 61.6 %

Table 2. Full frontal crash frequency by impact speed

Referring to Table 2, these three percentage frequencies were normalised as follows:

Impact Velocity (km/hr)	Proportion of crashes (%)	Normalised percentages (%)	Velocity Weighting (-)
28	26.5	26.5/0.616 = 43.0	0.430
48	23.2	23.2/0.616 = 37.7	0.377
56	11.9	11.9/0.616 = 19.3	0.193
	Total = 61.6 %	Total = 100 %	Total = 1

Table 3: Harm velocity weighting factors

Referring to Table 3, where a vehicle safety system must perform over these three velocities, the effectiveness of the system, expressed in terms of a harm function weighted by frequency of occurrence, may be expressed as follows:

$$\text{Harm} = 0.430 \times \text{Harm}_{28\text{ km/hr}} + 0.377 \times \text{Harm}_{48\text{ km/hr}} + 0.193 \times \text{Harm}_{56\text{ km/hr}} \qquad [14]$$

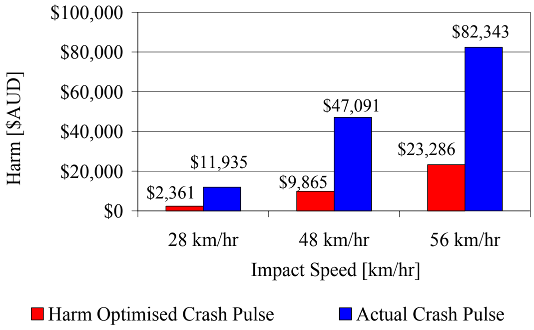
where $\text{Harm}_{28\text{ km/hr}}$, $\text{Harm}_{48\text{ km/hr}}$ and $\text{Harm}_{56\text{ km/hr}}$ are the calculated occupant harm values at impact speeds of 28, 48 and 56 km/hr respectively, using Equation [8].

RESULTS

Two different types of crash pulse optimisation study required different harm formulations:

- A harm optimisation at a single impact velocity [10].
- A weighted harm optimisation combining harm values at impact velocities of 28, 48 and 56 km/hr [9].

For both crash pulse optimisation studies, occupant harm results for optimised crash pulses were compared to harm results for representative real-life crash pulses provided by Holden Ltd.. Figure 4 below shows results for three separate harm optimisations performed at speeds of 28, 48 and 56 km/hr. Figure 5 shows results for a weighted harm optimisation across these three same speeds. For both Figures, the optimised harm values are compared to harm values for the representative vehicle crash pulses. Individual injury criteria are also presented.

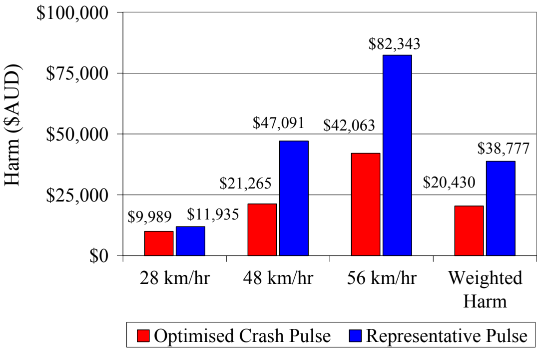


(a)

	28 km/hr		48 km/hr		56 km/hr	
	Repr. Pulse	**Opt. Pulse**	**Repr. Pulse**	**Opt. Pulse**	**Repr. Pulse**	**Opt. Pulse**
HIC (-)	127	28	462	100	686	263
Nij (-)	0.379	0.126	0.410	0.327	0.484	0.419
CTI (-)	0.591	0.276	0.918	0.571	1.083	0.725
Femur (N)	1841	731	2036	1740	1878	1938
Harm ($AUD)	11,935	2,361	47,091	9,865	82,343	23,286

(b)

Figure 4. Single speed harm optimisation - optimised vs. representative results [10].
(a) Estimated occupant harm. (b) Comparison of injury parameters



(a)

	28 km/hr		48 km/hr		56 km/hr	
	Repr. Pulse	**Opt. Pulse**	**Repr. Pulse**	**Opt. Pulse**	**Repr. Pulse**	**Opt. Pulse**
HIC (-)	127	97	462	197	686	435
Nij (-)	0.379	0.310	0.410	0.409	0.484	0.374
CTI (-)	0.591	0.589	0.918	0.765	1.083	0.874
Femur (N)	1841	1655	2036	1945	1878	1967
Harm ($AUD)	11,935	9,989	47,091	21,265	82,343	42,063

(b)

Figure 5. Multi-speed weighted harm optimisation - optimised vs. representative results [9].
(a) Estimated occupant harm. (b) Comparison of injury parameters

DISCUSSION

In terms of this optimisation study, there is no definite way to assess the effectiveness of this harm metric. The question is whether or not this objective function adequately describes total occupant injury, and whether it adequately balances the requirements of each injury criteria considered. The absolute dollar-value of harm predicted is largely irrelevant for optimisation purposes – all that matters is relative harm values.

Observing Figure 4 and Figure 5, it appears that the harm metric has proven to be an effective measure of total occupant injury for the two crash pulse optimisation processes it was designed for. In Figure 4 it can be seen that significant reductions in harm at each impact speed correspond to significant reductions in all of the injury criteria. The velocity-weighted harm optimisation results in Figure 5 show that even across different impact speeds, the weighted harm metric manages to balance the competing requirements of injury to different body regions. In both figures it can be seen that Femur load is not consistently reduced for each optimisation. An examination of the magnitudes of loads observed suggest that for the representative crash pulses, these Femur loads are already close to their optimum values.

It is believed, however, that a harm algorithm cannot provide accurate cost numbers. The harm metric draws from very broad and incomplete statistical data. Furthermore, the incremental improvements achieved in an optimisation study are an order of magnitude lower than the potential accuracy of the harm metric, therefore the magnitudes of the harm improvements have no actual meaning in themselves. There was no obvious means of validating the results obtained in this analysis.

However, the harm metric does provide a rational basis for developing an overall optimisation cost function. So whilst the accuracy of actual harm calculations may be questionable, the metric has the potential to preserve a logical weighting between the different injury criteria considered. Acknowledging these limitations, designers can use their judgment by tuning the harm algorithm to ensure sensible results.

CONCLUSION

It was shown that a harm metric could be used as an effective objective function in a crash pulse optimisation process. Based upon available injury probability and statistical cost data, the harm algorithm was able to adequately incorporate numerous crash variables into a single number. However, the statistical data required for the formulation of a harm metric is incomplete and inconsistent. Therefore it is believed that whilst the harm metric is a useful tool for optimisation studies, actual calculated harm values are not meaningful in themselves.

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