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ESTIMATION OF THE PROBABILITY OF HEAD INJURY AT A GIVEN ABBREVIATED INJURY SCALE LEVEL BY MEANS OF A FUCTION OF HEAD INJURY CRITERION

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Abstract: The paper presents a review of the basic literature on the determination of head injury effects. Introduction to the subject of Head Injury Criterion (HIC) applications as likelihood of head injury measures was made. Individual levels of Abbreviated Injury Scale (AIS) were listed as a representation of the consequences of head injury. Prasad and Mertz curves describing the relationship between the HIC value and the probability of injury for a given AIS level were presented. Exponential models, developed by the authors, representing individual curves were presented. The probability of head injuries at different AIS levels was estimated for selected case studies presented in the literature devoted to human workplace safety. The analysis was concluded with debate and conclusions on the use of the proposed models.
Keywords: occupational safety and health, head injury criterion, abbreviated injury scale, probabilistic measures, head injury likelihood

1. INTRODUCTION

In the assessment of operational safety there are often situations in which it is necessary to assess the consequences of undesirable events (Chybowski and Żółkiewski, 2015; Niciejewska and Klimecka-Tatar, 2018; Ulewicz and Mazur, 2013; Ulewicz et al., 2019). It is particularly difficult to estimate such consequences in terms of risk to the life and health of the operator (Chybowski et al., 2006; Chybowski and Matuszak, 2009).

During the operation of complex technical systems such as internal combustion engines (Chybowski et al., 2015; Chybowski and Kazienko, 2019; Chybowski and Matuszak, 2007), wheeled vehicles (Fábio et al., 2018; Ptak et al. 2019), industrial robots (Gao and Wampler, 2009) or work machines (Karliński et al., 2019; Karliński et al., 2014; Karliński et al., 2016) there are situations in which the heads of operators and bystanders can be injured (Kaczyński et al., 2019; Ratajczak et al., 2019; Wilhelm et al., 2017). The risk of injury can be significantly reduced by using suitable protective covers made of modern materials (Gawdzińska, 2017; Gawdzińska et al., 2018; Gawdzińska, et al., 2016; Gawdzińska et al., 2019; Gawdzińska et al., 2017;

Gawdzińska et al., 2017), the use of personal protective equipment (Fernandes et al., 2019; Fernandes et al., 2014; Kaczyński et al., 2019; Yang and Dai, 2010) and strict adherence to operational procedures (Chybowski and Gawdzińska, 2016a, 2016b; Chybowski, et al., 2019; Chybowski et al., 2006; Chybowski et al., 2016; Piasecki et al., 2017).
To measure the likelihood of a head injury due to an impact, the Head Injury Criterion (HIC) is often used (McHenry, 2004):

$$HIC = \max_{t_1,t_2}\left\{\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2-t_1)\right\} \quad (1)$$

Where *a*(t) is the resultant acceleration measured in g (standard gravity acceleration), t_1 and t_2 are the initial and final times (in seconds) chosen to maximize the HIC value, and the time duration, $t_2 - t_1$ is limited to a maximum value of 36 ms.
HIC considers only the linear, translational acceleration during the impact over its defined time window. Rotational components of acceleration, which occur naturally as well, are not considered in the assessment of HIC (Ptak et al., 2019). Usually 15 ms – HIC(15) and 36 ms – HIC(36) is used. An example of dummy's head acceleration analysis for mapping potential damage from a tyre explosion is shown in Figure 1. Presented acceleration plot was filtered with the CFC 1000 filter, and an HIC(36) value near 3000 was obtained (Karliński et al., 2019).

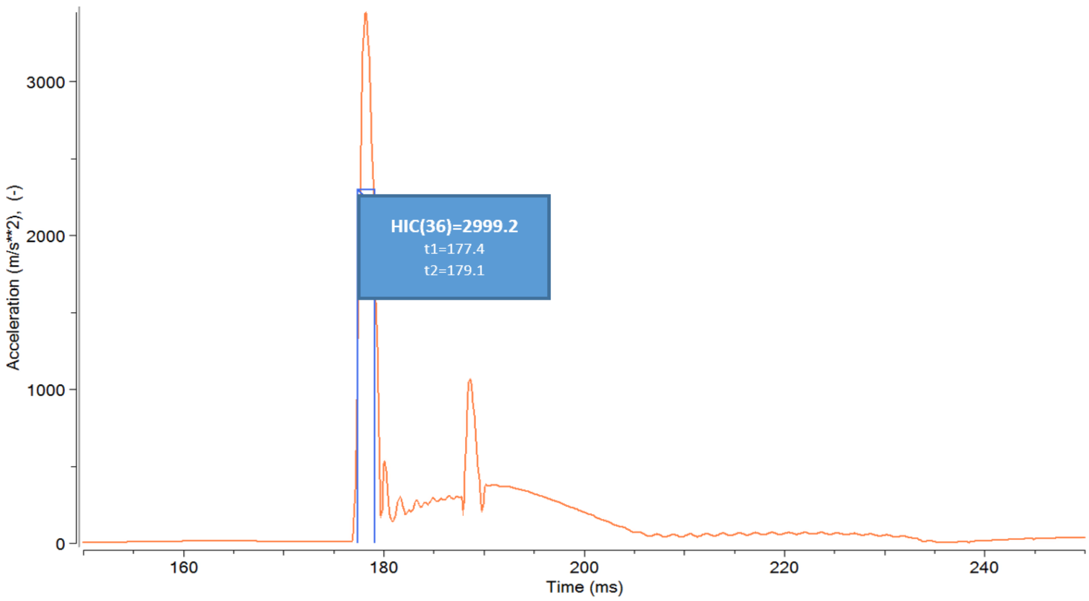

Fig. 1. Resultant acceleration of the dummy's head and HIC(36) value for the tyre explosion

Source: (Karliński et al., 2019)

HIC includes the effects of head acceleration and the duration of the acceleration. High accelerations can be tolerated for very short times, and the severity of injuries is assessed by the Abbreviated Injury Scale (AIS) (Karliński et al., 2019; Mackay, 2007). This scale assesses the tissue damage and threat to life on a six-division ordinal scale, running from minor (AIS 1) through moderate (AIS 2), serious (AIS 3), severe (AIS 4), critical (AIS 5), to generally unsurvivable/ usually fatal (AIS 6) (Prasad and

Mertz, 1985). Genarelli and Wodzin determined the criteria for each AIS level, which are presented in Table 1.

Table 1
Abbreviated Injury Scale for concussive injuries including severity level and associated human injury

Tissue damage	Description
Minor (AIS 1)	Mild Concussion, Headache, Dizziness, No Loss of Consciousness
Moderate (AIS 2)	Loss of Consciousness < 1 hour
Serious (AIS 3)	Loss of Consciousness 1-6 Hours
Severe (AIS 4)	Loss of Consciousness 6-24 Hours
Critical (AIS 5)	Loss of Consciousness > 24 Hours
Usually fatal (AIS 6)	Lethal

Source: (Gennarelli and Wodzin, 2006)

There are other classifications. For example according to Canadian Playground Advisory, a minor head injury occurs when there is a skull trauma without loss of consciousness, superficial face injuries, and fracture of nose or teeth (Yang and Dai, 2010). A moderate head injury occurs when there is a skull trauma with or without dislocated skull fracture and brief loss of consciousness, fracture of facial bones without dislocation, and deep wounds (Yang and Dai, 2010). A critical head injury occurs when there is a loss of consciousness for more than 12 hours with intracranial haemorrhaging, recovery is uncertain, cerebral contusion, and other neurological signs (Yang and Dai, 2010).

2. METHODOLOGY

The relation between the probability of head injuries with different severities and HIC were provided by Prasad and Mertz (Prasad and Mertz, 1985). It is presented in the graphical form in Figure 2.

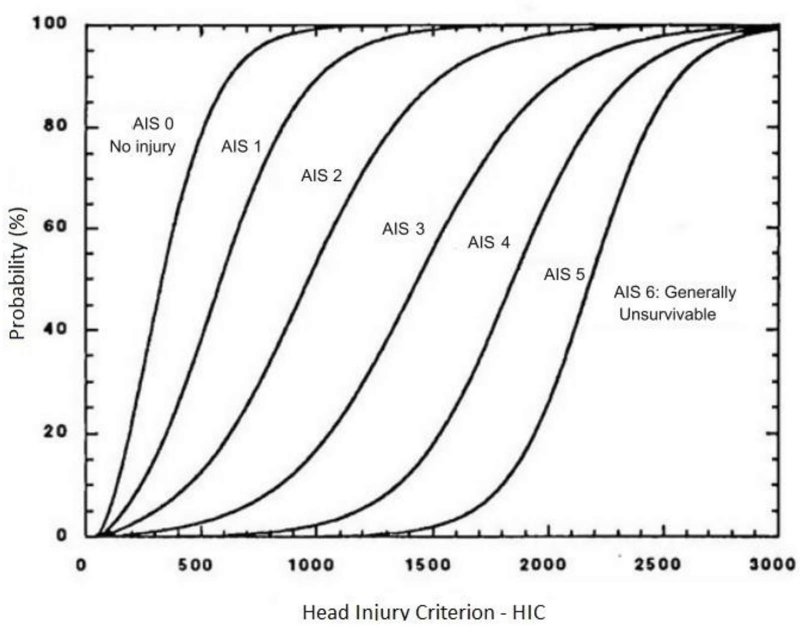

Fig. 2. Probability of head injuries of different severities for given HIC values
Source: (Dionne et al., 1997; Mackay, 2007)

For example, at an HIC of 1100, there is an 18% probability of a severe head injury, a 55% probability of a serious injury, and a 90% probability of a moderate head injury to an average adult. The Prasad and Mertz curves are sigmoidal models and can be mapped using an exponential model described by the formulae:

$$\Pr(AIS) = 1 - \exp(-a \cdot HIC^{b}) \tag{2}$$

Table 2 contains the values of coefficients determined by the authors on the basis of the relationship between likelihood and HIC values presented in the literature (Mackay, 2007; Prasad and Mertz, 1985).The different formulae are also summarised in the Annex.

Table 2
Coefficients values of the proposed exponential model

Tissue damage	*a*	*b*
Minor (AIS 1)	8.79×10^{-06}	1.94
Moderate (AIS 2)	4.18×10^{-07}	2.24
Serious (AIS 3)	9.00×10^{-09}	2.64
Severe (AIS 4)	2.34×10^{-09}	2.69
Critical (AIS 5)	2.23×10^{-19}	5.66
Usually fatal (AIS 6)	4.76×10^{-31}	9.03

The values of standard errors σ and coefficients of derminantionR^2 for the proposed models are presented in Table 3.

Table 3
The indicators for the adjustment of the proposed exponential model

Tissue damage	σ (-)	R^2 (-)
Minor (AIS 1)	0.004699	0.999618
Moderate (AIS 2)	0.006239	0.999753
Serious (AIS 3)	0.008357	0.999643
Severe (AIS 4)	0.037552	0.994547
Critical (AIS 5)	0.011755	0.999597
Usually fatal (AIS 6)	0.012543	0.999528

The proposed models show good reflection of the Prasad and Mertz curves, in all cases exceeding the correlation coefficient of 0.994.

3. RESULTS AND DISCUSSION

The authors analysed the consequences of selected head injury accidents presented in the literature (Table 4).

Table 4
Analysed scenarios of events resulting in head injuries

HIC	Description	Detailed scenario
54	Shot in the helmet with a bullet without piercing the armor	(Yang and Dai, 2010)
600	Impact from above on helmet with protective foam	(Levadnyi et al., 2018)
816	Motorcycle impact on protective barrier	(Wilhelm et al., 2017)
1600	Explosion of 5 kg explosive at a height of 0.5 m	(Haladuick, 2014)

	at a distance of 2.5 m.	
2130	Impact from above on a helmet without foam	(Levadnyi et al., 2018)
2900	Explosion of 5 kg explosive at a height of 1 m at a distance of 2.5 m.	(Haladuick, 2014)
2999	Explosion of a tyre during its inflation	(Karliński et al., 2019)
6525	Cyclist accident without helmet	(Matsui and Oikawa, 2018)
7000	Explosion of 10 kg of explosive at a height of 1 m at a distance of 2.7 m.	(Haladuick, 2014)

Scenarios in the table based on experimental research using dummies and simulation studies using finite element methods.

Detailed presentation of assumptions and boundary conditions of individual experiments and detailed description of scenarios are included in the mentioned source literature. They are not presented in detail because of the limited volume of the text.

The authors have selected cases that reflect the gradually increasing probability of brain and skull damage. For particular cases, the probabilities of head injuries were determined using the proposed exponential models. The results obtained are summarised in Figures 3 and 4.

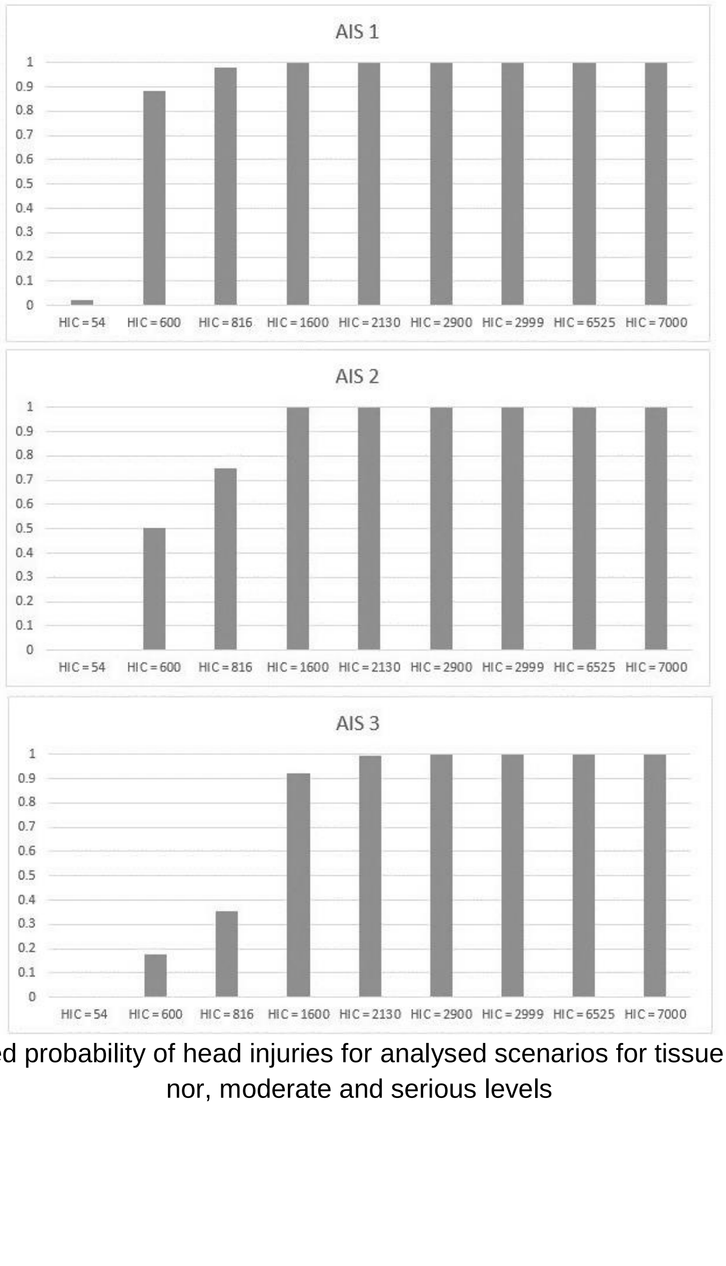

Fig. 3. Estimated probability of head injuries for analysed scenarios for tissue damage at minor, moderate and serious levels

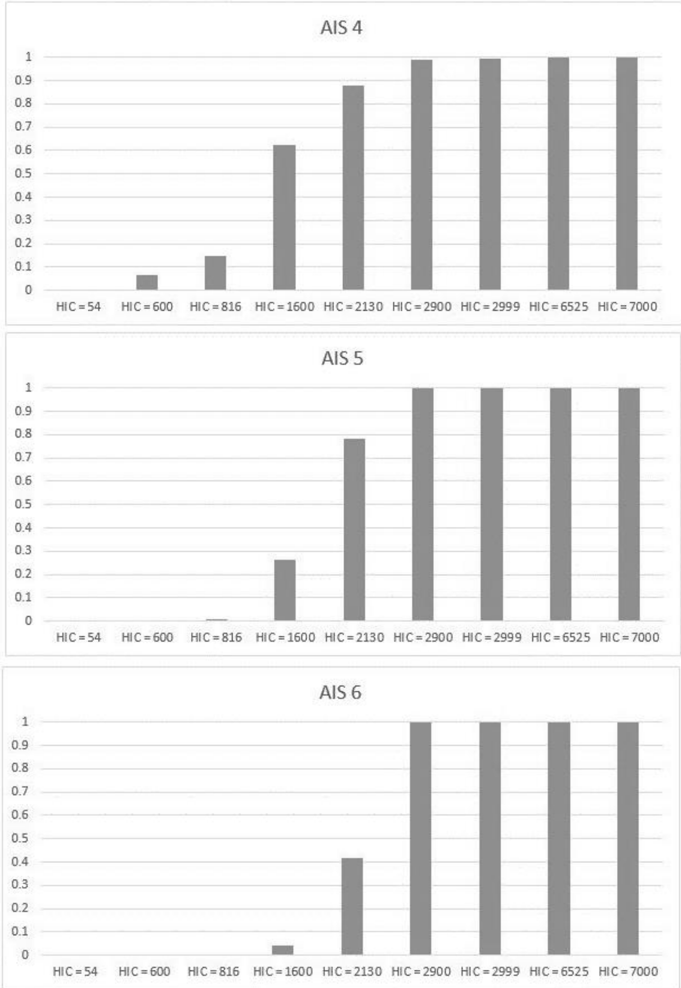

Fig. 4. Estimated probabilities of head injuries for analysed scenarios for tissue damage at severe, critical and fatal levels

With the increasing value of HIC, the probability of injury attributed to an increasingly higher level of AIS becomes more and more important in the analysis. In the first case, the user of the helmet did not suffer any significant head injuries (Pr(AIS 1) = 0.020). In the second case, probability values greater than 0.05 already apply to AIS 3, in the following cases AIS 4 and AIS 5. Cases 5-9 depict fatal injury situations, including the last 4 cases Pr(AIS 6) > 0.97.

4. CONCLUSION

The presented models can be used as a tool to support safety and reliability analysis and probabilistic risk assessment for all cases where the operator's head is injured as a result of translational forces. This applies in particular to analyses that take into account human reliability aspects, since the models presented can be integrated with indicators that take into account operator error.

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mentation of innovations using novel materials and modifying the object's structure" performed at the Maritime University of Szczecin, Poland.

APPENDIX

Summary of the compiled relationships

1. Probability of minor head injury:

$$\Pr(\mathrm{AIS1}) = 1 - \exp\left(\frac{-8.79 \cdot HIC^{1.94}}{10^{6}}\right) \tag{3}$$

2. Probability of moderate head injury:

$$\Pr(\mathrm{AIS2}) = 1 - \exp\left(\frac{-4.18 \cdot HIC^{2.24}}{10^{7}}\right) \tag{4}$$

3. Probability of serious head injury:

$$\Pr(\mathrm{AIS3}) = 1 - \exp\left(\frac{-9.00 \cdot HIC^{2.64}}{10^{9}}\right) \tag{5}$$

4. Probability of severe head injury:

$$\Pr(\mathrm{AIS4}) = 1 - \exp\left(\frac{-2.34 \cdot HIC^{2.69}}{10^{9}}\right) \tag{6}$$

5. Probability of critical head injury:

$$\Pr(\mathrm{AIS5}) = 1 - \exp\left(\frac{-2.23 \cdot HIC^{5.66}}{10^{19}}\right) \tag{7}$$

6. Probability of fatal head injury:

$$\Pr(\mathrm{AIS6}) = 1 - \exp\left(\frac{-4.76 \cdot HIC^{9.03}}{10^{31}}\right) \tag{8}$$

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