DEVELOPMENT OF A PROBABILISTIC SKULL FRACTURE MODEL FOR A 50TH PERCENTILE ADULT MALE MOTORCYCLIST ATD HEADFORM

R. M. Van Auken
T. A. Smith
J. W. Zellner
Dynamic Research, Inc.
United States of America
Paper Number 11-0035

ABSTRACT

The ability to measure and quantify the differences in injuries between helmeted and unhelmeted riders of motorcycles, quadricycles and other small open vehicles as well as injuries to other unhelmeted vulnerable road users such as pedestrians has led to the desire to extend motorcyclist injury assessment methods such as those in ISO 13232 (2005) to include the potential for skull fracture due to head contact forces (e.g., direct impact and crushing type injury mechanisms), in addition to the closed-skull brain injury probability calculations based on head accelerations which are currently in the ISO 13232 Standard (2005). A probabilistic injury model was developed for a 50th percentile adult male by correlating human biomechanical data on skull fractures with cranial vault and facial contact mechanical "work." This injury model was then transformed into an "equivalent work" model applicable to Motorcyclist Anthropometric Test Device (MATD) headform contact forces based on the series of assumptions listed. The biomechanical data comprised 64 cases involving temporoparietal region, maxilla and zygoma fractures as reported in Nahum et al. (1968) and Schneider and Nahum (1972). Laboratory tests were also conducted to measure the MATD contact forces during impact conditions that replicated those of the human cadaver tests reported in the scientific literature. The results demonstrated that the MATD headform contact forces can be measured and used to estimate the probabilities of an AIS 1, 2, 3, and 4 human cadaver face or vault fracture. The AIS probabilities generated from MATD testing were in substantial agreement with the scientific literature. Since the proposed skull fracture criteria are closely related to the forces acting on the skull that can result in bone fracture, rather than indirect measurements of these forces such as head acceleration, it is better suited for predicting skull fractures in some types of injury mechanisms (e.g., crushing type injury mechanisms) that may result in high contact forces but low resultant head accelerations. The resulting injury criteria for a 50th percentile adult male can be used to assess the probabilities of an AIS 2, 3, and 4 vault or AIS 1, 3, and 4 facial fracture resulting from unhelmeted head contact forces, using specialized test sensors and methods or calibrated ISO 13232 type computer simulations. The criteria are well suited for evaluating skull fracture injuries resulting from head contact forces and are complementary to existing head acceleration based injury criteria for closed skull brain injuries that are currently in the Standard. Limitations of the injury criteria are the relatively small number of available biomechanical data and the series of assumptions made. In addition, for potential use in crash tests, an ATD headform with specialized force sensors would also be needed to measure head contact forces in crash tests. The resulting probabilistic injury criteria provide a useful tool to assess the change in injury risks and benefits of potential protective devices for unhelmeted motorcycle and quadricycle riders, as well as pedestrians, using ISO 13232 type computer simulation methods.

INTRODUCTION

Background

ISO Standard 13232 (2005) [3] currently provides a method to assess the probability of injury and injury severity for specific types of injury to the head (closed skull brain), neck, chest (thorax), abdomen and lower extremities (femur, tibia and knee dislocation) based on objective measurements from a Motorcycle Anthropometric Test Device (MATD). These measurements may be based on either full-scale tests or calibrated computer simulation (e.g., [4]).

Research involving injuries to unhelmeted motorcycle, quadricycle, and all-terrain vehicle (ATV) riders has increased the need to extend the ISO 13232 type injury assessment methods to include the potential for skull fracture which can result from opposing contact forces, in addition to the closed-skull brain injury probability calculations based on head accelerations which are currently in the Standard.

Objectives

The objective of this study was to develop probabilistic skull fracture injury criteria for skull fractures that are:

- consistent with the model forms for the other body regions in Part 5 of ISO 13232,
- based on contact deformation work time histories, which can be obtained either from computer simulations or specialized test devices and procedures (e.g.,[5]),
- suitable for predicting the AIS level [6] associated with skull fractures.

It is also recognized that skull fracture and injury severity depend on the fracture location. This is addressed by criteria specific to the face and vault.

METHODOLOGY

Probabilistic skull fracture injury criteria based on the maximum contact deformation work were developed by correlating injury severity with objective impact test data for 64 human cadaver tests reported in the scientific literature based on various assumptions listed below. The contact deformation work is given by the equation

$$W = \int_0^D F(x)dx \qquad (1).$$

where $F(x)$ is the contact force at deflection x, and D is the maximum deflection. The maximum contact deformation work was chosen because it tends to be less sensitive to variations in the contact force vs deflection (i.e., the biofidelity of the MATD headform) compared to other indices such as the peak contact force.

Assumptions

The skull fracture model is based on the following assumptions:

1. The skull fracture occurs as the result of contact with a blunt object (i.e., the object is not sharp).
2. The probability of skull fracture depends on whether the contact was to the vault (AIS-2005 body region 1) or face (AIS-2005 body region 2) and on the "mechanical work" to deform the skull resulting from the normal component of the contact force. For the purposes of this model,
   - The face comprises the zygoma and maxilla;
   - The vault comprises the entire head excluding the face.
3. Vault and facial fractures comprise AIS-2005 injuries listed in Tables 1 and 2. The vault fractures listed in Table 1 are AIS 2 though 6. The facial fractures listed in Table 2 are either AIS 1, 2, 3, or 4. However, since there were no AIS 2 facial fractures indicated in Nahum et al [1] and Schneider and Nahum [2] (see Table 12), it was further assumed that the probability of an AIS 2 facial fracture is small compared to the probability of AIS 1 or AIS 3 facial fracture in this analysis and can be assumed to be zero.
4. For each contact location, the probability of $AIS \geq i$ injury vs maximum contact deformation work W_{max} is assumed to have a Weibull distribution as follows:

$$P(AIS \geq i | W_{max} = w) = 1 - \exp\left(-\left(\frac{w}{\eta_i}\right)^{\beta_i}\right) \qquad (2).$$

   where η_i and β_i are parameters to be determined. The Weibull distribution is descriptive of many types of mechanical failure, and is used to describe the probability of injury to other body regions in ISO 13232-5.
5. The probability of injury and injury severity is independent on the shape of the contacting blunt object (Note: these injury criteria do not estimate the probability of skull fracture due to contacts with sharp objects).
6. The AIS injury severity was assumed to correspond to the skull fracture severity reported in Nahum et al [1] and Schneider and Nahum [2] according to Table 3.
7. The force vs deflection characteristic of the human skull comprises linear-elastic, elastic, and plastic regions defined by the parameters D_l, D_e, and F_f as illustrated in Figure 1. This implies that the ultimate strength and yield strength are assumed to be the same. Figure 2 illustrates a measured force vs deflection characteristic from Allsop et al [7] that can be approximated by this characteristic. The linear-elastic deflection region is between 0 and D_l. The skull begins

to fracture when the contact force reaches F_f and the contact force remains constant at this level for larger deflections. Permanent deflection occurs if the maximum deflection is greater than the elastic limit D_e. This assumed force vs deflection characteristic is based on the results reported in [7][8] (e.g., Figure 5 in [7]).

8. The parameters D_l and D_e for the 50th percentile human male are deterministic and depend only on the whether the contact is to the vault or face. Assumed values are summarized in Table 4.
   a. Human vault - It was assumed that D_l =3.4 mm and D_e = 10.0 mm based on results in [7]. The value for D_l is based on the results in Table 8. The value for D_e is based on Figure 5 in [7], which indicates that a 12 mm maximum deflection rebounds by 10 mm after the load is released, resulting in a 2 mm permanent deflection. Therefore $\Delta_e = D_e - D_l$ =6.6 mm.
   b. Human face - It was assumed that D_l =10.9 mm and D_e = 17.5 mm based on results in [8]. The value for D_l is based on the results in Table 9. The value for $\Delta_e = D_e - D_l$ is assumed to be 6.6 mm based on the data for the human vault.
9. The amount of permanent deflection (Δ_p) is equal to the maximum deflection ($D_{\max}$) relative to the elastic limit (D_e), as illustrated in Figure 1.
10. The injury severity is dependent on the maximum deflection and permanent deflection of the human head according to Table 10. The rationale is also listed in this table. This assumed relationship between the contact force, deflection, deformation work, and injury is illustrated in Figure 3 where $\Delta_2 = \Delta_e$ and $\Delta_3 = 20$ mm.
11. The impactor shapes used in the Nahum and Schneider data [1][2] are representative of real-world impact conditions for unhelmeted motorcycle and quadricycle riders.
12. The impact conditions in the Nahum and Schneider data resulted in contact forces that were primarily normal to the skull surface (i.e., tangential movement and friction forces are small and can be neglected).
13. The total energy in the Nahum and Schneider tests were conserved. This energy comprised:
    a. Potential and kinetic energy of the impactor.
    b. Energy transferred to the head and supporting structure by the mechanical work of the impactor. This energy comprises:
       - Potential and kinetic energy of the head and supporting structure,
       - Work to "deform", fracture, and crush the skull.
       - Energy dissipated by the supporting structure (i.e. foam).
14. Changes in potential energy in the 5 ms time interval after initial impact are small and can be ignored.
15. The peak contact force in the Nahum and Schneider data is "uncensored" if fracture occurs (e.g., vault $AIS \geq 2$) (i.e., the fracture occurs at the measured force value). The peak contact force is "right censored" if the fracture does not occur (e.g., vault $AIS < 2$) because the fracture force would be greater than the measured value [9].
16. The deformation work done on the human skull during an impact is equivalent to the work done on a Hybrid III (e.g., MATD) headform when subjected to impacts similar to those reported in the scientific literature.
17. The mortality rate is dependent on the most severe head injury (brain, face or vault) and the mortality rate can be determined from the ISO 13232-5 mortality rate tables using the most severe head injury.
18. Medical and ancillary costs for a head injury are assumed to be related to the most severe brain or vault fracture injury; the same for brain, face or vault injuries; and that values in ISO 13232-5 [3] for the head injury are valid for all three.

Table 1.
AIS-2005 (Update 2008) Vault Fractures

Injury Severity	AIS-05 Code	Description
2	150000.2	Vault fracture NFS[a] (may involve frontal, occipital, parietal, sphenoid, or temporal bones)
	150402.2	Closed (simple; undisplaced; diastatic; linear)
3	116000.3	Penetrating injury NFS
	116002.3	Penetrating injury, superficial (≤2cm beneath entrance)
	150404.3	Comminuted (compound; depressed ≤ 2cm; displaced)
4	150406.4	Complex (open with loss of brain tissue)
	150408.4	Massively depressed (large areas of skull > 2cm)
5	116004.5	Penetrating injury, major (>2 cm penetration)
6	113000.6	Massive destruction of both cranium (skull), brain and intracranial contents (crush)

Source: AAAM (1998)
Notes:
a)"NFS" indicates "Not Further Specified"

Table 2.
AIS-2005 (Update 2008) Facial Fractures

Injury Severity	AIS-05 Code[a]	Description
1	25060x.1	Mandible fracture, closed or NFS[b]
	2510xx.1	Nose fracture, closed or NFS
	2514xx.1	Teeth
	2518xx.1	Zygoma fracture, non-displace, displaced
2	25061x.2	Mandible fracture, open
	25080x.2	Maxilla fracture, NFS, closed, LeFort I, or LeFort II
	251002.2	Nose fracture, open/displaced/comminuted
	2512xx.2	Orbit fracture, closed or NFS
	251814.2	Complex zygoma fracture[c]
	2512xx.2	Orbit fracture, open/displaced/comminuted
3	250808.3	Maxilla fracture, LeFort III
4	250810.4	Maxilla fracture, LeFort III, blood loss > 20%

Source: AAAM (2008)
Notes:
a) "x" indicates any number in this position
b) "NFS" indicates "Not Further Specified"
c) Zygoma fractures were reclassified as an AIS 1 or AIS 2 injury in AIS-2005, depending on the type of fracture.

Table 3.
Assumed Nahum and Schneider Data Fracture Severity Score

Nehum and Schneider Fracture Severity Scale		AIS-2005 Injury Severity
Code	Description	
0	"none"	0
1	"minimal detectable change, not clinically significant"	0
2	"readily detectable fracture, clinically significant"	2[a]
3	"comminuted, and/or depressed fractures"	3[a]

Note:
a) All Zygoma fractures were assumed to be AIS 1 because this represents all Zygoma fractures except complex fractures.

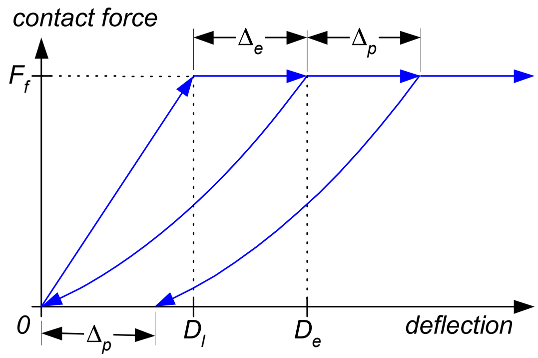

Figure 1. Assumed Human Skull Contact Force vs. Deflection Characteristic.

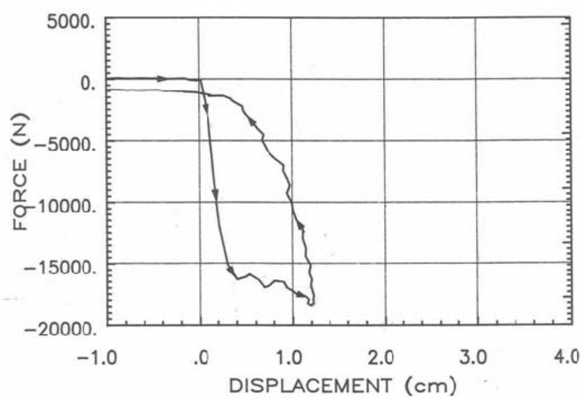

Figure 2. Example Human Skull Contact Force vs. Deflection (Allsop et al [7]).

Table 4.
Assumed Human Male Skull Force vs Deflection Characteristic Parameters

Characteristic Parameter		Assumed Value		Units
		Vault	Face	
D_l	Linear range	3.4 (0.5) [a]	10.9 (7.8) [b]	mm
$\Delta_e = D_e - D_l$		6.6 [d]	6.6 [e]	mm
D_e	Elastic limit	10.0 [c]	17.5 [f]	mm

Sources and Notes:

a) Table 8 (derived from data in Allsop et al [7]).

b) Table 9 (derived from data in Allsop et al [8]).

c) Figure 5 in [7], which indicates that a 12 mm maximum deflection rebounds by approximately 10 mm after the load is released, resulting in a 2 mm permanent deflection

d) Computed, $\Delta_e = D_e - D_l$

e) Assumed equal to the Vault value

f) Computed, $D_e = D_l + \Delta_e$

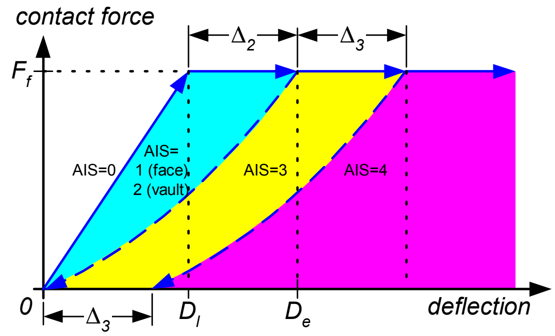

Figure 3. Assumed Relationship between Contact Force, Deflection, Work, and Skull Fracture Injury Severity.

Adult Human Male Cadaver Data

Data on skull fracture injuries and contact forces from over 200 human cadaver tests were compiled from results in [1][2][7][8] and [10]. These tests comprised various impactor shapes ranging in area from 302 mm² to 5200 mm². Of these, 128 tests using a flat circular plate with 645 mm² area were reported in the Nahum and Schneider studies. Therefore the Nahum and Schneider data were used because it represented the majority of the available data with a single medium-sized impactor shape. This eliminates the impactor shape and size as a potential confounding factor, yet the data are assumed to be representative of real-world impacts with blunt surfaces of this general area.

Of the Nahum and Schneider data, only the human male cadaver data were used. The frontal region tests were not used because they were a relatively small sample (8 cases), and tended to have larger peak forces than the temporo-parietal tests. Data for the remaining 64 tests are listed in Table 11 and Table 12. The tests comprised 45 embalmed and 19 unembalmed cadavers with 51 to 81 years age at time of death. The number tests by impact region are summarized in Table 5.

Table 5.
Number of Male Nahum and Schneider Tests Used

AIS-2005 Body Region	Impact Region	Number of Tests
Head (Vault)	Temporo-Parietal	27
Face	Zygoma	27
	Maxilla	10
Total		64

Estimation of Injury Probability Curves

Given the data in Table 11 and Table 12 the Weibull distribution parameters for the probability of fracture vs peak contact force can be estimated. Rank ordered data and estimated cumulative probability distribution curves are illustrated in Figure 4 and Figure 5. The symbol type indicates the data source. The open symbols are the tests that did not result in fracture and are assumed to be right censored. The filled symbols are the tests that resulted in a fracture, which was assumed to be force limiting and uncensored. The vertical axis of the data is plotted on a Kaplan-Meier empirical distribution, which accounts for data censoring.

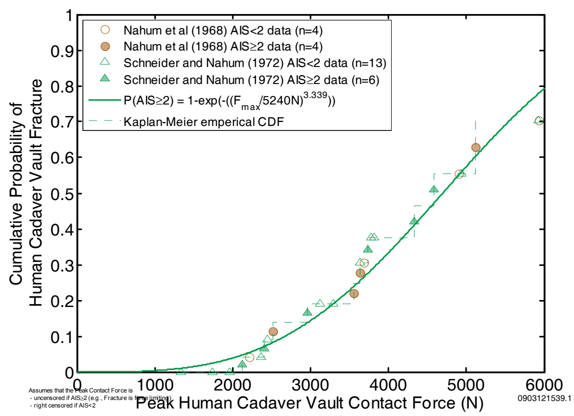

Figure 4. Probability of Human Cadaver $AIS \geq 2$ **Vault Fracture vs Peak Contact Force.**

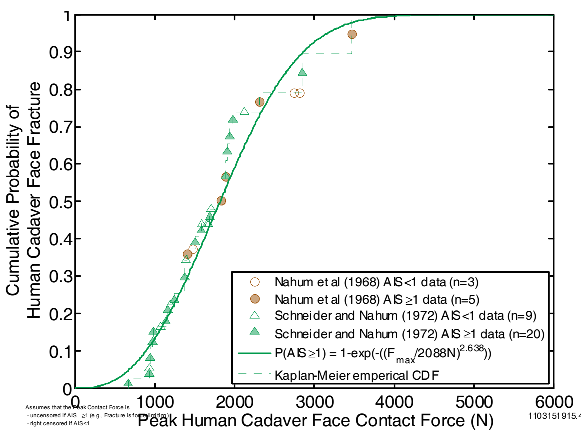

Figure 5. Probability of Human Cadaver $AIS \geq 1$ **Facial Fracture vs Peak Contact Force.**

Assuming the following Weibull distribution for the probability of an $AIS \geq 2$ vault fracture (or $AIS \geq 1$ facial fracture) vs the peak contact force,

$$P(AIS \geq 2 | F_{\max} = f) = 1 - \exp\left(-\left(\frac{f}{\eta'} \right)^{\beta'} \right) \quad (3).$$

Maximum likelihood estimates and 95% confidence intervals for η' and β' were estimated using the MATLAB Statistics Toolbox "WBLFIT" routine [11]. The MATLAB WBLFIT routine supports right-censored data using methods described in [9]. The results for the vault are η'=5240 (4302, 6384) N and β'=3.34 (2.09, 5.33); the results for the face are η'=2088 (1800, 2423) and β'=2.64 (1.98, 3.52) for the face. The values in parentheses "( )" are the lower and upper bounds for the 95% confidence interval for the estimated value.

<u>Fracture Injury Risk</u> - The probability of a vault or facial fracture can be expressed in terms of the equivalent contact deformation work based on the assumed force vs deflection characteristic illustrated in Figure 1. For example, the contact deformation work needed to fracture the skull, resulting in an $AIS \geq 2$ vault fracture is

$$W_2 = \int_0^{D_l} F(x)dx = \int_0^{D_l} \frac{F_f}{D_l} x\, dx = \frac{F_f D_l}{2} \quad (4).$$

where D_l is assumed to be a constant, depending on the contact location. Since W_2 is proportional to F_f (i.e., $W_2 = F_f\, D_l/2$), W_2 has the same statistical properties (e.g., censoring) as F_f. Therefore, equations (2) for $AIS \geq 2$ and (3) are equivalent provided that:

$$\eta_2 = \eta' \left(\frac{D_l}{2} \right) \qquad \beta_2 = \beta' \quad (5).$$

Scaled Nahum and Schneider data for W_2 and corresponding Weibull distribution curves are illustrated in Figure 6 and Figure 7, assuming D_l is 3.4 mm for the vault, and 10.9 mm for the face.

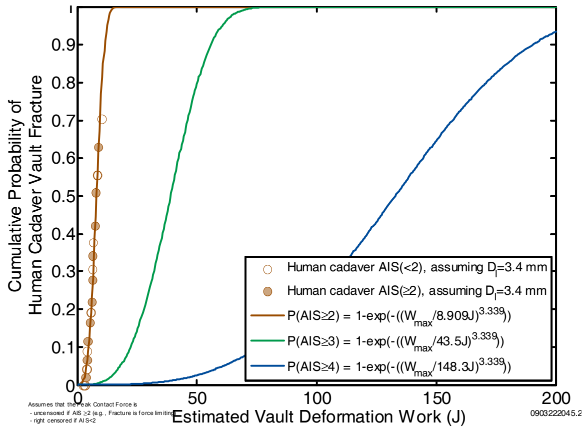

Figure 6. Probability of Vault Fracture vs Estimated Vault Deformation Work.

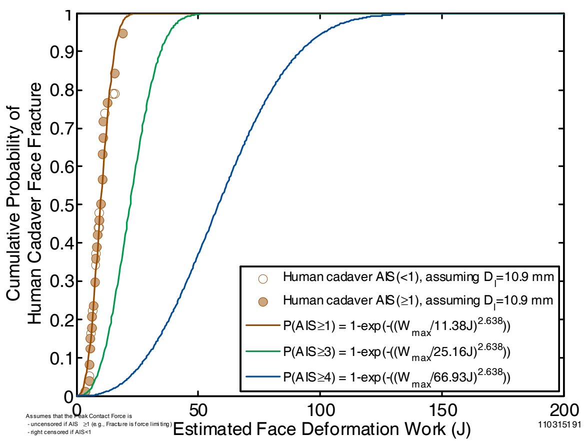

Figure 7. Probability of Facial Fracture vs Estimated Facial Deformation Work.

The estimated "deformation work" to fracture the skull tends to be a small portion of the initial kinetic energy of the impactor reported by Nahum and Schneider. This "deformation work" does not include:

- the kinetic energy that remains in the impactor,
- the energy transferred to the kinetic energy of the head,
- the energy absorbed by the skull after fracture, or
- the energy absorbed by the supporting foam.

$AIS \geq 3$ **Injury Risk -** The probability of an $AIS \geq 3$ skull fracture can also be expressed in terms of equivalent deformation work based on the assumed force vs deflection characteristic illustrated in Figure 1. The contact deformation work needed to fracture the skull and just begin permanent deformation is

$$W_3 = \int_0^{D_e} F(x)\,dx = \int_0^{D_l} \frac{F_f}{D_l} x\,dx + \int_{D_l}^{D_e} F_f\,dx = F_f\left(\frac{D_l}{2} + \Delta_2\right) \quad (6).$$

If an $AIS \geq 2$ fracture was observed in the Nahum and Schneider data for a given F_f and W_2, then we can assume that an additional $F_f \Delta_2$ amount of contact deformation work would have increased the maximum deflection by Δ_2, resulting in some permanent deflection and an $AIS \geq 3$ injury. Therefore the probability of an $AIS \geq 3$ fracture vs W_3 is the same as the probability of an $AIS \geq 2$ fracture vs W_2; and equations (2) for $AIS \geq 3$ and (3) are equivalent provided that:

$$\eta_3 = \eta'\left(\frac{D_l}{2} + \Delta_2\right), \quad \beta_3 = \beta' \quad (7).$$

Scaled Nahum and Schneider data for W_3 and corresponding Weibull distribution curves are also illustrated in Figure 6 and Figure 7, assuming $\Delta_2 = \Delta_e$=6.6 mm.

$AIS \geq 4$ **Injury Risk -** In a similar manner, the probability of an $AIS \geq 4$ skull fracture can also be expressed in terms of equivalent work. The contact deformation work needed to fracture the skull and result in Δ_3 (20 mm) of permanent deformation is

$$W_4 = F_f\left(\frac{D_l}{2} + \Delta_2 + \Delta_3\right) \quad (8).$$

It follows that equations (2) for $AIS = 4$ and (3) are equivalent provided that:

$$\eta_4 = \eta'\left(\frac{D_l}{2} + \Delta_2 + \Delta_3\right), \quad \beta_4 = \beta' \quad (9).$$

Scaled Nahum and Schneider data for W_4 and corresponding Weibull distribution curves are also illustrated in Figure 6 and Figure 7, assuming Δ_3 is 20 mm.

MATD INJURY CRITERIA

The probability of an $AIS \geq i$ skull fracture can be estimated based on the contact deformation work according to equation (2), where the values for parameters η_i and β_i depend on the contact location. Maximum likelihood estimates and 95% confidence intervals of η_i and β_i are listed in Table 6 for contacts with the vault, and Table 7 for contacts with the face.

Table 6.
Estimated Vault Fracture Weibull Distribution vs Injury Severity Parameters

$P(AIS \geq i)$	η_i (J)	β_i
2	8.91 (7.31,10.9)	3.34 (2.09, 5.33)
3	43.5 (35.7,53.0)	3.34 (2.09, 5.33)
4	148. (122.,181.)	3.34 (2.09, 5.33)

Table 7.
Estimated Facial Fracture Weibull Distribution vs Injury Severity Parameters

$P(AIS \geq i)$	η_i (J)	β_i
1	11.4 (9.81,13.2)	2.64 (1.98, 3.52)
3	25.2 (21.7,29.2)	2.64 (1.98, 3.52)
4	66.9 (57.7,77.7)	2.64 (1.98, 3.52)

For comparison purposes the work to fracture the vault and face can also be computed from the Allsop data listed in Table 8 and Table 9. The mean work to fracture the vault from the data in Table 8 is 10.4 (3.5) J. The mean work to fracture the face from the data in Table 9 is 9.9 (8.0) J. These results are not statistically significantly different than the results for $AIS \geq 2$ in Table 6 and Table 7.

APPLICATION TO ISO 13232 MATD

The skull fracture injury criteria can be applied to the MATD (Hybrid III) headform provided the contact deformation work can be determined. The contact deformation work can be determined using computer simulation or special measurement of contact force (e.g., impactor force, pressure film, custom headform [5]).

Measured MATD Force-vs-Deflection

The force vs deflection characteristics of the MATD headform in the temporoparietal region were measured by a quasi-steady laboratory test illustrated in Figure 8. The headform was placed between two circular disks, each with 645 mm contact area. The contact force was measured by a load cell. The total displacement, which included deformation on both sides of the headform, was measured by a string potentiometer. The total displacement was divided by two to obtain the deflection for a single side.

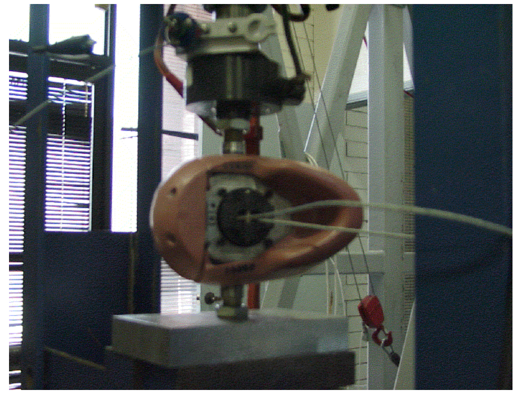

Figure 8. Quasi-Steady MATD Force vs Deflection Test Setup.

The force and displacement of the MATD headform was measured while slowly applying the contact force until the headform ultimate limit was reached at 23.8 kN. The test was done in two stages. The resulting force vs deflection characteristic of the MATD headform is illustrated in Figure 9.

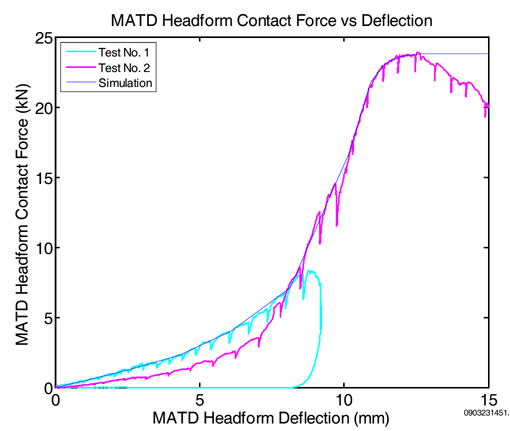

Figure 9. Measured MATD Headform Contact Force vs. Deflection.

MATD Injury Risk Curves

As previously indicated the probability of skull fracture can be estimated from the maximum contact deformation work according to equation (2) and the coefficients in Table 6 or Table 7, depending on the contact location. These probability curves were illustrated in Figure 6 and Figure 7.

The probability of skull fracture can be also estimated from the peak MATD headform contact force provided the contact deformation work can be uniquely and accurately determined from the peak contact force. This condition can be satisfied if the contact force is a monotonically increasing function of the contact deformation.

Note that in order to address the ultimate limit of the MATD headform at 23.8 kN, the monotonically increasing "simulation" curve in Figure 9 was used in computer simulations. This curve was extrapolated with a small positive slope to obtain a monotonically increasing curve.

Provided the simulated MATD contact force is based on the force-deflection characteristic in Figure 9, the probability of injury versus peak MATD contact force ($F_{\max,MATD}$) can be determined as follows:

1. Refer to the MATD contact force vs deflection curve in Figure 9 to determine the contact deflection $D_{\max,MATD}$ from $F_{\max,MATD}$.
2. Integrate MATD contact force vs deflection curve from 0 to $D_{MATD,\max}$ to determine the maximum contact deformation work $W_{\max}$.
3. Estimate the probability of injury from the contact deformation work according the equation (2) and the coefficients in Table 6 or Table 7, depending on the contact location.

The resulting probability of injury versus the MATD contact force is illustrated in Figure 10 and Figure 11.

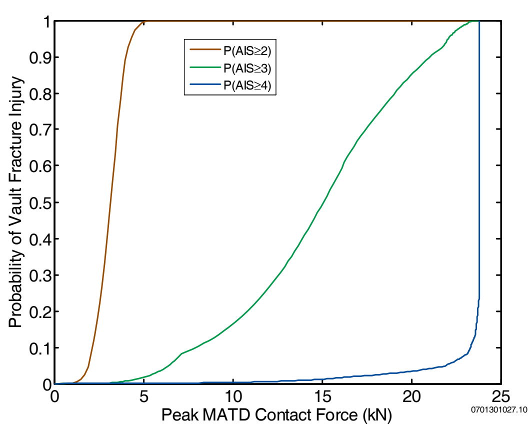

Figure 10. Estimated Probability of Vault Fracture Injury vs Peak Simulated MATD Contact Force.

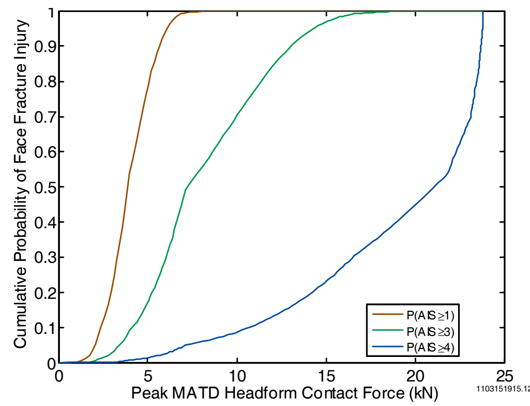

Figure 11. Estimated Probability of Facial Fracture Injury vs Peak Simulated MATD Contact Force.

Validation tests

Drop tests to replicate the conditions of the Nahum and Schneider human cadaver tests were accomplished in the Dynamic Research, Inc. Impact Test Laboratory. The test setup comprised a 3.275 kg impactor mounted on a vertical slide rail which was allowed to free-fall, impacting either in the vault (temporoparietal) or facial (zygoma) regions of the MATD headform, as illustrated in Figure 12. The MATD headform was supported by 100 mm of soft foam rubber as described in [1].

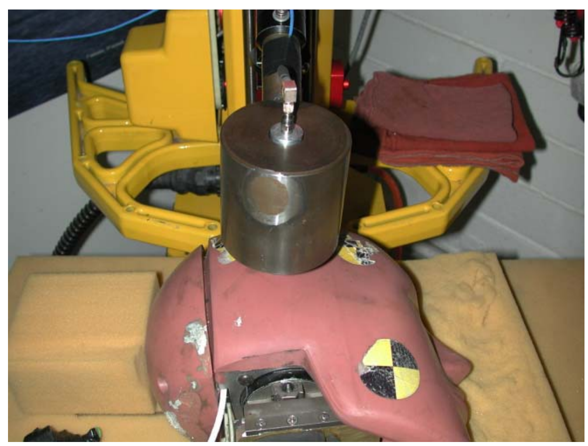

Figure 12. Impact Test Setup.

Results for a series of vault tests are summarized in Figure 13. The circle symbols represent the test data and the solid lines represent reconstructions of the tests using the US DOT and US Air Force Articulated Total Body (ATB) program [12]. The peak contact forces for the test data were derived from the peak measured impactor accelerations. The vault deflections were not measured in these tests, and were therefore estimated from time-domain reconstruction simulations. However these estimated deformation data are considered reliable because of the close agreement between the test data and reconstructions.

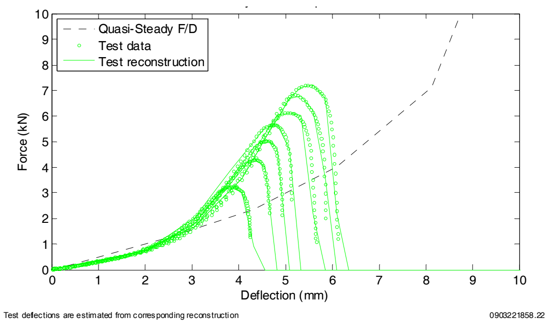

Figure 13. Measured and Reconstructed Vault Force vs Deflection in Impact Test Series.

The results in Figure 13 indicate that the force vs deflection characteristics for these tests are not monotonically increasing, and therefore the deformation work for these tests cannot be determined from the peak contact force. Instead the maximum deformation work for these tests was estimated by integrating the force vs deflection characteristic over the range of reconstructed deformation values. The non-monotonic characteristic observed in these tests is attributed to velocity-dependent characteristics of the elastomer MATD headform skin.

The green symbols and curves in Figure 14 and Figure 15 illustrate the measured and reconstructed time histories for an example vault test with 3.02 m/s impact speed. Figure 14 illustrates the acceleration vs time. Figure 15 illustrates the distribution of energy vs time. The test data impactor kinetic energy was computed from the impactor velocity, which was determined by integrating the acceleration. The test data "head energy" was computed by integrating the impactor force vs time. These figures illustrate that the reconstructed tests are in close agreement with the measured test data up until the point of maximum deflection and deformation work. Therefore the reconstructed test deformations are reliable estimates of the unknown actual values. The maximum vault contact deformation work was 8.9 J and the estimated probability of $AIS \geq 2$ fracture is 0.63.

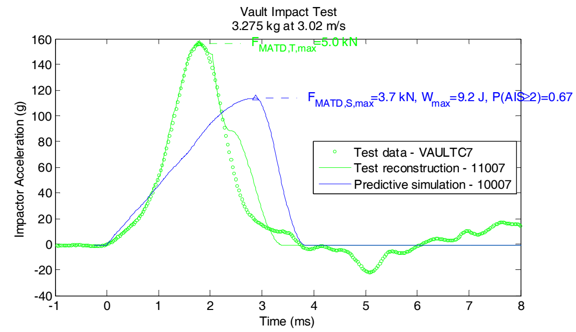

Figure 14. Measured and Simulated Acceleration Response of Vault Impact Test (3.02 m/s).

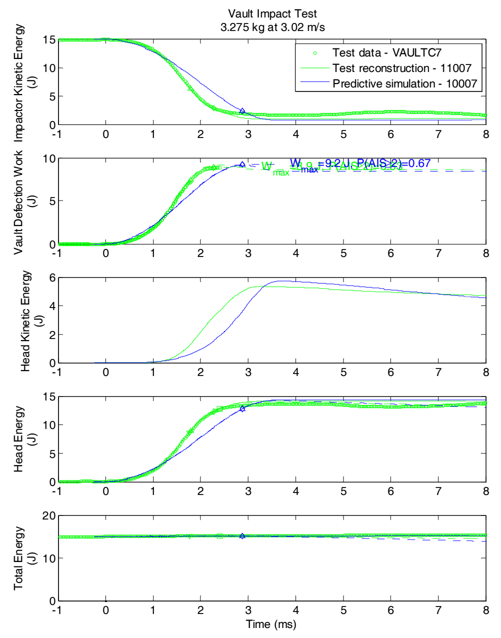

Figure 15. Measured and Simulated Energy Response of Vault Impact Test (3.02 m/s).

The blue curves in Figure 14 and Figure 15 illustrate the predicted responses for the same 3.02 m/s impact assuming a monotonically increasing force vs deflection function. These results indicate that whereas the predicted peak forces are different than the test values, the maximum vault contact deformation work was 9.2 J and the estimated probability of $AIS \geq 2$ fracture is 0.67, which is in close agreement with the test values.

Note the maximum vault contact deformation work can also be estimated according to the following equation

$$W_{max} = \left(1 - \left(\frac{m_{impactor}}{m_{impactor} + m_{headform}}\right)\right) KE_0 \quad (10).$$

where $m_{impactor}$ is the mass of the impactor (3.275 kg) and $m_{headform}$ is the effective mass of the head (approximately 5 kg). Therefore $W_{max} \cong 0.6 \times KE_0$ in these example tests.

Figure 16 illustrates the close overall agreement between the predicted and estimated vault deformation work for the vault test series. The estimated probabilities of injury for these test cases are also in close agreement since they are functions of the deformation work.

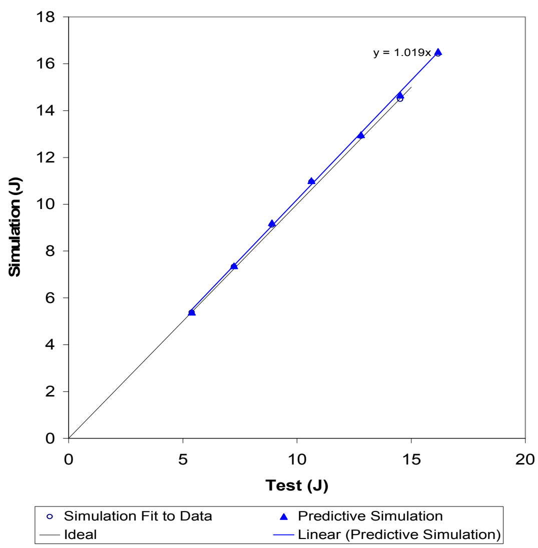

Figure 16. Comparson of Predicted and Estimated Vault Test Contact Deformation Work.

INJURY COST MODEL

The probabilistic skull fracture injury criteria can be incorporated into the ISO 13232 injury cost model in order to extend the ISO 13232 type injury assessment methods so as to include probability of skull fractures for unhelmeted riders of motorcycles and quadricycles. The changes to ISO 13232 that would be necessary are listed in Table 13 and Table 14.

CONCLUSIONS

A probabilistic skull fracture injury criteria has been developed for a 50^{th} percentile adult male that is suitable for ISO 13232 type injury analysis for unhelmeted motorcycle and quadricycle (and ATV) riders. The skull fracture criteria are complementary to the existing closed skull brain injury criteria based on acceleration which is currently implemented in the Standard. This new skull fracture criteria address the injury potential due to crushing type injury mechanisms that have very low acceleration levels.

The skull fracture criteria estimate the probabilities of an AIS 2, 3, and 4 vault and AIS 1, 3 and 4 facial fractures based on the contact deformation work. The contact deformation work is assumed to be insensitive to the differences in the force vs deflection characteristics of the MATD headform compared to the adult male human head. It is assumed that the contact deformation work can be determined by ISO 12323 type computer simulations, or specialized laboratory and full scale test measurement methods.

ACKNOWLEDGMENTS

Dynamic Research, Inc. staff members Jeff Porter, Alex Ricardo, and others assisted in various aspects of this analysis, including compiling the data and conducting the laboratory tests.

REFERENCES

[1] Nahum, A.M., Gatts, J.D., Gadd, C.W., Danforth, J., “Impact Tolerance of the Skull and Face”, Paper No. 680785, Proc. of the 12th Stapp Car Crash Conference, Detroit, 1968, pp. 302-316.

[2] Schneider, D.C., Nahum, A.M., “Impact Studies of Facial Bones and Skull”, Paper No. 720965, Proc. of the 16th Stapp Car Crash Conference, Detroit, 1972, pp 186-203.

[3] ISO 13232-5, Motorcycles – Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motor Cycles – Part 5: Injury Indices and Risk/Benefit Analysis, ISO 13232-5, International Organization for Standardization, Geneva, 2005.

[4] Kebschull, S.A., Zellner, J.W., Van Auken, R.M., “Injury Risk/Benefit Analysis of Motorcycle Protective Devices Using Computer Simulation and ISO 13232”, Paper Number 98-S10-W-26, proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles, Windsor, Canada, National Highway Traffic Safety Administration, Washington, 1998, pp. 2357-2374.

[5] Hatano, K., Kawai, H., Hatamura, Y., Uchimura, T., “An Application of Car Crash Test Technology to a Causal Investigation of a Revolving Door

Accident", Paper No. 2006-01-0717, Society of Automotive Engineers, Warrendale, PA, 2006.

[6] AAAM, The Abbreviated Injury Scale, 2005, Update 2008, Association for the Advancement of Automotive Medicine, Des Plaines, IL, 2008.

[7] Allsop, D.L., Perl, T.R., Warner, C.Y., "Force/Deflection and Fracture Characteristics of the Temporo-parietal Region of the Human Head", Paper No. 912907, Proc. of the 35th Stapp Car Crash Conference, San Diego, 1991, 269-278.

[8] Allsop, D.L., Warner, C.Y., Wille, M.G., Schneider, D.C., Nahum, A.M., "Facial Impact Response - A comparison of the Hybrid III Dummy and Human Cadaver", Paper 881719, Proc. of the 32nd Stapp Car Crash Conference, Atlanta, 1988, 139-155.

[9] Kent, R.W., and Funk, J.R., "Data Censoring and Parametric Distribution Assignment in the Development of Injury Risk Functions from Biomechanical Data", Paper No. 2004-01-317, Society of Automotive Engineers, Warrendale, PA., 2004.

[10] Yoganandan, N., et al, "Steering Wheel Induced Facial Trauma", Paper No. 881712, Proc. of the 32nd Stapp Car Crash Conference, Atlanta, 1988, 45-69.

[11] Mathworks, Statistics Toolbox for use with MATLAB®, Users Guide, Version 5, The Mathworks, Natick, MA, 2006.

[12] Fleck, J.T., and F. E. Butler, Validation of the Crash Victim Simulator, Vol. 1: Engineering Manual – Part 1: Analytical Formulation, DOT HS-806-279, Washington, 1981.

[13] Blincoe, L., et al, The Economic Impact of Motor Vehicle Crashes, DOT HS 809 446, National Highway Traffic Safety Administration, Washington, May 2002.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AIS Abbreviated Injury Scale
NFS: Not Further Specified
D: Deflection
F: Force
W: Work
Δ: Change in deflection

Subscripts

e Elastic limit
l Linear range limit
p Plastic deformation

APPENDIX

Table 8.
Human Male Cadaver Temporo-parietal Force/Deflection and Fracture Characteristics for Circular Plate Impacts

Cadaver ID	Fracture Force (N)	Stiffness (N/mm)	Linear Range Deflection (mm)
M26329	4,800	1,480	3.24
M26350	6,400	1,470	4.35
M26368	7,700	2,570	3.00
M26372	7,300	1,800	4.06
M26373	10,000	3,140	3.18
M26383	5,000	1,540	3.25
M26903	3,100	830	3.73
M26922	4,000	1,440	2.78
Mean	6,038	1,784	3.45
Std. Deviation	1,801	881	0.54
95% confidence interval for the Mean			(0.46)

Source: Allsop et al [7] Tables 2 and 4.

Table 9.
Human Male Cadaver Facial Force/Deflection and Fracture Characteristics

Impact Location	ID	Fracture Force (N)	Stiffness (N/mm)	Linear Range Deflection (mm)
Zygoma	2278	1,700	110	15.45
	2201	2,300	230	10.00
	mean	1,738	148	12.73
Maxilla	2185	1,800	130	13.85
	2291	1,100	250	4.40
	mean	1,350	142	9.12
Mean		1,571	145	10.93
Std. Deviation		492	70	4.92
95% confidence interval for the Mean				(7.82)

Source: Allsop et al [8] Table 1.

Table 10.
Assumed Injury Severity vs Maximum Deflection and Permanent Deflection of the Human Skull

AIS Injury Severity	Maximum Deflection D_{max}	Permanent Deflection $\Delta_p = D_{max} - D_e$	Rationale
0	$D_{max} \leq D_l$	None	No fracture
1 (face) 2 (vault)	$D_l < D_{max} \leq D_e$	None	AIS 2 Vault fractures include: "fracture NFS"*; "closed (simple; undisplaced; diastatic; linear)". AIS 1 Zygoma fractures include "non-displaced" and "displaced"
3	$D_e < D_{max}$	$0 < \Delta_p \leq 20$ mm	AIS 3 fractures of the vault include: 116002.3 – superficial penetrating injury "(≤2 cm beneath entrance)" 150404.3 - "comminuted (compound; depressed ≤ 2 cm; displaced"
4	$D_e < D_{max}$	20 mm $< \Delta_p$	AIS 4 fractures of the vault include: 116004.5 – Major penetrating injury (> 2 cm) 150408.4 - "massively depressed (large areas of the skull depressed > 2 cm)"

Note: *"NFS" indicates "Not Further Specified"

Table 11.
TemporoParietal (Vault) Fracture Injury Data from Nahum and Schneider

Specimen	Force (N)	Fracture Severity	AIS-2005 Severity[a]
1	2518	3	3
1	2215	1	0
2	5115	2	2
2	3634	2	2
3	3683	1	0
3	3550	2	2
5	5934	1	0
5	4902	1	0
18 EM	3290	0	0
18 EM	5920	0	0
19 EM	2360	0	0
19 EM	4580	2	2
20 EM	4330	3	3
20 EM	1340	0	0
31 FM	4940	0	0
31 FM	2960	3	3
34 FM	3640	1	0
34 FM	2450	0	0
35 EM	3120	0	0
35 EM	3820	1	0
38 EM	1740	0	0
38 EM	2400	3	3
39 EM	3740	2	2
39 EM	2360	0	0
40 EM	3780	0	0
41 EM	2120	3	3
41 EM	1960	0	0

Sources: Nahum et al[1], Schneider and Nahum [2]
a) All fractures with Fracture Severity 2 were assumed to have AIS-2005 code 150402.2; All fractures with Fracture Severity 3 were assumed to have AIS-2005 code 150404.3.

Table 12.
Facial Fracture Injury Data from Nahum and Schneider

Impact Location	Specimen	Force (N)	Fracture Severity	AIS-05 Severity
Zygoma	1	1828	3	1
	1	1477	1	0
	2	2740	1	0
	2	2816	1	0
	3	1406	3	1
	3	1890	3	1
	5	3469	3	1
	5	2304	3	1
	18 EM	1580	3	1
	18 FM	1140	3	1
	19 EM	970	3	1
	19 EM	2850	2	1
	20 EM	930	0	0
	20 EM	1910	3	1
Zygomatic Arch	31 FM	930	3	1
	34 FM	1590	0	0
	34 FM	2120	0	0
	35 EM	1670	0	0
	35 EM	1940	2	1
	38 EM	1510	3	1
	38 EM	1390	0	0
	39 EM	1690	3	1
	39 EM	1250	3	1
	40 EM	1660	0	0
	40 EM	1710	0	0
	41 EM	1890	3	1
	41 EM	1370	3	1
Maxilla[b]	31 FM	1980	3	3
	34 FM	1370	3	3
	34 FM	940	3	3
	35 EM	980	3	3
	38 EM	1200	0	0
	38 EM	1160	3	3
	39 EM	940	3	3
	40 EM	1070	0	0
	40 EM	1370	3	3
	41 EM	660	3	3

Sources: Nahum et al [1], Schneider and Nahum [2]
a) All Zygoma and Zygomatic Arch fractures in these data are assumed to have AIS-2005 code 251800.1
b) All Maxilla fractures in these data are assumed to have AIS-2005 code 250808.3 (i.e., LeFort III).

Table 13.
Changes to ISO 13232-5 Injury Cost Model

Clause		Change
5.1	Injury variables	Add computation of vault and face contact deformation work
5.3	Injury severity probabilities	Compute the vault fracture injury severity probability ($ISP_{vault,H,j}$) for each $AIS \geq j$ injury severity level according to equation (2) using the coefficients in Table 6.[a] The head ISP, $ISP_{H,j}$, for each AIS injury severity level is redefined in clause 5.3.1 as the larger of either $ISP_{Gmax,H,j}$, $ISP_{HIC,H,j}$, or $ISP_{Vault,H,j}$.
		Compute the facial fracture injury severity probability ($ISP_{F,j}$) for each $AIS \geq j$ injury severity level according to equation (2) using the coefficients in Table 7. [b]
5.4	Probability of discrete AIS injury severity level	Add the Face body region as a separate region to subclause 5.4.1
5.5	Injury costs	Add the Face body region as a separate region
5.6	Probability of fatality	Add the Face body region as a separate region
5.7	Probable AIS	Add the Face body region as a separate region
Annex A		Add the Face injury costs listed in Table 14

Note:
a) The probability of an AIS 1, 5, and 6 vault fracture is assumed to be zero, therefore $ISP_1 = ISP_2$ and $ISP_j = 0$ for *j*=5 and 6.
b) The probability of an AIS 2, 5, and 6 face fracture is assumed to be zero, therefore $ISP_2 = ISP_3$ and $ISP_j = 0$ for *j*=5 and 6.

Table 14.
Facial Injury Cost

AIS Injury Severity Level	Costs (2000 US Dollars)[a]	
	Medical Costs	Ancillary Costs[b]
1	$ 1 183	$ 2 961
2	12 020	32 908
3	56 149	90 727
4	178 285	142 605
5	92 107	568 701

Source: Blincoe [13]
Notes:
a) Costs do not include emergency services, insurance administration and non-economic costs (e.g., pain and suffering)
b) Ancillary costs include lost market and household productivity (including wages), workplace, and legal/court costs