DEVELOPMENT OF AN IMPROVED NECK INJURY ASSESSMENT CRITERIA FOR THE ISO 13232 MOTORCYCLIST ANTHROPOMETRIC TEST DUMMY

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ABSTRACT

The Motorcyclist Anthropometric Test Dummy (MATD) and injury risk/benefit analysis methods standardized under International Standard ISO 13232 allow the relative injury benefits and risks of rider protective devices fitted to motorcycles to be assessed, for a specific set of injury types. Research involving the feasibility of airbags fitted to motorcycles intensified the need to upgrade the crash test dummy neck injury assessment methods, and an improved dummy neck with multi-directional biofidelity and injury assessment capabilities and corresponding probabilistic four-axis neck injury criteria (upper neck axial compression and tension forces, lateral bending, extension and flexion, lateral bending, and torsion moments) were subsequently developed. The four-axis neck injury criteria originally proposed for ISO 13232 had a “trapezoidal egg” shaped injury index, based on mechanical stress ratio principles, which tended to under-predict injuries under tension-only loading conditions, compared to injurious tension force levels reported in the technical literature. A revised neck injury criteria was then developed having a “clipped trapezoidal egg shape” index that is similar in concept to the two-axis “clipped kite” shape criteria specified by the US Motor Vehicle Occupant Crash Protection Standard (FMVSS 208). The improved Neck injury criteria were developed by fitting the distributions of neck injury severities observed in on-scene in-depth investigations of 565 real-world motorcycle crashes, including the direction of neck motion indicated by special detailed neck dissections in 67 fatal cases, to the distributions of upper neck forces and moments measured in calibrated computer simulations of the MATD with the improved neck in the 565 crashes. The improved injury criteria can estimate the probability of neck injury, based on four-axis upper neck forces and moments measured with the new MATD neck with a higher level of overall agreement with neck injury severity levels and directions observed in real world crashes, compared to the previous four-axis criteria.

INTRODUCTION

Background

INTERNATIONAL STANDARD 13232 specifying test and analysis procedures for the research and evaluation of rider crash protective devices fitted to motorcycles, first approved and published in 1996 [1], has undergone a comprehensive review as a result of experience with the Standard (e.g., Zellner, et al. [2]). Recommendations for changes and improvements were made in all aspects resulting in the draft first revision of ISO 13232 [3].

The recommendations included proposed changes to the motorcycle anthropometric test dummy (MATD) neck (in Part 3 of the revised Standard [3]), described in Withnall et al. [4]; and the neck injury probability analysis (in Part 5 of the revised Standard [3]), described in Van Auken et al. [5] and herein. These changes were considered necessary because the neck injury criteria in the original (1996) Standard:

- did not provide an indication of the AIS injury severity level;
- were “pass/fail” in nature, indicating either "likely [neck] fracture or dislocation [with] a fatal propensity" or non-injury [1], rather than probabilistic; and
- tended to over predict the number and likelihood of neck injuries ($\geq$30%) for a census sample, compared to actual injury data ($\leq$6%);

as explained in Annex J of Part 5 of the revised Standard [3]. Furthermore, the 1996 “pass/fail” neck injury criteria is fundamentally different than the probabilistic injury severity (AIS) and injury cost model for the head, chest, abdomen, and lower extremities, based on injury assessment variables measured by the MATD, specified in Part 5 of the Standard. The initial basis for this injury model was reported in Newman et al. [6], with example application in Kebschull et al. [7]. These limitations in the 1996 neck injury criterion, due to the limited injury tolerance data that was available at the time, became especially important in airbag evaluations that involved severe neck loading. For example, Ramet et al. [8] reported severe upper neck lesions with cadavers positioned on prototype motorcycle airbags, suggesting that a better estimate of neck injury probability would be required.

A probabilistic four-axis neck injury criteria described by Van Auken et al. [5] was initially proposed for the revised Standard. This criteria was based on a “trapezoidal egg” shaped injury index which combined the effects of axial neck tension/compression force, flexion/extension moments, lateral bending moment, and torsion moment. This index was derived according to mechanical stress ratio principals. However, this “trapezoidal egg” based criteria tends to under-predict injuries under tension only loading conditions, compared to injurious force levels reported in the technical literature. For example, Wilber (AAMA) [9] reported that a neck tension limit of F_T=4170 N corresponds to a 3% probability of AIS 3+ neck injury, which is a much larger probability than would be predicted by the “trapezoidal egg” criteria in [5] at this force level. This paper describes the development of improved four-axis criteria that does not under-predict injuries in tension only loading conditions.

Objectives

The objectives of this study were to develop a new, improved, probabilistic neck injury criterion compatible with the criteria employed in other body regions of the MATD, and taking into consideration available information on the probability of neck injury due to neck tension. The criteria would be appropriate for assessing AIS 0 to 6 skeletal and ligamentous injuries to the upper neck defined by AO/C1/C2. The new neck design and injury criteria have been proposed in the draft first revision of the Standard for use in the risk/benefit analysis and injury severity and cost models.

In order to achieve these objectives the following refinements were accomplished:

- the computer simulations of the new neck were refined to better match existing and new test data,
- The LA/Hannover neck injury data were further screened to exclude non-relevant injuries such as abrasions and lacerations,
- Three LA/Hannover cases were excluded from the analysis because they occurred at higher speeds than the corresponding USC fatal cases.
- The neck injury index was modified to include an additional term to account for increased injury potential due to axial tension/compression forces.

REQUIREMENTS FOR THE NECK INJURY CRITERIA DEVELOPMENT

The objective was to develop a probabilistic, objective injury criterion that would be:

- consistent with the form of the injury criteria for the other body regions in ISO 13232-5,
- consistent in general form with other neck injury criteria applicable to other mechanical necks (e.g., Eppinger et al., [10], [11])
- based on the force and moment time histories obtained from either computer simulations or full scale tests using the new MATD neck, according to the relevant parts of ISO 13232,
- suitable for predicting AIS 1 to 6 level injuries to the AO/C1/C2 region of the cervical spine,
- consistent with the frequency distributions of:
    - neck injury severities observed in the census of LA/Hannover non-fatal and fatal motorcycle-car accidents (ISO-13232-2) and USC fatal motorcycle-car accidents ([12], [13]);
    - AO/C1/C2 neck injury severities and directions observed in the USC fatal motorcycle-car accidents;
    - peak AO forces and moments observed in calibrated computer simulations of the LA/Hannover non-fatal and fatal motorcycle-car accidents and USC fatal motorcycle-car accidents, assuming the baseline helmet and opposing vehicle were present in all cases, and a GPZ 500 motorcycle was the subject motorcycle in all cases.

REFINED COMPUTER SIMULATION OF THE MATD NECK

A computer simulation of the new MATD neck was developed using the US Air Force Articulated Total Body (ATB) Program [7], [14] in order to estimate the neck forces and moments that would have been measured by the MATD in the LA/Hannover and USC accidents. The mathematical model of the new neck comprised 8 segments (lumped mass rigid bodies) connected in series between the lower neck pivot point and the head, with 26 motion degrees of freedom, as illustrated in Figure 1. The model was originally validated by comparing the predicted results to those observed in component and full-scale tests as reported in [15]. This model was then further refined to improve the force-deflection characteristics of the "stops" in the neck slider, and to match the response to a vertical impact laboratory test (Figure 2). For example, Figure 1 illustrates a comparison of still images from high-speed video of a rearward neck extension sled test and the corresponding computer simulation. Figure 3 illustrates a similar comparison for a full-scale test. Time histories comparing the digitized motions and computer simulations for these and other laboratory tests are illustrated in Appendix A.

The distribution of the maximum neck forces and moments from computer simulations of 498 LA and Hannover cases and 67 USC fatal cases are illustrated in Appendix B.

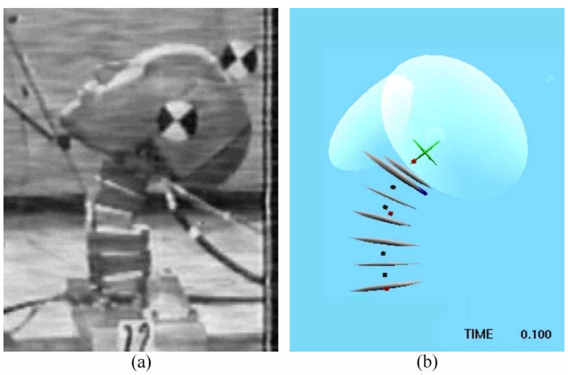


Figure 1. Rearward neck extension: a) dynamic laboratory sled test and b) computer simulation at 0.1 sec.

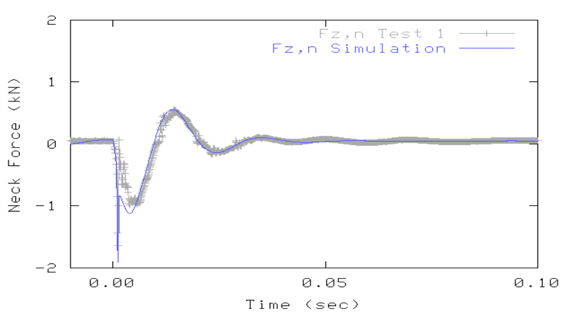


Figure 2. Axial neck force time responses measured in a laboratory head impact test and computer simulation.

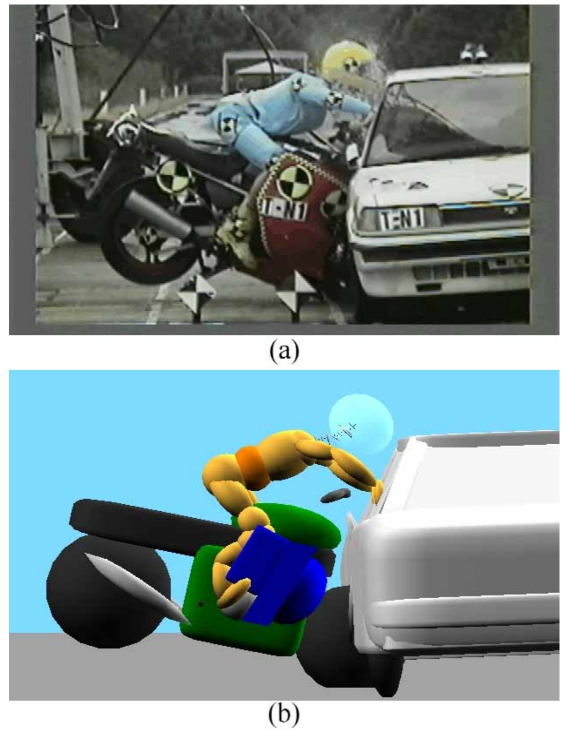


Figure 3. Impact configuration 413-0/30: a) full scale test and b) computer simulation 0.1 sec after initial contact.

NECK INJURY PROBABILTY MODEL FORM

In order to maintain consistency of form with other injury functions in ISO 13232 and other scientific literature, it was assumed that the probability of a maximum $AIS_{AO/C1/C2} \geq k$ neck injury is related to an objective injury index NII_{max} as follows:

$$P\left(MAIS_{AO/C1/C2} \geq k \middle| NII_{max} = x\right) = 1 - e^{-\left(\left(\frac{x-\gamma_k}{\eta_k}\right)^{3.5}\right)} \quad (1).$$

where γ_k and η_k are injury risk distribution coefficients to be determined. It was further assumed that this distribution approximates a normal distribution with mean μ_k, and standard deviation σ_k, according to the equations from SAE AE-9 [16] and Råde and Westergren [17]:

$$\mu_k = \gamma_k + 0.8997\eta_k \quad (2).$$

$$\sigma_k = 0.2847\eta_k \quad (3).$$

The objective injury index NII_{max} is defined as follows:

$$NII_{max} = \max_t NII(t) \quad (4).$$

$$NII(t)=\max\left(\underbrace{\left(\left(\frac{F_C(t)}{F_C^*}+\frac{F_T(t)}{F_T^*}+\left(\left(\frac{M_X(t)}{M_X^*}\right)^2+\left(\frac{M_E(t)}{M_E^*}+\frac{M_F(t)}{M_F^*}\right)^2\right)^{1/2}\right)^2+\left(\frac{M_Z(t)}{M_Z^*}\right)^2\right)^{1/2}}_{Term\,1},\ \underbrace{\alpha\left|\frac{F_C(t)}{F_C^*}+\frac{F_T(t)}{F_T^*}\right|}_{Term\,2}\right) \quad (5).$$

where *NII(t)* is defined by equation (5) and where

- F_C is the neck axial compression force, $F_C = -\min(F_Z,0)$,
- F_T is the neck axial tension force, $F_T = \max(F_Z,0)$,
- M_X is the neck lateral flexion moment,
- M_E is the neck extension moment, $M_E = -\min(M_Y,0)$,
- M_F is the neck flexion moment, $M_F = \max(M_Y,0)$,
- M_Z is the neck torsion moment,
- F_I^* and M_I^* are model coefficients corresponding to single axis failure criteria, to be determined for $I=\{C,T,X,E,F,Z\}$.

The first term in equation (5) corresponds to equation (5) in Van Auken et al. [5], which has a "trapezoidal egg" shape. It was adapted from the generalized stress ratio method for estimating the strength of materials under combined loading conditions described in many references (e.g., Shanley et al. [18], Bruhn [19], and US Department of Defense MIL-HDBK-5D [20]) and assuming that the generalized exponent has a value of either 1 or 2. For example Figure 1.5.2.5 of MIL-HDBK-5D ([20], pp 1-29) indicates that for various materials, the exponents in equation (5) in general can have real values in the range of n=1 to 3. The assumption is that biological material such as ligaments and vertebral facets exhibit material characteristics analogous to those for metallic materials. For strength of materials, in general, bending and axial stresses are considered to be linearly additive (i.e., n=1); moments about orthogonal axes are considered to be resultants (i.e., n=2); and combinations of shear (i.e., torsion) and axial stress are considered to be resultants. Equations C4.11, C4.16, and C4.16 in Bruhn [19] are examples of stress ratios for these types of interactions. Equation (5) allows for asymmetric strengths (e.g., extension-flexion), and strengths in each direction which are independent of the strengths in the other directions, which was considered to be appropriate for composite structures such as the human neck.

The second term in equation (5) is only a function of axial neck force, and effectively "clips" the "trapezoidal egg" shape if the α "clipping" coefficient is greater than 1. This term is modeled after NHTSA's neck injury criteria [21], which limit the allowable neck tension and compression forces to values less than those of allowed for a "Nij" limit based on a combination of axial tension/compression force and flexion/extension moment. This limit was incorporated into the criteria recommended by Eppinger et al.[11] and appears to be based on axial neck tension/compression limits recommended by Wilber (AAMA) [9] .

Neck shear forces are not included in this model because shear motions were observed in 64 of the 67 cases in the USC fatal accident database with AO/C1/C2 neck injuries. As a result, it was considered that there was insufficient information in this database to identify injury criteria based on shear force. Possible explanations for this are that neck shear motion may be uniformly associated with motorcycle (and perhaps nearly all motor vehicle) neck injuries; or alternatively, that neck shear motion is a fully coupled variable, uniformly associated with the other motions that are present (e.g., bending, torsion, and compression-tension).

Equation (5) can be re-expressed in terms of normalized neck force and moment components according to equations (6) and (7) as follows:

$$NII_I(t)=\begin{cases}\left(\dfrac{F_I(t)}{F_I^*}\right) & \text{for} \quad I=\{C,T\}\\[2ex] \left(\dfrac{M_I(t)}{M_I^*}\right) & \text{for} \quad I=\{X,E,F,Z\}\end{cases} \quad (7).$$

It was then furthermore assumed that if an $MAIS_{AO/C1/C2} \geq k$ injury does occur, then the injuries

$$NII^2(t)=\max\left(\left(NII_C(t)+NII_T(t)+\left(NII_X^2(t)+\left(NII_E(t)+NII_F(t)\right)^2\right)^{1/2}\right)^2+NII_Z^2(t),\ \alpha\left(NII_C(t)+NII_T(t)\right)^2\right) \quad (6).$$

are associated with the neck force and/or moment directions, I, which satisfy the equation:

$$NII_I(t_{max}) \geq Q_k^* \mu_k \quad (8).$$

where t_{max} is defined such that

$$NII(t_{max}) = NII_{max} \quad (9).$$

The Q_k^* coefficients have positive values between 0 and 1 which are also to be determined.

MOTORCYCLE ACCIDENT DATABASES

The coefficients for the assumed neck injury probability model were estimated from data describing 498 Los Angeles and Hannover motorcycle-car accidents (ISO 13232-2) and 67 USC fatal motorcycle-car accidents [13]. Features of these databases are summarized in Table 1. Note that 3 LA/Hannover cases were excluded from the analysis because the relative normal closing velocity was greater than the range of speeds in the USC fatal accident data (i.e., less than 121 km/h).

METHODOLOGY FOR INJURY CRITERIA DEVELOPMENT

The neck injury criteria were estimated using methods based on the available motorcycle accident data and several assumptions.

Basic Assumptions

Basic assumptions for this analysis were that:

- The sought for neck injury criteria would be applicable to a majority of motorcycle-car crashes. However, the range of crash conditions is the available accident databases limit the domain

Table 1.
Summary of Accident Databases

Sample Criteria			Accident Database		
			LA	Hannover	USC
Accident		Reporting criteria	Police reported	Police reported	Police reported
		No. of vehicles	2	2	2
		Accident configurations	All, except untestable configurations	All, except untestable configurations	All, except runover/snag
		Investigation method	On scene, in-depth	On scene, in-depth	On scene, in-depth, including in-depth medical autopsies, neck dissections
Subject vehicle			Motorcycle with seated, solo rider	Motorcycle with seated, solo rider	Motorcycle with solo rider
	Person		Rider	Rider	Rider
		Injury severity	Injured or killed	Injured or killed	Death within 10 days
Other vehicle			Passenger car	Passenger car	Passenger car
Region			Los Angeles	Hannover	Los Angeles County
Time period			1976-1977	1980-1985	Aug 1978-Mar 1981
Sample size			501		67
	Relative normal closing velocity ≤ 121 km/h		498		67
		Non fatal neck injuries	≤2%		92.5%
		Fatal neck injuries	Unknown, but ≤3%		7.5%
		Fatal (all causes)	3%		100%
Comment			No neck dissections, neck injuries for fatal cases unknown		Detailed injury information
Reference			ISO-13232-2	ISO-13232-2	[12], [13]

Notes:

a) Ruptures, dislocations, and fractures

b) The fatal sample indicates that nearly all of these motorcycle accidents involved non-fatal neck injuries. This confirms the assumption that 3 percent of LA/Hannover accidents that were fatal all involved some (i.e., non fatal) levels of neck injury.

of validity of the injury criteria. The neck injury criteria are not applicable to high-speed crashes with relative normal closing velocity greater than 121 km/h.
- The assumed mathematical injury probability model described by equations (1) to (9) are valid within the sought for domain of validity.
- The neck rupture, dislocation, and fracture injuries reported in the LA/Hannover databases are AO/C1/C2 neck injuries.
- The distribution of neck AO/C1/C2 injury severities in the 67 USC fatal accidents are the same as the distribution of neck rupture, dislocation, and fracture injury severities in the 13 fatal LA/Hannover accidents.
- The distribution of neck forces and moments predicted by computer simulations (based on ISO 13232 computer simulations) of 67 USC fatal motorcycle accidents with a GPZ 500 motorcycle and a helmeted rider, are the same as those which occurred in the 67 USC fatal motorcycle accidents, and that these distributions are representative of all fatal motorcycle accidents.
- The distribution of forces and moments predicted by the 498 ISO 13232 calibrated computer simulations with a GPZ 500 motorcycle and a helmeted rider are the same as those which occurred in the 498 LA/Hannover injury accidents, and that these distributions are representative of all injurious motorcycle accidents.

These assumptions are also based on the underlying assumption that neck forces and moments and resulting injury severity are independent of helmet use. Orsay et al. [22] have found that there is no relationship between helmet use and the prevalence of neck injuries.

Additional Assumptions

It was further assumed that:

- The forces in the new MATD dummy upper neck are those that are relevant and correlated with human upper neck injuries. The new MATD neck dynamic response in three axes has been validated against volunteer human response corridors as described by Withnall et al. [4]. This general approach for developing neck injury criteria has been commonly used by others in the past;
- The simulated dynamic response of the new MATD neck correlates strongly with the dynamic response from full-scale tests, as described herein and in [15];
- The distributions of neck forces and moments from calibrated computer simulations of a GPZ 500 and a helmeted rider for the 67 USC fatal accident cases are assumed to correspond to the distributions of the observed injury severities and motions;
- The coefficients that describe the relative distribution of neck injuries by direction (F_C^*, F_T^*, M_X^*, M_E^*, M_F^*, M_Z^*, and Q^*) are assumed to be the same for both fatal and non-fatal motorcycle-car accidents, and for all neck injury severity levels;
- F_C^*, F_T^*, M_X^*, M_E^*, M_F^*, and M_Z^* have positive values, which are assumed to be less than the overall maximum values for F_C, F_T, M_X, M_E, M_F, and M_Z that occur in the computer simulations of the 67 USC fatal cases, because observed injuries were previously associated with motions in each of these axes;
- The α "clipping" coefficient that describes the injury potential for axial forces relative to the injury potential for combined forces and moments may be different in the LA/Hannover and fatal USC motorcycle accidents. It is furthermore assumed that there were no injuries in the fatal USC motorcycle accidents resulting from only axial forces and that $\alpha = 1$ for these cases.
- The overall probabilities of neck injury in fatal and non-fatal subsamples of motorcycle-car accidents may be different (i.e., the intercept value μ_k for riders in fatal accidents may be different from μ_k for injured riders);
- The standard deviation of the injury risk, σ_k, which is related to the slope of the probability of injury vs. injury index curve, is the same for all AIS injury severity levels (i.e., failure mechanism is similar at all AIS levels, e.g., as assumed with the ISO 13232-5 thoracic compression injury probability). This assumption eliminates the possibility of overlapping injury risk curves (e.g. the probability of an AIS 3+ injury being greater than the probability of an AIS 2+ injury for a given injury index value);
- The coefficient of variation (standard deviation divided by the mean) of the AIS ≥ 3 injury risk curve is 0.2 (i.e., $\sigma_3/\mu_3 = 0.2$). This assumption is based on results for neck extension moment and tension described by Mertz and Prasad [23];
- The probability of AIS>3 injury due to a 4.17 kN tension force is 0.03, based on AAMA [9].
- "Direction of force" corresponds to "direction of motion" for each neck injury observed in the USC fatal accidents. The later was based on detailed reconstructions of rider motions and in particular head and neck kinematics by a panel of experts.

Methods

The coefficients for the assumed mathematical injury probability model were identified in two steps. First, the injury direction coefficients were estimated from the neck injury severities and directions observed in the 67 USC fatal accident cases. Then, the injury risk probability coefficients were estimated from the neck injury severities observed in the 498 LA/Hannover cases. This process is further detailed in the informative annexes to the draft first revision of ISO 13232-5 [3].

Injury direction coefficients

The values for F_I^*, M_I^*, Q_k^*, and S_k were estimated by fitting the distribution of neck injury severities and direction components, which were predicted by the model from computer simulations of the 67 USC fatal accidents, to the observed distribution of injury severities and directions observed in the USC 67 fatal accident database. S_k was defined such that $NII_{max} \geq S_k$ corresponded to a $MAIS \geq k$ injury in the 67 USC fatal accidents.

The distribution of neck injuries in the USC fatal accident database can be described by the frequencies with which the contributing directions occur by injury severity level. Let $n_{k,c,t,x,e,f,z}$ be the number of riders in the USC fatal accident database according to the AO/C1/C2 neck injury severity and axis/ direction, where the subscripts c, t, x, e, f, z are either 0 or 1 as follows:

i=1 if the rider had an $MAIS_{AO/C1/C2} \geq k$ injury, and the injury was associated with direction F_I or M_I.

i=0 otherwise.

Note that $n_{k,0,0,0,0,0,0}$ represents the number of riders with $MAIS_{AO/C1/C2} < k$ injuries. Values of $n_{k,0,0,0,0,0,0}$ for the USC fatal accident database are listed in Table 2. The total number of cases in the fatal accident database is

$$n_{total} = \sum_{c=0}^{1}\sum_{t=0}^{1}\sum_{x=0}^{1}\sum_{e=0}^{1}\sum_{f=0}^{1}\sum_{z=0}^{1} n_{k,c,t,x,e,f,z} \quad (10).$$

which is a constant (n_{total}=67) for all injury severity levels k.

In a similar manner, let $m_{k,c,t,x,e,f,z}$ be the number of computer simulations where AO/C1/C2 neck injury is indicated, where the subscripts c, t, x, e, f, z are either 0 or 1 as follows:

i=1 if $NII_{max} \geq S_k$ and $NII_I(t_{max}) \geq Q_k^* S_k$.

i=0 otherwise.

The total number of computer simulation cases is

$$m_{total} = \sum_{c=0}^{1}\sum_{t=0}^{1}\sum_{x=0}^{1}\sum_{e=0}^{1}\sum_{f=0}^{1}\sum_{z=0}^{1} m_{k,c,t,x,e,f,z} \quad (11).$$

which is also a constant (m_{total}=67) for all injury severity levels k.

Table 2.
Distribution of neck AO/C1/C2 injuries in the USC fatal motorcycle accident database

k	Number of Cases with $MAIS_{AO/C1/C2} = k$	Number of Cases with $MAIS_{AO/C1/C2} < k$ ($n_{k,0,0,0,0,0,0}$)
0	3	0
1	0	3
2	9	3
3	39	12
4	0	51
5	11	51
6	5	62

The injury criteria coefficients F_I^*, M_I^*, Q_k^*, and S_k were selected to minimize the difference between the distributions of predicted and observed injuries. Specifically, the coefficients $S_k F_I^*$, $S_k M_I^*$, and Q_k^* were determined by the numerical searches described in Annex M of ISO 13232-5 to minimize the difference function J,

$$J = \sum_{k=1}^{6} J_k \quad (12).$$

where

$$J_k = \sum_{c=0}^{1}\sum_{t=0}^{1}\sum_{x=0}^{1}\sum_{e=0}^{1}\sum_{f=0}^{1}\sum_{z=0}^{1}\left(\frac{n_{k,c,t,x,e,f,z}}{n_{total}} - \frac{m_{k,c,t,x,e,f,z}}{m_{total}}\right)^2 \quad (13).$$

and where

$m_{k,0,0,0,0,0,0} = n_{k,0,0,0,0,0,0}$,

$S_1 = 1$, and

Q_k^* is the largest value that satisfies $NII_I(t_{max}) \geq Q_k^* S_k$ for at least one direction, I, for each of the cases that satisfy $NII_{max} \geq S_k$.

The constraint that $m_{k,0,0,0,0,0,0}=n_{k,0,0,0,0,0,0}$ was imposed in order to facilitate the model coefficient identification process. With this constraint, S_k can be directly calculated from the F_I^* and M_I^* coefficients, thus eliminating one coefficient from the model coefficient search. The constraint that $S_1 = 1$ was chosen in order to uniquely define the absolute magnitude of the F_I^* and M_I^* coefficients.

Injury risk probability coefficients

The values for μ_k were then estimated by fitting the distribution of neck injury indices predicted by the model from the computer simulations of the 498 generic LA/Hannover cases to the distribution of injury severities listed in Table 3. The injury severity distribution in Table 3 was estimated using the data and method described in Appendix C. The values for γ_k and η_k were then calculated from μ_k and σ_k assuming as noted previously that $\sigma_k = 0.2\ \mu_3$.

Table 3.
Distribution of neck AO/C1/C2 injury severities in the LA/Hannover motorcycle accident database

k	Estimated Number of Cases with $MAIS_{AO/C1/C2} = k$ (from column 9 of Table C-1)	Estimated Number of Cases with $MAIS_{AO/C1/C2} < k$
0	479	0
1	4	479
2	3	483
3	9	486
4	0	495
5	2	495
6	1	497

For each injury severity level k, the numbers of LA/Hannover cases with $MAIS_{AO/C1/C2} \geq k$ injuries and computer simulation cases with $NII_{max} \geq \mu_k$ can be expressed according Table 4, where μ_k and m_k are to be determined. If the cases are sorted such that $NII_{max,i} \leq NII_{max,i+1}$, for i = 1 to 497, then μ_k and m_k satisfy the equation

$$NII_{max,m_k} < \mu_k \leq NII_{max,m_k+1} \qquad (14).$$

The values for μ_k that satisfy equation (14) can be calculated from m_k according to the equation for the logarithmic mean,

$$\mu_k = \sqrt{NII_{max,m_k} NII_{max,m_k+1}} \qquad (15).$$

The best estimate of μ_k, for k=1 to 6, satistifies equation (14) with $m_k=n_k$, the number of cases with $MAIS_{AO/C1/C2}<k$ listed in the 3rd column of Table 3. As a result, the distribution of $MAIS_{AO/C1/C2}$ injuries predicted by the 498 computer simulations will match the distribution of neck injuries observed in the LA/Hannover database as illustrated in Figure 4.

Table 4.
Number of cases with observed and predicted injuries

	Number of Cases	
	$MAIS_{AO/C1/C2} \geq k$ (LA/Hannover data)	$NII_{max} \geq \mu_k$ (computer simulations)
No	n_k	m_k
Yes	498-n_k	498-m_k
Total	498	498

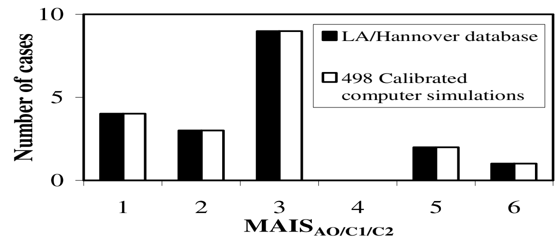


Figure 4. Distribution of observed and predicted neck injuries.

The 95% confidence intervals for μ_k can be considered to be the range of values for μ_k such that the portion of cases with $NII_{max} \geq \mu_k$ is not statistically significantly different than the portion of cases with $MAIS_{AO/C1/C2} \geq k$. This condition is satisfied for $m_k^- \leq m_k \leq m_k^+$ such that $\chi^2 \leq 3.84$, where χ^2 is calculated according to the following equation (based on equation 5.39 in Box, Hunter, and Hunter [24])

$$\chi^2 = \frac{\left(n_k(498 - m_k) - m_k(498 - n_k)\right)^2 (2 \times 498)}{(n_k + m_k)(498 - n_k + 498 - m_k)(498)^2} \quad (16).$$

The range of values for m_k^- and m_k^+ that satisfy $\chi^2 \leq 3.84$ are listed in Table 5. These values are used in conjunction with equation (15) to estimate the 95% confidence limits for μ_k. The upper confidence limits for m_4, m_5, and m_6 (and thus μ_4, μ_5, and μ_6) are undefined because $\chi^2 \leq 3.84$ is satisfied for all $m_k^- \leq m_k \leq 498$.

Table 5.
95% Confidence limits for m_k

k	m_k^-	m_k^+
1	466	489
2	471	491
3	475	493
4	488	-
5	488	-
6	492	-

RESULTING MATD NECK INJURY CRITERIA

Injury Direction Coefficients

The injury direction coefficients listed in Tables 6 and 7 were identified according to the method described above. The resulting value for J was $462/67^2$=0.103. Table 8 lists the number of observed and predicted injuries by injury severity and direction, which summarizes the fit to the 64 individual bins. The correlation between the predicted and observed bin counts ($m_{k,c,t,x,e,f,z}$ and $n_{k,c,t,x,e,f,z}$), excluding the non-injury cases, was r^2=0.56.

Table 6.
Force and moment normalizing coefficients for the new MATD neck

Coefficient	Estimated Value
F_C^*	6.53 kN
F_T^*	3.34 kN
M_X^*	62.66 Nm
M_E^*	58.0 Nm
M_F^*	204.2 Nm
M_Z^*	47.1 Nm

Table 7.
Injury threshold coefficients for the 67 USC fatal cases with the new MATD neck

k	S_k	Q_k^*
1	1	0.619
2	1.00	0.619
3	1.50	0.650
4	3.74	0.594
5	3.74	0.594
6	5.20	0.564

The shape and step-wise fit of the NII_{max} criteria to the USC data is illustrated in Figure 5. There are six scatter plots, one for each pair of F_z, M_x, M_y, and M_z axes. The numbers in each scatter plot are the maximum $AIS_{AO/C1/C2}=k$ predicted by $NII_{max}\geq S_k$ computed from the forces and/or moments at t_{max}, using the coefficients listed in Tables 6 and 7, for injuries associated with the forces and moments on the plot. For example, the graph in the upper left corner is a scatter plot of injuries that were only associated with tension ($NII_T(t_{max}) \geq Q_k^* S_k$), compression ($NII_C(t_{max}) \geq Q_k^* S_k$), and/or lateral bending ($NII_X(t_{max}) \geq Q_k^* S_k$) motion vs F_z and M_x. Envelopes of constant $NII_{max}=S_k$ are also shown on each plot, corresponding to the S_k values in Table 7. The envelopes tend to separate out the injuries by AIS level as intended.

Injury Risk (Probability) Coefficients

The injury severity coefficients listed in Table 9 were identified from the LA/Hannover data according to the methods as previously described and based on the clipping coefficient $\alpha = 3.1$. The value of 3.1 was selected for α in order that $F_T = 4.17$ kN would correspond to a 0.03 probability of a MAIS≥3 injury (AAMA [9]) as illustrated in Figure 6. The corresponding injury risk curves are illustrated in Figure 7. The distribution of neck injuries for the 498 computer simulations also matches the distribution of injuries in the LA/Hannover database, as previously illustrated in Figure 4.

A comparison of resulting injury criteria for the new ISO 13232 MATD neck to NHTSA's criteria for the Hybrid III 50th Percentile Adult Male [21] is located in Appendix D, bearing in mind that the two different dummy necks and injury criteria were developed entirely independently, and therefore would not be expected to be similar.

Table 8.
Comparison of Number of Observed and Predicted Injuries by Injury Severity and Direction

Number of cases in the USC fatal motorcycle accident database with $MAIS_{AO/C1/C2}\geq k$ and indicated direction							Number of computer simulations of the USC fatal cases with $NII_{max}\geq S_k$ and $NII_I(t_{max})\geq Q_k^* S_k$						
Direction	k						I	k					
	1	2	3	4	5	6		1	2	3	4	5	6
Compression	5	5	4	0	0	0	*C*	8	8	1	0	0	0
Tension	18	18	16	4	4	0	*T*	12	12	11	1	1	0
Lat. Bending	42	42	35	11	11	2	*X*	42	42	30	7	7	1
Extension	33	33	29	8	8	4	*E*	28	28	23	6	6	2
Flexion	20	20	17	4	4	0	*F*	16	16	10	0	0	0
Torsion	20	20	17	7	7	2	*Z*	28	28	16	5	5	2
All	64	64	55	16	16	5	-	64	64	55	16	16	5

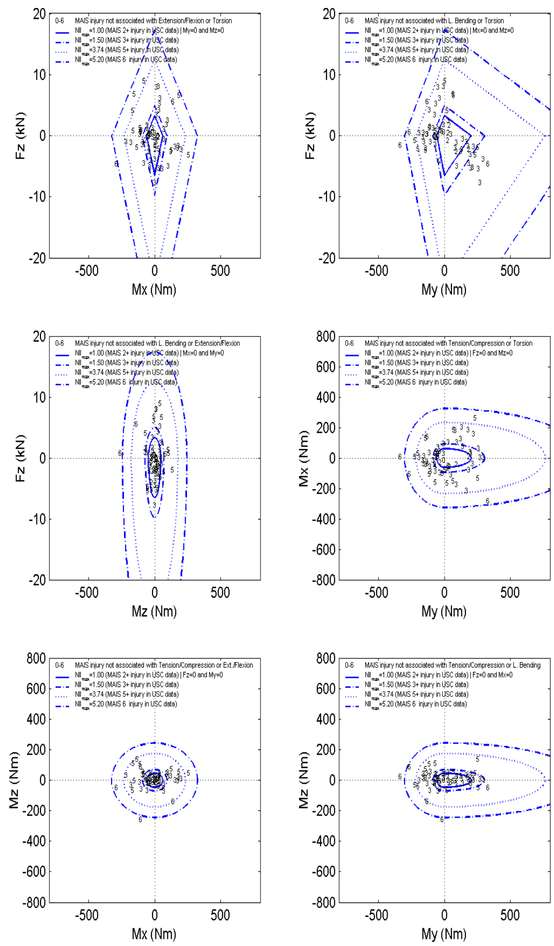


Figure 5. Forces and Moments at t_{max} from computer simulations of 67 fatal cases and the best step-wise fit envelopes of constant NII_{max}, providing the basis for the envelope shape (assuming α=0).

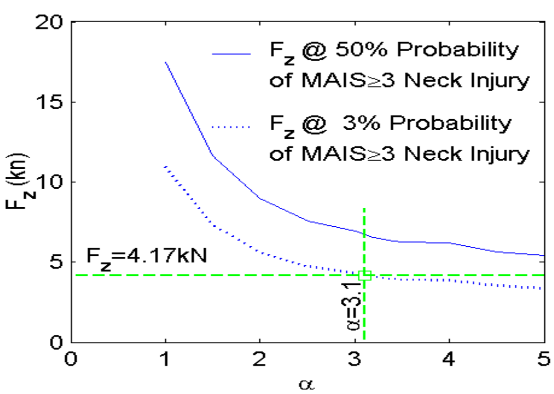
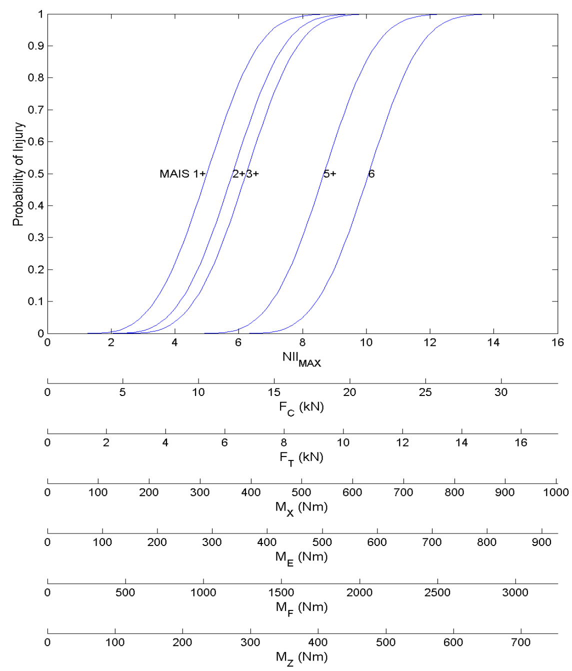


Figure 6. Critical neck tension force vs the α "clipping" coefficient, providing the basis for selecting $\alpha = 3.1$.

Table 9.
Injury severity risk coefficients for the new MATD neck

k	μ_k	σ_k (=0.2μ_3)	γ_k	η_k
1	5.00 (4.33, 6.96)	1.247	1.06	4.38
2	5.80 (4.46, 7.42)	1.247	1.86	4.38
3	6.23 (4.70, 7.84)	1.247	2.29	4.38
4	8.67 (6.62, -)	1.247	4.73	4.38
5	8.67 (6.62, -)	1.247	4.73	4.38
6	10.07 (7.59, -)	1.247	6.13	4.38



Note: Each force and moment scale is only applicable if all of the other upper neck forces and moments are set equal to zero.

Figure 7. Neck AO/C1/C2 injury risk curves for the new MATD Neck.

CONCLUSIONS AND RECOMMENDATIONS

The need for a new multi-directional motorcycle test dummy neck and neck injury assessment method was identified during previous research studies with protective devices, in particular with prototype motorcycle airbags. A new neck and new improved neck injury criteria have been developed which satisfactorily meets these and other injury assessment needs of ISO 13232. The new neck and improved injury criteria are included in the draft first revision of the Standard [3].

The new improved probabilistic injury assessment criteria was developed to allow injury risk/benefit analysis of protective devices while incorporating the injury predictions for the neck at the AO/C1/C2 level for ligamentous and skeletal injuries at the AIS (1990) 1 to 6 level. The criteria employs the measured upper neck axial forces, and AP flexion-extension, lateral bending, and torsional moment responses from the new MATD neck to predict the injury outcome for use with injury risk/benefit analysis methods. The model currently predicts the same injury outcome for 565 reconstructions representative of field accident data based on the Los Angeles and Hannover studies. This is a substantial improvement from the previous criteria in ISO 13232 (1996) which resulted in the number of predicted injuries being 10 times larger than the number of observed injuries. The improved criteria are also in agreement with other published injury risk information for neck tension only forces.

The new neck injury criteria is based on several key assumptions which may be limiting: the equal injury-probability slopes at all injury severities, which might imply similar injury mechanisms for all severities; the accuracy of the N=565 computer simulations which have been only partially validated in component and full-scale tests; and the observed "associated neck motions" for the most severe upper neck injury in each accident being based on detailed case review and reconstructions by one group of experts. Although these assumptions could be subject to further refinement, the neck injury criteria are based on the best information available at this time, and produce predictions that are in closer agreement to real world accident data, using the specified methodology of ISO 13232. Additional in-depth motorcycle accident data would provide a larger validation sample.

ACKNOWLEDGEMENTS

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APPENDIX A

The observed and simulated responses of the neck in component and full-scale tests are illustrated in Figures A-1 to A-5.

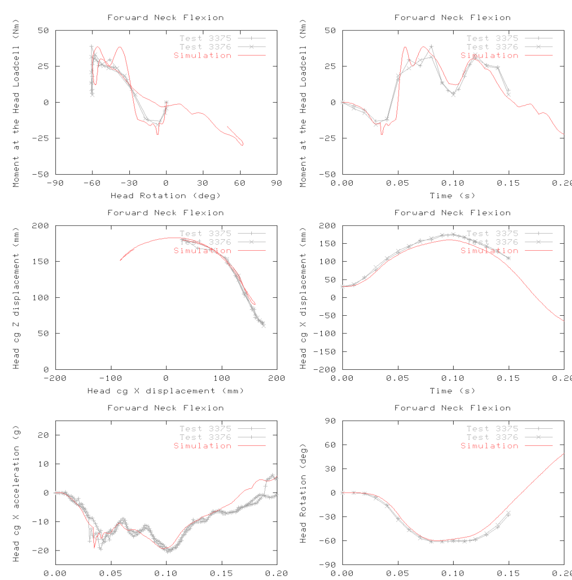

Figure A-1. Forward neck flexion sled test and computer simulation time responses.

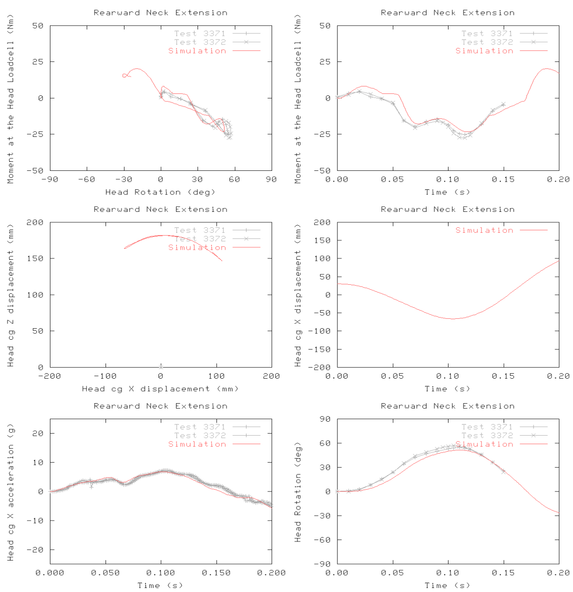

Figure A-2. Rearward neck extension sled test and computer simulation time responses.

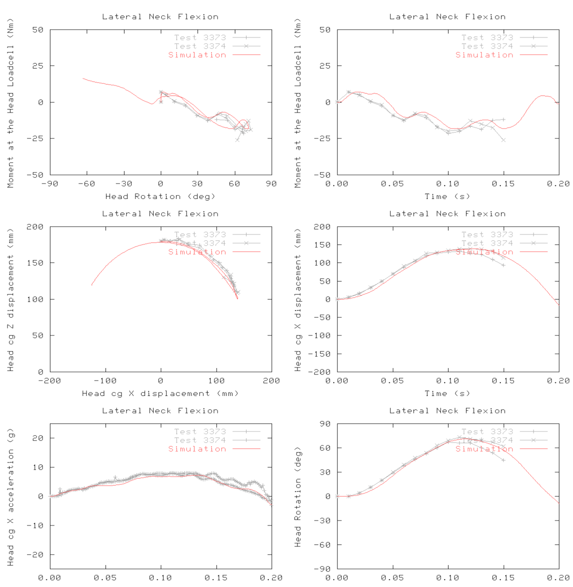

Figure A-3. Lateral neck flexion sled test and computer simulation time responses.

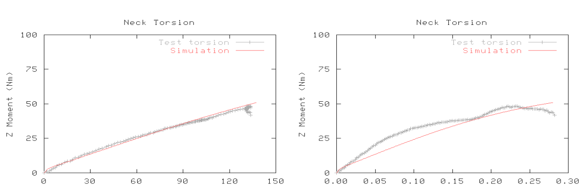

Figure A-4. Neck torsion test and computer simulation time responses.

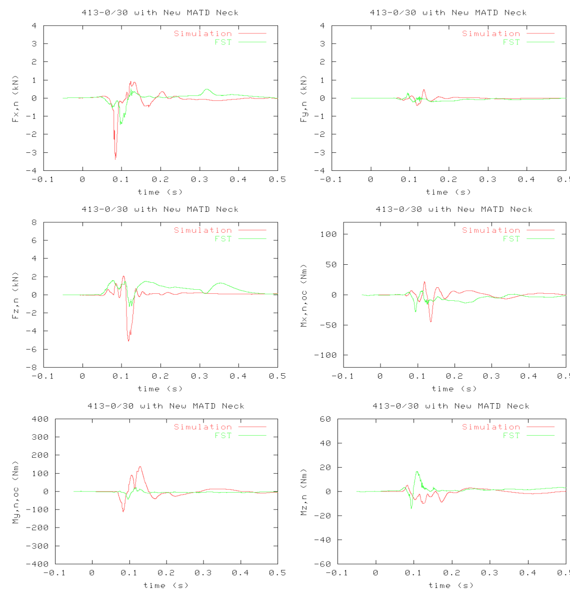

Figure A-5. Full scale test and computer simulation of impact configuration 413-0/30.

APPENDIX B

Figure B-1 illustrates the distributions of maximum neck forces and moments for the 498 computer simulations used to identify the neck injury criteria for the new MATD neck. Note that these maximum forces and moments were the maximum values observed in the entire impact sequence, including ground contacts, up to 5 sec from the time of initial contact, for the purpose of correlating with injuries reported in the accident data. Furthermore, some of the collisions in this accident database represent high speed, severe impacts, with relative normal closing velocities up to 121 km/h. This could explain why some of the maximum forces and moments are of relatively large magnitude.

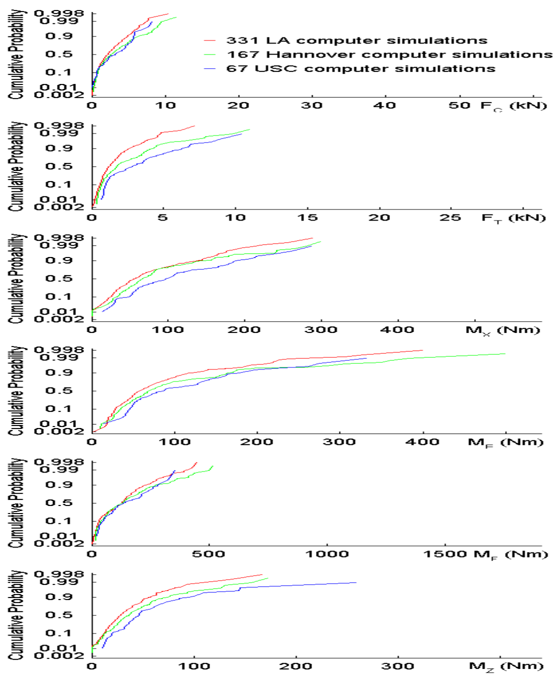

Figure B-1. Maximum neck force and moment distributions from computer simulations of 498 LA/Hannover cases and 67 USC fatal cases, including cases with high speed, severe impacts up to 121 km/h relative normal closing velocity.

APPENDIX C

The distribution of neck injuries in the 498 LA/ Hannover accident database was estimated by

- imputing the distribution of neck injuries in the 13 fatal LA/Hannover cases according to the distribution observed in the 67 USC fatal cases; and
- redistributing the remaining 3 unknown injuries amongst the valid cases.

The data and results of this analysis are listed in Table C.1. The columns in Table C.1 are as follows:

(1), (10) The maximum AO/C1/C2 AIS injury severity level ($MAIS_{AO/C1/C2}$).

(2), (4) The numbers of non-fatal and fatal cases in the LA/Hannover database by neck rupture, dislocation, and/or fracture $MAIS_{AO/C1/C2}$. Note that 3 non-fatal cases and all 13 fatal cases have unknown neck injuries.

(3), (5) The percentages of cases in the LA/Hannover database corresponding to columns 2 and 4. The percentages in these columns are equal to the number of cases/498 x 100%.

(11) The numbers of cases in the USC fatal accident database by $MAIS_{AO/C1/C2}$.

Table C-1.
Distribution of neck AO/C1/C2 injury severities in the LA/Hannover and USC fatal accident databases

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$MAIS_{AO/C1/C2}$	LA/Hannover Database							
	Non Fatal		Fatal			All		
	Observed Number of Cases[1]	Observed Percentage of all Cases	Observed Number of Cases	Observed Percentage of all Cases	Estimated Percentage of all Cases	Estimated Percentage of Cases	Estimated Valid Percentage of Cases	Estimated Number of Cases
0	476	95.58%			0.12%	95.70%	96.28%	479
1	4	0.80%			0.00%	0.80%	0.81%	4
2	1	0.20%			0.35%	0.55%	0.55%	3
3	1	0.20%			1.52%	1.72%	1.73%	9
4	0	0.00%			0.00%	0.00%	0.00%	0
5	0	0.00%			0.43%	0.43%	0.43%	2
6	0	0.00%			0.19%	0.19%	0.20%	1
unknown	3	0.60%	13	2.61%	0.00%	0.60%	-	0
Total	485	97.39%	13	2.61%	2.61%	100.00%	100.00%	498

Note:
[1]Ruptures, dislocations, and/or fractures

(10)	(11)	(12)	(13)
$MAIS_{AO/C1/C2}$	USC Database		Observed Percentage of USC Fatal Cases x 2.61%
	Fatal		
	Observed Number of Cases	Observed Percentage of Fatal Cases	
0	3	4.48%	0.12%
1	0	0.00%	0.00%
2	9	13.43%	0.35%
3	39	58.21%	1.52%
4	0	0.00%	0.00%
5	11	16.42%	0.43%
6	5	7.46%	0.19%
Total	67	100.00%	2.61%

(12) The percentages of cases in the USC fatal accident database by $MAIS_{AO/C1/C2}$.

(6), (13) The estimated percentage of LA/Hannover cases which were fatal by $MAIS_{AO/C1/C2}$. The percentages in this column are equal to the values in column 12 x 2.61%.

(7) The estimated percentage of all LA/Hannover cases by $MAIS_{AO/C1/C2}$. The percentages in this column are equal to the values in column 3 plus the values in column 6.

(8) The estimated valid percentage of LA/Hannover cases by $MAIS_{AO/C1/C2}$, which reapportions the remaining 3 unknown cases amongst the valid cases. The percentages in this column are equal to the values in column 7 x 498 / (498-3).

(9) The estimated number of LA/Hannover cases by $MAIS_{AO/C1/C2}$. The numbers in this column are equal to the values in column 8 x 498 / 100%. The estimated numbers of cases were rounded to the nearest integer values.

APPENDIX D

Figure D-1 illustrates the shapes of the new injury criteria for the MATD neck and NHTSA's criteria for the Hybrid III 50th percentile adult male neck [21]. Keeping in mind that the respective dummy necks are mechanically quite different, and the <u>two dummy necks and criteria are not interchangeable</u>, this figure indicates that the shapes of the two criteria are very similar in the Fz vs My plane. This figure also illustrates the differences between the two criteria in lateral flexion and torsion.

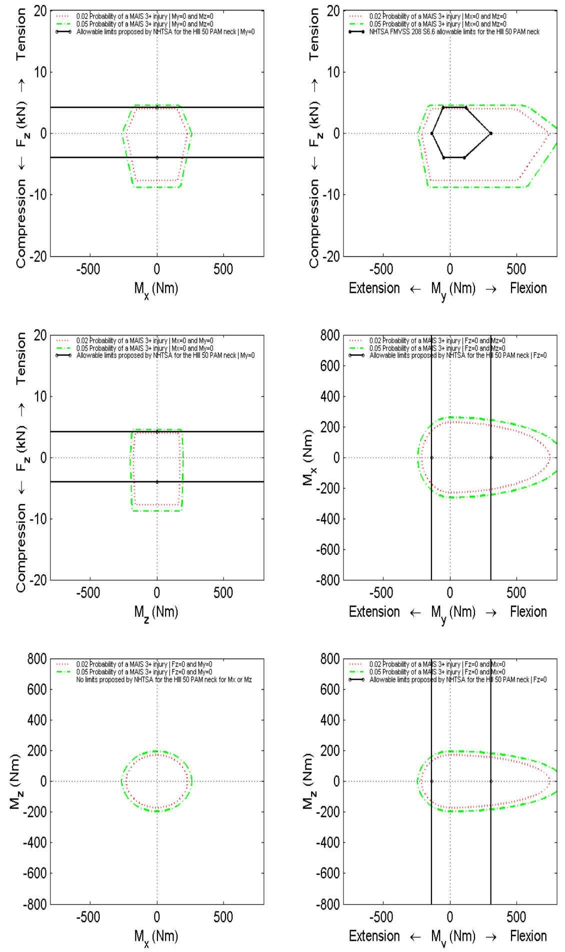

Figure D-1. Comparison of the general shape and axes of the improved neck injury criteria for the new ISO 13232 MATD neck to the allowable limits proposed by NHTSA for the HIII 50 PAM neck (recognizing that the necks have very different stiffness)