DEVELOPMENT OF NECK INJURY ASSESSMENT CRITERIA FOR THE ISO 13232 MOTORCYCLIST ANTHROPOMETRIC TEST DUMMY WITH THE REVISED NECK

R. Michael Van Auken
John W. Zellner
Scott A. Kebschull
Kenneth D. Wiley
Dynamic Research, Inc.
United States
Terry Smith
Head Protection Research Laboratory
United States
Nicholas Shewchenko
Biokinetics and Associates Ltd.
Canada
Nicholas M. Rogers
International Motorcycle Manufacturers Association
Switzerland
Paper No. 417

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. This involved the development of an improved dummy neck with multi-directional biofidelity and injury assessment capabilities and corresponding probabilistic four axis neck injury criteria. The neck injury criteria were developed by fitting the distributions of neck injury severities observed in on-scene in-depth investigations of 568 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 568 crashes. The result is a probabilistic injury criterion that can estimate the probability of neck injury, based on four axis upper neck forces and moments measured with the new MATD neck. The model has a high level of overall agreement with neck injury severity levels and directions observed in real world crashes.

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 recently 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 committee 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]), which is the subject of this paper.

The changes were considered necessary because the neck injury criteria in the original Standard:

- did not provide an indication of the AIS injury severity level;
- were "pass/fail" in nature, 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].

The injury risk/benefit analysis methods specified in Part 5 of the 1996 Standard incorporated a rider injury severity (AIS) and injury cost model, for injuries to the head, chest, abdomen, and lower extremities, based on probabilistic functions of objective injury assessment variables measured by the MATD. The initial basis for this injury model was reported in Newman et al. [5], with example application in Kebschull et al. [6].

The 1996 edition of the Standard did not include a probabilistic neck injury model, due to the limited injury tolerance data that was available at that time. Instead, a criterion to indicate either "likely [neck] fracture or dislocation [with] a fatal propensity" or non-injury was incorporated [1]. This limitation became especially important in airbag evaluations that involved severe neck loading. For example, Ramet et al. [7] reported severe upper neck lesions with cadavers positioned on prototype motorcycle airbags, suggesting that a better estimate of neck injury probability would be required.

Objectives

The objectives of this study were to develop a new, probabilistic neck injury criterion compatible with the criteria employed in other body regions of the MATD. 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 committee draft first revision of the Standard for use in the risk/benefit analysis and injury severity and cost models.

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., [8], [9])
- 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 487 non-fatal LA/Hannover motorcycle-car accidents (ISO-13232-2) and 67 USC fatal motorcycle-car accidents ([10], [11]);
    - AO/C1/C2 neck injury severities and directions observed in the 67 USC motorcycle fatal accidents;
    - peak AO forces and moments observed in calibrated computer simulations of the 501 LA/Hannover non-fatal and fatal motorcycle-car accidents and 67 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.

COMPUTER SIMULATION OF THE MATD NECK

In order to simulate real accidents for which neck injuries were known, a computer simulation of the new neck was developed using the US Air Force Articulated Total Body (ATB) Program [6], [12]. The mathematical model of the 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 validated by comparing the predicted results to those observed in component and full-scale tests as reported in [13]. For example, Figure 1a and b illustrate a comparison of still images from high speed video of a rearward neck extension sled test and the corresponding computer simulation. Figure 1c illustrates the digitized motions from the full-scale test and from the corresponding computer simulation, indicating close agreement. Figure 2a, b and c illustrate a similar comparison using full-scale test data.

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 [14] and Råde and Westergren [15]:

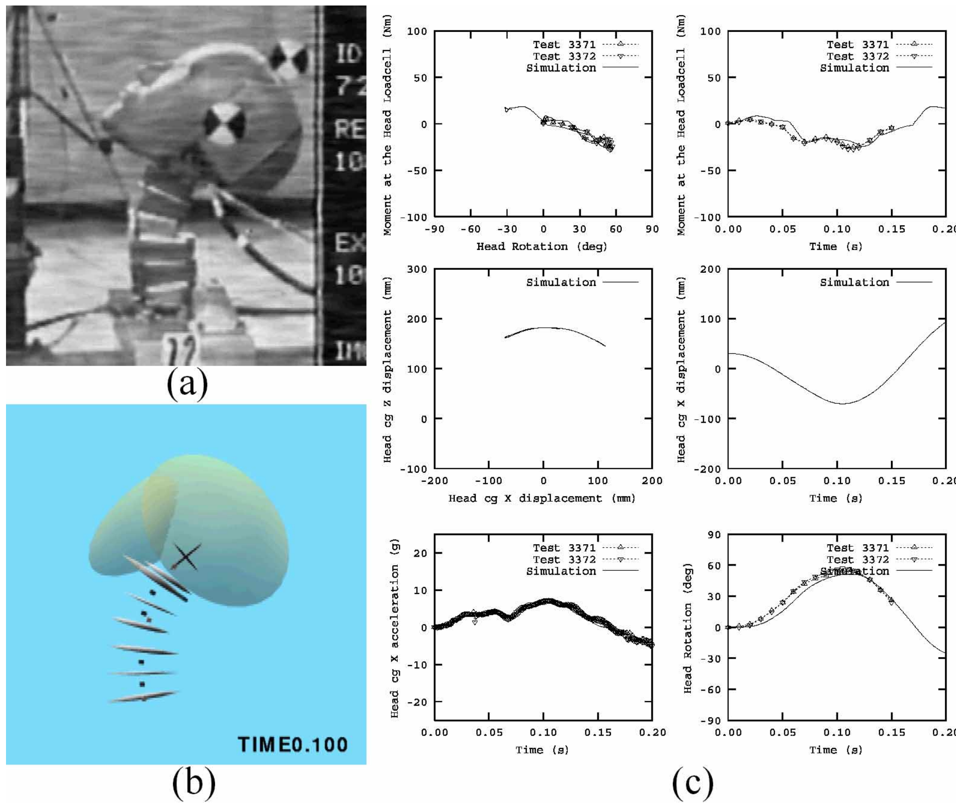


Figure 1: a) Laboratory test, b) computer simulation of rearward neck extension at 0.1 sec., and c) corresponding time response of laboratory test and computer simulation.

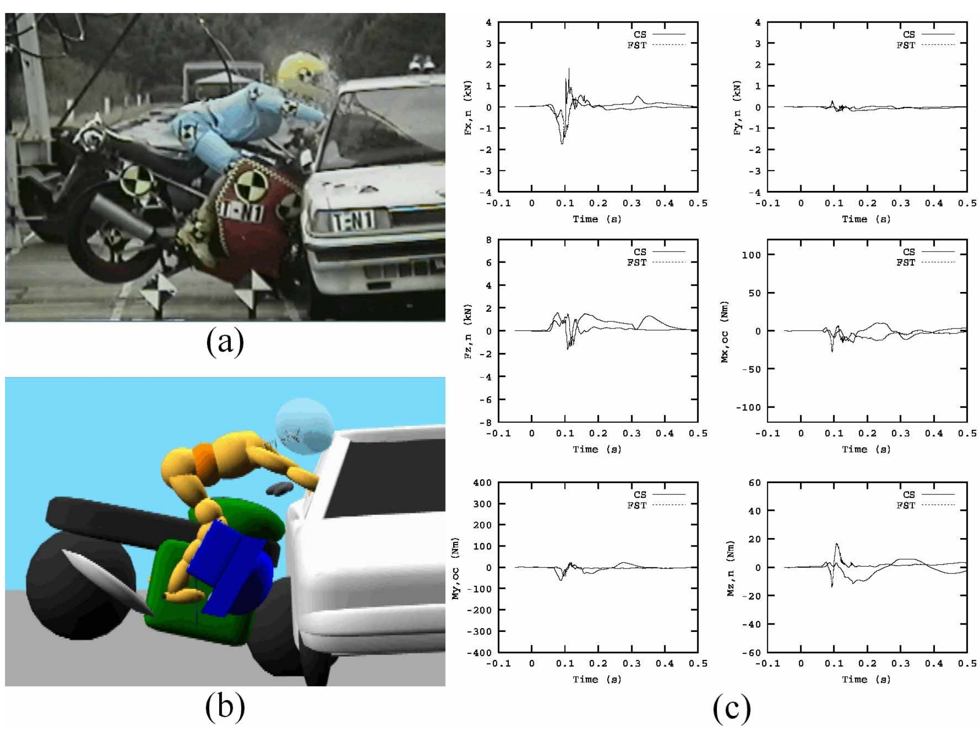


Figure 2: a) Full scale test, b) computer simulation of impact configuration 413-0/30 0.1 sec after initial contact, and c) corresponding measured and predicted response from full scale test and computer simulation.

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

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

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

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

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 objective injury index defined by equations (4) and (5) 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. [16], Bruhn [17], and US Department of Defense MIL-HDBK-5D [18]) 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 ([18], 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 [17] 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.

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:

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

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

$$NII(t) = \left(\left(\frac{F_C(t)}{F_C^*} + \frac{F_T(t)}{F_T^*} + \left(\left(\frac{M_X(t)}{M_X^*}\right)^2 + \left(\frac{M_E(t)}{M_E^*} + \frac{M_F(t)}{M_F^*}\right)^2 \right)^{1/2} \right)^2 + \left(\frac{M_Z(t)}{M_Z^*}\right)^2 \right)^{1/2} \quad (5.)$$

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

MOTORCYCLE ACCIDENT DATABASES

The coefficients for the assumed neck injury probability model were estimated from data describing 501 Los Angeles and Hannover motorcycle-car accidents (ISO 13232-2) and 67 USC fatal motorcycle-car accidents [11]. Features of these databases are summarized in Table 1.

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 assumed mathematical injury probability model described by equations (1) to (9) are valid.
- The distribution of neck injury severities in the 67 USC fatal accidents are the same as the distribution of neck injury severities in the 14 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 501 ISO 13232 calibrated computer simulations with a GPZ 500 motorcycle and a helmeted rider are the same as those which occurred in the 501 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. [19] 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 which are relevant and correlated with

Table 1. Summary of Accident Databases

Sample Criteria		Database: LA	Database: Hannover	Database: 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
	Non fatal neck injuries	$\leq$3%		92.5%
	Fatal neck injuries	Unknown, but $\leq$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	[10], [11]

human upper neck injuries. The new MATD neck dynamic response in three axes has been validated against volunteer human response corridors as described in [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 [13];
- 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 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 [20];
- “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 501 LA/Hannover cases. This process is further detailed in the informative annexes to the committee draft first revision of ISO 13232-5 [3].

<u>Injury direction coefficients</u>

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 $n_{k,0,0,0,0,0,0}$ is 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.

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

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.

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 501 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 A. 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 A.1)	Estimated Number of Cases with $MAIS_{AO/C1/C2} < k$
0	474	0
1	10	474
2	4	484
3	10	488
4	0	498
5	2	498
6	1	500

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 500, then μ_k and m_k satisfy the equation

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

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

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

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	$501\text{-}n_k$	$501\text{-}m_k$
Total	501	501

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 501 computer simulations will match the distribution of neck injuries observed in the LA/Hannover database as illustrated in Figure 3.

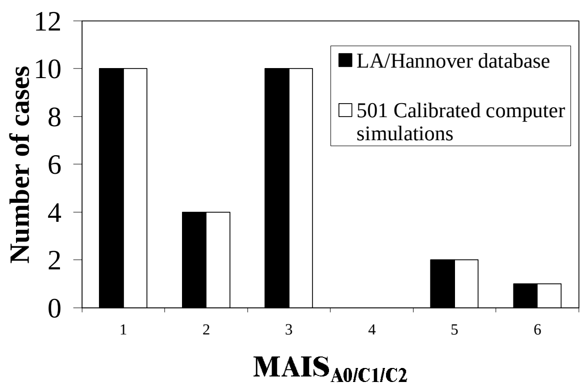


Figure 3. Distribution of observed and predicted neck injuries.

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 [21])

$$\chi^2 = \frac{(n_k(501-m_k)-m_k(501-n_k))^2(2\times 501)}{(n_k+m_k)(501-n_k+501-m_k)(501)^2} \quad (16.)$$

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 $m_k^- \leq m_k \leq 501$.

Table 5. 95% Confidence limits for m_k

k	m_k^-	m_k^+
1	459	486
2	471	493
3	477	496
4	491	-
5	491	-
6	495	-

RESULTING MATD NECK INJURY CRITERIA

Injury Direction Coefficients

The injury direction coefficients were identified according to the method described above, and are listed in Tables 6 and 7. 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^*	3.53 kN
F_T^*	4.21 kN
M_X^*	61.8 Nm
M_E^*	55.66 Nm
M_F^*	224.8 Nm
M_Z^*	72.3 Nm

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

k	S_k	Q_k^*
1	1	0.583
2	1.00	0.583
3	1.45	0.477
4	2.93	0.606
5	2.93	0.606
6	4.23	0.688

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

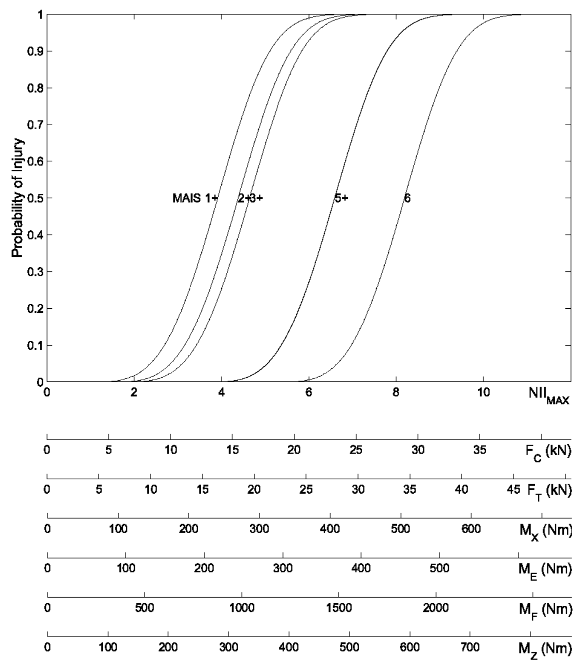
Number of cases in the USC fatal motorcycle accident database with $MAIS_{AO/C1/C2} \geq k$ and indicated direction							Number of computer simulations of the USC fatal cases with $NII_{max} \geq S_k$ and $NII_I(t_{max}) \geq Q_k^* S_k$						
Direction	k						I	k					
	1	2	3	4	5	6		1	2	3	4	5	6
Compression	5	5	4	0	0	0	*C*	14	14	11	0	0	0
Tension	18	18	16	4	4	0	*T*	5	5	5	0	0	0
Lat. Bending	42	42	35	11	11	2	*X*	43	43	37	8	8	1
Extension	33	33	29	8	8	4	*E*	29	29	22	8	8	4
Flexion	20	20	17	4	4	0	*F*	12	12	7	0	0	0
Torsion	20	20	17	7	7	2	*Z*	17	17	12	1	1	0
All	64	64	55	16	16	5	-	63	63	55	16	16	5

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 separate out the injuries by AIS level as intended.

Injury Risk (Probability) Coefficients

The injury severity coefficients were identified from the LA/Hannover data according to the methods as previously described. The resulting coefficients are listed in Table 9 and the injury risk curves are illustrated in Figure 4. The distribution of neck injuries for the 501 computer simulations also matches the distribution of injuries in the LA/Hannover database, as previously illustrated in Figure 3.

A comparison of resulting injury criteria for the new ISO 13232 MATD neck to criteria proposed by NHTSA for the Hybrid III 50th Percentile Adult Male [22] is located in Appendix C, 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.



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

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

k	μ_k		σ_k (=0.2μ_3)	γ_k	η_k
1	3.91	(3.50, 4.50)	0.928	0.97	3.26
2	4.38	(3.86, 5.36)	0.928	1.45	3.26
3	4.64	(4.07, 6.20)	0.928	1.71	3.26
4	6.59	(5.13, -)	0.928	3.66	3.26
5	6.59	(5.13, -)	0.928	3.66	3.26
6	8.19	(5.94, -)	0.928	5.25	3.26

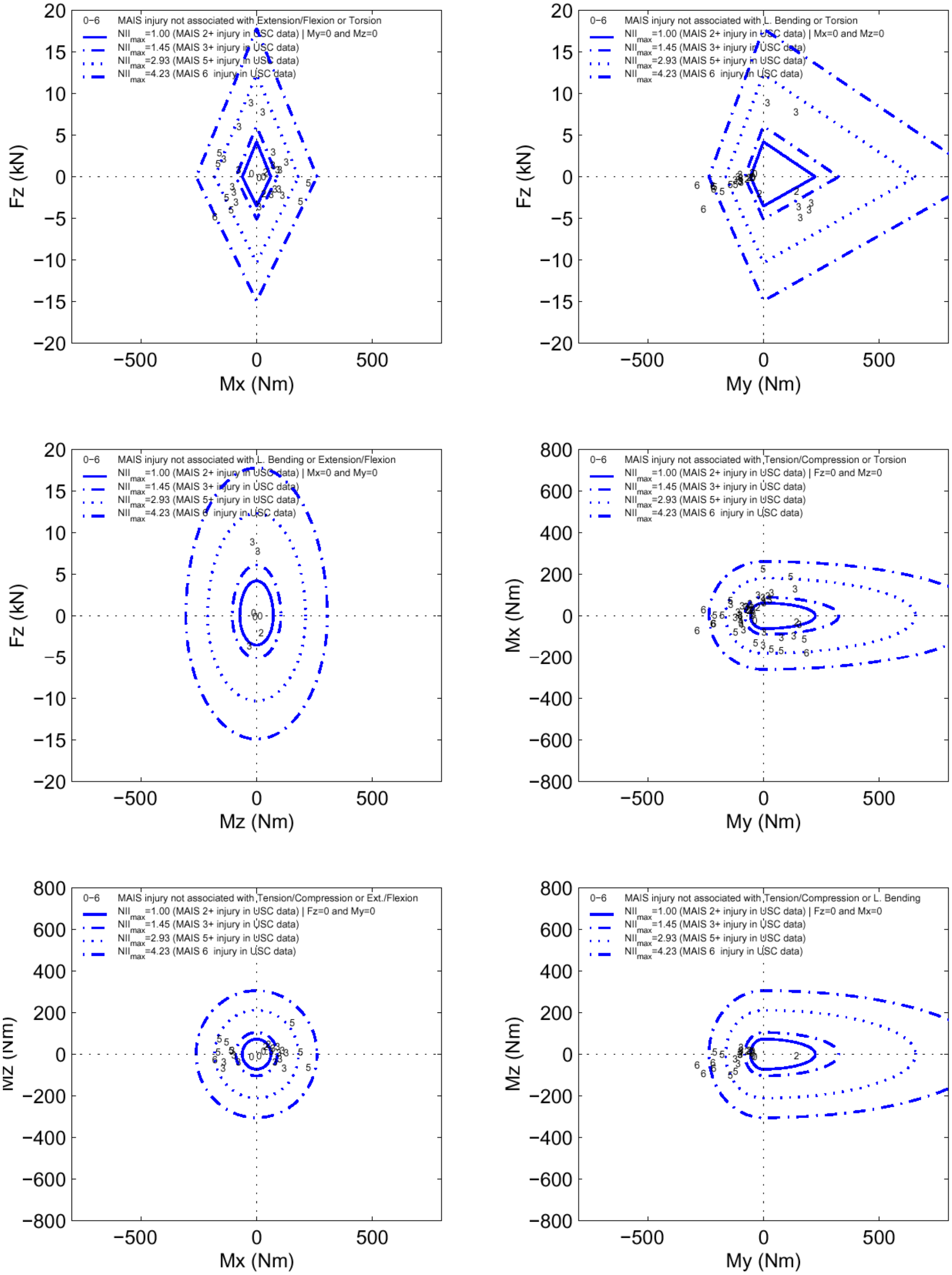


Figure 5. Forces and Moments at t_{max} from computer simulations of 67 fatal cases and the best step-wise fit envelopes of constant NII_{max}, providing the basis for the envelope shape.

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 corresponding neck injury criteria were developed which satisfactorily meets these and other injury assessment needs of ISO 13232. The new neck and injury criteria are included in the committee draft first revision of ISO 13232 [3].

The new 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 568 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 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=568 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

This work was funded by the International Motorcycle Manufacturers Association. The full-scale test was funded by the Japan Automobile Manufacturers Association, and was conducted at the Japan Automobile Research Institute.

REFERENCES

[1] Anonymous, Motorcycles – Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motorcycles, ISO 13232, International Organization for Standardization, Geneva, 1996.

[2] Zellner, J.W., J.A. Newman, N.M. Rogers, "Preliminary Research into the Feasibility of Motorcycle Airbag Systems", proceedings of the 14th International Technical Conference on the Enhanced Safety of Vehicles, Munich, Germany, National Highway Traffic Safety Administration, Washington DC, 1994, pp. 1198-1210.

[3] Anonymous, Motorcycles – Test and Analysis Procedures for Research Evaluation of Rider Crash Protective Devices Fitted to Motorcycles, ISO/CD 13232, International Organization for Standardization, Geneva, 2002.

[4] Withnall, C., N. Shewchenko, K. Wiley, N. Rogers, "An Improved Dummy Neck for the ISO 13232 Motorcycle Anthropometric Test Dummy", proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles, Nagoya, Japan, National Highway Traffic Safety Administration, Washington D.C., May 2003.

[5] Newman, J.A., S. Tylko, "Toward a Comprehensive Biomechanical Injury Cost Model", proceedings of the 36th Annual Conference of the Association for the Advancement of Automotive Medicine, AAAM, Des Plaines, USA, 1992, pp. 271-287.

[6] Kebschull, S.A., et al., "Injury Risk/Benefit Analysis of Motorcycle Protective Devices Using Computer Simulation and ISO 13232", proceedings of the 16th International Technical Conference on the Enhanced Safety of Vehicles, Windsor, Canada, National Highway Traffic Safety Administration, Washington D.C., 1998, pp. 2357-2374.

[7] Ramet, M., et al., "The Effect of Air Bag Inflation on the Cinematic and the Lesions of a Motorcyclist", proceedings of the 14th International Technical Conference on the Enhanced Safety of Vehicles, Munich, Germany, National Highway Traffic Safety Administration, Washington D.C., 1994, pp. 1241-1246.

[8] Eppinger, R., et al., Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems – II, National Highway Traffic Safety Administration, Washington D.C., November 1999.

[9] Eppinger, R., E. Sun, S. Kuppa, R. Saul, Supplement: Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems – II, National Highway Traffic Safety Administration, Washington D.C., March 2000.

[10] Thom, D.R., H.H., Jr., Hurt, T.A. Smith, and I. Rehman, "Atlas and axis injuries in fatal motorcycle collisions," Proceedings of the 39th Annual Conference of the Association for the Advancement of Automotive Medicine, 1995.

[11] Smith, Terry A., Summary report of the analysis of the USC fatal motorcycle accident data set, Head Protection Research Laboratory, July 2001.

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

[13] Van Auken, M., et al., Comparison of the new MATD neck computer simulation model to the full scale test and laboratory test responses, ISO/TC22/SC22/WG22 N305, 2001-05-22.

[14] Anonymous, Automotive Electronics Reliability Handbook, Publication No. AE-9, Society of Automotive Engineers, Warrendale, PA, February 1987, pp 32-33.

[15] Råde, L., and B. Westergren, Beta Mathematics Handbook, Second Edition, CRC Press, Boca Raton, FL, 1990, pp. 395.

[16] Shanley, F. R. and E. I. Ryder, "Stress Ratios; the answer to the combined loading problem", Aviation, June 1937, pp. 28-29:43:66:69-70.

[17] Bruhn, E. F., Analysis and Design of Flight Vehicle Structures, Jacobs Publishing, Inc., Indianapolis, 1973.

[18] Anonymous, Military Standardization Handbook Metallic Materials and Elements for Aerospace Vehicle Structures, MIL-HDBK-5D, US Department of Defense, Washington, D.C., June 1983.

[19] Orsay, E.M., et al., “Motorcycle helmets and spinal injuries: Dispelling the myth", Annals of Emergency Medicine 1994 April 23(4):802-6.

[20] Mertz, H.J., and P. Prasad, “Improved Neck Injury Risk Curves for Tension and Extension Moment Measurements of Crash Dummies”, Paper No. 2000-01-SC05, Society of Automotive Engineers, Proceedings of the 44th Stapp Car Crash Conference, November 2000.

[21] Box, G.E.P., W.G. Hunter, and J.S. Hunter, Statistics for Experimenters, John Wiley & Sons, New York, 1978.

[22] Anonymous, U.S. DOT/NHTSA - Final Rule; Interim Final Rule – Notice 1, Docket No. NHTSA 00-7013-1, RIN 217-AG70, National Highway Traffic Safety Administration, Washington, D.C., May 2001.

APPENDIX A

The distribution of neck injuries in the 501 LA/Hannover accident database was estimated by

- imputing the distribution of neck injuries observed in the 67 USC fatal cases in the 14 fatal LA/Hannover cases; and
- redistributing the remaining 3 unknown injuries amongst the valid cases.

The data and results of this analysis are listed in Table A.1. The columns in Table A.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 $MAIS_{AO/C1/C2}$. Note that 3 non-fatal cases and all 14 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/501 x 100%.

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

(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 2.79%.

(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

Table A.1. Distribution of Neck A0/C1/C2 Injury Severities in the LA/Hannover and USC Fatal Accident Databases

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$MAIS_{A0/C1/C2}$	LA/Hannover Database							
	Non Fatal		Fatal			All		
	Observed Number of Cases	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	470	93.81%			0.13%	93.937%	94.50%	474
1	10	2.00%			0.00%	1.996%	2.01%	10
2	2	0.40%			0.38%	0.775%	0.78%	4
3	2	0.40%			1.63%	2.026%	2.04%	10
4	0	0.00%			0.00%	0.000%	0.00%	0
5	0	0.00%			0.46%	0.459%	0.46%	2
6	0	0.00%			0.21%	0.209%	0.21%	1
unknown	3	0.60%	14	2.79%	0.00%	0.599%	-	0
Total	487	97.21%	14	2.79%	2.79%	100.000%	100.00%	501

(10)	(11)	(12)	(13)
$MAIS_{A0/C1/C2}$	USC Database		Observed Percentage of USC Fatal Cases x 2.79%
	Fatal		
	Observed Number of Cases	Observed Percentage of Fatal Cases	
0	3	4.48%	0.13%
1	0	0.00%	0.00%
2	9	13.43%	0.38%
3	39	58.21%	1.63%
4	0	0.00%	0.00%
5	11	16.42%	0.46%
6	5	7.46%	0.21%
unknown	0	0.00%	0.00%
Total	67	100.00%	2.79%

reapportions the remaining 3 unknown cases amongst the valid cases. The percentages in this column are equal to the values in column 7 x 501 / (501-3).

(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 501 / 100%. The estimated numbers of cases were rounded to integer values such that the total number of cases is 501.

APPENDIX B

Figure B-1 illustrates the distributions of maximum neck forces and moments for the 501 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 motorcycle speeds up to 195 km/h, and the opposing vehicle speeds up to 150 km/h. This is the probable reason why some of the maximum forces and moments are of relatively large magnitude.

APPENDIX C

Figure C-1 illustrates the shapes of the new injury criteria for the MATD neck and the criteria proposed by NHTSA for the Hybrid III 50th percentile adult male neck [22]. 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.

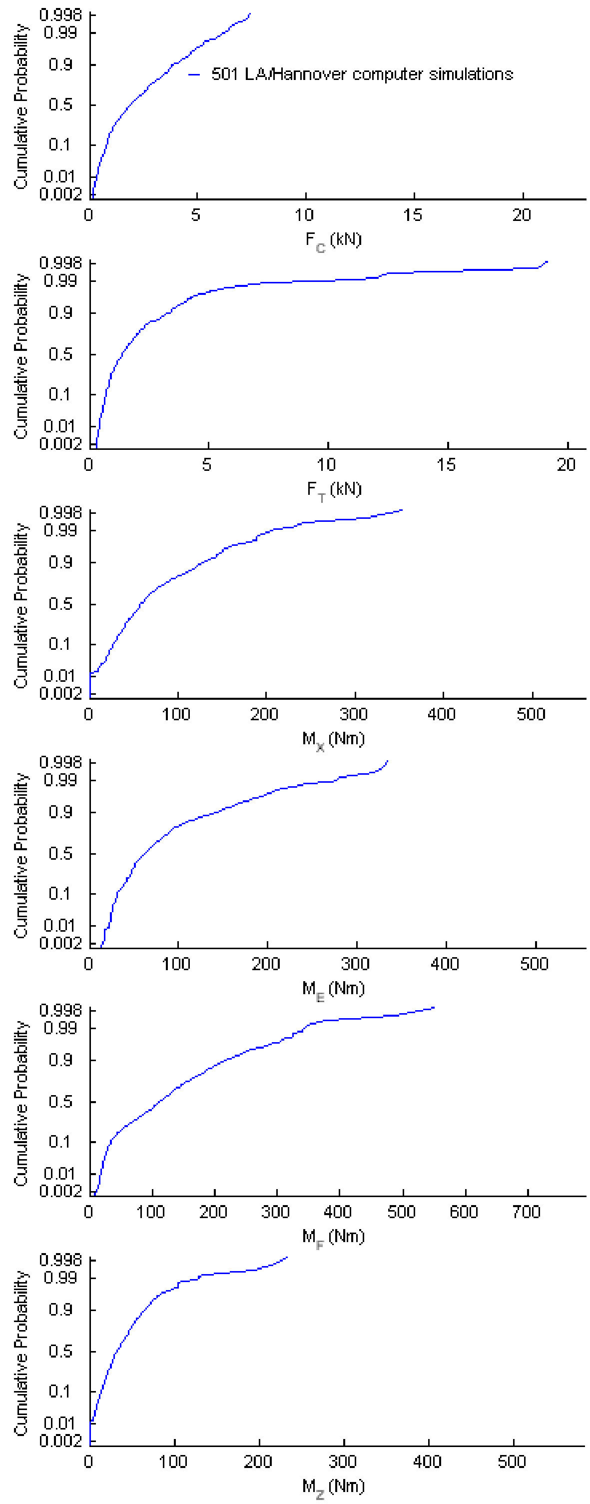


Figure B-1. Maximum neck force and moment distributions from computer simulations of 501 LA/Hannover cases, including cases with high speed, severe impacts

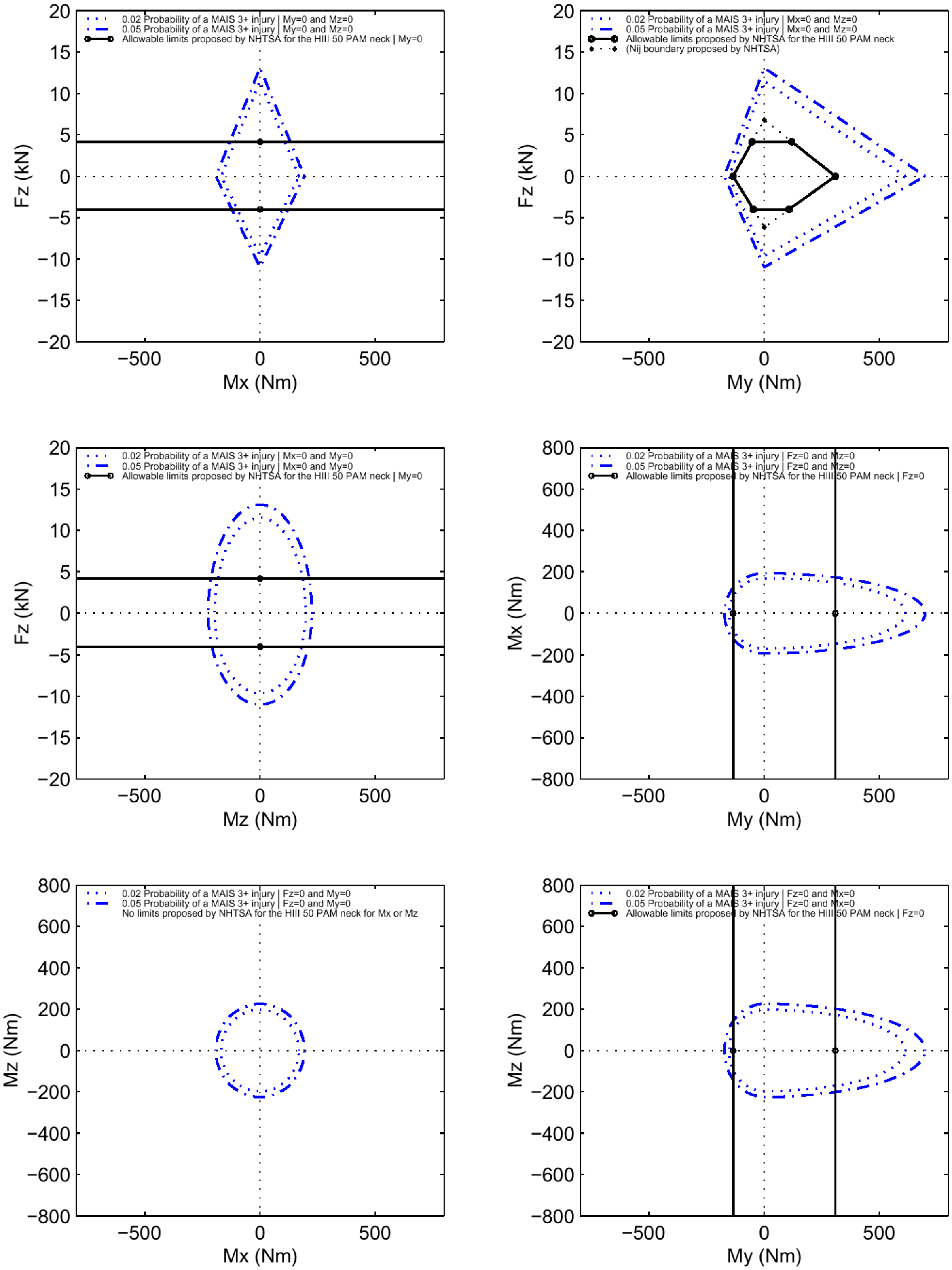


Figure C-1. Comparison of the general shape and axes of the Injury Criteria for the New ISO 13232 MATD Neck to the allowable limits proposed by NHTSA for the HIII 50 PAM neck (recognizing that the necks have very different stiffness)