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Injury Risk Curves for Children and Adults in Frontal and Rear Collisions

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ABSTRACT

This paper describes the development of injury risk curves for measurements made with the CRABI and Hybrid III family of biofidelic child and adult dummies that are used to evaluate restraint systems in frontal and rear-end collision simulations. Injury tolerance data are normalized for size and strength considerations. These data are analyzed to give normalized injury risk curves for neck tension, neck extension moment, combined neck tension and extension moment, sternal compression, the rate of sternal compression, and the rate of abdominal compression for children and adults. Using these injury risk curves dummy response limits can be defined for prescribed injury risk levels. The injury risk levels associated with the various injury assessment reference values currently used with the CRABI and Hybrid III family of dummies are noted.

INTRODUCTION

A number of investigators have developed injury risk curves for various dummy response measurements for frontal impacts. Prasad and Mertz (1) and Mertz et al (2, 3) have published injury risk curves for skull fracture and for AIS ≥ 4 brain injury due to forehead impacts based on the 15 ms HIC criterion and for skull fracture based on peak head acceleration (Figures A1 - A3 of the Appendix). These curves represent the injury risks for the adult population since adult cadavers were used to obtain the biomechanical data which were not normalized for size and mass effects. Mertz et al (4) have developed an injury risk curve for AIS ≥ 3 thoracic injury based on the sternal deflection of the Hybrid III mid-size adult male dummy being restrained by an automotive 3-point belt system (Figure A4). Viano and Lau (5) have proposed an injury risk curve for AIS ≥ 4 thoracic organ injury based on the maximum value of the instantaneous product of the ratio of sternal compression normalized by the thoracic depth and the rate of sternal compression, the Viscous Criterion (Figure A5). This curve can be applied to adults and children because equal viscous criterion levels experienced by both children and adults will produce equal thoracic organ stresses. Rouhana et al (18) have published injury risk curves for AIS ≥ 3 and 4 abdominal injuries which can be used to assess the severity of abdominal loading measured by the crushing of a special foam abdominal insert which is available with the Hybrid III small female and midsize male dummies. Mertz and Weber (6) have published injury risk curves for measurements made with the 3-year old "airbag" dummy (7). These curves were based on animal and child dummy data of Mertz et al (8) obtained from tests where the subjects were exposed to forces produced by inflating passenger airbags. These data will be combined with similar data obtained by Prasad and Daniel (9) to obtain normalized injury risk curves that can be used with the CRABI and Hybrid III family of child and adult dummies. In addition, the blunt thoracic cadaver impact data of Neathery et al (10) will be updated and normalized to give injury risk curves for AIS ≥ 3 and AIS ≥ 4 thoracic injury based on maximum sternal deflection of the various child and adult dummies.

NECK INJURY RISK CURVES

Mertz et al (8) and Prasad and Daniel (9) have conducted tests to assess the effects of deploying passenger airbag interactions with animals (10-week old pigs) that were chosen to represent the size, weight and state of tissue development of 3-year old children. In their studies, a series of matched tests was conducted where for every pig test a similar test was conducted using the 3-year old "airbag" dummy. This allowed the various injury severities experienced by the pig to be correlated with corresponding dummy response measurements. The neck injuries observed in both studies initiated by the tearing of small blood vessels of the membranes encasing the occipital condylar joint capsules and progressed to rupture of the alar ligament, damage to the spinal cord and brain stem, and finally to fatality as the impact severity increased. Blood in the synovial fluid of the occipital condylar joint capsules was rated as AIS = 3 and occurred in all the cervical neck injuries rated as AIS ≥ 3.

Based on the location and nature of the neck injuries, neck tension, neck extension moment, and a combination of tension and extension moment measured at the occipital condyles of the 3-year old air bag dummy were proposed as indicators of neck injury severity. Both studies showed that neck tension was the best indicator of the onset of AIS ≥ 3 neck injury with no AIS ≥ 3 neck injury occurring below a neck tension load of 1160 N. However, the severity of the neck injury that corresponded to the neck tension of 1160 N was fatality. As noted in the introduction, Mertz and Weber (7) analyzed the Mertz et al (8) data and provided an injury risk curve for AIS ≥ 3 neck injury based on neck tension measured with the 3-year old airbag dummy. This injury risk curve will be updated by analyzing the combined data sets of Mertz and Prasad. Injury risk curves for extension moment and the combination of tension and extension moment will be developed based on the combined data sets. Since both of these data sets are estimates of the tolerance of a 3-year old child, they will be normalized for size and strength considerations to give estimates of injury risk curves for any ages of children or sizes of adults.

The following is a discussion of the development of injury risk curves for AIS ≥ 3 neck injury for tension/extension loading of the neck based on peak neck tension, peak neck extension moment and the combination of tension and extension moment which can be used with the CRABI and Hybrid III family of child and adult dummies.

SIZE SCALE FACTORS - Neck circumference was used to characterize neck size. Table 1 gives the neck circumferences for 6-month, 12-month, 18-month, 3-year old, 6-year old, small adult female, mid-size adult male and large adult male which are based on various anthropometry studies (11-14). Since the reference tolerance data pertains to the 3-year old, the neck size scale factor, λ_c, will be defined as,

$$\lambda_c = \frac{\text{Neck Circumference of Subject}}{\text{Neck Circumference of 3-year old}} \qquad (1)$$

The λ_cs for the various children and adults are given in Table 1.

STRENGTH SCALE FACTORS - A search was done of the biomechanical literature for dynamic failure data of ligamentous tissue as a function of age. While static data was found for the adult, no child data and no dynamic data were found. In the absence of such data, maximum tissue stress was chosen as the failure criterion and the failure stress level was assumed to be independent of age. These assumptions allow the elastic modulus of the ligament to vary with age and consequently the strain at failure to vary with age. If, at a later date, child and adult data are obtained for ligamentous failure at appropriate loading rates, then the analyses given in this paper can be updated.

However, it should be noted that the three neck criteria, maximum neck tension, maximum neck extension moment and the maximum value of the combination of neck tension and extension moment are measures of "macro" structural load carrying capacities of the neck structure for tension - extension loading of the neck. As such their failure values will be dependent not only on the ligament load, but also on the corresponding load being transmitted by the muscle groups. This latter load will be dependent on the degree of muscle tension which is assigned to the occupant and its variation could mask the variation in ligament strength.

NECK TENSION - The relationship between the ratios of neck tension forces, λ_F, the sizes of the necks λ_A, and the average tensile stresses, λ_σ, can be expressed as,

$$\lambda_F = \lambda_\sigma \, \lambda_A \qquad (2)$$

For children and adults, the average stresses based on the cross-sectional areas of their necks will be taken as equal for equal injury severity, ie, $\lambda_\sigma = 1$. The ratio of their cross-sectional areas, λ_A, will be taken as the ratio of the square of their neck circumferences, λ_c^2. From Equation 2, the ratio of the tensile forces that corresponding to equal injury severity is,

$$\lambda_F = \lambda_c^2 \qquad (3)$$

Since data for neck tension forces and corresponding neck injury severities for the 3-year old child exist, the neck tension forces causing the same injury severity in other size occupants can be determined by simply multiplying the 3-year old forces by the square of the ratio of their circumferences.

The neck tension force and corresponding neck injury severity data of Mertz et al (8) and Prasad and Daniel (9) are given in Table A1 of the Appendix. These data were analyzed using the Mertz/Weber Method (6) to obtain the injury risk curve shown in Figure A6 for AIS ≥ 3 neck injury based on neck tension forces experienced by a 3-year old child. For convenience, the neck forces are normalized by the tension force, F_1, that corresponds to a 1 percent risk of AIS ≥ 3 neck injury. For the 3-year old, this force is 1070 N. For any size person, the corresponding value of F_1 can be determined from Equation 3, or

$$F_1 = \lambda_c^2 \; 1070 \text{ N} \qquad (4)$$

where λ_c is defined by Equation 1.

The normalized injury risk curve for the 3-year old child is identical to the normalized risk curve for, any size occupant provided the normalized force is computed by the relationship given by Equation 4. Figure 1 gives the injury risk curve for AIS ≥ 3 neck injury based on normalized neck tension for any size person. Normalizing values for various child and adult dummies are given in the legend. These values were calculated using Equation 4 and the values of λ_c given in Table 1. Note that the normalized values are the neck tensions that produce a 1 percent risk of AIS ≥ 3 neck injury for the corresponding dummy. Further, this curve gives an estimate of the injury risk when the neck is being loaded in tension and extension which is the loading mode experienced by the pigs and child dummy in the biomechanical tests.

NECK EXTENSION MOMENT - For structures whose cross-sectional area can be characterized by a single length scale factor, λ_L, Mertz et al (13) have shown that the relationship between the ratios of the internal bending moments, λ_M, and the internal bending stresses, λ_σ, can be expressed as,

$$\lambda_M = \lambda_\sigma \lambda_L^3 \quad (5)$$

Again we specify $\lambda_\sigma = 1$ for equal injury severity and $\lambda_L = \lambda_c$. From Equation 5, the ratio of neck extension moments associated with neck injury is,

$$\lambda_M = \lambda_c^3 \quad (6)$$

Since data for neck extension moments and corresponding neck injury severities for the 3-year old child exist, the neck extension moments causing the same injury severity in other size occupants can be estimated from Equation 6.

The neck extension moment and corresponding neck injury severity data of Mertz et al (8) and Prasad and Daniel (9) are given in Table A1 of the Appendix. These data were analyzed using the Mertz/Weber Method (6) to obtain the injury risk curve shown in Figure A7 for AIS ≥ 3 neck injury based on the neck extension moments experienced by a 3-year old child. The neck extension moments are normalized by the moment, M_1, that corresponds to a 1 percent risk of AIS ≥ 3 neck injury. For the 3-year old, this moment is 13 Nm. For any size person, the corresponding value of M_1 can be determined from Equation 6, or

$$M_1 = \lambda_c^3 \; 13.0 \text{ Nm} \quad (7)$$

where λ_c is defined by Equation 1.

The normalized injury risk curve for the 3-year old child is identical to the normalized risk curve for any size occupant provided the normalized moment is computed by the relationship given by Equation 7. Figure 2 gives the injury risk curve for AIS ≥ 3 neck injury based on normalized neck extension moment for any size person. Normalizing values for various child and adult dummies are given in the legend. These values were calculated using Equation 7 and the values of λ_c given in Table 1. Note that the normalized values are the neck extension moments that produce a 1 percent risk of AIS ≥ 3 neck injury for the corresponding dummy. Further, this curve gives an estimate of the injury risk when the neck is being loaded in tension and extension, which is the loading mode experienced by the pigs and child dummy in the biomechanical tests.

COMBINED TENSION AND EXTENSION MOMENT - The following is an approach to combining the tension and extension moment loadings. Let A be the cross-sectional area of the membrane and D be the distance from the anterior surface of the atlas to its posterior surface. Assume that one half the measured tensile force is carried by the membrane and that the membrane tensile force produced by the extension moment is equal to the measured extension moment divided by D. With these assumptions, the total force in the anterior membrane is,

$$P = M_E / D + F_T / 2 \quad (8)$$

and the stress is,

$$\sigma = P/A = (AD)^{-1} [M_E + DF_T/2] \quad (9)$$

In terms of neck scale factor, λ_c, defined by Equation 1, Equation 9 can be written as,

$$\sigma = (\lambda_c^3 A_3 D_3)^{-1} [M_E + \lambda_c D_3 F_T/2] \quad (10)$$

where A_3 and D_3 are the 3-year old dimensions.

Now a kernel, K, of M_E and F_T can be defined as

$$K = [M_E + \lambda_c D_3 F_T/2] = \sigma \lambda_c^3 A_3 D_3 \quad (11)$$

and represents lines of constant stress with a slope of $-\lambda_c D_3/2$ on a plot of M_E versus F_T. Table A2 gives values of K calculated from the data of Mertz et al (8) and Prasad and Daniel (9) along with the corresponding neck injury severity ratings. Since these data are representative of a 3-year old child, $\lambda_c = 1$ and $D_3 = 25.2$ mm were used in the calculations. These data were analyzed by the Mertz / Weber Method (6) to give an injury risk curve shown in Figure A8 for AIS ≥ 3 neck injury based on K values for a 3-year old child. For a 1 percent risk of AIS ≥ 3 neck injury, K = 20.0. The corresponding stress, σ_1, can be calculated from Equation 11 and is,

$$\sigma_1 = 20.0 / A_3 D_3 \quad (12)$$

The stress level given by Equation 10 can be normalized by σ_1, the stress level corresponding to a 1 percent risk of AIS ≥ 3 neck injury or,

$$N_{TE} = \sigma / \sigma_1 = [M_E + \lambda_c D_3 F_T/2] / (20.0 \lambda_c^3) \quad (13)$$

The normalized stress can be expressed in terms of the ordinate value, M_C, and the abscissa value, F_C, of the constant stress line corresponding to 1 percent risk of AIS ≥ 3 neck injury for any size occupant, or,

$$N_{TE} = M_E/M_C + F_T/F_C \quad (14)$$

where from inspection of Equation 13,

$$M_C = 20.0 \lambda_c^3 \text{ Nm} \quad (15)$$

$$F_C = 1590 \lambda_c^2 \text{ N} \quad (16)$$

The injury risk curve for AIS ≥ 3 neck injury for combined normalized neck tension and extension moment for the 3-year old child can be obtained by dividing the tension and extension moments given in Table A2 by the corresponding values of M_C and F_C given by Equations 15 and 16 noting that $\lambda_c = 1$ for the 3-year old child. The resulting curve is identical to the injury risk curve for any size occupant provided M_C and F_C are calculated using Equations 15 and 16.

Figure 3 gives the injury risk curve for AIS ≥ 3 neck injury based on the normalized stress, N_{TE}, produced by combined neck tension and extension moment for any size person. Values of M_C and F_C for various sizes of child and adult dummies are given in the legend. These values were calculated using Equations 15 and 16 and the values of λ_c given in Table 1.

THORACIC INJURY RISK CURVES

RATE OF STERNAL COMPRESSION - Table A3 in the Appendix gives data of Mertz et al (8) and Prasad and Daniel (9) for the injury severities experienced by the heart and lungs of their animals and the corresponding maximum rates of sternal deflection measured with the 3-year old child dummy. These data were analyzed with the Mertz/Weber Method (6) to give the injury risk curve for AIS ≥ 3 heart/lung injury as a function of the maximum rate of sternal deflection for a 3-year old child shown in Figure 4. Since no age dependent, dynamic loading failure stress data were found in the literature, the failure stresses of the heart and lung tissues were assumed to be independent of age. With this assumption, the risk curve of Figure 4 can be used for all size occupants since equal rates of sternal deflection produce equal stress levels in the heart and lungs (13, 14).

An estimate of the risk curve for AIS ≥ 4 heart/lung injury can be obtained from the data given in Table A3. Because of the limited amount of AIS ≥ 4 data, the Mertz/Weber Method is used only to estimate the rate of sternal deflection corresponding to a 50 percent risk of AIS ≥ 4 injury. This value is 10.2 m/s. The corresponding standard deviation is assumed equal to that of the AIS ≥ 3 risk curve. The resulting AIS ≥ 4 risk curve is shown on Figure 4.

STERNAL COMPRESSION - Neathery et al (10) have summarized the thoracic impact data of various investigators who have subjected cadavers to distributed chest impacts. The data were presented in terms of ratios of peak chest compression divided by chest depth and the corresponding thoracic injury severities. These data were reviewed and the AIS ratings were updated. In addition, two cadavers which were impacted twice were deleted from the data set. The revised data are given in Table A4 of the Appendix.

The chest deflections of the mid-size adult male were obtained by multiplying the P/D values by 229 mm which is the chest depth of the mid-size adult male. To account for the effect of compression of the flesh covering the sternum, the chest compressions were reduced by 13 mm to get estimates of the sternal deflections which are also given in Table A4. These values of sternal deflections and the associated injury severities were analyzed by the Mertz/Weber Method to get injury risk curves shown on Figure A9 for AIS ≥ 3 and 4 thoracic injury for the mid-size adult male. The following is a discussion of how these risk curves were extended to other size adults and children.

AIS ≥ 3 INJURY RISK CURVE - Rib fractures are the predominant injury in the AIS ≥ 3 data set. Since the bending modulus of bone varies with age, it will affect the amount of sternal deflection required to produce rib fracture. Again, because of a lack of age-dependent, dynamic loading failure data, an equal failure stress level was assumed, or

$$\lambda_\sigma = \lambda_E \lambda_\varepsilon = 1 \qquad (17)$$

where λ_σ is the ratio of failure stresses, λ_E is the ratio of bending moduli, and λ_ε is the ratio of bone strains. Now bone strain, ε, can be defined in terms of the sternal deflection, δ, and the thoracic depth, D, or,

$$\varepsilon = \delta / D \qquad (18)$$

Using Equations 17 and 18, the relationship between sternal deflections that produce the same rib stress is,

$$\delta_i = \lambda_E^{-1} \lambda_x \delta_M \qquad (19)$$

where

$$\lambda_x = D_i / D_M \qquad (20)$$

$$\lambda_E = E_i / E_M \qquad (21)$$

Equations 19, 20 and 21 provide the necessary relationships to calculate injury risk curves for AIS ≥ 3 rib fractures for any size occupant using mid-size adult male data given in Table A4 and knowledge of the elastic bending moduli of the ribs.

For rib fractures, we have chosen to normalize the sternal deflection by the sternal deflection, δ_c, corresponding to a 5 percent risk of AIS ≥ 3 injury. From Figure A9, δ_c = 47.7 mm for the mid-size adult male. The δ_c for any size occupant can be calculated from Equation 19, or,

$$\delta_c = \lambda_E^{-1} \lambda_x \, 47.7 \text{ mm} \qquad (22)$$

where λ_E and λ_x are given in Table A5 for various sizes and ages of occupants.

Figure 5 gives the injury risk curve for AIS ≥ 3 thoracic injury based on the normalized sternal deflection for any size occupant. This curve was developed by dividing the sternal deflections for the mid-size adult male given in Table A4 by 47.7 mm and then analyzing the normalized values and corresponding injury severity values using the Mertz/Weber Method. The legend gives the sternal deflections for 5 percent risk of AIS ≥ 3 thoracic injury for the various size dummies. Note that no values are listed for the CRABI and Hybrid III child dummies because rib fracture, which is the predominant AIS ≥ 3 injury in the data set, is unlikely to occur with children of these ages due to the low elastic bending moduli of their ribs.

AIS ≥ 4 INJURY RISK CURVE - Heart and/or aortic rupture are the predominant AIS ≥ 4 injury. These types of injury are dependent on the ratio of sternal deflection to chest depth being equal between different size subjects. The relationship between sternal deflection that produce equal stress in the heart is,

$$\delta_i = \lambda_x \delta_M \qquad (23)$$

where λ_x is the ratio of chest depth of the two subjects. Again, the sternal deflection will be normalized by the deflection corresponding to a 5 percent risk of AIS ≥ 4 heart injury. From Figure A9, this value is 64.3 mm for the mid-injury. From Figure A9, this value is 64.3 mm for the mid-size adult male. For any size occupant, the corresponding sternal deflection, δ_c, can be computed from Equation 23, or,

$$\delta_c = \lambda_x \; 64.3 \text{ mm} \qquad (24)$$

Figure 5 gives the injury risk curve for AIS ≥ 4 heart injury based on normalized sternal deflection for any size person. This curve was obtained by dividing the sternal deflections of the mid-size adult male given in Table A4 by 64.3 mm. These normalized values and the corresponding AIS ≥4 values were analyzed by the Mertz/Weber Method to obtain the curve of Figure 5. The legend gives the sternal deflections for 5 percent risk of AIS ≥4 thoracic injury for various dummy sizes. Note that even the 6-month, 12-month and 18-month old children have a risk of experiencing an AIS ≥4 heart rupture due to crushing of the chest.

ABDOMINAL INJURY RISK CURVES

RATE OF ABDOMINAL COMPRESSION - Table A3 gives the data of Mertz et al (8) and Prasad and Daniel (9) for the injury severities experienced by the abdominal organs of the animals and the corresponding maximum rates of abdominal compression measured with the 3-year old child dummy. These data were analyzed with the Mertz/Weber Method to give injury risk curves for AIS ≥3 and AIS ≥ 4 abdominal injury as function of the maximum rate of abdominal compression (Figure 6). For the AIS ≥ 4 injury, the 50 percent value was obtained by the Mertz/Weber Method, but the standard deviation of the AIS ≥3 curve was used. Note that there is very little difference between the risk curves. Again, these risk curves can be used for all size occupants since equal rates of abdominal compression will produce equal stresses in the abdominal organs.

EFFICACY OF INJURY RISK CURVES

The efficacies of the various injury risk curves are the best when used to assess risks for subjects of the same age and size as that of the original test subjects. The normalization for size and material strength consideration is based on the laws of classical structural mechanics. The size scale factors have excellent efficacy since they are based on average dimensions taken from anthropometry studies. The strength scale factors lack rigorous supporting data since tissue failure stress data based on variations of age and dynamic loading rate were not found in the technical literature. In lieu of such data, it was assumed that equal stress would produce equal injury severity, independent of age. This assumption allows for variation of the elastic modulus with age and consequently variations in the strain level at failure as a function of age. For materials with time-dependent properties, this is a necessary requirement.

For the neck, the load it can carry prior to injury will be dependent not only on the failure stress level of the ligament, but more importantly, the degree of muscle tensing that has occurred prior to and during loading. It is the neck muscles that protect the neck ligaments from being overloaded. To assess the potential for neck injury based on measured internal reactions between the head and the neck, the degree of muscle tone must be specified in order to determine how the internal neck load is distributed among the muscle groups and ligaments. The animals whose data were used to develop the neck injury risk curves were anesthetized. They had some passive muscle reaction which was well below maximum active muscle tension. Upper bounds of neck injury risk curves corresponding to maximum active muscle tension can be obtained by adding such levels to the critical values listed in the legends of each risk curve. Based on analysis of human volunteer tests, Mertz et al (19, 20) noted that statically the average size man could resist 1100 N (255 lb) in pure tension and 23.7 Nm (17.5 ft-lb) moment when resisting neck extension. Using Equations 3 and 6 and the neck circumference data given in Table 1, corresponding static neck muscle strength values were calculated for the other sizes of people and are given in Table 2. These static strength values were added to the critical values for neck injury risk curves (Figs. 1 - 3) to give critical values for maximum muscle tensing which are given in Table 2. Thus, neck injury risks can be calculated with minimal or maximal neck tension by using the critical values shown in the legends of Figures 1 - 3, or by using instead the values given in Table 2, respectively.

To assess the efficacy of the neck injury risk curves for peak tension and for peak extension moment, injury risks associated with the various published Injury Assessment Reference Values (IARV) for the neck (15-17) for minimal and maximal muscle tensing were obtained from the graphs of Figures 1 and 2 and are given in Table 3. Note that if an IARV is not exceeded, then the risk of significant neck injury is judged to be unlikely; i.e., ≤ 1 percent risk for children and ≤ 5 percent risk for adults. Based on the comparisons given in Table 3, there was excellent agreement between the calculated risks, both with and without muscle tone, and the IARVs for neck extension moment for adult and children, and for neck tension of children. For neck tension IARVs for adults, the risks are quite high if muscle tension is minimal, but quite low if muscle tension is maximal. This clearly points out the need to have a consensus on the degree of muscle tone to be assumed when using the risk curves. Perhaps the minimal muscle tension risk curves could be used for children, while 80 percent of the maximum static muscle tension levels could be used for the adult.

In general, it would seem appropriate to prescribe the desired protection level for a given simulation condition and then use the injury risk curves to set the performance limits for various dummy measurements.

SUMMARY

Biomechanical tolerance data for the neck, thorax and abdomen have been normalized for body size and tissue failure properties to give normalized injury risk curves for neck tension, neck extension moment, combined neck tension and extension moment, sternal compression, rate of sternal compression and the rate of abdominal compression for children and adults. The efficacies of the risk curves are best when used to assess risks of dummy data where the dummy represents the size and age of the original test subjects. Of the three neck criteria, neck tension is the preferred criterion since the correlation with the animal injury was the best for this measure. Once the degree of muscle tone and desired level of protection are prescribed for a given collision simulation condition, the injury risk curves can be used to prescribed design limits for the corresponding dummy measurements.

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Table 1 - Neck Circumferences for Various Ages of Children and Sizes of Adults.

Dummy	Circum. (mm)	λ_C	Ref.
CRABI 6	221	0.906	11
CRABI 12	226	0.918	11
CRABI 18	226	0.926	11
H III - 3 Yr.	244	1.000	11
H III - 6 Yr.	264	1.082	11
H III - Sm. Fem.	304	1.246	12
H III - Mid-Male	383	1.570	12
H III - Lg. Male	421	1.725	12

Table 2 - Critical Values for Neck Injury Risk Curves Based on Maximum Static Muscle Strengths.

	Maximum Static Muscle Strengths		Critical Values for Risk Curves Based on Maximum Static Muscle Strengths			
Dummy	Tension (N)	Ext. Mom. (Nm)	F_1 (N)	M_1 (Nm)	F_C (N)	M_C (Nm)
CRABI 6	366	4.6	1246	14.3	1676	19.5
CRABI 12	383	4.9	1303	15.2	1723	20.4
CRABI 18	383	4.9	1303	15.2	1743	20.8
H III - 3 Yr.	446	6.1	1516	19.1	2036	26.1
H III - 6 Yr.	522	7.8	1772	25.6	2382	33.1
H III - Sm. Fem.	693	11.9	2353	37.0	3163	50.6
H III - Mid-Male	1100	23.7	3740	74.0	5020	101.1
H III - Lg. Male	1330	31.5	4520	98.3	6060	134.2

Table 3 - Risks of AIS ≥ 3 Neck Injury Associated with Injury Assessment Reference Values (IARV)

	Neck Tension			Neck Ext. Mom.		
		Risk AIS ≥ 3 (%)			Risk AIS ≥ 3 (%)	
Dummy	IARV (N)	Min. Muscle	Max. Muscle	IARV (Nm)	Min. Muscle	Max. Muscle
CRABI 6	500	< 0.1	< 0.1	5	0.2	< 0.1
CRABI 12	920	1.0	< 0.1	7	0.4	< 0.1
CRABI 18	920	1.0	< 0.1	7	0.4	< 0.1
H III - 3 Yr.	1000	0.2	< 0.1	10	0.5	0.2
H III - 6 Yr.	1300	2.0	< 0.1	13	0.4	0.1
H III - Sm. Fem.	2200	50	0.2	31	2.0	0.5
H III - Mid-Male	3300	30	< 0.1	57	1.4	0.4
H III - Lg. Male	4050	35	< 0.1	78	1.6	0.4

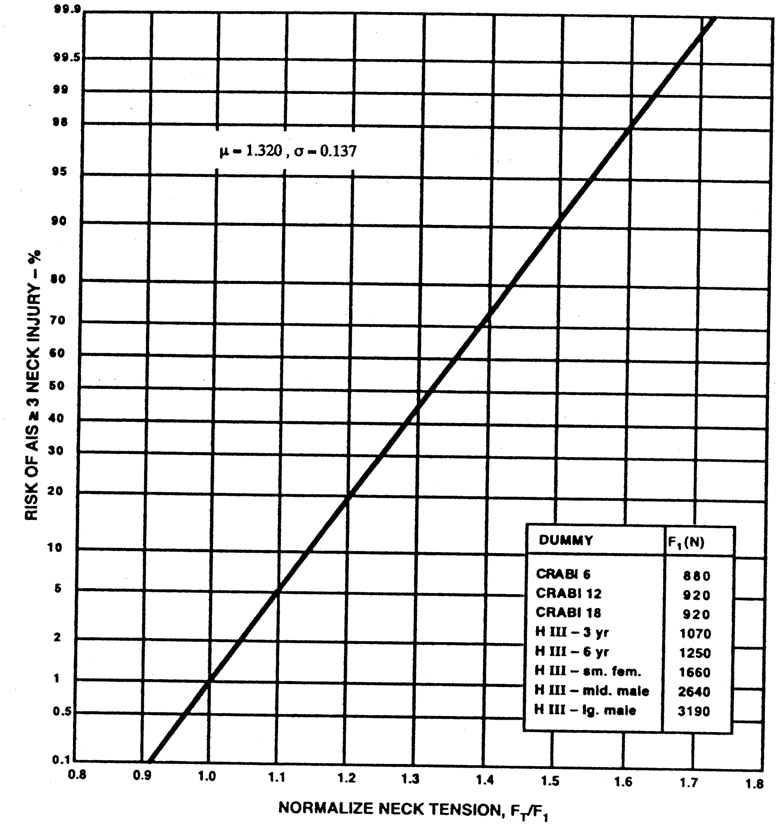


Figure 1 - Risk of AIS ≥ 3 Neck Injury for CRABI and Hybrid III Dummy Families as a Function of Normalized Neck Tension for Tension - Extension Loading of the Neck.

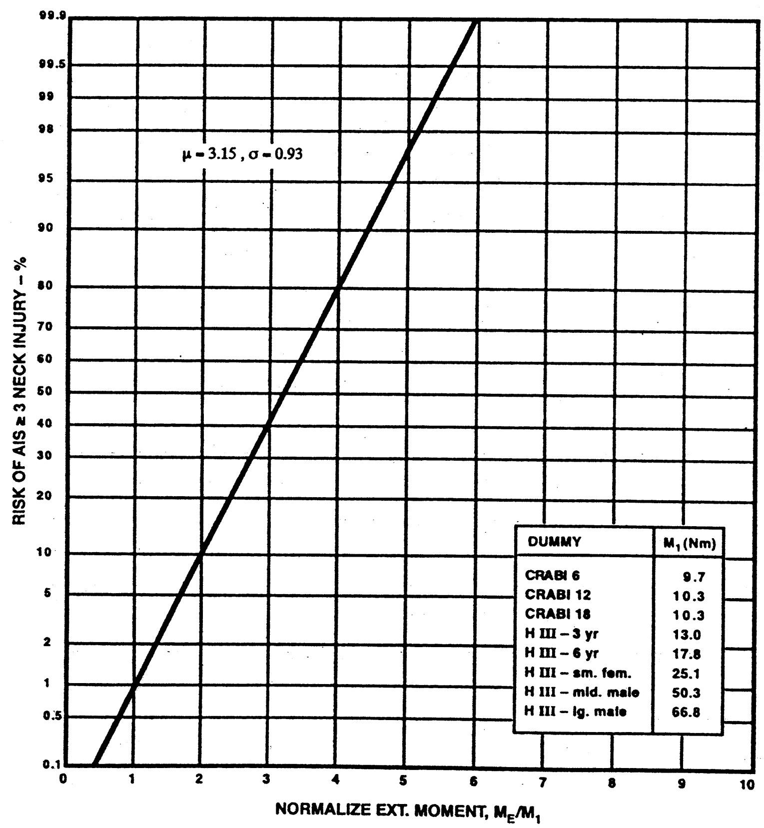


Figure 2 - Risk of AIS ≥ 3 Neck Injury for CRABI and Hybrid III Dummy Families as a Function of Normalized Neck Extension Moment for Tension - Extension Loading of the Neck.

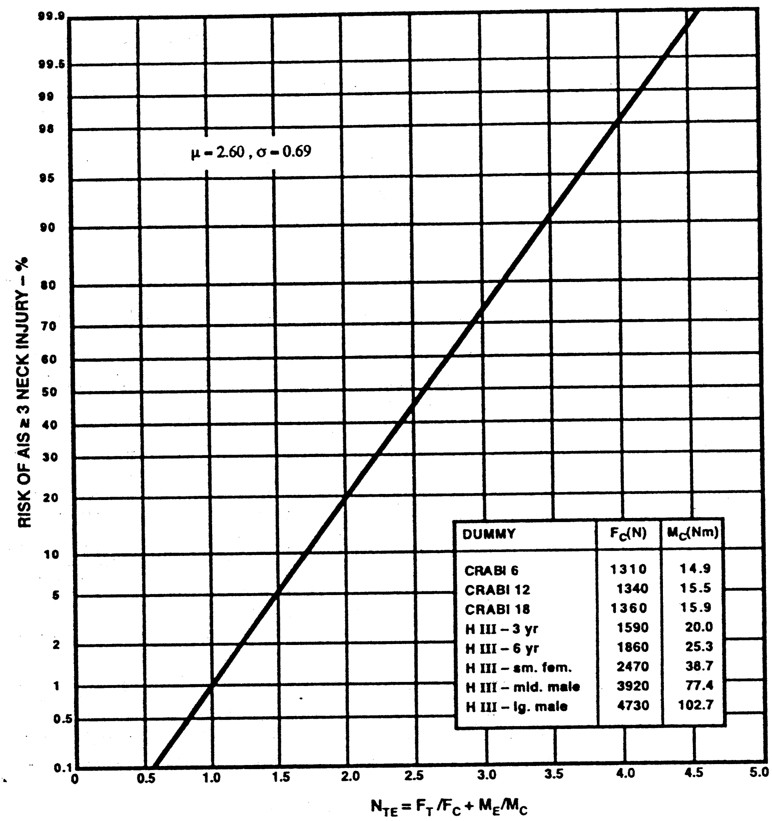


Figure 3 - Risk of AIS ≥ 3 Neck Injury for CRABI and Hybrid III Dummy Families as a Function of Combined Normalized Neck Extension Moment and Tension.

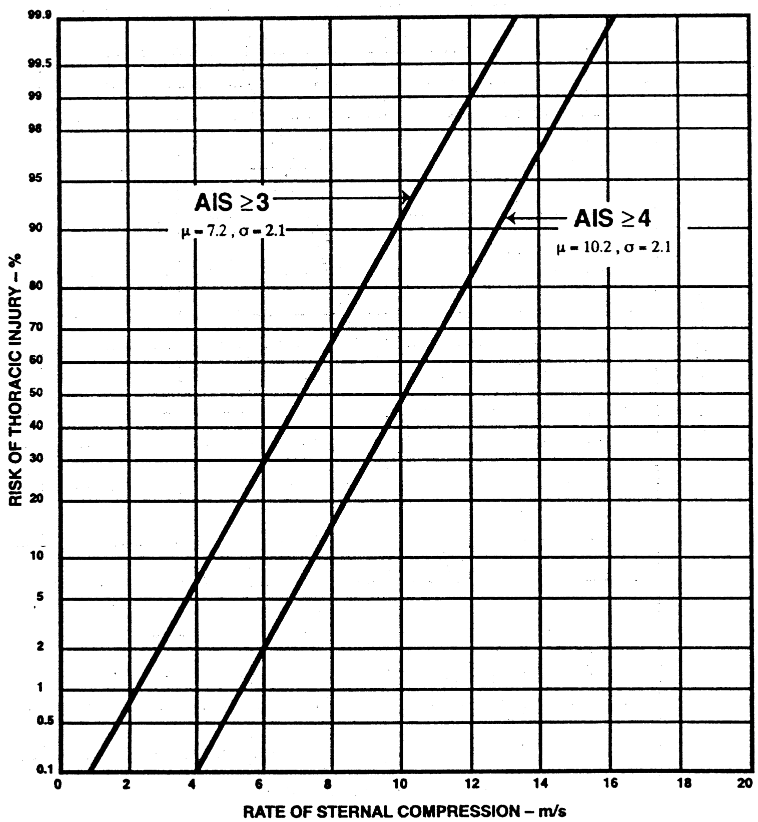
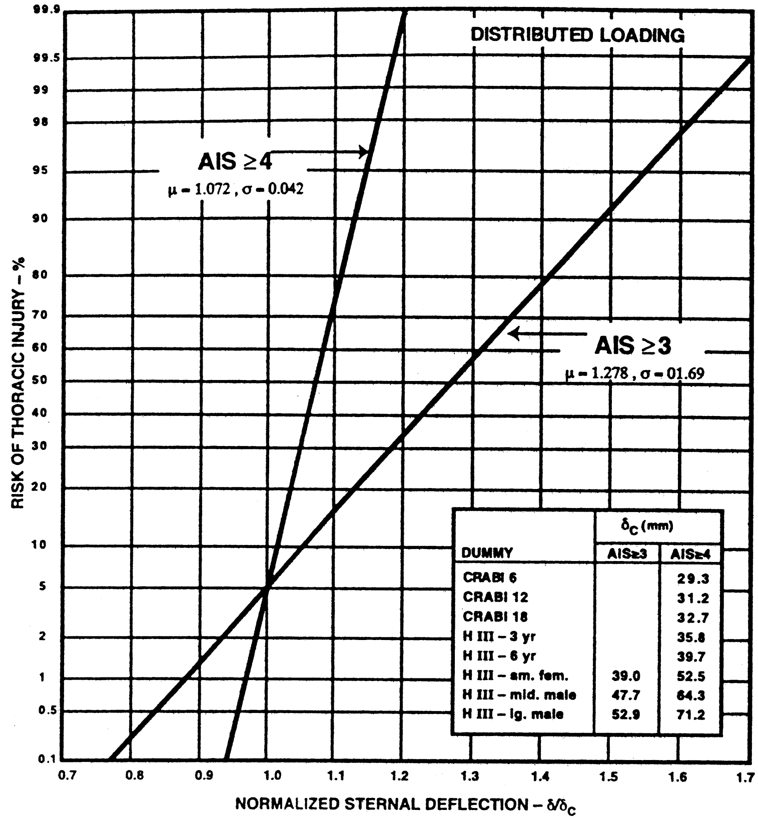


Figure 4 - Risk of AIS ≥ 3 and AIS ≥ 4 Heart/Lung Injury as a Function of Rate of Sternal Compression.



DUMMY	δ_C (mm) AIS≥3	AIS≥4
CRABI 6		29.3
CRABI 12		31.2
CRABI 18		32.7
H III – 3 yr		35.8
H III – 6 yr		39.7
H III – sm. fem.	39.0	52.5
H III – mid. male	47.7	64.3
H III – lg. male	52.9	71.2

Figure 5 - Risk of AIS ≥ 3 and AIS ≥ 4 Thoracic Injuries for Distributed Chest Impacts as a Function of Normalized Sternal Deflection.

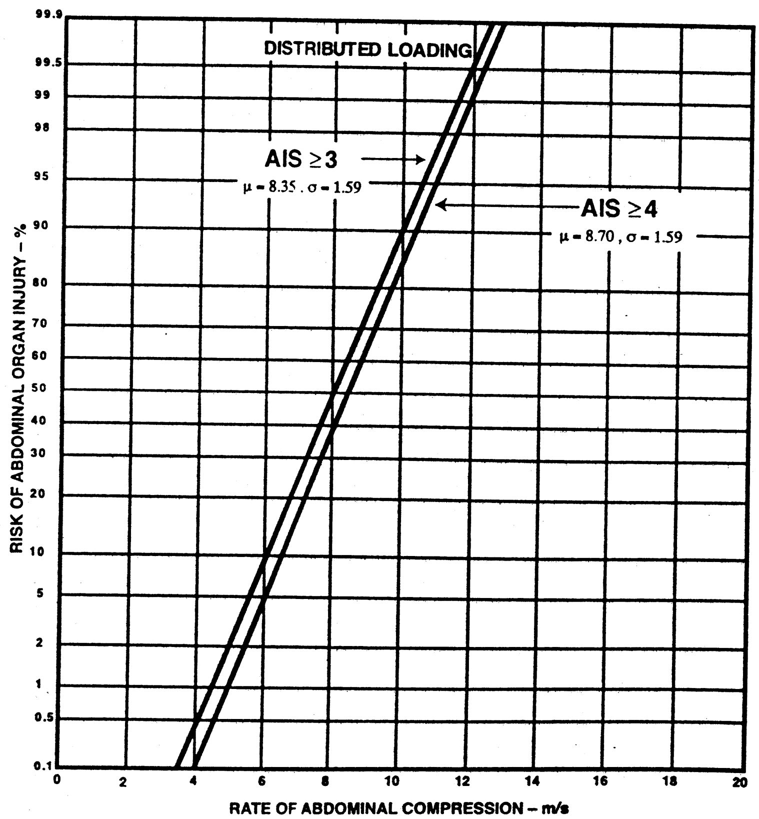


Figure 6 - Risk of AIS ≥ 3 and AIS ≥ 4 Abdominal Injuries as a Function of Rate of Abdominal Compression.

Table A1 - Mertz et al (8) and Prasad & Daniel (9) Data for Peak Neck Tension and Peak Neck Extension Moment with Corresponding Neck Injury Severities.

Pk. Neck Tension				Pk. Neck Extension Moment			
Tension (N)	AIS	Tension (N)	AIS	Ext. Mom. (Nm)	AIS	Ext. Mom. (Nm)	AIS
400	0	1410	0	11.3	0	26.0	0
525	0	1430	6	14.0	0	26.0	0
525	0	1445	3	15.0	4	26.0	0
525	0	1460	0	15.8	0	29.4	6
560	0	1480	4	17.0	0	30.0	0
574	0	1490	4	18.0	1	33.9	6
588	0	1500	3	18.0	3	37.3	4
625	0	1500	4	18.0	0	37.3	0
635	0	1530	3	20.0	4	42.4	4
680	0	1570	0	20.0	3	46.0	5
805	1	1920	4	20.0	4	46.3	4
813	0	1925	4	20.0	0	46.3	6
813	0	1925	6	20.0	0	47.5	6
855	0	2270	4	20.0	0	63.0	3
938	0	2270	6	23.0	0	64.0	4
943	2	2270	6	23.0	0	64.0	6
960	0	2680	3	23.2	0	64.0	6
1050	0	2820	6	24.0	5	66.0	4
1150	0	2960	4	25.0	0	66.0	3
1160	6	3040	5	25.0	0	67.0	2
1250	4	4100	5	25.4	0	80.0	5
1260	5			25.4	0		

Table A2 - Mertz et al (8) and Prasad & Daniel (9) Data for Instantaneous Peak Kernel (K) of Neck Extension Moment and Neck Tension with Corresponding Neck Injury Severity.

Ext. Mom (Nm)	Tension (N)	K (Nm)	AIS	N_{TE}	Ext. Mom. (Nm)	Tension (N)	K (Nm)	AIS	N_{TE}
5.6	1030	18.6	0	0.93	18.0	1530	37.3	3	1.87
14.0	680	22.6	0	1.13	20.0	1445	38.2	3	1.91
0	1925	24.3	4	1.22	20.0	1490	38.8	4	1.94
18.0	574	25.2	0	1.26	15.0	1920	39.2	4	1.96
7.9	1460	26.3	0	1.32	30.0	938	41.8	0	2.09
20.0	588	27.4	0	1.37	22.6	1660	43.5	0	2.18
15.8	960	27.9	0	1.40	46.3	0	46.3	6	2.32
20.0	635	28.0	0	1.40	37.3	1164	52.0	4	2.60
18.0	805	28.1	1	1.41	37.8	1254	53.6	0	2.68
23.0	625	30.9	0	1.55	47.5	760	57.1	6	2.86
26.0	525	32.6	0	1.63	46.0	1260	61.9	5	3.10
26.0	525	32.6	0	1.63	24.0	3040	62.3	5	3.12
26.0	525	32.6	0	1.63	67.0	943	78.9	2	3.95
29.4	313	33.3	6	1.67	42.4	2960	79.7	4	3.99
26.4	560	33.5	0	1.68	66.0	1500	84.9	3	4.25
23.0	855	33.8	0	1.69	66.0	1500	84.9	4	4.25
33.9	0	33.9	6	1.70	64.0	2270	92.6	4	4.63
20.0	1150	34.5	0	1.73	64.0	2270	92.6	6	4.63
25.0	813	35.2	0	1.76	64.0	2270	92.6	6	4.63
25.0	813	35.2	0	1.76	63.0	2680	96.8	3	4.84
20.0	1250	35.8	4	1.79	80.0	4100	131.7	5	6.59

Note: $K = M_E + 0.0126\, F_T$ (See Equation 11)
$N_{TE} = K/20.0 = M_E / M_C + F_T / F_C$ (See Equations 14, 15 & 16)

Table A3 - Rates of Sternal and Abdominal Deflections and Corresponding Thoracic and Abdominal Injury Severities of Mertz et al (8) and Prasad & Daniel (9).

Sternal Deflection Rate (m/s)				Abdominal Deflection Rate (m/s)			
$\dot{\delta}$	AIS	$\dot{\delta}$	AIS	$\dot{\delta}$	AIS	$\dot{\delta}$	AIS
0.6	2	5.6	1	0.6	2	4.0	2
1.1	2	5.6	2	0.8	2	4.6	0
1.4	1	6.4	2	1.1	2	4.7	2
1.4	2	6.4	3	1.1	0	4.9	2
1.7	2	6.7	1	1.1	0	5.0	1
1.9	2	7.8	4	1.2	2	5.6	3
2.2	1	8.3	4	1.4	1	5.6	2
2.2	1	8.5	3	1.4	2	5.8	0
2.5	2	8.6	3	1.5	0	5.8	0
3.0	3	8.6	4	2.2	0	5.8	4
3.3	3	8.6	5	2.2	0	6.1	3
3.6	1	9.7	2	2.5	0	6.1	5
3.6	1	9.7	2	2.5	2	6.1	6
3.9	1	10.7	3	2.5	0	6.7	4
3.9	2	10.7	2	2.8	0	7.6	5
4.7	2	11.3	3	3.1	1	7.8	4
4.7	1	11.3	3	3.3	0	8.2	3
4.9	2	11.3	2	3.3	0	8.5	3
5.0	3	11.6	4	3.3	2	8.5	0
5.3	1	11.9	3	3.4	0	9.8	3
5.3	1	12.5	3	3.4	0	10.7	3
5.3	0	12.8	4	3.6	0	11.6	2
				3.9	2		

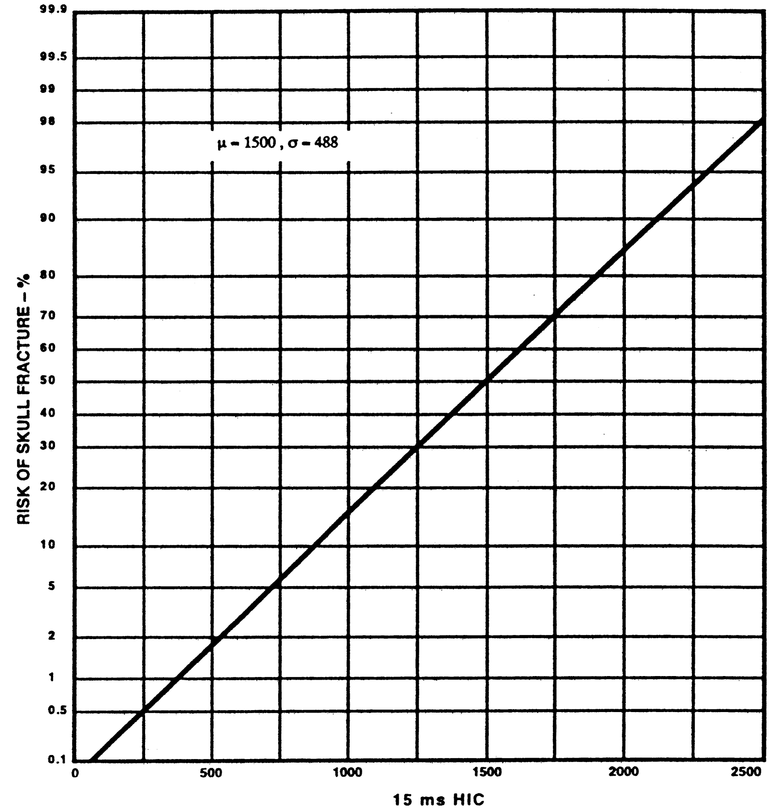


Figure A1 - Risk of Skull Fracture as a Function of 15ms HIC.

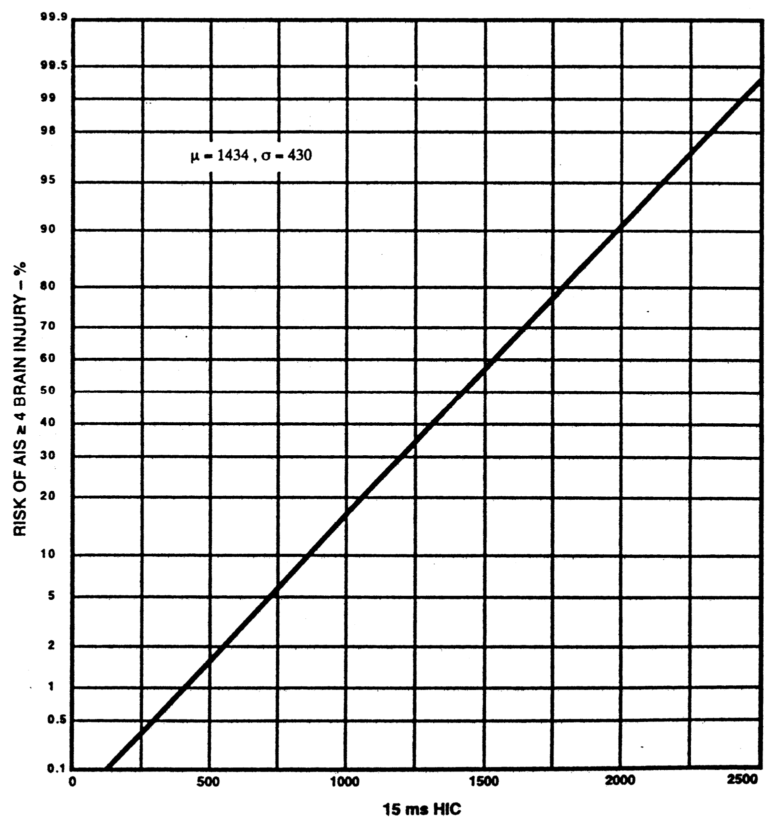


Figure A2 - Risk of AIS ≥ 4 Brain Injury as a Function of 15ms HIC.

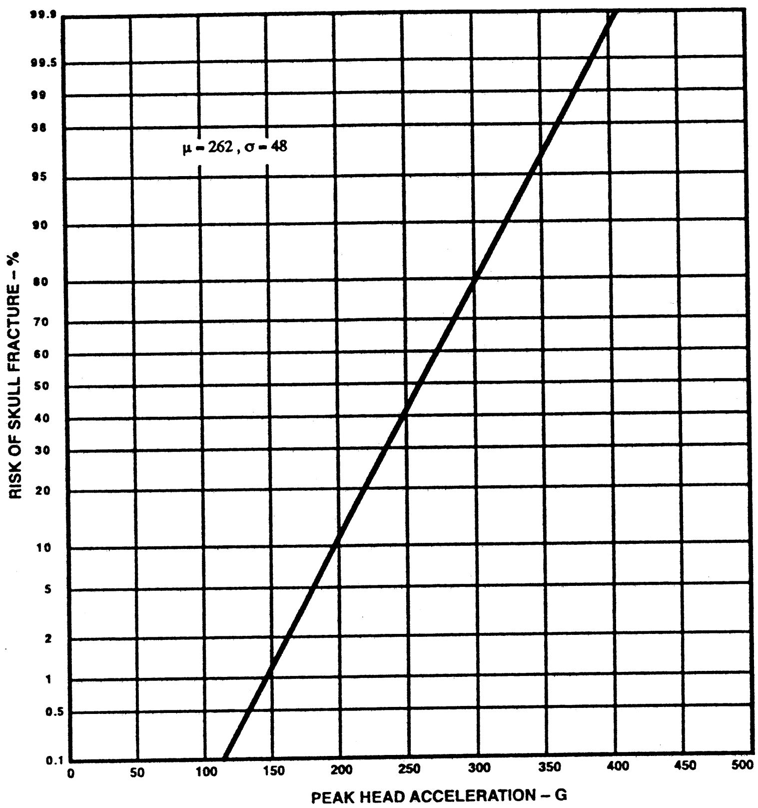


Figure A3 - Risk of Skull Fracture as a Function of Peak Resultant Acceleration of the Center of Gravity of the Head.

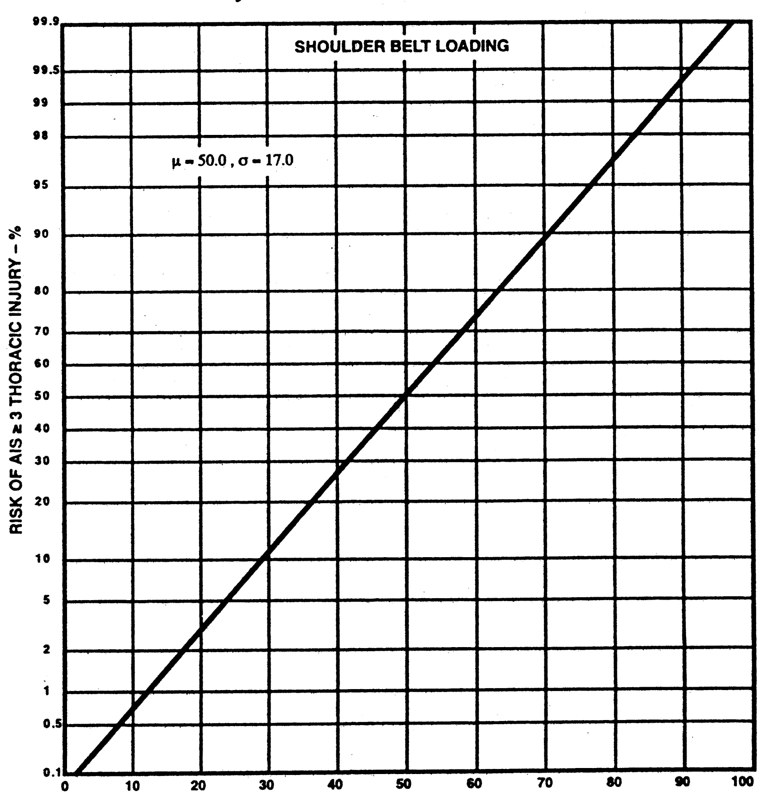


Figure A4 - Risk of AIS ≥ 3 Thoracic Injury Due to Shoulder Belt Loading as a Function of Hybrid III Sternal Deflection.

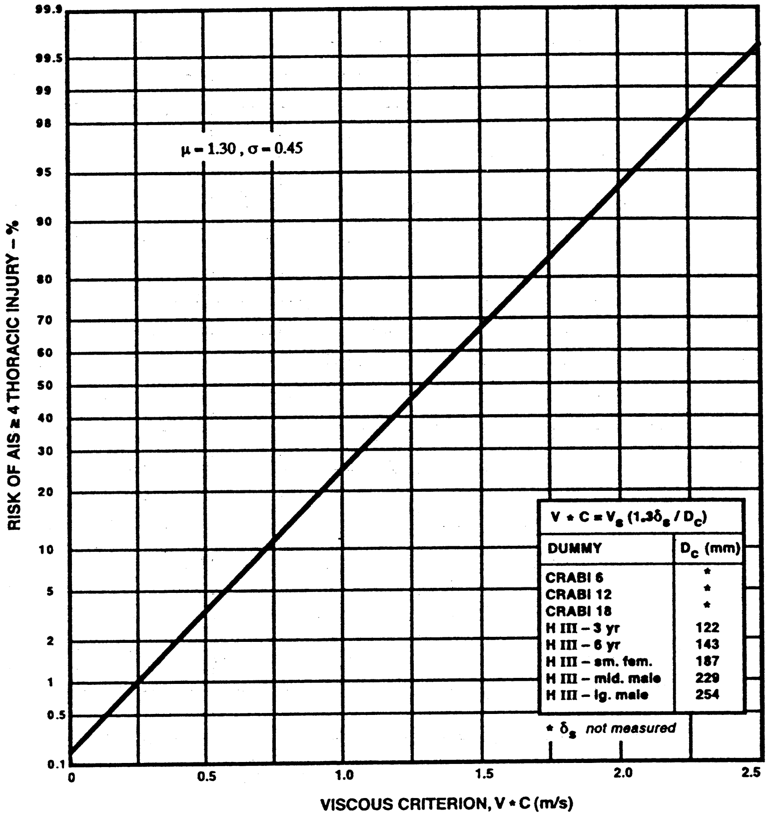


Figure A5 - Risk of AIS ≥ 4 Thoracic Injury as a Function of the Viscous Criterion, V*C.

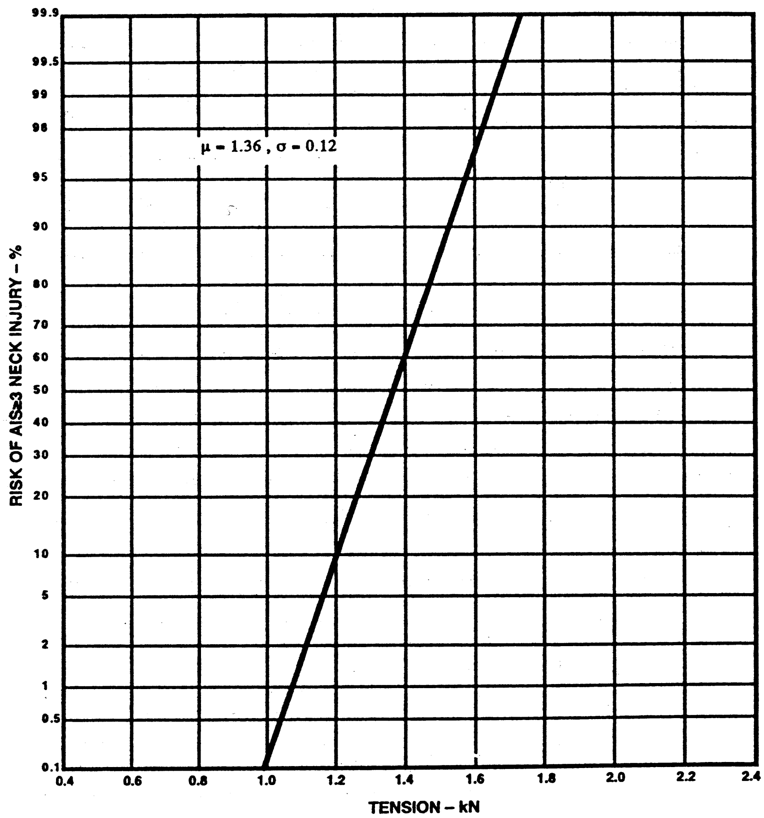


Figure A6 - Risk of AIS ≥ 3 Neck Injury for 3 Year Old Child as a Function of Neck Tension for Tension - Extension Loading of the Neck.

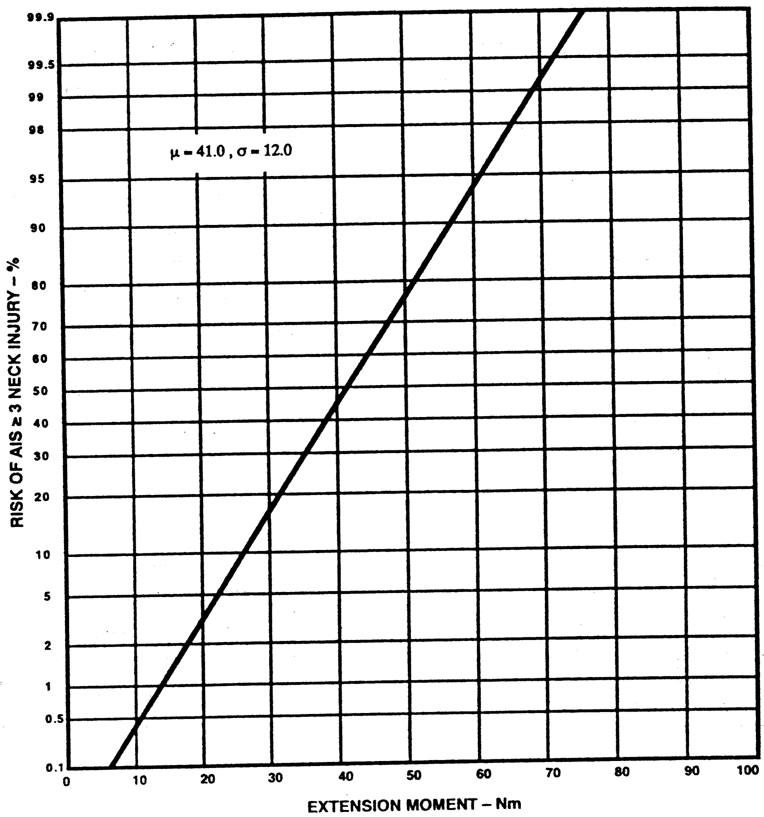


Figure A7 - Risk of AIS ≥ 3 Neck Injury for 3 Year Old Child as a Function of Neck Extension Moment for Extension - Tension Loading of the Neck.

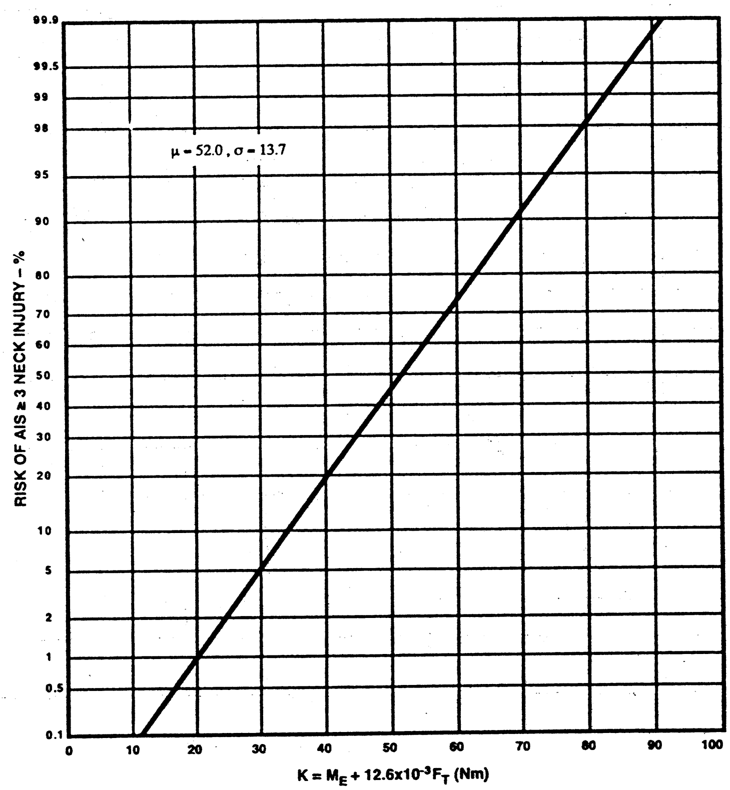


Figure A8 - Risk of AIS ≥ 3 Neck Injury for 3 Year Old Child as a Function of Combined Neck Extension Moment and Neck Tension for Extension - Tension Neck Loading.

Table A4 - Normalized Chest Compression (P/D), Thoracic Injury Severity Ratings, and Sternal Deflection (δ_M) of Mid-Size Adult Male Based on Cadaver Data Summarized by Neathery et al (10).

P/D	AIS	δ_M (mm)	P/D	AIS	δ_M (mm)
0.185	0	29	0.371	3	72
0.194	0	31	0.375	2	73
0.257	2	46	0.393	4	77
0.269	3	49	0.395	4	77
0.310	1	58	0.418	4	83
0.310	2	58	0.425	5	84
0.315	3	59	0.428	5	85
0.321	1	61	0.435	5	87
0.346	4	66	0.444	5	89
0.350	1	67	0.447	4	89
0.363	3	70	0.459	5	92

Note: $\delta_M = 229\,(P/D) - 13$

Table A5 - Chest Depth and Rib Bending Modulus Scale Factors for Various Sizes and Ages of Occupants Based on the Data of Mertz and Irwin (14).

Subject	λ_X	λ_E
6-Month Old	0.455	0.282
12-Month Old	0.485	0.322
18-Month Old	0.508	0.362
3-Year Old	0.556	0.473
6-Year Old	0.618	0.667
Sm. Adult Fem.	0.817	1.000
Mid-Size Male	1.000	1.000
Lg. Adult Male	1.108	1.00

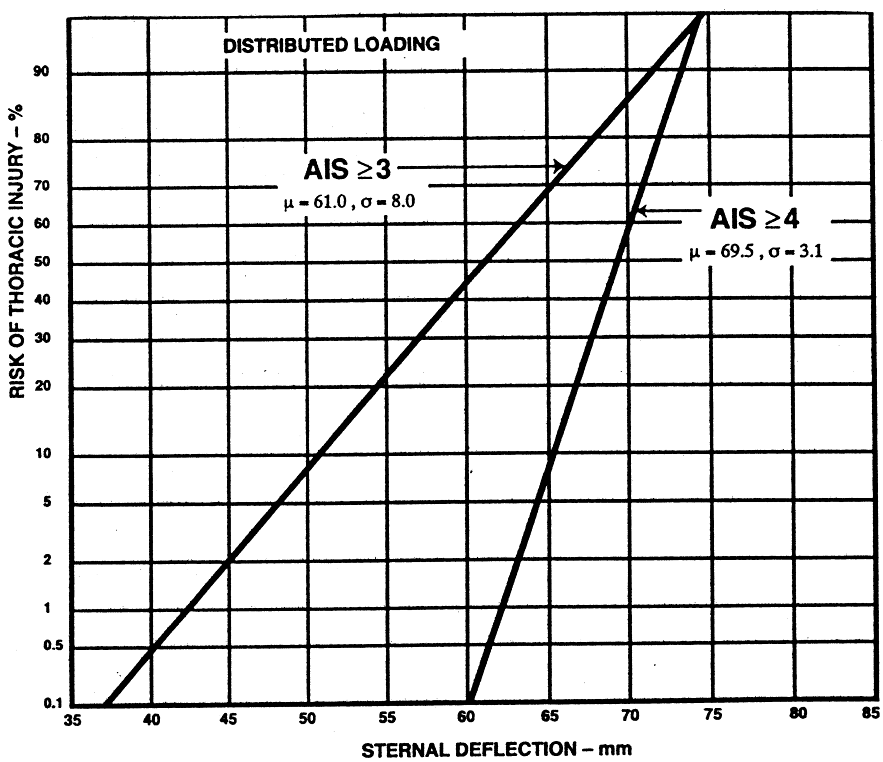


Figure A9 - Risk of AIS ≥ 3 and AIS ≥ 4 Thoracic Injuries for Distributed Chest Loading as a Function of Sternal Deflection of a Mid-Size Adult Male.