SYNTHESIS OF DATA TOWARDS NECK PROTECTION CRITERIA FOR CHILDREN

by

Ingrid Planath, Camilla Rygaard and Stefan Nilsson
Automotive Safety Center
Volvo Car Corporation
S-405 08 Göteborg
Sweden

ABSTRACT

Neck injuries to restrained children in frontal impacts have been reported. Thus, a need for protection criteria for the child neck has emerged.

The paper describes new research on the subject as well as a study on available data:

* Accident reconstruction:
  Reconstruction of two accidents with children in forward facing child seats using TNO dummies were reported by Lowne et al. at ESV 1987 (1). These tests were repeated with a 3-year old US child dummy equipped with an instrumented neck.
* Rearward facing child seat test data:
  Results from the test series above were compared with results from sled tests with rearward facing child seats. No serious neck injuries have been recorded in the Volvo accident files for the CRS in the tested rearward facing configuration.
* Other research:
  Scaling of adult neck protection criteria as well as results from out-of-position work performed by other researchers were also used as input.

Synthesis from this set of data is performed for neck tensile axial force, shear force and forward bending moment respectively. Levels from the input sources above are compared and the data set is analysed with respect to the relation with neck and, where possible, head injuries. Using the synthesis as a basis, the following values are suggested as guidelines for neck protection criteria for child neck injury assessment:

Tensile axial force:	1000 N
Shear force:	300 N
Forward bending moment:	30 Nm

CHILD RESTRAINT SYSTEMS (CRS) provide a high level of protection for the youngest car occupants. Countries that have introduced mandatory CRS use, have seen the injury rate among children in car collisions drop significantly (2,3).

In Europe, children in the two lowest mass groups according to ECE R44 (4), approximately corresponding to children aged 0-4 years, can be protected by either rearward or forward facing CRS. The CRS's are certified by national and/or ECE regulations.

Sweden introduced a law in 1988, requiring all children up to 4 years of age to be restrained by a forward or rearward facing system when travelling in a car.

In an accident study presented by Carlsson et al. (5), it is shown that among 97 children restrained by a rearward facing child seat in an accident, only ten sustained any injury at all. For the injured children, in one case the AIS level was 2-3; in the remaining nine cases it was AIS 1. The effectiveness of the rearward facing child seat can be calculated by a comparison with the injury rates for the unrestrained. For children in the age group 1-4 years, the effectiveness in reducing AIS 2-6 injuries is about 90% for the rearward facing CRS.

Lowne et al. comment on the low injury rates for restrained children (1). In a sample from the UK, in which forward facing child restraints are studied, two to three fatalities per year among children up to five years of age were reported.

Among the rare number of accidents with serious or fatal injuries to small children in CRS, neck injuries in combination with forward facing systems have gained special attention during the last few years.

When travelling forward facing, a frontal collision can lead to significant loads being imposed onto the neck. For a small child, the ratio of the masses for the head and the body is approximately 1:2. The corresponding figure for an adult is close to 1:6. Consequently, the child neck will be subjected to a higher degree of loading, e.g. when a forward facing occupant is subjected to a frontal collision. Other factors making young children more susceptible to high cervical loading are e.g. the not fully developed cervical musculature and ligaments, allowing a greater degree of spinal mobility (6).

This paper presents a synthesis of different sets of data on child neck injuries and neck loads. The aim has been to gain knowledge on what could be possible guidelines for neck injury assessment in crash tests. The following items, which are described in detail below, were used as input to the synthesis:

A) Reconstruction of accidents with forward facing CRS
B) Sled tests with rearward facing CRS
C) Scaling of adult dummy data
D) Other research

A) RECONSTRUCTION OF ACCIDENTS WITH FORWARD FACING CRS

In 1987, Lowne, Gloyns and Roy presented a paper on fatal injuries to restrained children in car accidents (1).

To gain knowledge on the amount of load imposed on a child neck during a collision, two of the cases described by Lowne et al. were selected for reconstruction. The children, who had been restrained by forward facing systems, had sustained a fatal head and neck injury, respectively, although no signs of head impact could be found.

Case 1 (reference 86/x in (1)) was a 19 month old child sustaining a complete separation of C1 and C2 and a macerated spinal cord. The child seat was a two point frame seat placed in the rear seat of a car involved in a frontal crash. The CRS was equipped with a four point harness. The velocity change for the crash was about 40 km/h.

In case 2 (reference 82/3 in (1)), a 15 month old baby was travelling in a four point child seat in the car rear seat. In the severe frontal car-to-car crash at approximately 55 km/h, the child sustained brain contusion without skull fracture.

Both restraints were approved by British Standard and/or ECE R44. The CRS installation in the car had in both cases been accomplished by straps between the CRS and the car, according to user instructions. By using both upper and lower pair of straps, the seat in 82/3 was anchored to the car in four points. In 86/x one pair of straps, attached in the lower part of the CRS, was used.

Reconstruction Test Conditions

Reconstructions of the two selected cases with a dummy without neck measurements were already reported in (1). Lowne et al. worked out CRS positioning, strap and belt adjustments to be as close to the assumed pre-accident situation as possible. This data was used when preparing our reconstruction tests.

For both of the selected cases, three sled tests were performed with the child seat positioned forward facing on the standard seat specified in ECE R44.

Comparison of the standard R44 seat and the actual seats involved in the accidents would show differences in geometrical and stiffness characteristics. These were however not judged to be of critical importance in this intial study of injury mechanisms.

The dummy used was a 3-year US dummy (P572C) where the original neck had been replaced by a straight neck intended for a 3-year old airbag dummy (7). The neck instrumentation allows measurement of shear and axial forces as well as bending moment. Directions for the neck measurements are shown in figure 1.

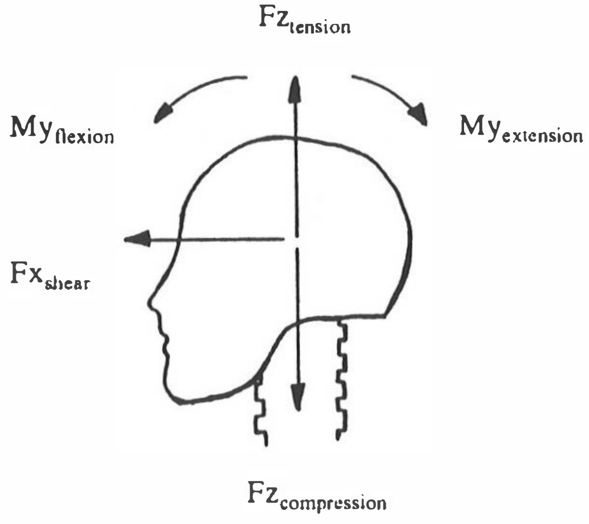


Figure 1: Neck measurement directions

Since the children in the accidents were 15 and 19 months respectively, data on child sizes were studied to evaluate the relevance of using the 3-year old dummy in the tests. Anthropometric data, like sitting height, weight, neck and head circumferences from (8) were looked at.

As expected, the variation between children within one age group can be significant. For the age groups considered, the difference between the average values for children in the age group including the 19 month old and a 50th percentile child in the group of the 3 year old lies within the standard deviation from the averages for 19 months.

For the age group including the 15 month old child, the correlation to the 50% 3-year is not as obvious, as expected. Most measures considered important here are however considered sufficiently close to use the test results as input to the further analysis.

The test velocity was 40 km/h for case 1, while 50 km/h was chosen for case 2. Although the latter speed differed from the assessed real accident condition, this lower speed was chosen to avoid separations of the seat due to the higher mass of the occupant in the test compared to that in the real accident.

Results

As could be expected, the graphs for the axial force (Fz) and the bending moment (My) show that one portion of the measurement is dominating; i.e. tensile force and flexion moment respectively.

In table 1, a summary of these and other measurements considered relevant can be found. The values shown are the averages from three sled tests.

	HIC 36 ms	Cr (g)	Neck measurements Fx_{shear} (kN)	Fz_{tens} (kN)	My_{flex} (Nm)
Case 1 average std.dev.	319 79	50 1.5	.37 .06	1.15 .040	31 1.51
Case 2 average std.dev.	809 58	54 1.0	.28 .06	2.57 .016	33 1.53

Table 1: Summary of reconstruction sled test

Analysis

In the analysis of the test results, the emphasis was put on neck measurements. Within each of the reconstructed cases, the repeatability was considered acceptable.

Neck injury - The fatal neck injury in the accident reconstructed in case 1 consisted of a complete separation between C1 and C2. For the child in case 2, no neck injury was noted. The shear force (Fx_{shear}) is the only neck measurement having a higher maximum for case 1 . The tensile force (Fz_{tens}) is lower, and the bending moment (My_{flex}) is of similar magnitude.

High speed films reveal that a chin-chest contact is possible. Maxima for the head accelerations and Fz_{tens} occur close in time to this contact. The higher impact severity in case 2 is a probable explanation to the higher values in the second test configuration.

Another approach could be that the shearing force has been a critical factor in the production of the neck injury. In that case, Fx_{shear}=370 N would correspond to injury occurrence, while Fx_{shear}=280 N would not.

Head injury - A fatal head injury was sustained by the child in case 2. No head injury is known for case 1. Even if the average HIC for case 2 (875) highly exceeds that in case 1 (340), the absence of evidence of head contacts may make the use of HIC as the only explanation questionable, since this injury criterion initially was intended for cases of impact.

The use of the reconstruction for head injury criterion validation may therefore be limited. Case 2 is however of importance when trying to distinguish what produced a fatal neck injury in one non-contact case and no such injury in the other.

Conclusion Part A:

Values corresponding to a fatal neck injury in the reconstructed accidents:

axial tensile force	Fz_{tens} :	1.15 kN
shear force	Fx_{shear}:	370 N
note:	Fx_{shear}:	280 N in case 2 (no neck injury)
forward bending moment	My_{flex} :	31 Nm

B. SLED TESTS WITH REARWARD FACING CRS

Since the beginning of the seventies, Volvo has offered rearward facing child restraints. The accident experience with this type of child seat is very good; the Volvo Accident Research Team has not registered any severe or fatal neck injury for children sitting in a rearward facing restraint (9).

It was considered useful to compare the accident reconstruction results reported in part A with data from a test series in a configuration where no serious or fatal neck injuries have occurred according to available accident data.

A rearward facing Volvo child seat was placed on the front seat in a Volvo car body. The standard three point seat belt was used to fasten the CRS. The test velocity was 50 km/h. The same dummy as in part A was used.

Results, represented by average values from three tests, are shown in table 2.

Axial force; tension Fz_{tens} compression Fz_{comp}	201 N 404 N
Shear force; $F{+}x_{shear}$ $F{-}x_{shear}$	208 N 70 N
Bending moment; forward My_{flex} rearward My_{ext}	14 Nm 23 Nm

Table 2: Summary of sled tests with a rearward facing Volvo child seat

C. SCALING OF ADULT DUMMY DATA

In 1982, Wolanin et al. presented corridors that had been used when designing a child dummy for out-of-position airbag testing (7). Lack of biomechanical data for children resulted in performance corridors based on scaling of corresponding adult data. For the neck, Wolanin et al. derived corridors for the bending moment by using the relationship

$$M = S \times A \times D \qquad \text{(i)}$$

where

M = bending moment
S = average muscle stress level
A = muscle cross sectional area
D = effective moment arm

and

$$S_{3year} = S_{50\%adult} \qquad \text{(ii)}$$

which for the 3-year old dummy results in

$$M_{3year} = 0.25 \times M_{50\%adult} \qquad \text{(iii)}$$

Similar scaling was not presented for the forces.

Using (iii) with criteria for the 50% Hybrid III-dummy proposed in (12), the values in table 3 are found:

	50% adult	3year (by scaling)
My_{flex}	190 Nm	47 Nm
My_{ext}	57 Nm	14 Nm

Table 3: Bending moment by scaling

D. OTHER RESEARCH

Prasad and Daniel (10) and Mertz and Weber (11), respectively, presented matched tests with a 3 year old airbag dummy and piglets.

Attempts to correlate injuries sustained by the animals with values measured by the dummy in a parallel test were made. Injuries to head and neck were considered in conjunction with neck loads.

A number of geometrical and response characteristics differ between the piglet and the child. However, the cervical vertebral columns of children and piglets can be considered to be of sufficient resemblance in size and development stage (10). The obvious differences in the shape of the head may cause different loads in the neck in some cases. Also, the fore-aft range of motion of the pig head is much less than for a child, which is more critical for bending moments than for axial forces. Although no absolute translation of injuries from animals to humans of similar size should be made, the tests in (10) and (11) give useful information when assessing levels of impact that may contribute to human injuries.

In table 4, the lowest forces for neck injury mentioned in the papers (10) and (11) are summarized together with the highest neck loads that where measured without the animal sustaining any neck injury in a corresponding test. Corresponding data for head injuries can also be found in table 4. Bending moments presented in (10) have also been included in the table, although they represent the rearward bending of the neck.

	Fz_{tens}	AIS	Fx_{shear} (N)	AIS	My_{flex} (Nm)	AIS
Max w/o neck inj. (10)	1660	0	1460	0	37.3	0
Min with neck inj.(10)	1430	6	540	4,6	33.9	6
Max w/o concuss. (10)	1925	0,5	1460	0	46.3	0
Min with concuss. (10)	1050	2	540	5	17.0	2
Max w/o neck inj. (11)	1200	0	-	-	-	-
Min with neck inj.(11)	800	1	-	-	-	-
Max w/o head inj. (11)	1500	0	-	-	-	-
Min with head inj.(11)	500	1	-	-	-	-

Table 4: Neck loads and injury severity for head and neck, from (10) and (11).

A maximum likelihood analysis for head and neck injuries was performed using the data in (10) and (11). The results can be found in the appendix.

The data in (11) was also a part of an analysis performed by Mertz in (12), where neck tensile forces ranging from 1060 N to 1160 N are suggested as injury assessment reference values for the three year old child airbag dummy. According to (12), 1060 N corresponds to a 1% risk of neck injury, while 1125 N and 1160 N are suggested for the 10% and 25% risk levels respectively.

Although the load conditions in the airbag tests presented in (10) and (11) differ from those for forward facing child seats, they are nevertheless considered useful when searching for guidelines for injury assessment values for the child dummy, since they represent a link between observed injuries and dummy measurements.

SYNTHESIS OF AVAILABLE DATA

The data presented under A-D above, is summarized in figures 2-4. The contents are analysed and used for deriving guidelines for injury assessment values for a three year old child as measured by a dummy.

Axial Tension

As can be observed in figure 2, the lowest values of maximum neck tension force have been measured in the tests with the rearwardfacing child seat. The reconstructed case with a fatal neck injury (see part A above) indicates that severe injuries are known above 1100 N.

A maximum-likelihood approach to the out-of-position tests in part D above suggest that the risk for significant head and neck injury occurrence, respectively, at 1000 N is below 1%.

This is in correlation with (12), where 1060 N corresponds to 1% risk. It has to be noted, however, that the 25% risk in (12) occurs at only 100 N higher force (1160 N).

In (10) 1660 N has been recorded without any injury to either the head or the neck.
On the other hand, the lowest tensile forces recorded for neck and head injury occurrence were 1430 N and 1050 N respectively.

(11) presented 1200 N without neck injuries and 1500 N without noticing head injuries.
AIS 1 injuries were recorded for both the head and the neck at 500 N and 800 N respectively.

Based on the findings above, 1000 N is suggested as guideline for the axial tension for avoidance of severe head and neck injuries.

Shear Force

For the shear force, the synthesis of available data gives a somewhat confusing correlation to the injury occurrence. A summary of the different values is shown in figure 3.

While in the rearward facing child seat tests forces up to 300 N have been measured without any known injuries, the reconstruction tests in part A suggest 280 N for the head injury case and 370 N for the fatal neck injury.

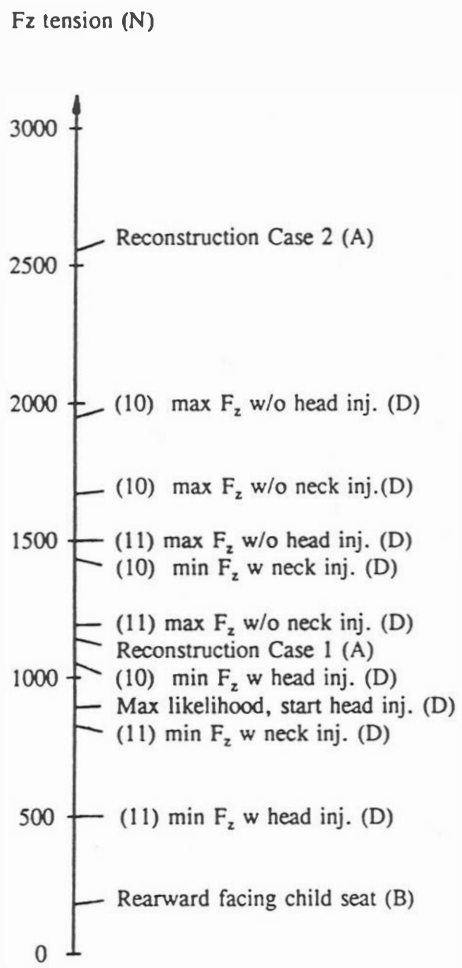


Figure 2: Neck tension force

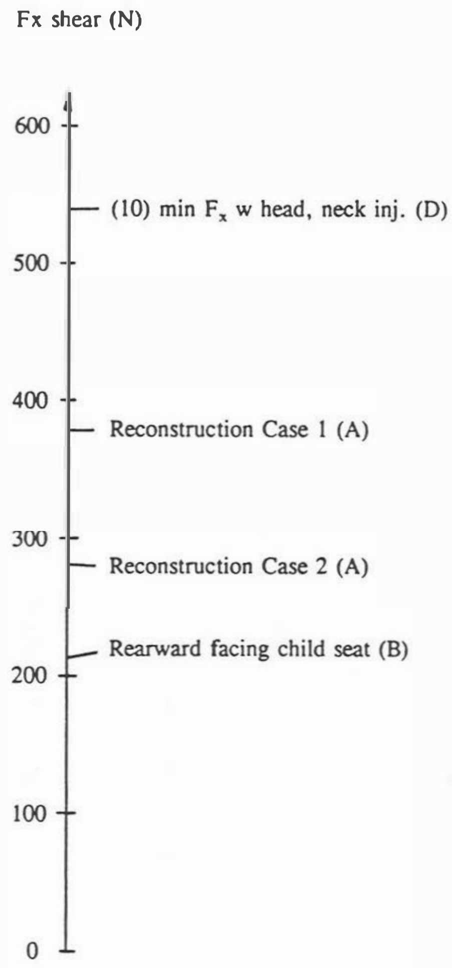


Figure 3: Neck shear force

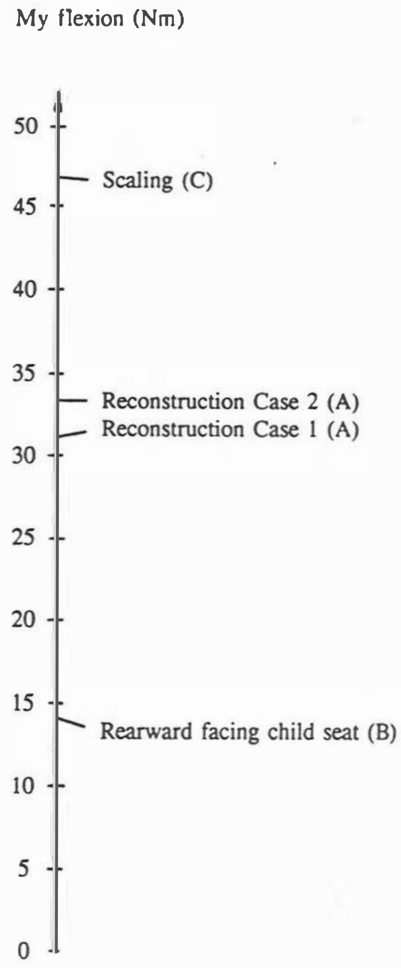


Figure 4: Neck flexion moment

Note: numbers in parenthesis refer to litterature reference, letters in parenthesis refer to chapter in paper.

The lowest neck shear force presented by Prasad and Daniel is 540 N, a value that is measured in the dummy both in a test where the animal sustained a fatal neck and an AIS 5 head injury (10). For 560 N the animal however has neither neck nor head injury.

This latter finding possibly suggests that the neck shear force as measured by the dummy may not be the most relevant mechanism for the injuries occurred.

A conservative proposal for a guideline of neck shear force could be 300 N. If a similar relationship with the proposed adult dummy data in (12) exists as for the axial tensile force, this level might however be somewhat low.

Bending Moment

A summary of the different levels for neck forward bending moment is shown in figure 4.

The flexion average found in the tests with the rearward facing child seat (part B) is 14 Nm. This can thus be considered as an non-injurious level.

Scaling of adult data suggests a bending moment of 47 Nm. The reconstructions however indicate that lower levels of neck flexion could be injurious.

By chosing 30 Nm as a guideline for a protection criteria, both the head and neck injuries in the reconstructed cases would be covered.

Correlation with animal data described in part D has not been used, since it is based on extension data.

SUMMARY AND CONCLUDING REMARKS

In the absence of biomechanical data for the child neck, a synthesis of available data, as the one just described, is one means to get an idea of possible values that could be used as guidelines in child restraint designs.

Reconstructions of real accidents, tests of child restraints with a known real world accident score as well as matched tests with child dummies and animals were used as input to the synthesis. In all cases a three year old P572 dummy with an instrumented neck was used.

The analysis of the data concentrated on axial tensile force and forward bending moment (flexion). Shear force has also been discussed.

The axial tension was the most readily analysed parameter, which might suggest its suitability as neck injury mechanism. For the three year old dummy with an instrumented neck, 1000 N is proposed as a guideline to avoid serious neck injury.

For the flexion, 30 Nm can be used as a guideline, although this parameter was not as straight forward to analyse as was the axial tension.

Available data on shear force is even more sparce than for the other parameters. However, based on the findings in parts A-D above, 300 N probably can be used as a conservative guideline until further research has been presented.

This study doesn't claim to give precise performance criteria for the dummy used, but should merely be regarded as the synthesis of available and new data that it is intended to be.

A general issue of interest when discussing child protection criteria is the limited knowledge on biofidelity and biomechanical data for children. To somewhat compensate for this lack of data, reconstructions can be used as a tool, even though biofidelity of existent child dummies still remains to be proven satisfying. Also, animal tests, as those in (10) and (11), give useful indications of injury, although direct translations of injuries to human beings of suitable size have to be made with careful judgement.

Recently, two new possibilities to gain more knowledge on the child neck biomechanics in automotive safety testing have been presented. The 6 month Child Restraint and Airbag Interaction dummy (CRABI) (13) and TNO's neck transducer for the 9 month old TNO dummy, the P3/4, (14) are new tools having potential to encourage more tests with neck load data being performed. A synthesis of the already available data and any new results obtained would certainly lead to a better understandning of the biomechanics of the neck of the youngest car occcupants and be of significant importance when designing future protection systems for them.

REFERENCES

(1) Lowne, R.; Gloyns, P. and Roy, P: "Fatal Injuries to Restrained Children Aged 0-4 Years in Great Britain 1972-86"; 11th ESV Conference, Washington DC, 1987.

(2) Trinca, G.: "Child Protection in Passenger Cars - The Australian Scene", IN: Proceedings from Volvo/TNO European Workshop on Child Safety in Passenger Cars, 1986.

(3) Petrucelli, E.: "The USA's Experience with Child Passenger Safety" IN: Proceedings from Volvo/TNO European Workshop on Child Safety in Passenger Cars, 1986.

(4) ECE Regulation 44. Uniform provisions concerning the approval of restraining devices for child occupants of power driven vehicles. Economic Commission for Europe, Geneva, 1981.

(5) Carlsson, G.; Holmgren, J. and Norin, H.: "The Child in the Volvo Car", 11th ESV Conference, Washington D.C., 1987.

(6) Fuchs, S., et al.: "Cervical Spine Fractures Sustained by Young Children in Forward-Facing Car Seats", Pediatrics, Vol 84, No 2, August 1989.

(7) Wolanin, M.J. et al.: "Description and Basis of a Three-Year-Old Child Dummy for Evaluating Passenger Inflatable Restraint Concepts", 9th ESV Conference, Kyoto, Japan, 1982.

(8) SAE: "Anthropometry of U.S. Infants and Children."; SAE-394, SAE Congress 1975.

(9) Carlsson, G.; Norin, H. and Ysander, L.: "Rearward facing child seats - the safest car restraint for children?"; 33rd AAAM Conference, Baltimore, MD, 1989.

(10) Prasad, P. and Daniel, R.P.: "A Biomechanical Analysis of Head, Neck, and Torso Injuries to Child Surrogates Due to Sudden Torso Acceleration.", SAE paper no. 841656, 1984.

(11) Mertz, H.J. and Weber, D.A.: "Interpretations of the Impact Responses of a 3-Year-Old Child Dummy Relative to Child Injury Potential.", 9th ESV Conference, Kyoto, Japan, 1982.

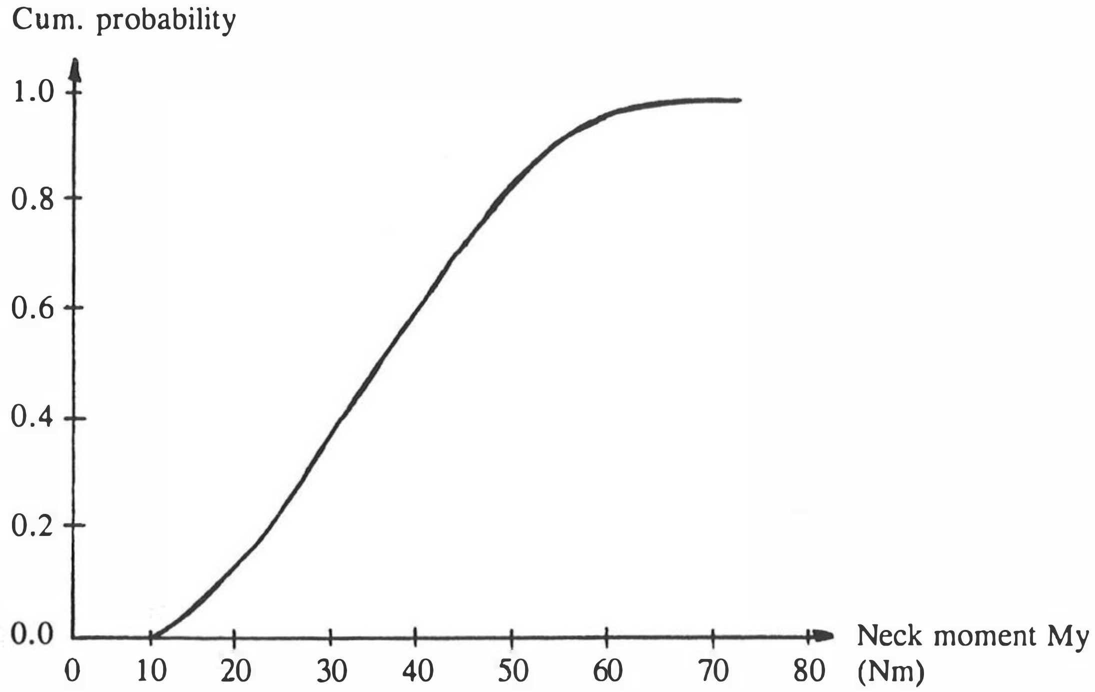
(12) Mertz, H.J.: "Anthropomorphic Test Devices"; ISO/TC22/SC12/WG5: N312; Nov. 1991.

(13) A series of minutes of the SAE Infant Dummy Task Group of the SAE Mechanical Human Simulation Subcommittee; 1991-1992.

(14) Janssen, E.G. et al.:"Cervical Spine Loads Induced in Restrained Child Dummies", SAE paper no 912919, IN: Proceedings 35th STAPP Car Crash Conference, San Diego, CA, 1991.

Appendix : Results from a maximum likelihood analysis based on data from (10) and (11); chapter D.

Neck injury



Head injury