PREDICTION OF NECK INJURIES IN REAR IMPACTS BASED ON ACCIDENT DATA AND SIMULATIONS

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ABSTRACT

Whiplash associated disorders, occurring in car accidents, are an increasing problem worldwide. According to real-life data from police records, the struck car's velocity change (Δv) and the gender of the occupant are two of the most important factors related to AIS 1 neck injuries.

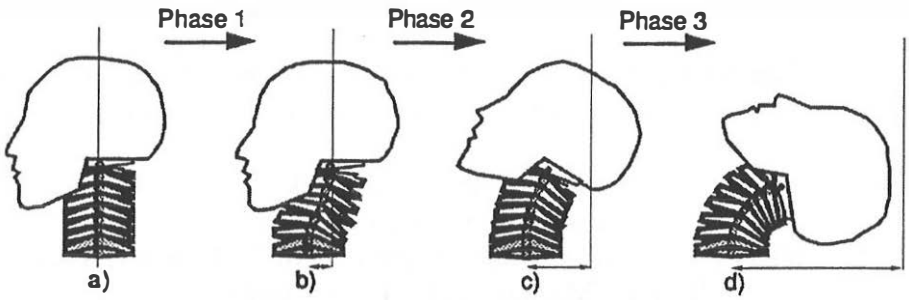
A new rear-impact ranking of cars based on 4 432 police reported accidents is presented. The ranking concerns the relative neck injury risk and compensates for the influences of car weight and gender. Moreover, some important factors influencing the risk of AIS 1 neck injury are proposed. These include the stiffness, damping and yielding characteristics of the seat-back, the muscle response of the occupant, and the Δv of the struck car and acceleration pulse.

Using a mathematical model it is shown that the influence from these factors can be explained by a recently proposed neck injury criterion (NIC). This criterion is based on the neck motion at the passage of full neck retraction. In this study the NIC, based on a number of volunteer tests, is analysed and validated. The consequence of injury outcome of an observed overall seat-back stiffening is also discussed.

In conclusion, for Δv below 20 km/h, real-life data show that the geometry of the head restraint is of minor importance. A seat-back with low yielding limit or soft performance may be preferable. Moreover, the new neck injury criterion seems to be a good predictor of real-life neck injuries.

NECK INJURIES account for almost 50% of all traffic injuries with long term consequences (von Koch et al., 1994). In rear impacts, current head-restraint designs may prevent hyper extension of the neck. Recent research (Mc Connel et al., 1993; Svensson, 1993) supports the argument that hyper extension may not be the cause of neck-related injuries. However, in a rear impact the neck may pass the form of maximal retraction or s-shape, see Figure 1 (Alfredsson et al., 1993; Svensson et al., 1993; Matshusita 1994; Boström et al., 1996; Panjabi, 1996; Kaneoka, 1997). A transition of upper neck (hyper) flexion to upper neck (hyper) extension (McKenzie, 1990) is more likely the cause of injury. The neck load limits suggested by Mertz and Patric (1971) seem only to be relevant to

Figure 1 - Schematic view of four parts of the head-neck motion during a rear-end collision: a) initial posture, b) maximum retraction, c) maximum rearward angular velocity of the head is reached, d) hyper extension. (from Svensson et al., 1993)



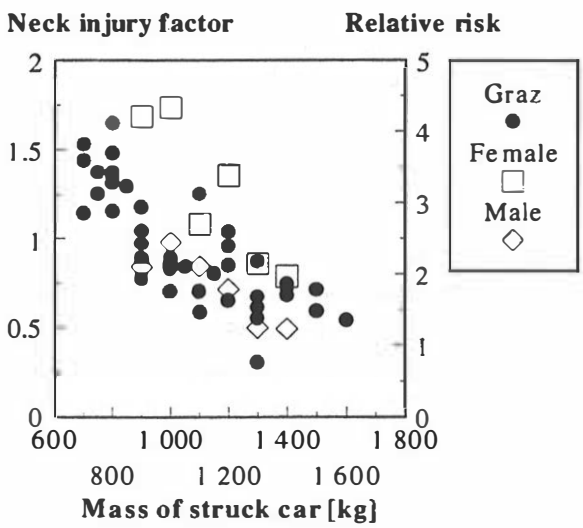
violent crashes that constitute only a small part of the neck injury problem (Kahane, 1982; Romilly, 1989; Olsson et al. 1990). The risk of neck injury in rear-end collisions seems to decrease when the seat-back yields or collapses (Martinez, 1968; Foret-Bruno et al., 1991; Warner et al., 1991, Saczalski et al., 1993, Thomson et al., 1993, Parkin et al. 1995, Song 1996). Moreover, regarding neck injury risk, occupants seated in the rear seat are safer compared to the front seat (Kihlberg, 1969; States et al., 1972; Carlsson et al., 1985; Lövsund et al., 1988; Otremski et al., 1989), and males are statistically at lower risk compared to females (Otremski et al., 1989; Krafft et al., 1996; Maag et al., 1993).

In 1986, Aldman presented a hypothesis regarding hydrodynamic pressure phenomena in the central nervous system. Later, injuries to cervical spinal ganglia were found in experiments with anaesthetized pigs exposed to swift head/neck motions (Örtengren et al., 1996). Boström et al. (1996), presented a new neck injury criterion candidate (NIC), based on pressure effects in the neck during the passage of maximal retraction.

According to Krafft et al. (1996) and Eichberger et al. (1996) the mass ratio between the struck and striking car, and the gender of the occupant seem to be the most important factors influencing the risk of neck injury, see Figure 2.

The aim of the current study was to test the validity of the new neck injury criterion, NIC, by means of analysis of accident data, volunteer test data, and mathematical simulations. It focused on seat-occupant dynamics, and more specifically on lower neck acceleration for different seat characteristics and crash pulses resulting in Δv's below 20 km/h. This restriction was motivated by several previous articles (Svensson 1993; Håland, 1996).

Figure 2 - Neck injury factor for several car models in German traffic (filled black circles) and neck relative risk for the averaged car-weight classes in Swedish traffic for male and female occupants.



MATERIAL AND METHODS

ACCIDENT ANALYSIS - The neck injury risk AIS 1, was calculated from matched two car accidents (Hägg et al., 1992), reported to the National Bureau of Statistics (SCB) in Sweden by the police during 1991-95. The injuries are classified by the policeman

in the field as minor, severe or fatal. Among these reports, 4 432 accidents involving rear impacts, where at least one of the drivers had a minor injury, were identified. The specific injury was not known, but research has shown that almost all injuries classified as minor and occurring in rear-end accidents are AIS 1 neck injuries (v Koch, 1994; Larder, 1985 and Nygren, 1984).

In order to normalise for exposure, the paired comparison method was used in analysing the occupant injury risk and the severity of the accident. The method has been described previously (Hägg et al., 1992; Krafft et al., 1995).

Since the frequency of female drivers varies between different car models and the neck injury risk is twice as high for females compared to males (Krafft et al. 1996), the relative risk was compensated for in terms of gender distribution in different car models.

NIC CALCULATIONS - The new neck injury criterion (NIC) and tolerance level proposed by Boström et al. (1996) has been defined as,

$$NIC = a_{rel} * 0.2 + v_{rel}^2 \qquad \text{Tolerance level} = 15\ m^2/s^2 \qquad (1)$$

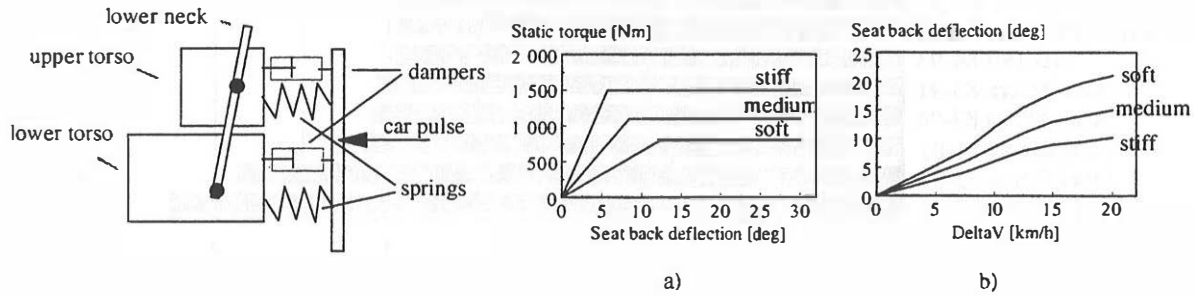
The NIC value is calculated at the neck form passage of maximal retraction (s-shape), that is posture b) in Figure 1, and v_{rel} is the time integral of a_{rel}, set to zero at the time of impact. The acceleration a_{rel} is assumed to be the acceleration difference between T1 and C1. Because there is no dummy with a curved spine and appropriate retraction properties, the C1 acceleration and the passage of maximal retraction have to be assumed. Also, for reasons of simplicity, the NIC value calculated at 50 mm of relative T1-C1 displacement, NIC50, was used as the evaluation measure.

$$NIC50 = \text{NIC at the time when the double integral of } a_{rel} = 50 \text{ mm} \qquad (2)$$

In the case of head to head-restraint contact, a_{rel} was lowered. In this study the resulting impact on NIC50 was not taken into account. This restriction of the neck dynamics is motivated, as indicated in the introduction, by results from this study and by earlier reports on the low efficiency of head restraints (O'Neil et al., 1972; Nygren et al., 1985; Lövsund et al., 1988). Instead, the C1 acceleration was assumed to be 0 g or 2.5 g or 5 g after a certain response time (0, 60 and 100 ms) as a result of neck muscle response.

Mathematical modelling - Mathematical simulations were carried out in the Δv range from 0 to 20 km/h. The influence of six factors was studied: 1) the elastic stiffness, 2) the yield limit, 3) the damping of the seat-back, 4) the muscle strength, 5) the response time of the occupant and 6) the seat acceleration level, see Figure 3.

Figure 3 - A schematic drawing of the mathematical occupant-seat model used in this report. The diagram a) shows the static torque for a defined stiff, medium and soft seat back while diagram b) shows the maximal seat back angle for these seats for different Δv.



The occupant model represents a 50% HIII dummy with respect to size and weight. The model was tuned with emphasis on the lower neck acceleration for a reference seat. The aim was for the seat model to constitute a useful tool for parameter studies rather than to accurately resemble a particular seat.

Analysis of volunteer tests - The chest, head and sled pulses of the 34 volunteer sled tests by Eichberger et al. (1996) were analysed regarding head to head restraint contact as well as NIC values. The NIC values for the tests were calculated from the chest acceleration since there are no accurate lower neck acceleration data yet.

RESULTS

ACCIDENT ANALYSIS - In Figure 4 the relative risk of neck injury in different car models in rear impacts is shown.

Figure 4 - The relative risk of neck injury in the struck car for different car models, in rear impacts. The list has been compensated for gender distribution.

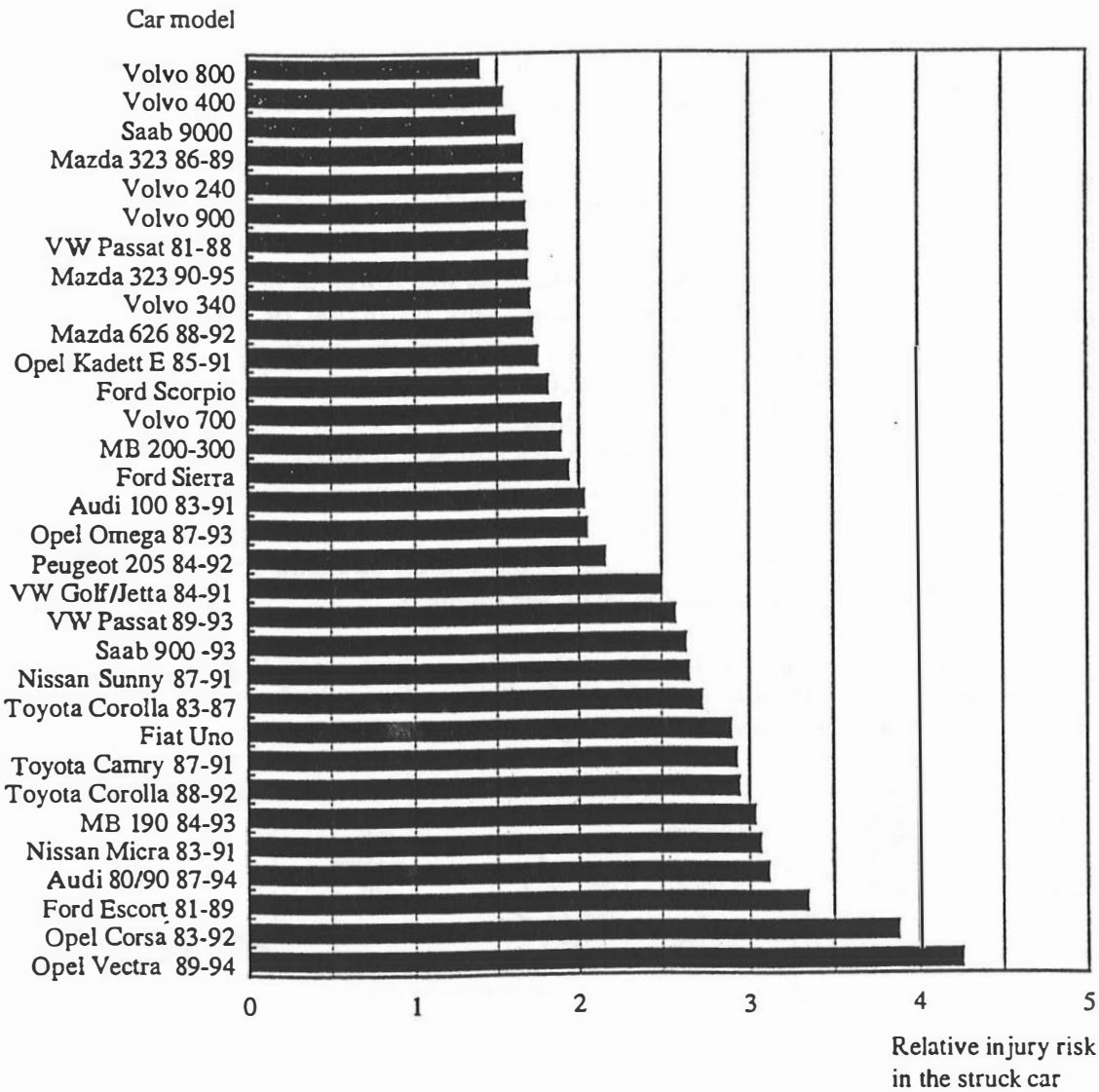
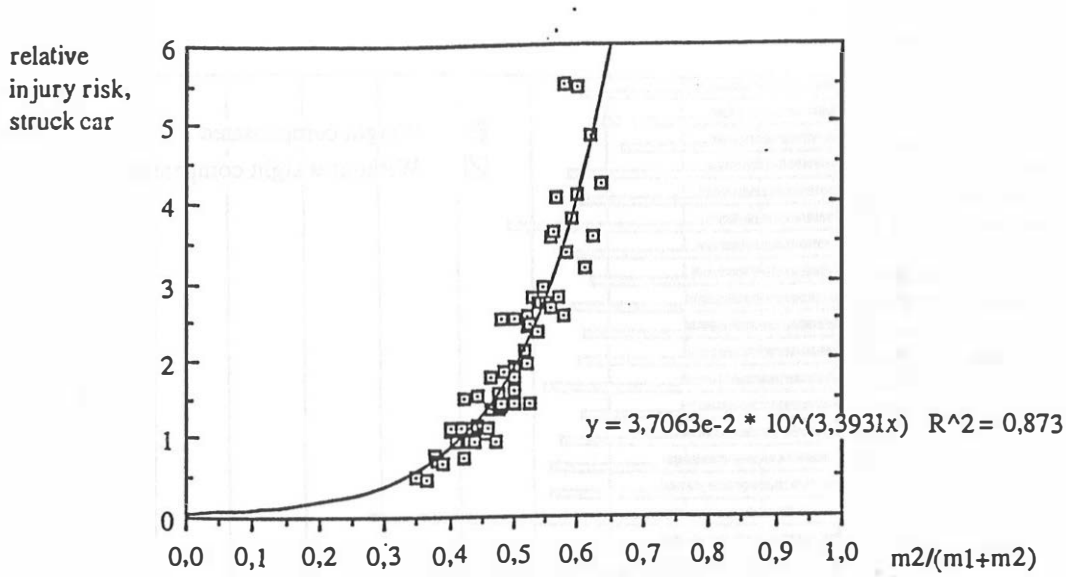


Figure 5 - The relative risk of neck injury in the struck car, in rear impacts, for different mass of striking car divided by sum of mass struck and striking car.



Despite similar weight ranges, there are large differences between the models. In general, the relative risk of injury was greater in small, lightweight cars than in larger and heavier ones. There are, however, many exceptions, for instance Mazda 323 1986-89 (1000 kg) and Peugeot 205 1984-92 (890kg). The results indicate that not only the weight of the car (i.e. the change of velocity) but also the construction of the car, including seat-back design are of importance. In the least safe cars, the relative risk of injury was almost four times as high as in the safest cars.

By dividing the weight of the struck car by the total weight of the struck and striking cars and correlating the ratio to the relative risk of injury in the struck car, (Figure 5), the influence of Δv was more or less given, although the relative velocity and the influence of deformation was not known. Thus,

$$\Delta v = V_{rel} \cdot C_d \cdot m_2 / (m_1 + m_2) \qquad (3)$$

where m_1 = mass in struck car, m_2 = mass in striking car, V_{rel} = relative velocity between struck and striking car and C_d = influence of deformation.

The risk increased considerably when Δv increased. The correlation between mass ratio and risk can be calculated (Figure 5) and described by a power function with the power of constant 3.39.

In Figure 6, total weight has been compensated for different car models by using the equation from the curve in Figure 5. Thus only the construction of the car is rated. Thus the difference in relative risk of injury between different car models decreased, but still the relative risk of injury varied from 0.7 to 2.6, although a slight bias might have been present due to the above mentioned risk function possibly overestimating the weight factor. Table 1 shows that there was a lower relative risk of injury for car models produced during the early 1980 than for car models produced in the beginning of the 1990. Only cars that did not have a production period of more than 7-8 years (to avoid major redesign of the cars during the production time), were selected. Volvo 850 and Opel Vectra 89-95 were excluded since they constitute outliers.

Figure 6 - The relative risk of neck injury in the struck car for different car models, in rear impacts, with and without compensating for car weight. The list has been compensated for gender distribution.

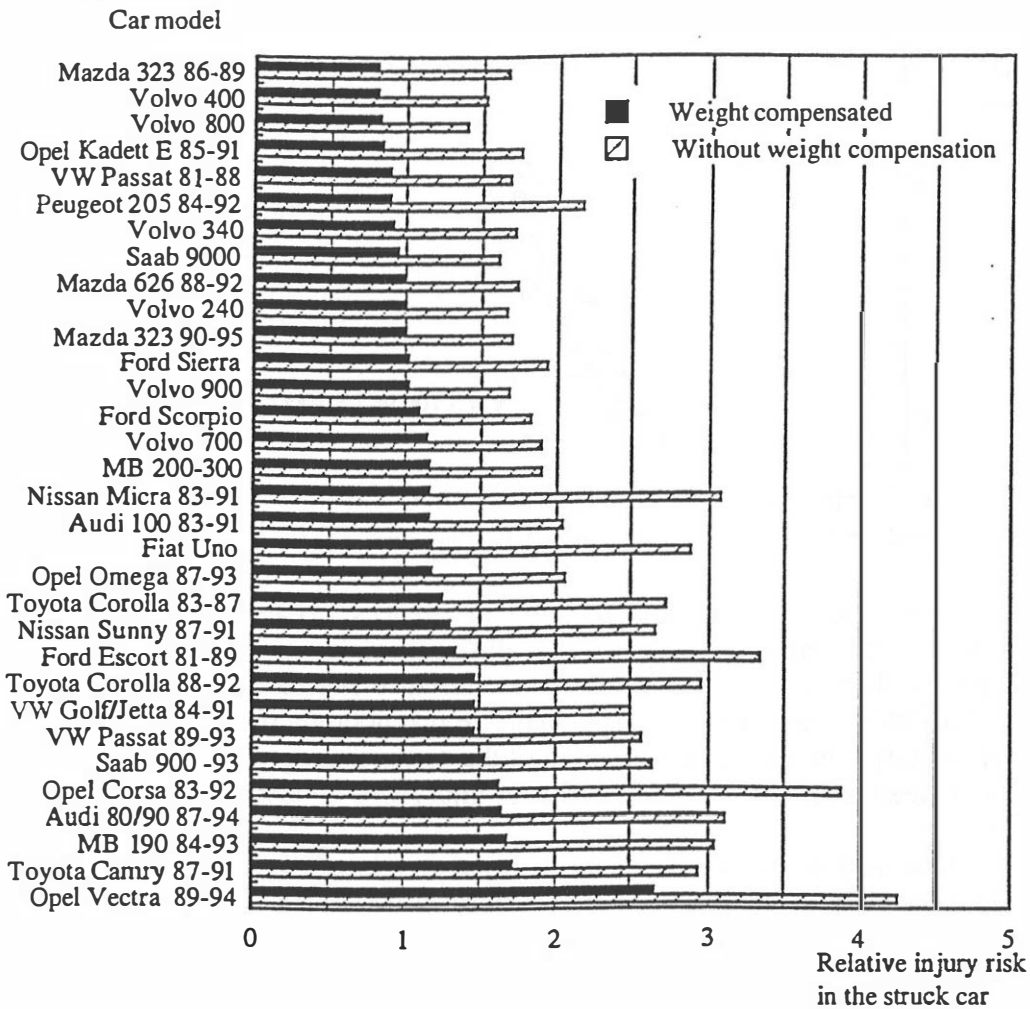


Table 1 - The mean relative risk of injury for car model production years in the beginning of the 80s and the 90s. The relative risk has been compensated for gender distribution and car weight.

	Year of production 1980s	Year of production 1990s	
Relative Risk	1.1	1.3	
Car models	Mazda 323 86-89	Audi 100 92-97	Ford Escort 90-
	VW Passat 81-88	Mazda 626 92-	Mazda 323 90-95
	Toyota Corolla 83-87	Opel Astra	VW Golf 92-
	Audi 100 83-91	VW Passat 89-95	Ford Mondeo
	Ford Escort 81-89	Toyota Camry 92-	Toyota Corolla 93-96
	Opel Kadett 85-91	Toyota Carina 92-95	Saab 900 94-
	VW Golf 84-91	Honda Civic 92-95	Nissan Primera 91-96
	Ford Scorpio		
	Ford Sierra		

NIC CALCULATIONS

Influence of pulse - The impact pulse was varied for a totally unaware occupant (no muscle resistance to neck retraction response) in a medium stiff seat. The used pulses were square shaped acceleration pulses of 2.5 g, 5 g, 7 g, 10 g and 15 g. As can be seen in Figure 7a, a car pulse below 2.5 g does not cause NIC50 values above the tolerance limit. Also, at acceleration levels above 7 g and 5 g, the NIC50 value was not sensitive to the acceleration level for any $\Delta v>12.5$ km/h and $\Delta v>15$ km/h.

Influence of muscle response - The neck muscle onset-time and strength were varied. The pulses used were constant pulses of 2.5 g, for Δv 7.5 km/h, 5g for Δv 7.5-10 km/h, 7 g for Δv 10-12.5 km/h, 10 g for Δv 12.5-15 km/h, 15 g for Δv 15-17.5 km/h and 20g for Δv 17.5-20 km/h. Figure 7b shows that 100 ms onset delay was too long to influence the level of NIC50. Thus, 100 ms delay gave the same results as for a totally unaware and relaxed occupant. Moreover, 5 g of muscle strength keeps NIC50 below the tolerance limit of 15 m^2/s^2 for all Δv's if the reaction time was 0 ms. The influence of muscle strength is shown in Figure 7c for a 60 ms onset delay.

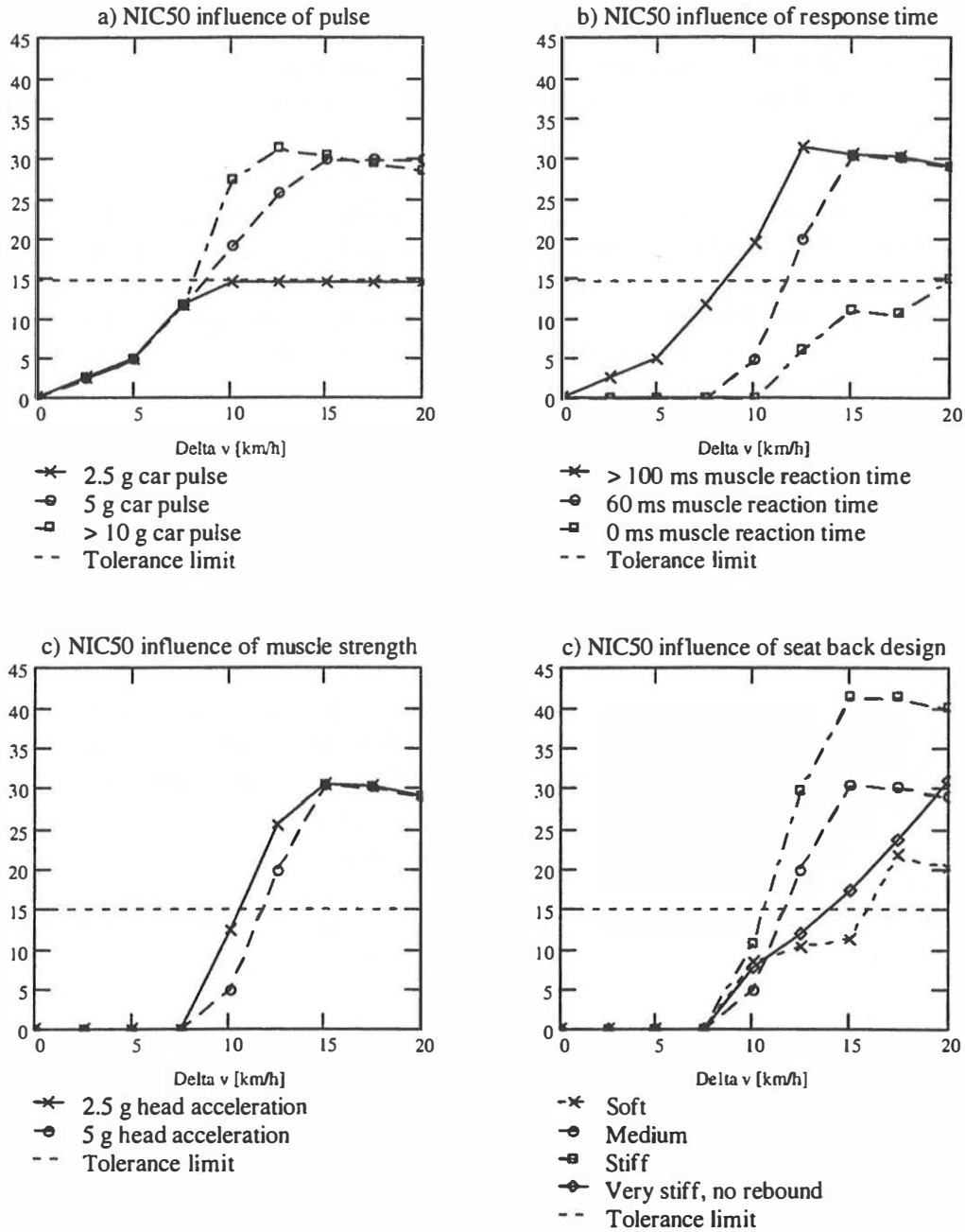
Influence of seat-back design - Here, the occupant had a 60 ms reaction time and muscle strength enough to produce a 5 g C1 acceleration. The choice of pulse was the same as for the muscle response study. In Figure 7d, it is shown that for these circumstances, according to NIC50, an elastically soft seat with low yielding limit was much better than an elastically stiff one with higher yielding limit and with the same damping characteristics for the whole Δv range. However, for a very stiff seat with high yielding limit (doubled), the 50mm of relative displacement with/without muscle response, took place at the rebound phase in the whole Δv range. This means that NIC50 for such a seat without rebound will equal the v^2 term since the neck acceleration then equals zero, see Figure 7d. Note that a rear seat may have such properties. For the stiff/medium/soft seat, the 50mm of relative displacement occurred before the rebound phase for Δv's above 12/10/10 km/h with or without muscle response. In other words, for the seats described in Figure 3, rebound properties matter far less than they do for very stiff and strong seats.

To conclude, the NIC50-results show that non injurious situations in which a medium stiff seat was used (Figure 3b) are characterised by the following criteria:

* An unaware occupant (>100 ms reaction time) occupant and a constant car pulse below 2.5 g.
* An aware occupant (<0 ms reaction time) with muscle strength resulting in a 5 g head acceleration for any car pulse.
* An occupant with 60 ms reaction time and 2.5 g head acceleration below 10 km/h in Δv and with 5 g head acceleration below 12.5 km/h.

The injury risk increased up to a Δv of 15 km/h, and above that level the risk remained constant for increasing Δv. Moreover, according to statistics and the mathematical simulations, no conventional seat-back design adequately prevented neck injuries or keeps the NIC50 values below the injury threshold. It may be that an elastic soft seat with low plastic yielding limit may lower the risk (Figure 7d).

Figure 7 - The influence on NIC50 for a variation of: a) pulse, b) response time, c) muscle strength. d) seat back design.



Analysis of volunteer tests - The displacement and acceleration data indicated that the head restraint cannot normally prevent the development of maximal neck retraction, Figure 8. On the other hand, the acceleration pulse used in the volunteer tests was so low (2.5 g) that the muscle response resulted in a head acceleration compatible with the lower neck acceleration. This means that either no maximal retraction was attained or the passage of maximal retraction was relatively soft. For higher crash pulses of shorter duration, the effect of a head restraint or of the muscle action is likely to have less influence on NIC50.

The average NIC50 value for each seat was calculated with and without the head acceleration taken into account. As can be seen in Figure 9, the values were quite similar for all seats in the study, with one exception: the Mazda 323 -89 seat. This seat-back only has one recliner and can very easily be tilted backwards.

Figure 8 - One example of a volunteer test (Δv = 10.5 km/h) reported by Eichberger et al. (1996). The two (computer-enhanced) snapshots of the occupant shows the geometry at the start of the impact and after 140 ms. The left diagram shows the sled, head and chest acceleration. The right diagram shows NIC with and without the head acceleration taken into account. Obviously, the head restraint does not do much to prevent retraction (leading to an s-shape of the neck).

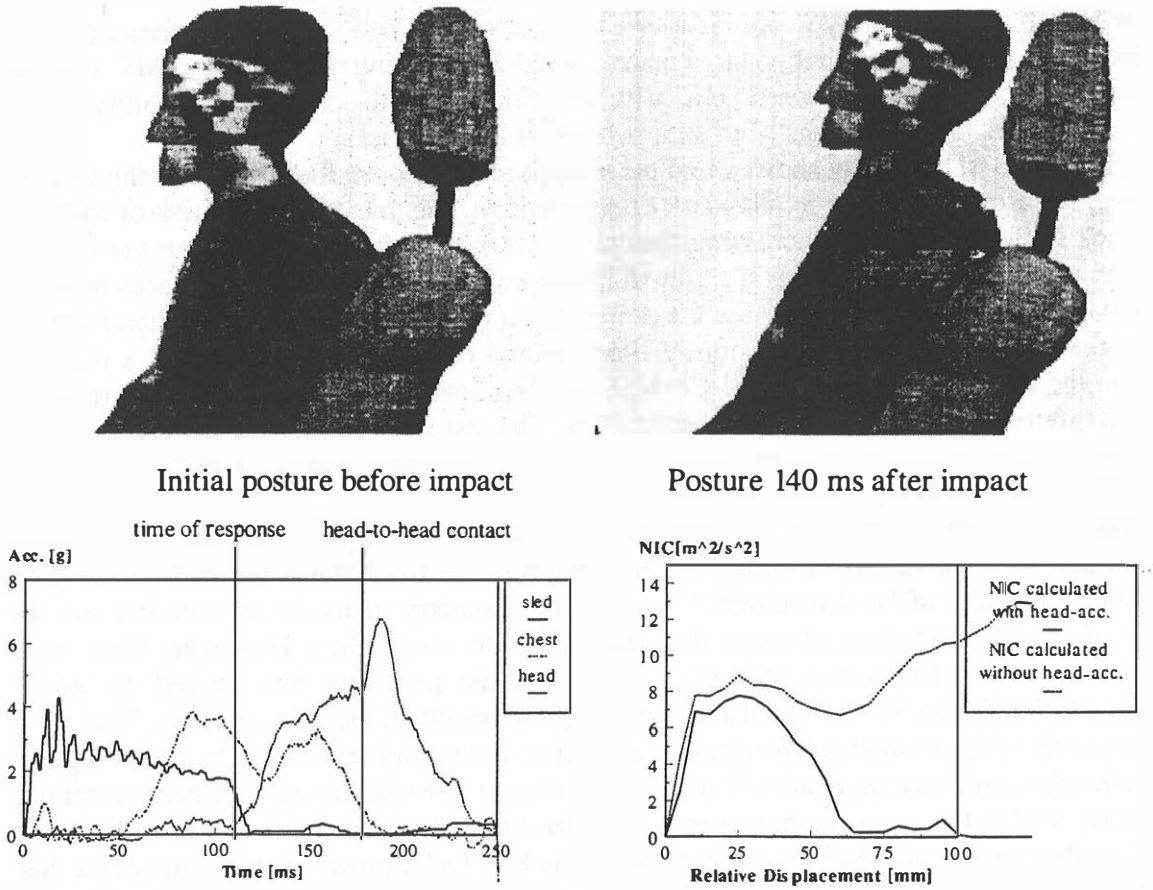
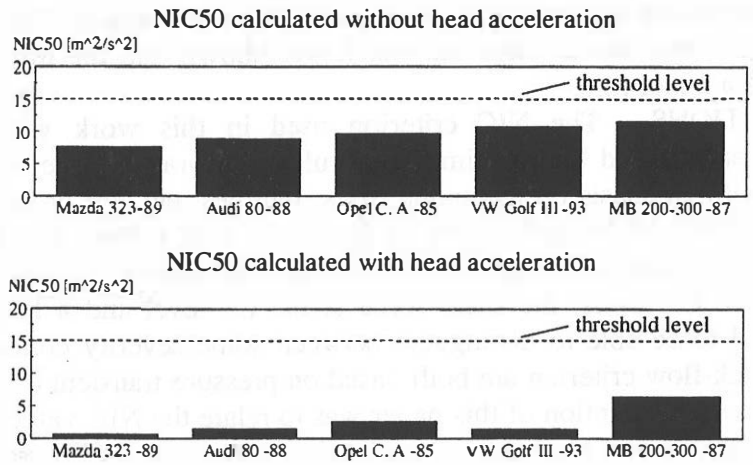


Figure 9 - Averaged NIC50 values according to chest and head acceleration values from 16 volunteer tests with seats from 5 different car models. Note that the NIC50 values calculated with the head restraint taken into account also reflect the head restraint geometry.



DISCUSSION

ACCIDENT ANALYSIS - The real-life data in this study were based on police reported rear-end accidents. They probably represent a more severe accident sample (higher change of velocity) than the average rear impact causing AIS 1 neck injury, and in this study the immediate outcome was registered. Nygren (1984) showed that only one out of ten occupants, after reporting the neck injury to the insurance company, sustained long-term consequences to the neck AIS 1. It is still unknown whether accidents causing neck injury AIS 1 as an immediate outcome actually correspond with accidents causing long-term disability to the neck. Until better knowledge has been attained, this is the assumption.

The results of this study showed that the weight ratio between the struck and the striking car strongly correlate with the relative risk of neck injury. This means that the risk of injury in the struck car increases with increasing change of velocity. After compensating the relative risk of injury for car weight for each car model, there still remained large differences between the models. The design of the seat and the deformation properties of the car are therefore two factors that probably influence the injury risk. Håland et al. (1996) reproduced a rear-end crash (in the laboratory) with an Opel Corsa A (relative risk 1.6) and a Peugeot 205 (relative risk 0.8), after switching the front passenger seats. The test showed that the different loading of the seat dummies in the two cars was caused by the different designs of the seats and not by the differences in design of the car bodies.

There does not seem to be a correlation between the geometrical design of the head restraint and the relative risk of injury. A comparison of the IIHS Status report from 1995 on the protection effect of head restraints based on the geometry of the head restraint, and the results of the real-life data, showed that there was no correlation. However, there were exceptions, for instance Volvo 850 which head restraint geometry was ranked as "good" according to IIHS. The Volvo 850 also presented good results in the current study. That there was no relationship between head restraint geometric rating and real-life data seems logical, when one takes into account results from studies showing low effectiveness of head restraints. This study shows that there is, however, a correlation between car model year and relative risk. Cars that were produced in the beginning of the 80s, had a lower relative injury risk than newer models. It may be that front seats have become stiffer due to the risk of ramping in severe rear impacts (Viano 1992). This however could be a negative factor in low-speed collisions. Parkin et al. (1995) showed that the plastic yielding of front-seat backs was beneficial in decreasing the risk of AIS 1 neck injuries occurring in rear-end collisions.

The results from real-life data indicate that the change of velocity in the struck car and the design of the occupant seat influence the severity of AIS 1 neck injuries. Therefore, a neck injury criterion must be sensitive to these factors. It was shown that the influence of head restraint seems to play a minor role.

NIC-CALCULATIONS - The NIC criterion used in this work was based on a hypothesis that was corroborated by experimental results of neural dysfunction. Also, other "initial" hypotheses with emphasis on the spinal discs, muscles, etc. are promising (Panjabi 1996, Kaneoka 1997, Krafft 1995). In the study by Jacobsson et al. (1994), some criteria were evaluated for different situations in a mathematically simulated rear-end collision. The tensile force at the T1 and the C1 levels, the shear force at the C1 level and a lower neck-flow criterion were reported to be able to distinguish between some severity conditions. As the NIC values and the neck-flow criterion are both based on pressure transient effects they may be related to each other. The intention of this paper was to relate the NIC values to the injury risk in real rear-end crashes and to highlight qualitative aspects of differences in seat and occupant properties regarding statistical risk of injury and NIC50 values. The aim was thus to

provide input to a successful development of AIS 1 neck-injury-preventing safety systems rather than to explain the injury mechanisms.

The mathematical seat-occupant model that was devised is linear and uses a small number of parameters. The model may be too simple to correctly simulate a real seat and a biofidelic test dummy. However, there exists no test dummy that is biofidelic regarding straightening of the kyphosis and with adequate neck retraction possibilities to validate the model against.

In the volunteer tests by Mertz and Patric (1971), the subjects straightened their spine by pressing hard against the back rest and head restraint. This may well have prevented the head and neck from rearward displacement beyond the point of maximal retraction under the experimental conditions used. In this study, the focus was on the initial neck dynamics, however, the occurrence of an initial injurious motion does not exclude an injurious motion occurring in a second stage, for example a hyper extension or a neck flexion after a rebound. The NIC theory can be applied to situations, e.g. after a seat rebound or in a frontal collision, when the head translates in a forward direction relative the lower neck without rotating. This however will be for future studies to determine.

CONCLUSIONS

The outcome of this work is valid only for low velocity rear-end crashes, below a Δv of 20 km/h. The focus was on lower neck acceleration. The results show that this focus was motivated by the prediction of neck injuries.

ACCIDENT ANALYSIS - According to the relative risk of AIS 1 neck injury, in the struck car in rear impacts:

* The injury risk increases dramatically with increased Δv.
* The injury risk in the struck car varies between different car models, even when the influence of the weight of the car was compensated for.
* Neck injury risk rating, based on seat system geometry evaluation does not seem to correlate with real-life data.

NIC-CALCULATIONS - According to a simple mathematical model of an occupant, seat and seat pulse:

* The influence on NIC of occupant/seat/car-pulse factors varies greatly depending on the Δv, see Figure 7. The muscle strength and onset time (as specified in this report) and also the seat-back plastic-yield-limit are the most important factors to influence NIC.
* An occupant aware of the impending impact in a medium stiff seat seems to have a greater chance of not exceeding the tolerance limit for any Δv.

According to the analysis of the volunteer tests, for non injurious motions with 2.5 g car pulse during 130 ms:

* The head restraint generally cannot prevent a maximal retraction of the neck.
* Elastically softer seats produce lower NIC values than do stiffer seats.

GENERAL CONCLUSION - As a first attempt to relate NIC to the statistical risk of neck injury from real-life data, the following tentative risk function has been suggested,

$$\text{Risk function} = ((\text{NIC50}-15\ m^2/s^2)/10\ m^2/s^2)^3 \qquad (4)$$

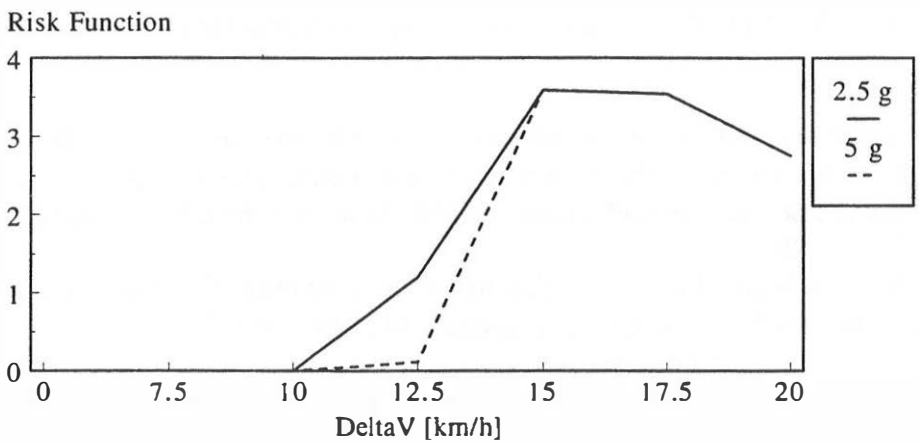
A more detailed study regarding the risk-Δv dependence (Krafft et al. 1997) motivated the power of 3 and the denominator of 10 m^2/s^2 in equation 4. In Figure 10, the NIC50 values of Figure 7c were translated to risk function values. Since, women on average have less muscle strength than men, the risk differences in Figure 10 may explain the statistical gender risk difference. If the main reason why women are at higher risk of sustaining neck injury depends on less muscle strength, the threshold of Δv would be excepted to be lower for women.

The high statistical Δv dependence of the neck injury risk, the gender risk difference, the front/rear seat occupant risk difference and the risk decrease of soft and weaker seats are explained here by a simple model and NIC calculations. NIC values were found to be below the injury threshold (15 m^2/s^2) for non-injurious motions (volunteer tests as Eichberger et al. 1996 and McConnel et al. 1995) and also predicted injurious loading in statistical data. Therefore,

* The new neck injury criterion NIC seems to be a useful predictor of real-life neck injuries.
* A gentle neck acceleration until the head restraint meets the head, alternatively until maximal retraction is passed, could prevent injuries.

This study may be useful in the evaluation of old seat designs and in the development of safer seats. Although the aim of this study was to identify some important factors rather than answers questions, hopefully new and more accurate and precise questions will have been raised.

Figure 10 - Risk function versus Δv (realistic pulse) for occupants with different muscle strength.



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