COMBINING CRASH RECORDER AND PAIRED COMPARISON TECHNIQUE: INJURY RISK FUNCTIONS IN FRONTAL AND REAR IMPACTS WITH SPECIAL REFERENCE TO NECK INJURIES

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ABSTRACT

Knowledge from real-world crashes is important in the design of a crashworthy road transportation system. Such design must be based on the human injury tolerance limits. Links between impact severity and injury outcome are important and could be used in order to achieve such tolerance limits. Traditionally impact severity has been calculated with retrospective reconstruction technique, although recently, injury risk functions have been presented where impact severity has been measured with crash pulse recorders.

The aims of this paper were to present injury risk functions, with special reference to neck injuries, calculated with crash recorder and paired comparison technique, and to propose a way of combining the two methods. By combining comprehensive statistical material with in depth crash recorder information, injury risk functions for injuries to different body regions were established. Risk functions for AIS1 neck injuries both in frontal and rear-end impacts have also been established.

It was found that the data from the crash pulse recorder generated risk functions could be used to validate and calibrate risk functions based on the matched-paired technique. Moreover, it was found that the shape of the injury risk curves differed significantly for injuries to different body regions. It was also found that the neck injury risk differed significantly for frontal and rear-end impacts.

It is concluded, that adding new techniques to the existing techniques based on reconstruction can further refine generating risk functions. The injury risks found are important for the understanding of injury tolerance limits for injuries to different body regions, but also for the understanding of injury mechanisms for different injury types.

INTRODUCTION

In the construction of a crashworthy road transportation system, knowledge from real-world collisions describing tolerance limits for occupants as well as knowledge of how well a vehicle can protect its occupants are fundamental. An essential issue from that perspective is injury probability functions versus crash severity or injury risk functions as they often may be called. Risk functions can be used to find threshold values for maximum mechanical force with injury occurring, or for finding any threshold level. Risk functions can also be used to validate injury criteria, especially looking at the elasticity of the criteria. This is done by estimating the rate at which an injury (or an injury criterion) will increase with increased impact severity (or mechanical force). An experimental test should be at least as sensitive to mechanical force as real-life analyses show. If the risk of injury increases with say 10%, with a 5% increase in mechanical force, this should be reflected in the experiment.

Risk functions can be calculated directly by studying the ratio in number of injured and uninjured at different crash severity levels. Several studies of injury risk functions have been presented by for example Norin (1995) and Evans (1994). In those studies the crash severity, most often change of velocity, was estimated by using crash reconstruction techniques. More recent studies, where crash severity have been measured with on-board crash pulse recorders, have been presented by for example Kullgren (1998), Kullgren et al (1999), and Krafft et al. (2002). Crash recorders might have the possibility to increase the quality of the estimates of impact severity, which has been shown to have an important effect on the estimates of risk functions (Kullgren 1998).

Another way of calculating risk functions from real-life crashes has been proposed by Krafft et al (2000). In that study, the injury risk functions were calculated with a statistical method based on the paired comparison technique (Hägg et al 1991). By directly comparing the injury outcome in two-car collisions, where the cars were categorised in mass intervals, a measure of relative injury risk versus a relative measure of change of velocity could be calculated (Krafft et al 2000).

The human tolerance to mechanical force may be estimated by cadaver crash tests. This could be done especially to establish the human tolerance to fractures. To establish tolerance levels for soft tissue injuries as for example AIS1 neck injuries, volunteer tests could be done. However, for ethical reasons it is only possible to run tests below injury tolerance levels. Results from cadaver tests and volunteer tests could be used to design and validate dummies and computer simulation models.

The aim of this paper is to present injury risk functions calculated with two different methods and to propose how these methods can be combined. The methods used are a direct measure of injury risk using on-board crash pulse recorder data and a relative measure of injury risk using a statistical method based on the paired comparison technique. An additional aim is to present injury risk functions for injuries to different body regions, and especially AIS1 neck injury risk functions in both frontal and rear impacts.

METHODS

Crash Pulse Recorders

Impact severity was measured with a Crash Pulse Recorder, CPR, which measured the acceleration time history in the impact phase in one direction. The CPR is based on a spring mass system where the movements of the mass in an impact are measured. The displacement of the mass is registered on a photographic film. The circuit has its own power cell and does not need an external power unit. The CPR has a trigger level of approximately 3g. When the characteristic parameters for each CPR have been measured, such as spring coefficient and frictional drag, and with knowledge of the displacement time history, the acceleration time history were calculated. The change of velocity was then calculated from the acceleration time history. The crash pulses were filtered at approximately 100 Hz. The CPR and the analysis of the recordings from the CPR have been described by Aldman et al. (1991) and Kullgren (1998). The standard deviation of the measurement of the CPR has been evaluated and estimated to be approximately 5% (Kullgren 1998).

The impact severity measurements were divided into intervals, and the injury risk was calculated in each interval. Smooth curve fits were used in the plots of injury risks.

Paired Comparisons

The basis for this statistical method is the paired comparison technique, where two car accidents are used to create relative risks. The method was initially developed by Evans (1986), but has been developed further for car to car collisions by Hägg et. al. (1992). The assumption for the method is that the risk of injury is a continuous function of change of velocity. This assumption might conflict with safety features such as airbags that might generate a step-function. Another assumption is that injuries in one car are independent from the injuries in the other car, given a certain crash severity. For a given change of velocity the risk of an injury is p_1 and p_2 in the two cars, respectively. Summing over all change of velocities, the outcome will be as presented in Table 1.

Basically, the change of velocity can be calculated from the law of the conservation of momentum, where:

$$\text{Delta v} = V_{rel}\,(M_2 / (M_1 + M_2)),$$

where V_{rel} is the relative velocity and M_1 and M_2 the masses of the two vehicles colliding.

This relation is true even if the two vehicles involved do not have a common velocity after the impact. If the masses are equal, both vehicles will undergo the same change of velocity. This method uses this fact, and that any deviation in mass can be transferred to differences in change of velocity, as long as the individual masses are known, see Figure 1. The method cannot generate absolute figures, only risks relative to each other.
Instead of generating new risk functions, the method uses the change on the exposure distributions and the resulting change in risk.

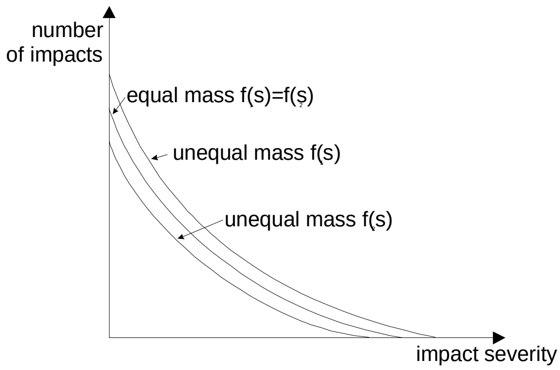

Figure 1. Impact severity (delta-V) for cars in matching crashes for equal mass: $f_1(s) = f_2(s)$ and unequal mass: $f_1(s) \neq f_2(s)$ where car 1 is of less mass than car 2.

Table 1. Sums of probability of injury to driver in car 1 and 2 for all segments of impact severity.

		Driver of Car 2		Total
		driver injured	driver not injured	
Driver of Car 1	driver injured	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} = x_1$	$\sum_{i=1}^{m} n_i P_{1i} (1-P_{2i}) = x_2$	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} + n_i P_{1i}(1-P_{2i}) = nP_1$
	driver not injured	$\sum_{i=1}^{m} n_i (1-P_{1i}) P_{2i} = x_3$	$\sum_{i=1}^{m} n_i (1-P_{1i})(1-P_{2i}) = x_4$	
	Total	$\sum_{i=1}^{m} n_i P_{1i} P_{2i} + n_i (1-P_{1i}) P_{2i} = nP_2$		

The relative risk of an injury, for vehicle 1 to 2, given a certain change of velocity distribution is therefore:

$$R = (x_1 + x_2) / (x_1 + x_3) = \frac{\sum n_i P_{1i}}{\sum n_i P_{2i}} = \frac{\sum n_i P_{1i} P_{2i} + \sum n_i P_{1i} (1 - P_{2i})}{\sum n_i P_{1i} P_{2i} + \sum n_i (1 - P_{1i}) P_{2i}}$$

The method is unbiased for any combination where the vehicles are of the same weight; i.e. the mass ratio is 1. If the vehicles are of different weights, the two vehicles will undergo different changes of velocity, which will have to be compensated for. Generally, we can introduce any component, K, that will affect the risk of injury in either, or both of the vehicles. If we let K_1 denote this factor in vehicle 1, and K_2 in vehicle 2, this will lead to:

$$\text{(Eq. 1)} \quad n_i P_{1i} P_{2i} K_1 K_2 / n_i P_{2i} K_2 + \ldots + n_i P_{1i} P_{2i} K_1 K_2 / n_i P_{2i} K_2 = \sum_{i=1}^{m} n_i P_{1i} P_{2i} K_1 / \sum_{i=1}^{m} n_i P_{2i}$$

$$= K_1 \sum_{i=1}^{m} n_i P_{1i} P_{2i} / \sum_{i=1}^{m} n_i P_{2i}$$

To solve the equation, cars of different weights will be used, where the weights are known. K will therefore denote the role of change of velocity, and could be a constant, or a function of, say, change of velocity.

(Eq. 1) is estimated by $K_1 (X_1 / (X_1 + X_3))$ (2) and,

$$K_1 = \frac{\left(X_1/(X_1 + X_3)\right)_{m_b}}{\left(X_1/(X_1 + X_3)\right)_{m_a}} \quad (3) \text{ where,}$$

m_a and m_b are mass relations in the matched pairs. These mass relations are transformed to relative change of velocity by

$$\frac{m_b}{m_a} = \left(m_2 \big/ (m_1 + m_2) \right)_b \Big/ \left(m_2 \big/ (m_1 + m_2) \right)_a .$$

The analytical functions chosen to describe the risk functions have been applied simply using either a linear function or a power function. This issue would have to be further investigated using more advanced material.

Combining crash pulse recorder and paired comparison technique

While the importance of a marginal change of velocity as well as parts of the risk function will be calculated using paired comparison technique, absolute values cannot be given with this method. Since the actual change of velocity in each crash not is known, only a relative change of velocity for each segment can be calculated. If absolute values are to be given, a key value must be brought into the equation. Such key values can be estimated by comparing the relative risk functions, derived from statistical data, with the absolute measures of injury risk calculated with data from crash pulse recorders. Both the relative risk and the relative change of velocity must then be related to the absolute values. By comparing the average change of velocity of the crashes using the crash recorder data, with a relative change of velocity of 1 for the mass data, a key factor for crash severity can be established. By comparing the shape of relative injury risks with absolute injury risks for the same injury type, a key factor for injury risk can also be established. The relative risk functions can by that be transformed from relative to absolute risks.

MATERIAL

Crash pulse recorder data

Since 1992, CPRs have been installed in approximately 170,000 vehicles aimed at measuring frontal impacts and approximately 50,000 vehicles aimed at measuring rear-end impacts. Regarding frontal impacts crash pulse recorders have been installed in 4 different car makes and 22 models and in rear-end impacts in 7 car models of the same make. The car fleet has been monitored since 1992, and regarding frontal impacts, accidents with a repair cost exceeding 5000 US$ have been reported via a damage warranty insurance. Rear-end impacts were reported irrespectively of repair cost. The accident data collection system has previously been described by Kamrén et al. (1991).

This study includes impact severity and driver injury data in 286 frontal impacts with an overlap of more than 25%. Eighty-three rear impacts were analysed with known impact severity and with injury data from 110 front seat occupants. In frontal impacts only restrained drivers were included, as the neck injury risks may differ between front seat passengers and drivers. There was not enough data to calculate the neck injury risk for the front seat passengers separately. Regarding rear-end impacts both drivers and front seat passengers were included as the neck injury risk in rear impacts could be regarded as similar for both positions. In the frontal impacts, belt use was verified from inspections of the seat belt system and in the rear impacts, belt use was verified from questionnaires to the involved occupants. Approximately 4% of the frontal impacts and none of the rear impacts were rejected due to lack of belt use. In the frontal impacts, 72% of the drivers were male and 28% were female. Regarding the rear impacts, 47% of the front seat occupants were males and 53% were females.

Data for the paired comparison risk functions

The material used was two car crashes, front to front and front to side, from Queensland, Australia, as well as rear-end crashes from Sweden for the analysis of neck injuries. In both materials, injuries were classified as to bodily localisation and severity in three classes, namely minor, serious and fatal injuries. The reason for using data from two sources is that very few data sets would allow the kind of analysis made here. Both material sources consisted of police reports, known to have some problems with quality. While using only a few variables from the police records, the main quality issue lies with the under-reporting, and weak injury classification due to the lack of in-depth medical data.

RESULTS

From the first two figures it can be seen that the shape of the upper part of the injury risk for all injuries in Figure 1 is equal to the relative injury risk presented in Figure 2. The average change of velocity for the collisions in Figure 1 was 21 km/h. The average change of velocity should be similar as the relative change of velocity of 1 in Figure 2. This means that the scaling for the x-axis in Figure 2 could be estimated and changed from a relative scale to a fix scale. The slope of the injury risk for all injuries in Figure 1 should then be similar as the risk of any injury in Figure 2.

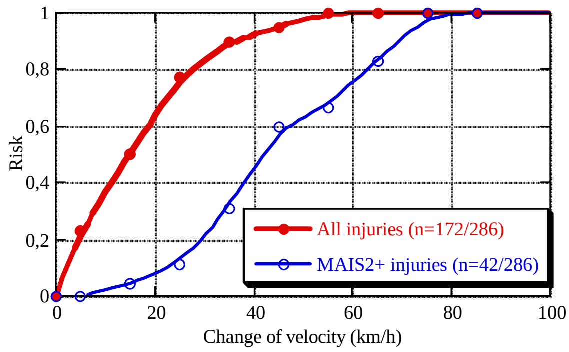

Figure 1. Injury risk, all injuries and MAIS2+ injuries, versus change of velocity from crash pulse recorder data.

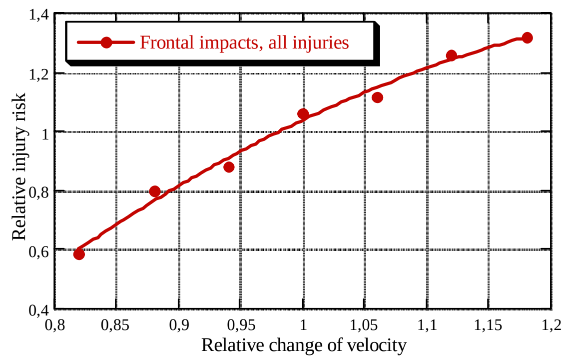

Figure 2. Relative injury risk versus relative change of velocity from police reported crashes in Australia.

A clear difference in risk of an AIS1 neck injury in rear impacts and of any injury in frontal impacts was found in the crash recorder data, see Figure 3. Also in the police reported crashes a clear difference was found, see Figure 4. The risk of a neck injury in the struck car increased rapidly with increased crash severity while the risk of any injury in the striking car was always lower and had a lower slope. In Figure 5, risk functions with both methods have been combined. The relative injury risk was adjusted so that the relative injury risk for the striking car, at the relative change of velocity of 1, was equal to the absolute injury risk for all injuries at the average change of velocity (11.9

km/h) in the crash recorder crashes. The slopes of the risk curves were similar for both methods.

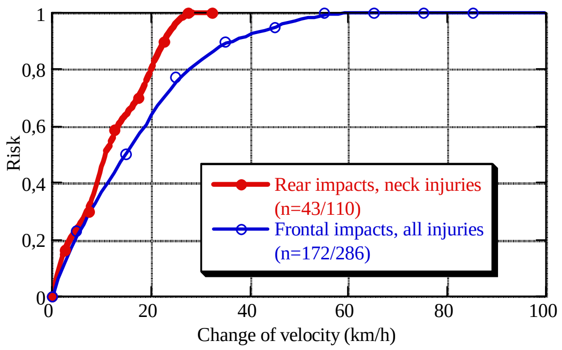

Figure 3. Risk of neck injury in rear impacts and any injury in frontal impacts versus delta-V, from crash pulse recorder data.

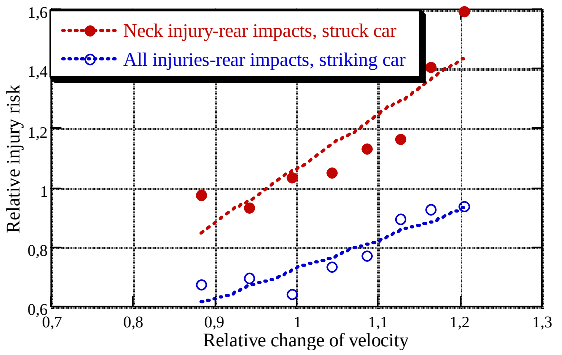

Figure 4. Relative risk of neck injury in the struck car and any injury in the striking car versus relative change of velocity, from police reported crashes in Sweden.

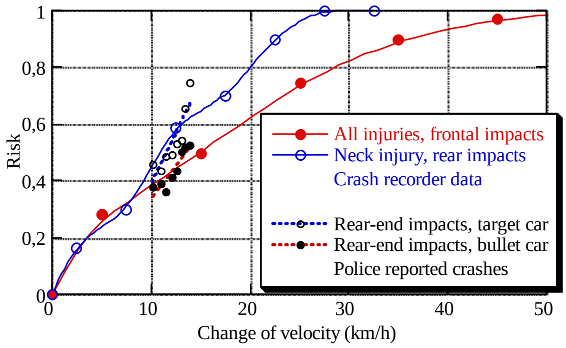

Figure 5. Risk of neck injury in rear impacts and any injury in frontal impacts versus delta-V, from crash pulse recorder and police reported data.

In Figure 6 it can be seen that the AIS1 neck injury risk in rear impacts differed significantly compared to the neck injury risk in frontal impacts. In rear impacts, the risk increased to 100% at approximately 25 km/h, while in frontal impacts the risk was only approximately 30% at the same change of velocity. The neck injury risk in frontal impacts never exceeded 45% and was lowered above 35 km/h.

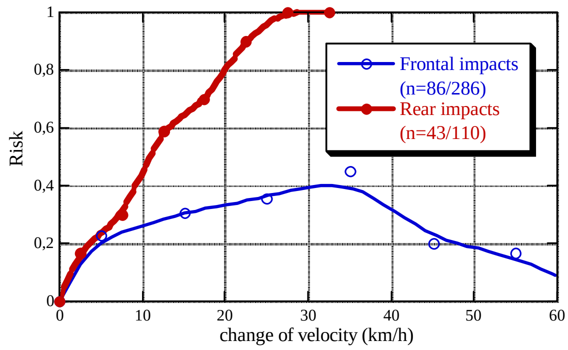

Figure 6. Risk of neck injury in frontal and rear impacts versus change of velocity, from crash recorder data.

Figures 7 and 8 present two attempts to differentiate injury probability in frontal impacts for injuries to different body regions. Similar differences in shapes of the risk functions were found for the two alternative methods. However, the head injury risk differed between Figures 7 and 8. In Figure 7 it can also be seen that the neck injury risk shows the highest increase in risk at low severity, while the neck injury risk at high severity decreased. The shape of the injury risk for lower spine has a similar decrease at high impact severity as the neck injury risk.

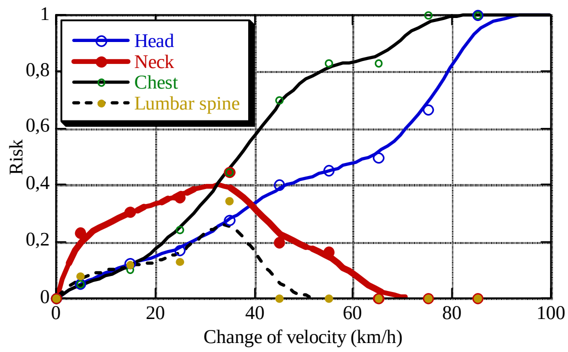

Figure 7. Injury risk for head, chest, neck and lower spine injuries versus change of velocity from crash pulse recorder data.

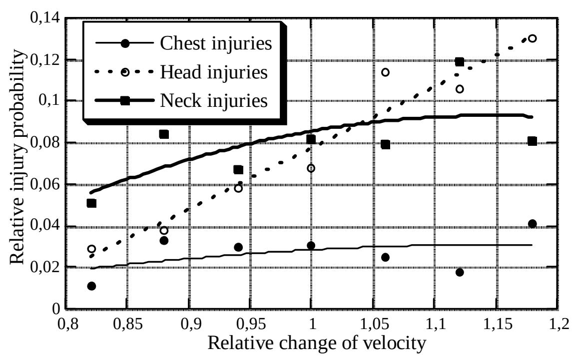

Figure 8. Relative risk of head, chest and neck injury versus relative change of velocity from police reported crashes in Australia.

DISCUSSION

Valid and reliable risk functions, describing the link between impact severity and risk of injury, can be used for many purposes. One of the most important areas is to validate injury criteria for experimental crash testing or simulations. The sensitivity and elasticity of an injury criterion would have to match real-life experience in order to be accepted as a valuable candidate. This study demonstrates that risk functions are different for different types of injury, and it demonstrates that two independent ways to generate risk functions can be combined. It is believed that calculations of injury risk functions based on data from low-quality crash reconstruction can fundamentally influence the shape of the risk curves, possibly guiding development of injury criteria in a wrong direction (Kullgren and Lie 1998). This study shows that risk functions possibly can be estimated with small errors.

The material used was a mix of collisions from Sweden and from Australia. The crash pulse recorder data did come from Sweden, while the police reported crashes showing injury risk to different body regions were from Australia. The results in Figure 6 were from police reported crashes in Sweden. As different car fleets were used in the study and as the belt use differs between the countries, it is difficult to directly compare risk curves from the different samples. Ideally, databases from the same country and with a similar mix of car models should be used. The number of car models included in the crash recorder project was low, which means that the results cannot be generalised to the whole accident population. The risk curves should because of that be handled with some care. Also, in the calculations of injury risks for injuries to different body regions, the number of injuries, especially at high impact severity, was relatively low. The differences between the risk curves for different body regions will still be valid, although the true shape of the risk curves could differ from the ones presented.

The advantage with large databases with police reported crashes is that risk functions for injuries to different body regions can be easily and accurately calculated, although only in a narrow interval in crash severity. This limitation might be resolved by combining risk functions for several types of injuries in a broader spectrum of impact severity.

The advantages with crash pulse recorders are primarily that accurate measurements of crash severity are available, allowing risk curves to be calculated for a large variation in crash severity and also for different crash severity parameters. However, the availability of data is often limited. Since the use of crash recorders in accident reconstruction is growing, more can be done in the future. There is a need for valid methodologies to get good value of this new opportunity.

Injury risk curves are most often regarded as continuously increasing functions versus impact severity. The findings in this study show that there might be large variations in the shape of the risk functions when studying injury risks for injuries to different body regions. Both methods showed that especially the neck injury risk in frontal impacts differed compared to head and chest injury risks. The results from crash pulse recorders showed that both neck and lower spine injury risks decreased to an almost zero-level above certain changes of velocity. This effect is not due to masking of other injuries. Since there are large variations in risk functions for different body regions and since the risk functions not always are increasing at increased impact severity, it will be important to take this into account in the design of crash tests. The chosen test speed will have a significant influence on the injury types that will be covered.

The reason for the decrease in neck injury risk at high crash severity might be due to a positive influence on neck injury risk of airbags (Kullgren at al. 2000, Morris et al. 2000). Another effect could be that other more severe injuries are dominating at high severity crashes, and may in these crashes lead to an under-reporting of AIS1 neck injuries.

The crash pulse recorder data showed that the highest risk at high severity impacts was for chest injuries, followed by head injuries, see Figure 7. In the police reported crashes, see Figure 8, head injuries showed the highest risk. The explanation for the discrepancy might be the classification of head injuries as well as different proportions of airbags in Sweden and Australia. Sweden has a higher proportion of airbags, which reduces the head injury risk.
Two injury risk functions showed continuously increasing risk values, namely the neck injury risk in rear impacts and the risk of any injury in the frontal impacts. Relative injury risks were compared with the absolute risk measures for these two risk functions. Both methods showed that the neck injury in rear impacts had the steepest slope in the risk function.

Better links between real-life and experimental data is needed. It is important to better understand how crash test dummies respond. In experimental tests, a change in test speed or acceleration level should be reflected in the measured dummy readings corresponding to the increase in injury risk calculated from real-life crashes.
With the paired comparison technique it is possible to study injury risk functions for several different

injury types and impact directions. However, future studies with more homogeneous data sources are necessary to be able to fully combine the different methods to be able to transform the relative risk functions into absolute ones. The paired comparison technique makes it possible to in the future calculate risk curves for different vehicle categories and even for separate car models. Even if the risk curves are relative ones, differences between car models and vehicle categories could be analysed. The possibility to use matched-paired technique to generate relative injury risks and risk functions, stresses the need for high-quality injury classification or mass data, whereas estimates of exposure is not important in this type of analysis. A material consisting of ICD-codes would therefor be beneficial to use.

CONCLUSIONS

• It was found that injuries to different body regions may have very different shapes of the injury risk curves. Most of them have continuously increasing risk functions, while injuries to the spine in frontal impacts showed increasing risks at low severity and decreasing risks at higher impact severity.

• Different shapes of risk functions for injuries to different body regions should be considered in crash tests chosen at different test speeds.

• A correlation between the risk curves calculated with matched-paired and crash recorder techniques was found, allowing the two methods to be combined and cross validated.

• In the interval 10 to 20 km/h, the neck injury risk in rear impacts increased from approximately 45% to 80%, while the neck injury risk in frontal impacts increased from approximately 27% to 33%. Such changes in risk for a certain change in crash severity should be reflected in dummy readings from crash tests and computer simulations.

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