DOSE-RESPONSE MODELS AND EDR DATA FOR ASSESSMENT OF INJURY RISK AND EFFECTIVENESS OF SAFETY SYSTEMS

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ABSTRACT

In order to design a safe road transport system, including almost all safety technologies, knowledge of the human injury tolerance and biomechanics is fundamental. It is important to understand the whole chain of events in a crash, how the impact speed relates to the injury outcome. Analyses of real-world car crashes are useful to gain such knowledge and to identify the effectiveness of safety technologies. Using dose-response models can be of great help in such work. The dose is the input, the impact severity, and the response is the injury outcome. The link deciding the response of the dose is the injury risk function.

The aims of this lecture are to present injury risk functions based on real-life frontal crashes with crash severity measured with on-board crash pulse recorders and to show how such information can be used in effectiveness studies using dose-response models, both regarding safety technology already introduced, but also regarding technologies to be introduced.

Key words: injury probability, accelerations, velocity, crash recorder, EDR

IN THE DESIGN OF A SAFE ROAD TRANSPORT SYSTEM it is important to have good knowledge of human tolerance for injury and of human errors. Knowledge of the human injury tolerance is fundamental in the design of all parts of the road transport system, including all safety technologies with the exception of those completely avoiding crashes. With this in mind biomechanics is one of the key areas in injury reduction.

In a vehicle accident situation, it is also important to understand the whole chain of events, how the forces related to the impact speed may influence the injury outcome.

The human tolerance for injury can be achieved from different sources and with different perspectives in mind. Traditionally, crash tests with volunteers, PMHS or animals have been conducted. However, during the latest 10 or 15 years studies aimed at evaluating injury tolerance based on real–life crashes have been presented. In these studies injury risks for different injury types versus recorded impact severity have been established. Findings from these studies will be further described in coming sections.

The quality of real-life data has often been a limiting factor in analyses of the effectiveness of safety systems (Kullgen and Lie 1998). By improving the validity and reliability in data from real-life crashes, studies of the link between impact severity and injury outcome could be a useful way of gaining such knowledge. Data from on-board crash recorders or Event Data Recorders (EDRs) entails a possibility to improve the measurement quality, both regarding validity and reliability

The aims of this lecture are to present injury risk functions based on real-life frontal crashes with crash severity measured with on-board crash pulse recorders and to show how such information can be used in effectiveness studies using dose-response models, both regarding safety technology already introduced, but also regarding technologies to be introduced.

DOSE-RESPONSE MODELS: Three aspects of an accident sample are important for the analysis of safety systems: frequency of collisions, frequency of injured occupants and injury risk versus impact severity, as illustrated by the three curves in Figure 1. In several studies these three curves have been assessed and used in analyses, eg Korner (1989), Evans (1994), Norin (1995), Mertz et al. (1997) and Kullgren (1998). This way of describing the three aspects of accidents can be denoted as a dose-response model. The dose is the input, the impact severity, and the response is the injury outcome. The link deciding the response of the dose is the injury risk function.

There are mainly three possibilities of reducing the number of injured occupants in car collisions; by reducing the severity of the impacts (1), or by reducing the number of collisions (2), or by reducing the injury risk at a given impact severity (3). The three possibilities are illustrated in Figure 1 by the arrows at numbers 1, 2 and 3 (from Kullgren 1998). The first possibility can be achieved by, for example, reducing speed limits, or by reducing impact speed or by redesigning the infrastructure. The second can be achieved by active safety measures aimed at preventing collisions from occurring. The third possibility addresses the passive safety of both vehicle and road infrastructure to prevent injuries to occur.

Safety technologies aimed at mitigating crash severity and at increasing the protection by preparing for a crash situation may address all of these three possibilities. And combining the possibilities will probably be the most effective way to proceed.

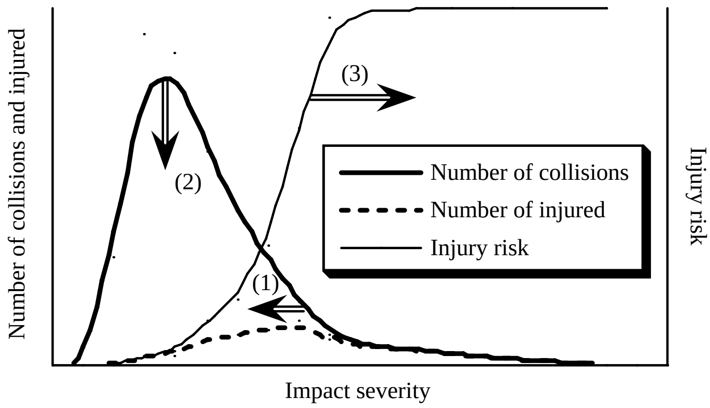

Fig. 1. Dose-response model including the three methods of reducing the number of injured occupants shown by moving the curves in the directions illustrated with the arrows at numbers 1, 2 and 3

INJURY RISK: The risk as a function of impact severity is often described as an S-shaped curve (see for example Korner 1989, Gabauer and Gabler 2006). The shape of the risk-curve depends on for example variations in biomechanical tolerances and the particular circumstances of each collision, such as type of restraint systems, restraint use etc. Furthermore the shape depends on what specific impact severity parameter is chosen, hence accurate knowledge of risk functions is important in injury preventive work. When these curves are drawn, errors can be foreseen in the estimate of the impact severity. Classification errors and biological variation in the injury outcome may also occur. An accurate knowledge of the risk function requires accurate measurements of both the impact severity and the injury outcome (Blalock 1981, Kullgren and Lie 1998).

Traditionally, crash tests with volunteers or animals have been conducted to gain knowledge of injury risk. Studies aimed at evaluating injury risk curves based on real–life crashes are not as common, but several studies have been presented (see for example Kullgren 1998, Kullgren et al 2000, Krafft et al 2005, Gabauer and Gabler 2008).

INJURY RISK FROM CRASH RECORDER DATA

FRONTAL IMPACTS: Since the 70’s several crash recorders or event data recorders (EDRs) have been used around the world. However, studies based on such recorded data are rare. Studies from three databases have been published. One is from the USA covering EDR data collected by NHTSA (see for example Gabauer and Gabler 2006 and Gabauer and Gabler 2008). Another is from Volvo (see for example Andersson et al 1997 and Gillander and Länje 1998). Several papers have been presented based on Swedish crash recorder data from Folksam. Summaries from some of these studies will be presented further.

In 1991 Folksam introduced a crash pulse recorder (CPR), initiated and developed by Folksam with support from Bertil Aldman, aimed at measuring the acceleration time history during the impact phase of a car accident (Aldman et al. 1991, Kullgren et al 1995, Kullgren 1998).

Since 1992, approximately 250 000 CPR's have been installed in vehicles in Sweden, comprising 4 different car makes and more than 20 models aimed at measuring frontal and rear-end impacts. The car fleet has been monitored since 1992. The results in figures 2 to 5, presented below, include impact severity and injury data for drivers and front seat passengers in 550 frontal impacts with an overlap of more than 25% (measured as the proportion of the front that was deformed) and with an angle within +/- 30 degrees. Another inclusion criterion is a repair cost of at least 7000 USD. Only restrained occupants were included. Belt use was verified from inspections of the seat belt systems. The injuries were collected from hospital records, questionnaires sent to the occupants or from insurance claims. The injuries were classified according to the 2005 revision of the Abbreviated Injury Scale (AAAM 2005).

The impact severity measurements were divided into intervals for each severity parameter. For delta-v the interval is 10 km/h and for mean acceleration 3 g. Injury risk was plotted and calculated as the proportion of injured occupants in each interval. In all plots the injury risk for each interval was plotted. To illustrate the shape of the injury risk versus impact severity, "smooth curve fits" in the software Kaleidagraph (Synergy Software 2000) were used to connect the observations. No mathematical injury risk functions were calculated.

The first two plots show frequency of collisions for intervals of impact severity. The majority of crashes had a change of velocity between 10 and 40 km/h, see Figure 2, and between 3 and 9 g in mean acceleration, see Figure 3. The average change of velocity for the sample was 23.9 km/h and the average mean acceleration was 6.3 g. The risk to sustain an injury with a maximum AIS value of 2 or greater (MAIS2+) was found to be 20% at either a delta-v of 33 km/h or a mean acceleration of 8 g, see Figures 4 and 5. And the risk to sustain an injury with a maximum AIS value of 3 or greater (MAIS3+) was found to be 20% at either a delta-v of 55 km/h or a mean acceleration of 16 g. In the US data from Gabauer and Gabler (2008) the 20% risk of an MAIS2+ and MAIS3+ injury for a belted and airbag restrained occupants occurred at a delta-v of 31 km/h and 51 km/h respectively, see Figure 6. The study from Gabauer and Gabler was based on 145 crashes with GM cars in the USA, and the risk curves were based on logistic regression, which is different from the method used in the Folksam studies.

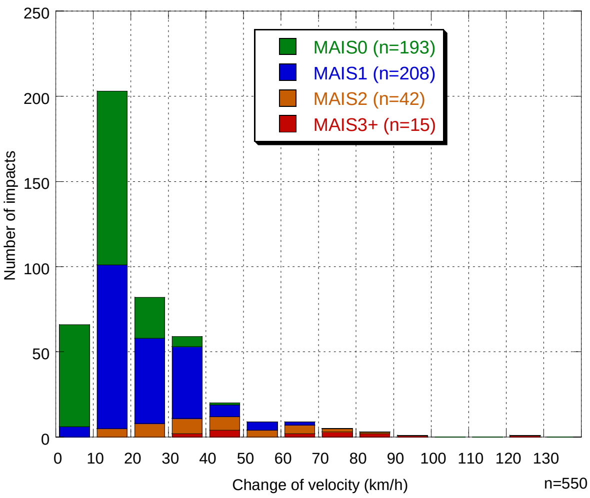

Fig. 2 - Number of crashes at different delta-v intervals of change of velocity in frontal impacts

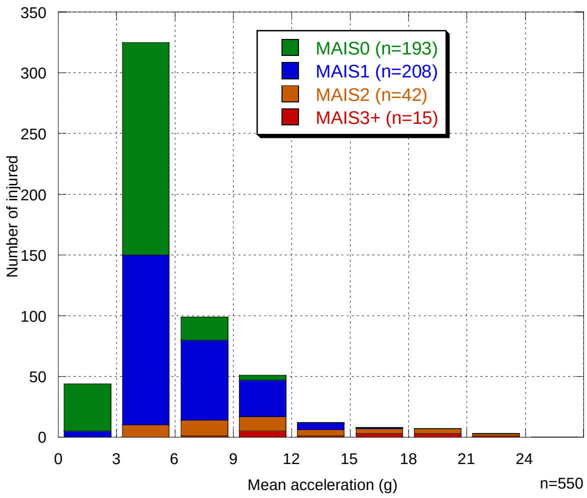

Fig. 3 - Number of crashes at different intervals of mean acceleration in frontal impacts

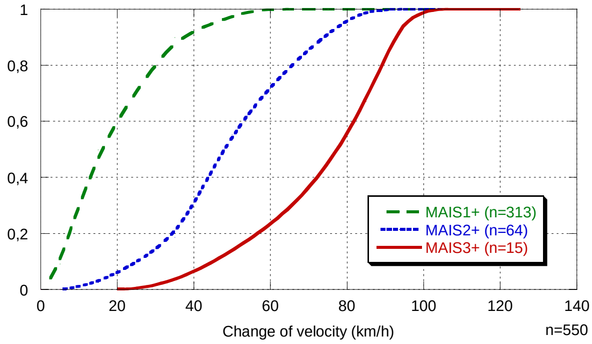

Fig. 4 - Injury risk, MAIS1+, MAIS2+ and MAIS3+ for front seat occupants versus delta-v in frontal impacts

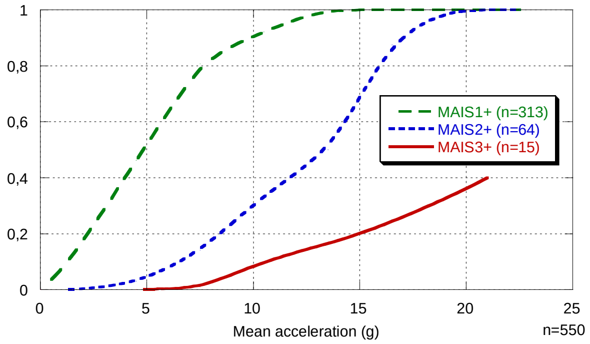

Fig. 5 - Injury risk, MAIS1+, MAIS2+ and MAIS3+ for front seat occupants versus mean acceleration in frontal impacts

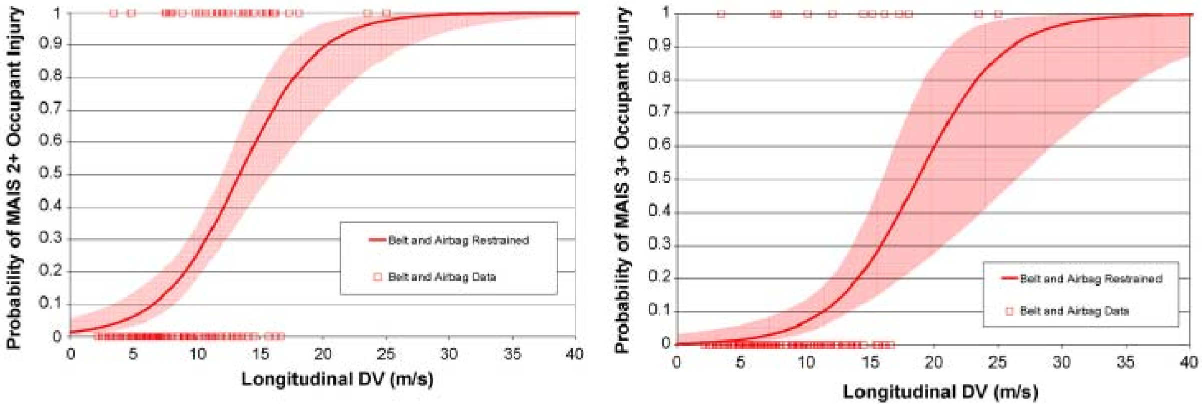

Fig. 6 - Injury risk, MAIS2+ and MAIS 3+, versus delta-v (Gabauer and Gabler 2008)

DIFFERENCES IN INJURY TOLERANCE: In designs of safety technology it is important to know the variation in injury tolerance for various populations or occupant groups. One example showing large differences in injury tolerance is occupant age (see for example Bedard et al 2002, Braver and Tremple 2004). The following example shows the risk for MAIS1+ and MAIS2+ divided for two age groups of front seat occupants, below and above 50 years age, see Fig. 7 and 8 (from Ydenius and Kullgren 2001). No major differences in risk of an MAIS1+ injury for the two age groups could be seen for either delta-v or mean acceleration. However, regarding MAIS2+ injury risk, older occupants were found to have higher risk.

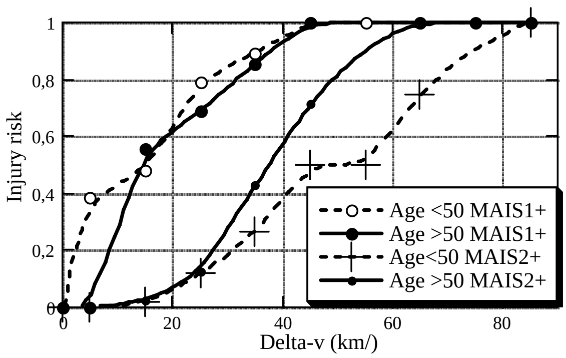

Fig. 7 - Injury risk, MAIS1+ and MAIS2+, for front seat occupants below and above 50 years age versus delta-v, n=216 (from Ydenius and Kullgren 2001)

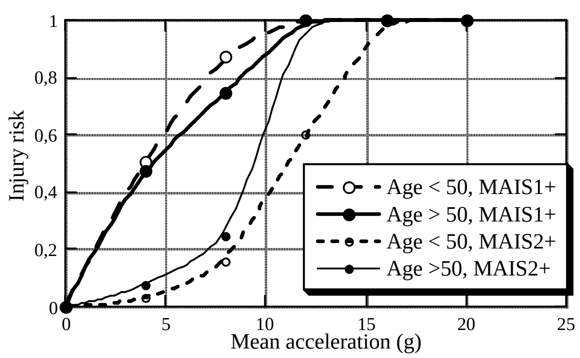

Fig. 8 - Injury risk, MAIS1+ and MAIS2+, for front seat occupants below and above 50 years age versus mean acceleration, n=216 (from Ydenius and Kullgren 2001)

WHIPLASH INJURY RISKS: Data from crash recorders has been especially useful regarding studies of whiplash injury risks. Many studies has been presented based on the Folksam crash recorder database, both regarding frontal and rear-end impacts. The next sections summarises the results from Krafft et al (2005).

<u>Whiplash injury risk in rear-end impacts:</u> Folksam crash recorders for measuring rear-end crashes has been installed since 1995 in Sweden, comprising 10 models of the same car make. All crashes irrespective of repair cost have been included.

Figures 9 to 12 show the latest published results regarding whiplash injury risk versus delta-v and mean acceleration (Krafft et al 2005). The study was based on 207 front seat occupants in 150 rear impacts with 8 car models of the same make. The whiplash injury status was defined according to symptom duration. Injury risk was calculated as the proportion of injured occupants in each interval of impact severity. Intervals with less than 3 observations were excluded in the plots. In order not to force the injury risk curve into a specific shape, no mathematical function was used. The risk values for all intervals were connected using “smooth” curve fit in the software KaleidaGraph (Synergy software 2000).

A correlation between injury risk and both crash severity measurements has been shown. The risk of more long-term symptoms exceeds 20% above approximately 20 km/h or 5 g for the car models included in the study. Studies have shown that whiplash prevention system may reduce the whiplash injury risk with more than 50% (Kullgren et al 2007, Kullgren et al 2008). Large differences in injury risks for various car models could therefore be anticipated. The information in figures 9 and 11 will be used further to demonstrate the possible effect of collision mitigation braking systems in rear-end crashes.

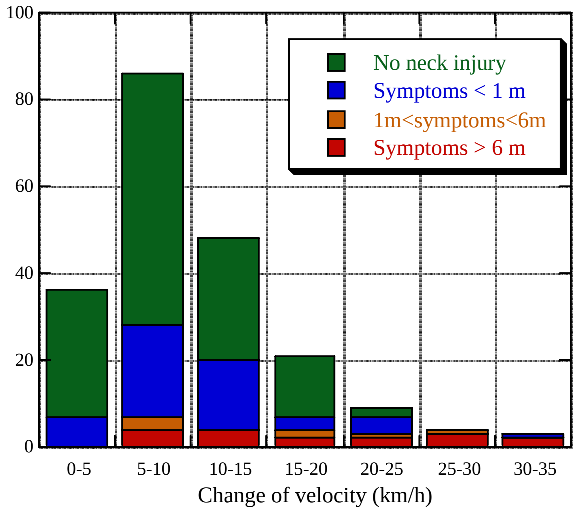

Fig. 9 - Numbers of injured and uninjured occupants in intervals of change of velocity

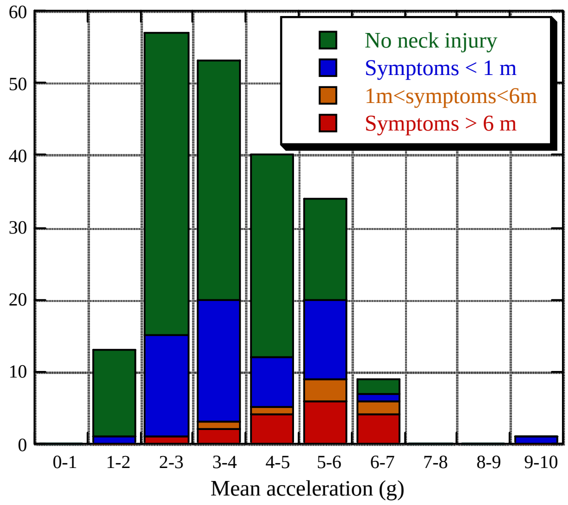

Fig. 10 - Numbers of injured and uninjured occupants in intervals of mean acceleration

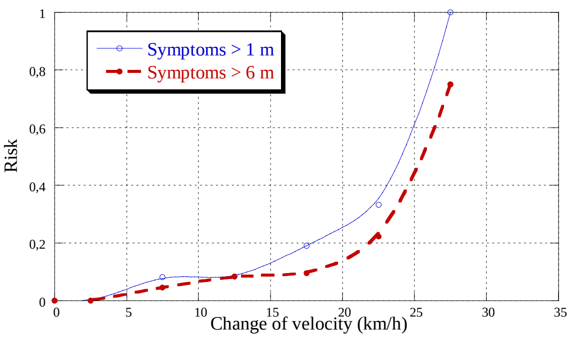

Fig. 11 - Risk of whiplash symptoms versus versus change of velocity in rear-end impacts

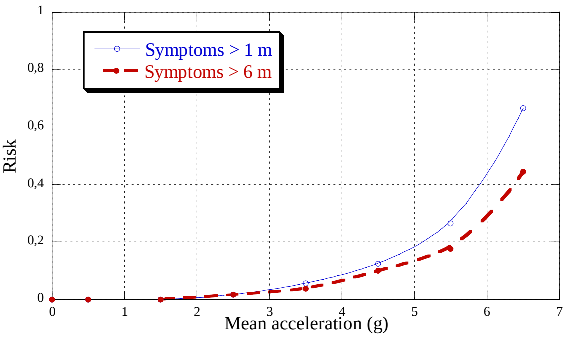

Fig. 12 - Risk of whiplash symptoms versus mean acceleration in rear-end impacts

Whiplash injury risk in frontal impacts: For some body regions the injury risk curve is not continuously increasing. Figures 13 and 14 show risk of AIS1 neck injury in frontal collisions (European Commission 2004). For both delta-v and mean acceleration the risk decreases in the mid severity segment. The drop in risk seems to a large extent to be explained by the positive effect of driver airbags, which has been shown to dramatically reduce the risk of AIS1 neck injuries in frontal impacts (Kullgren et al 1999, Morris et al 1999, Kullgren et al 2000). Figure 15 shows an example from Kullgren et al (2000). As the probability of airbag deployment increase, the risk curves for cars with and without airbags separates.

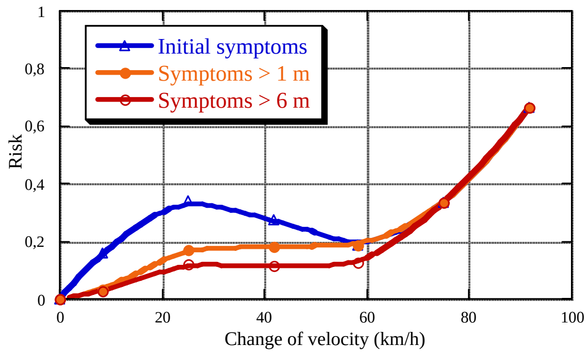

Fig. 13 - Risk of initial and long lasting symptoms versus change of velocity in frontal impacts

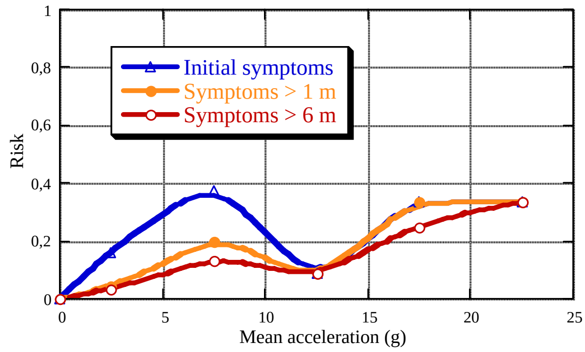

Fig. 14 - Risk of initial and long lasting symptoms versus mean acceleration in frontal impacts

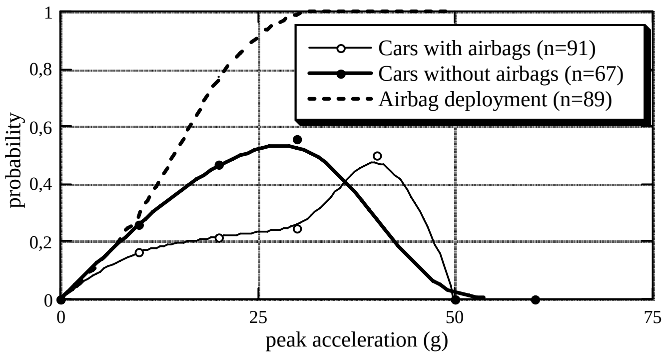

Fig. 15 - Probability of airbag deployment and neck injury risk for cars with and without airbags versus peak acceleration (from Kullgren et al 2000)

ACCIDENT RECONSTRUCTION USING CRASH SEVERITY DATA FROM EDRs

Several studies have been presented in the area of accident reconstruction with recorded crash pulses as input (see for example Kullgren et al 1999, Bohman et al 2000, Kullgren et al 2003, Linder et al 2004, Eriksson and Kullgren 2006). All of these studies concerned AIS1 neck injuries in frontal and rear-end crashes. The reconstruction can be made using either sled tests (Linder et al 2004) or by using computer simulations with numerical models. In such studies it is important to have valid models, numerical or physical, of the car seat, the restraint technologies and the occupants to be studied. The reconstruction technique is useful to study for example how well various injury criteria correlate with real-life injury outcome.

FRONTAL IMPACTS: The following example is from a study made together with Chalmers University of Technology in 1999 (Kullgren et al 1999). Frontal impacts with recorded crash pulses were reconstructed using MADYMO simulations. Figure 16 shows a plot of delta-v and peak acceleration for all included crashes to be reconstructed. Two crashes labelled A and B representing crashes with similar delta-V but different acceleration can be seen, the pulses are presented in Figure

17. The driver in Case A sustained a severe neck injury, while the driver in Case B was uninjured. The dummy readings from the reconstruction showed very different results in these cases.

A further comparison of these two simulations was made by comparing the animations of occupant response. Figure 18 represents three discrete times during the collisions, overlaying the occupant motions from both cases. After 66 ms, Case A has resulted in a larger occupant translation and head rotation. The last image at 90ms represents the most significant difference between the two cases. The injury case is reflected by a more pronounced head rotation and forward displacement of the occupant. The non-injury case exhibited lower values for all occupant parameters recorded.

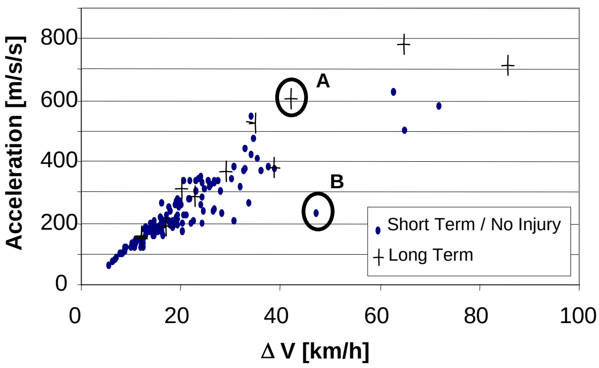

Fig. 16 - Head accelerations as a function of ΔV

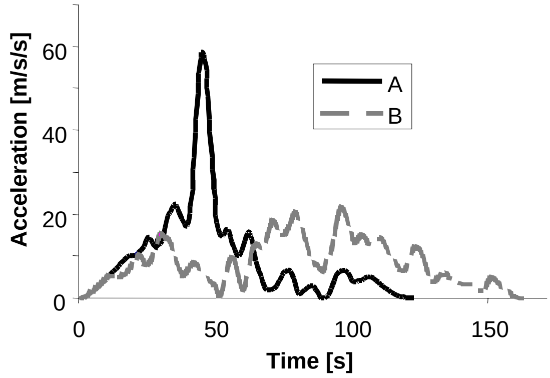

Fig. 17 - Crash pulses of similar crash severity

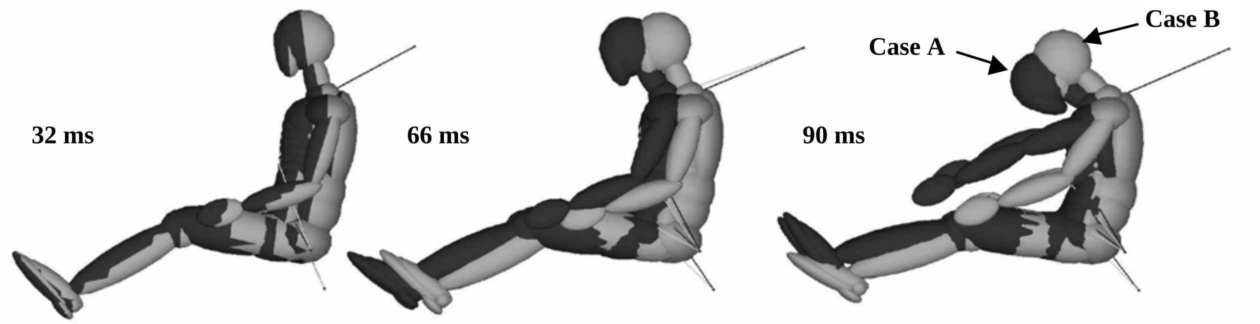

Fig. 18 - Simulated occupant response during two crashes with similar delta-V, 42 km/h (injury) and 47 km/h (no injury)

REAR-END IMPACTS: To study how well various neck injury criteria mirror whiplash injury risk, computer simulations with numerical models of the seat and the dummy can be conducted. This has been done in some studies (Kullgren et al 2003, Eriksson and Kullgren 2006). In Kullgren et al (2003) injury risk was presented for some proposed whiplash injury criteria. Figures 19 and 20 shows risk for initial whiplash injury symptoms and those lasting for longer than one month for NIC_{max} and N_{km}.

In the same study, the proportion of occupants with symptoms longer than one month, above and below a threshold (positive and negative predictive values), was studied for some whiplash injury criteria, see Table 1. For example, at a sensitivity of 0.77, the probability that an occupant is injured and correctly classified as injured was found to be 34% ± 17% for NIC_{max} and 77% ± 23% for N_{km}. The probability that an occupant is uninjured and correctly classified as uninjured at the sensitivity of 0.77 was between 94% and 100% for N_{km}, and between 92% and 100% for NIC_{max}. The lower neck moment showed lower predictive values.

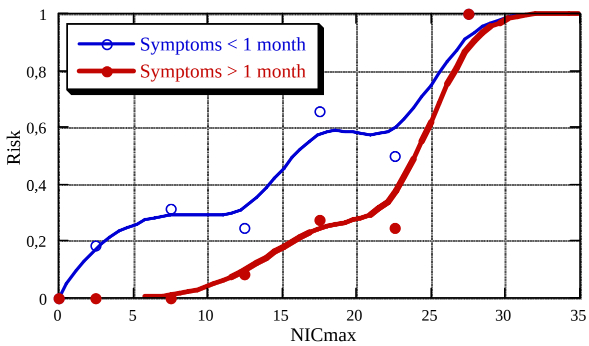

Fig. 19 - Neck injury risk versus NIC_{max}

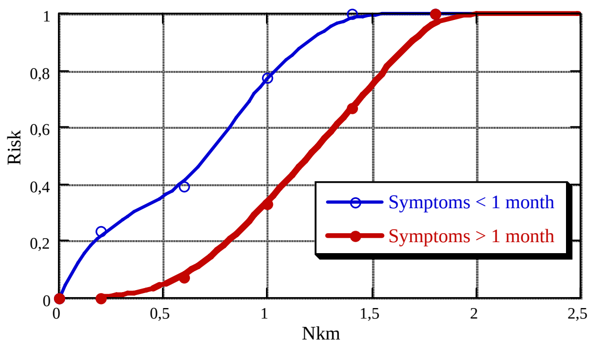

Fig. 20 - Neck injury risk versus N_{km}

Table 1. Positive and negative predictive values for occupants with symptoms more than one month

Injury criterion	Threshold*	$P_{specificity}$	Proportion of occupants **with** symptoms > 1 month above threshold (Positive Predictive Value)	Proportion of occupants **not** having symptoms > 1 month below threshold (Negative Predictive Value)
	P_{sens} = 0.77			
NICmax	16.04	0.80	10/29 = **34%** ± 17%	78/81 = **96%** ± 4%
N_{km}	0.9815	0.97	10/13 = **77%** ± 23%	94/97 = **97%** ± 3%
My	4.34	0.32	10/76 = **13%** ± 8%	31/34 = **91%** ± 10%
NIC-MIX	3.80	0.98	10/12 = **83%** ± 21%	95/98 = **97%** ± 3%
	P_{sens} = 0.92			
NICmax	15.30	0.75	12/36 = **33%** ± 15%	73/74 = **99%** ± 2%
N_{km}	0.4809	0.75	12/36 = **33%** ± 15%	73/74 = **99%** ± 2%
My	3.97	0.26	12/84 = **14%** ± 7%	25/26 = **96%** ± 8%
NIC-MIX	2.32	0.73	12/38 = **32%** ± 15%	71/72 = **99%** ± 2%

*Thresholds were chosen as the levels for each injury criterion where the proportions of occupants with symptoms > 1 month where 10/13 and 12/13. This means that the sensitivities chosen were 0.77 and 0.92 respectively.

EFFECTIVENESS STUDIES

When analysing how different approaches described in Figure 1 may reduce injuries, the three different approaches can be studied separately. Figure 21 show data picked from the figures 2 and 4. If the injury risk remains the same, a reduced delta-v with 10 km/h would reduce the number of MAIS2+ injuries with 44%, see Figure 22. A reduced number of collisions with 44% would of course also result in the same injury reduction, see Figure 23. When studying the third possibility to reduce the injury risk, a car that could have the same injury risk, but for a 10 km/h higher delta-v, would also lead to the same reduction, see Figure 24.

Similar reductions could also be achieved by reducing mean acceleration instead of change of velocity. In this case the information in the figures 3 and 5 could be used. Reducing means acceleration is probably more relevant to use in the design of road infra structure, such as posts, guardrails and median barriers.

In Figure 25 the safety level of new car models with older models of the same make is compared. The risk of MAIS1+ and MAIS2+ injuries are shown. Using this kind of technique, the reduction in MAIS2+ injuries can be calculated to 27%, see Figure 26.

AUTOMATIC BRAKING SYSTEMS: As mentioned earlier, dose-response models may successfully be used to study effectiveness of new safety technologies aimed at mitigating crash severity, preparing for crash protection or even avoid collisions. In this case some estimations must be made and at least one of the functions need to be known depending on what to be analysed.

If the injury or fatality risk functions as well as the crash distribution are known it is relatively straightforward to estimate the effect on injury outcome depending on the crash severity possible to be reduced. As an example, if a new technology could reduce the impact speed with 20 km/h at all travel speeds, this would lead to a reduction in number of MAIS2+ injuries with 44% when using the same injury risk and crash distribution as shown in Figure 21, and with the assumption that the reduction in change in velocity would be 50% of the reduced travel speed. Due to the fact that single-vehicle crashes account for half of the crashes, that assumption gives an underestimated reduction. If the reduction in impact speed could be 40 km/h, the injury reduction would be 70%, with the same assumptions.

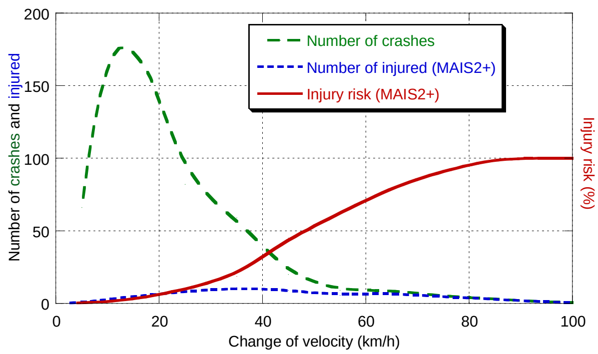

Fig. 21 – Dose-response model of car crashes

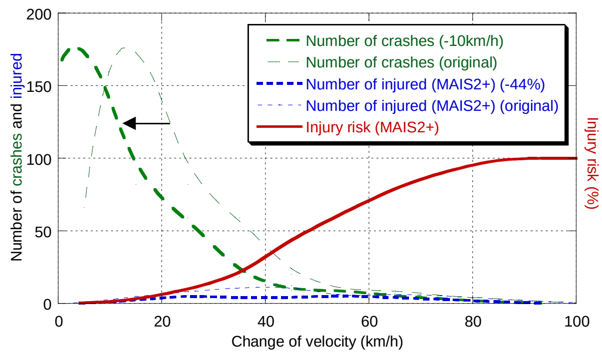

Fig. 22 – Reduction in injured occupant due to reduced delta-V

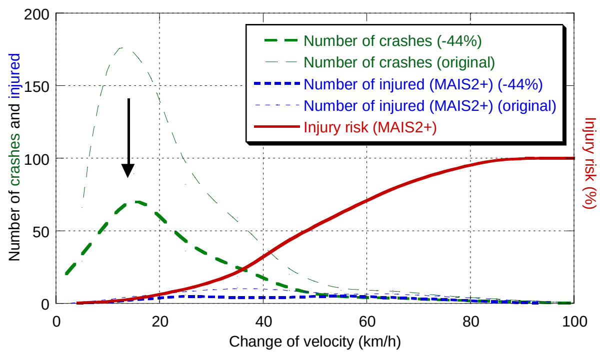

Fig. 23 - Reduction in injured occupant due to reduced number of crashes

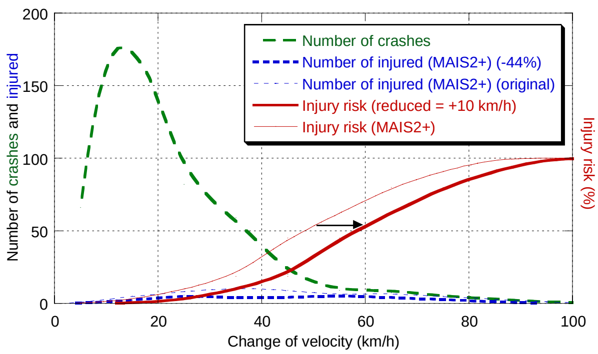

Fig. 24 - Reduction in injured occupant due to reduced injury risk

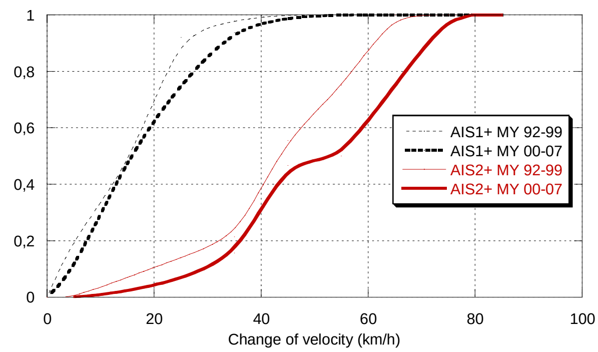

Fig. 25 - Injury risk, MAIS1+ and MAIS2+, for some car models and their successors

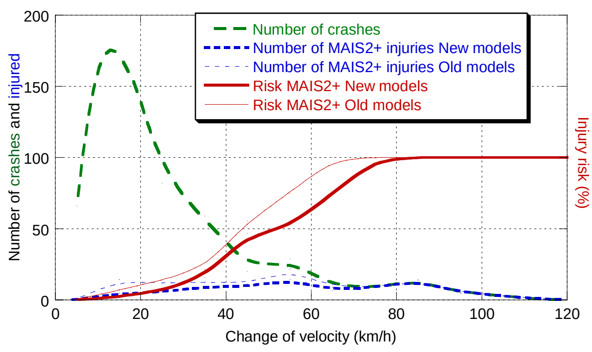

Fig. 26 – Numbers of injured occupants in some car models and their successors

In rear-end crashes, most often occurring at lower speed, there is a larger potential for improvement. Taking the risk curves and crash distribution presented in figures 9 and 11, the same analysis can be made as for the frontal impacts. If a system would be able to reduce the impact speed with 20 km/h, the effect on the number of occupant with long-term whiplash symptoms could be reduced significantly. Figure 27 shows the dose-response model for this rear-end crash scenario. Since all rear-end crashes can be regarded as car-to-car crashes, the reduction in delta-v would be approximately half of the reduction in impact speed. The number of occupants with symptoms lasting longer than 1 month was 24. Reducing the impact speed with 20 km/h would mean a reduced delta-v with 10 km/h. That would lead to a reduction in injured occupants with 83%. One manufacturer has presented a system that automatically brakes in rear end crashes with 15 km/h at impact speeds below 30 km/h (Volvo City Safety). The effect would be somewhat lower, approximately 60%, with the same assumptions.

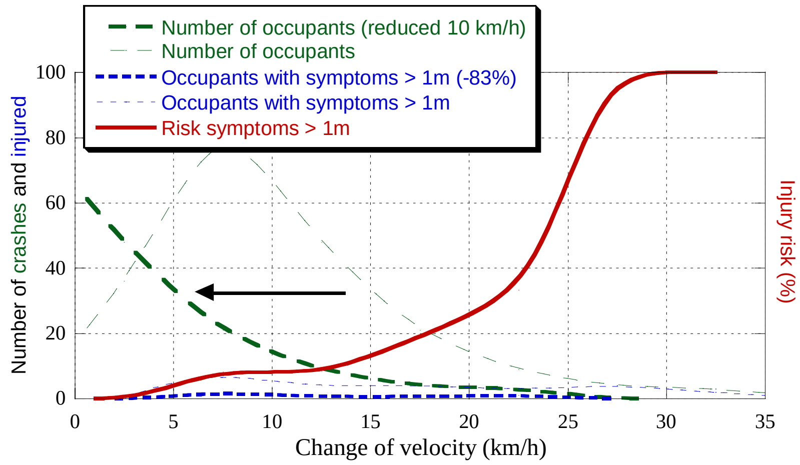

Fig. 27 – Dose-response model for rear-end crashes

DISCUSSION AND CONCLUSIONS

As long as crashes will occur there is a need to have knowledge of human injury tolerance and of biomechanics. Many of the new safety technologies, some already introduced and many more that will come, will focus on crash severity mitigation and to prepare the safety systems for crash in order to increase the crash protection. The combination of reduced risk and reduced crash severity has the potential to fully solve the problem of road traffic injuries. If a crash is detected 1 or 2 seconds before the crash, it will mean a lot in the possibilities to reduce the impact speed and to increase the crash protection. Braking with 0.5 g for 1 second leads to a reduction in impact speed of 18 km/h. Such reduction will lead to major reductions in number of seriously and fatally injured. As have been shown in this lecture the number of MAIS2+ injuries can be reduced by approximately 40%. The reduction in MAIS3+ injuries will be larger. And the combination of increased crash protection and reduced crash severity would lead to even larger reductions.

Lots of new safety technologies are introduced every year. It is important that the effectiveness of these systems is verified or estimated shortly after introduction or even before introduction. Such information is important also for governments and insurance industry, which can play an important role in the implementation of new safety technologies. But, in order to push for the most effective technologies, there is a need to identify the ones with highest effectiveness.

This lecture has demonstrated that dose-response models are useful in analyses of effectiveness and benefits of safety technologies. It is possible to estimate the potential in different approaches to reduce injuries in road traffic accidents. The method can successfully be used also to study the effectiveness of safety technologies aimed at mitigating crash severity.

Better quality of real-life data is necessary to be able to do such analyses. EDR data will increase the quality. Lots of cars are to date fitted with EDRs, but very few data collection systems including EDR data exist. There is a need for more and larger databases that includes EDR data.

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