Strategies to Optimise Car Safety for Real-world Collisions

Pete Thomas
Vehicle Safety Research Centre
Loughborough University
United Kingdom

Abstract

The concept of risk of injury is introduced and used to illustrate a number of crash scenarios. Injuries are shown to be a consequence of both risk and exposure. The separation of the injury risk and exposure curves by the reduction in injury risk for common conditions is seen as one goal of the vehicle safety engineer. Single point testing is compared with a population approach and the scenario of good performance in a crash test and poor performance overall is illustrated. Both high and lower speed testing is recommended to control injury risks across the collision severity spectrum. Higher speed crash testing has the potential to reduce intrusion related injuries considerably in frontal crashes with the possibility of these being partially offset by an increase in lower speed acceleration injuries. Real-world crash injury data is evaluated to quantify injury risks. Fatal injuries are shown to be sustained with a median EES of 70 km/h and substantial reductions are not anticipated following the 1998 Front impact Directive. A range of other factors contributing to injury severity in real world crash victims is identified. Finally measurement of injury risk curves of current car models is suggested as a method to further develop the practical application of injury risk management.

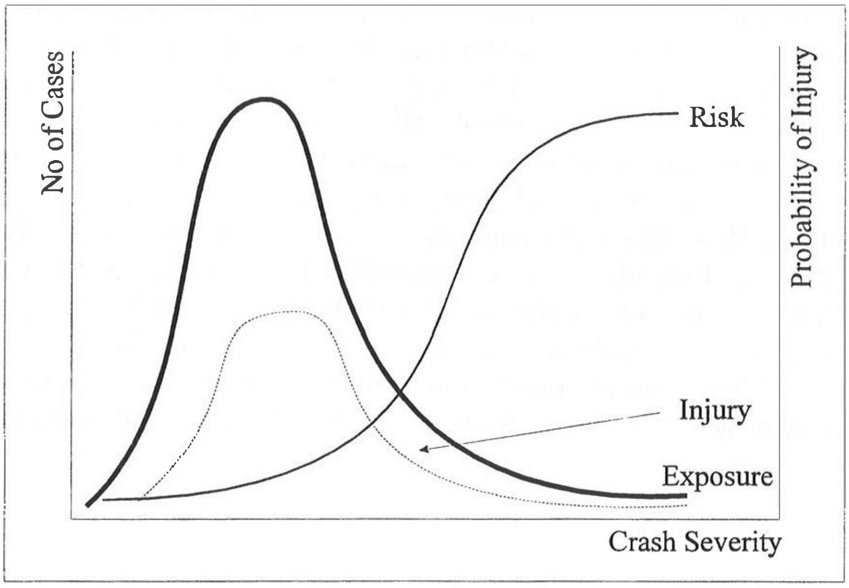
Background

The management of risk and exposure to risk is a concept frequently employed in epidemiology. However its application to vehicle safety is uncommon and little understood. The concept of risk as a continuous function of crash severity was applied by Schmid [1] who conducted an analysis of a vehicle structure to show that a crash test that was at too high a speed could increase injury risk. The assessment of injury risk has been identified by Korner [2] as a practical and promising evaluation instrument to aid vehicle design for real-world conditions. He presented a method that was a useful tool for selecting between design options. Norin[3] developed the method to show that a restraint designed for good performance at a high speed might give an inferior performance and hence greater injury numbers at lower speeds. Norin[4] [5]then showed a method that combined crash injury data with dummy data from experimental and simulated crashes. The method has been used to predict the performance of a vehicle before it gains much real-world crash experience.

EXPOSURE, RISK AND INJURY OUTCOME

Distributions of natural phenomena frequently show similar characteristics. The basic shape is often a normal distribution and this may be skewed to one side. The distribution of crash severity, measured in real-world collisions, shows such a skewed distribution (Figure 1). The modal value of the curve is determined by the case selection methods and the subject population. The lowest severity crashes may be excluded by the sampling requirements, for example if a towaway criterion is used, or they may simply not be reported, for example minor parking collisions in an insurance based sample. Relatively few vehicles travel at the highest speeds so collisions are less frequent, representative crash samples typically have over 90% of their collisions occurring below 56 km/h however most fatal collisions occur above this speed.

Figure 1: Characteristics of risk, exposure and injury curves



The risk of a particular injury is a concept frequently used in epidemiological analysis [6]. A range of responses is normally observed when assessing the effects of exposure to an injurious material, at any particular dose there will be some individuals who have an adverse reaction and others who do not. At low dosage levels the number of adverse reactions will be low but may not be zero, similarly at high levels these reactions will be frequent but there will be some who do not sustain an adverse reaction. The shape of the curve, describing the risk of adverse reaction from exposure to the dose is sigmoid and it is often fitted to a logistic, Weibull or probit curve. This dose-response curve can be applied to the relation between injuries of a particular type caused by a particular mechanism and crash severity in collisions.

The collision severity can be considered as the dose while the risk of an injury is the response. Injuries are sustained at all points in the crash severity spectrum and the numbers are a consequence of both exposure and injury risk. Figure 2 illustrates the risk and exposure curves together with the number of injuries sustained. Three zones can be identified where injuries are sustained. Zone 1 has the characteristics of low risk of injury but high exposure, Zone 2 shows medium levels of both parameters while Zone 3 has a low exposure but high levels of injury risk when a collision does occur. It can be observed that Figure 2 illustrates the conditions where the majority of injuries are sustained in Zone 1 - high exposure and low risk, few occur in Zone 3. In real-world collisions, of course, other exposure and risk curves may be found and either Zone 2 or Zone 3 could be the main zone for injuries. Figure 3 shows the conditions where the risk of injury has been reduced for the more frequent crashes and injuries are only sustained where the risks are high. One consequence of this is that the total number of injuries has been reduced.

Figure 2 : Injury causation zones

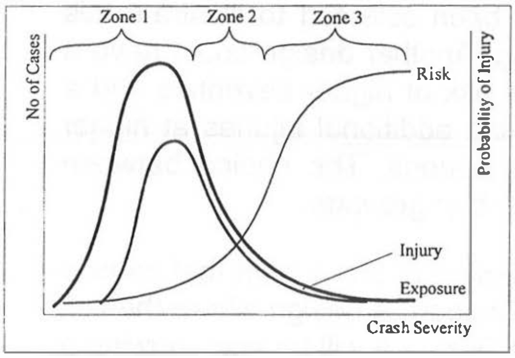
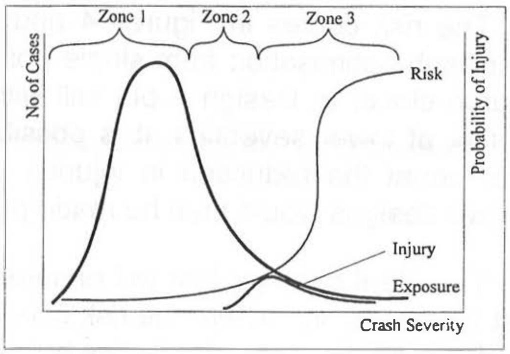


Figure 3 : Injuries sustained where injury risk is low



In general it is the goal of vehicle safety and traffic engineers to separate the risk and exposure curves so that risks are very low under the more common conditions. However this approach is not often adopted. More frequently a set of acceptance targets is adopted for a new vehicle design, performance below the target means that the design needs revision. These targets are typically generated from a number of sources including legal requirements, consumer organisation crash tests and in-house standards. Higher speed tests are used to evaluate injury potential while lower speed tests are used to evaluate sub-system performance (e.g. airbag fire/no fire). Essentially these tests are a collection of individual conditions - single point tests - rather than a group intended to optimise safety for the whole crash population. In a given crash test, dummy measures and other vehicle response indices must lie below a stated value. This type of requirement is readily incorporated to the engineering process, it is more difficult to use acceptance targets based on the performance of the car across the complete crash severity spectrum. However there are shortcomings to the conventional engineering approach since a good performance in a higher speed crash test does not automatically ensure the optimum performance over the whole range of crash severities.

SINGLE POINT TESTING AND POPULATION BASED PERFORMANCE REQUIREMENTS

During the design phase of a vehicle the engineer routinely has to make choices between alternative systems. Figure 4 illustrates the risk curves of two designs of car for one injury mechanism. A crash test carried out toward the higher end of the crash severity spectrum results in higher dummy readings for Design B. The design engineer, making a judgement on the basis of the crash test, would choose Design A as being substantially safer. Unfortunately at a lower crash severity the risk curves cross and Design A has the higher injury risk. Figure 5 enlarges the two injury outcome curves obtained by applying the risk curves to the population distribution. At higher speeds Design A results in fewer injuries than Design B however a greater number of crashes occur at lower speeds and the higher injury risk of Design A results in greater numbers of this type of injury overall.

The risk curves in Figures 4 and 5 have been selected to illustrate this effect of sub-optimisation from single point testing. Another design could have a risk curve closer to Design A but still with higher risk at higher severities and a lower risk at lower severities. It is possible that the additional injuries at higher speeds equal the reduction in injuries at lower speeds. The choice between these two designs would then be made purely on other grounds.

The ideal strategy that will ensure the selection of the design that causes fewest injuries is one where the risk curve is understood. A design where the risk curve, for example, consistently lies below that of Design A will be one showing a better all round safety performance.

Figure 4 : Comparison of designs

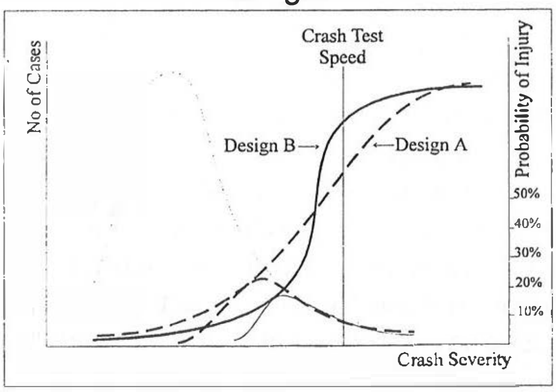
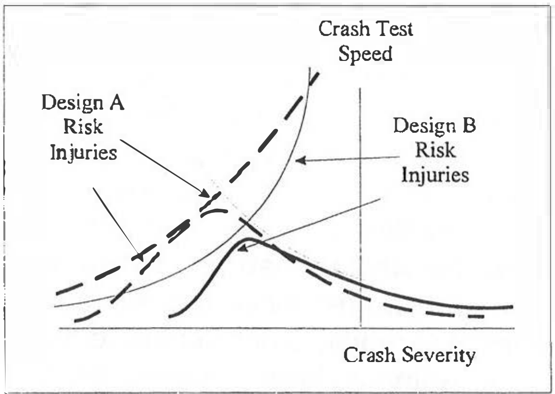


Figure 5 : Enlarged Injury outcome



Finally Figures 4 and 5 also illustrate that in this case it is possible to obtain a greater reduction in that type of injury by addressing the performance at lower speeds than at higher speeds. Real-world conditions can be more complex than the example would suggest as in practice many injury events tend to occur each of which can be modelled using risk analysis, given appropriate data. These factors are particularly important when considering the effect of increasing crash test speeds

EVALUATION OF INJURY RISKS - COLLISION SEVERITY

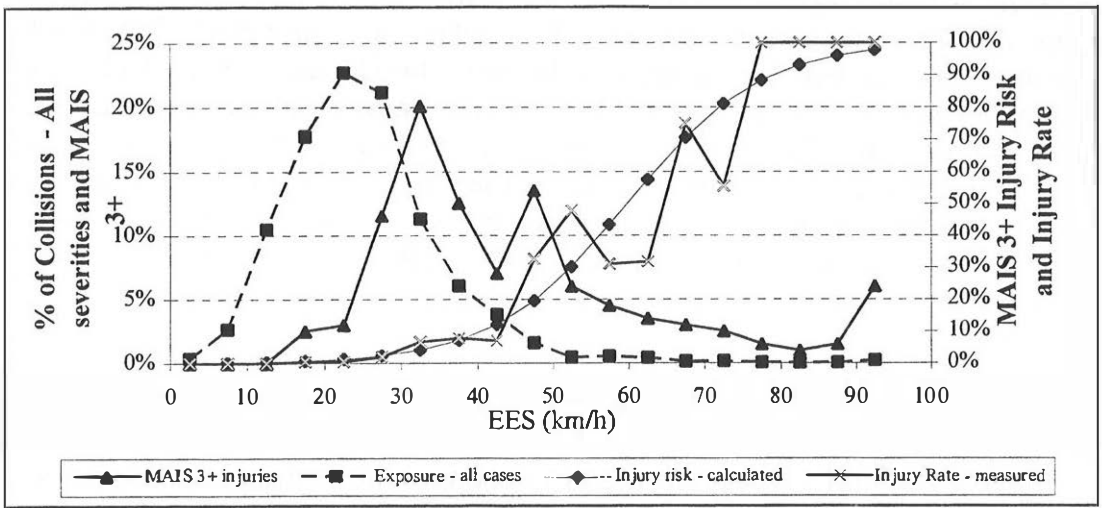
In-depth crash injury data is collected within the UK by the Co-operative Crash Injury Study (CCIS). When weighted the data is representative of the local population from which it is sampled. This local population is considered to be representative of the UK as a whole. Collision severity estimates are made using CRASH 3 on the basis of the deformation. This data can be used to quantify the injury risk and exposure curves defining EES as the measure of crash severity and MAIS 3+ injuries being those of interest. CRASH 3 may underestimate collision severity under certain conditions and, although it is the best tool available to estimate collision severity of modern vehicles it may be desirable to revalidate it against current car designs.

Figure 6 shows the distribution of EES for all frontal collisions in the data - a measure of exposure, together with that of the cases involving MAIS 3+ injury. The graph also shows the proportion of cases in each EES group that sustain MAIS 3+ injuries - the injury rate - and the logistic regression curve relating the risk of injury to EES.

The median EES for the whole population is 22 km/h and is 32 km/h for those cases with MAIS 3+ injury. From 1998 a European Directive will require a frontal crash test to be conducted at 56 km/h. The injury risk curve indicates that this corresponds to a risk of 39% of MAIS 3+ injury. 98% of crashes occur below this speed as do 70% of all MAIS 3+ injuries so the graph indicates that the majority of MAIS 3+ injuries in frontal collisions are generated under the conditions of low risk of MAIS 3+ injury with high exposure. Only 30% can be said to occur under conditions of high risk. The collision severity of the test in the Directive is therefore representative of the conditions where many of the MAIS 3+ injuries are sustained. However this is not true for fatal injuries. Figure 7 shows the cumulative collision severity distributions for all injury levels and fatalities for restrained drivers in frontal collisions. Only 33% of fatalities were involved in collisions below 56 km/h. The median severity was 70 km/h. The Directive does not therefore reproduce a collision where the typical outcome is a fatality. A crash test that is at a speed below the majority of injuries cannot guarantee that those injuries will be substantially reduced so a substantial decrease in fatalities as a result of the European Directive is not anticipated.

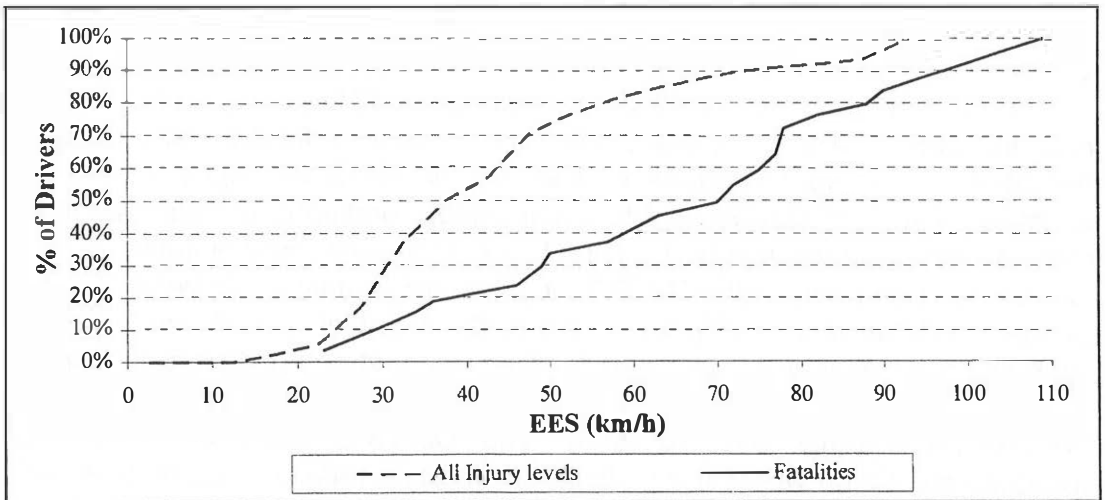
It is often assumed that the best way to increase the levels of protection offered to car occupants is to increase the speed at which crash tests are conducted while maintaining the same acceptance levels. The understanding is that this will inevitably reduce the risk of injuries at lower levels so that the car becomes safer overall. Figure 8 illustrates risk curves for two generations of a vehicle before and after the introduction of a higher speed crash test. The acceptance level indicates a constant set of dummy readings giving a constant level of injury risk for both vehicles. In order to meet the new requirement the risk curve must not increase at the new test speed.

Figure 6 : Quantified injury - risk curves for real-world crash injury data -EES - Frontal collisions



CCIS data 1992 - 1995

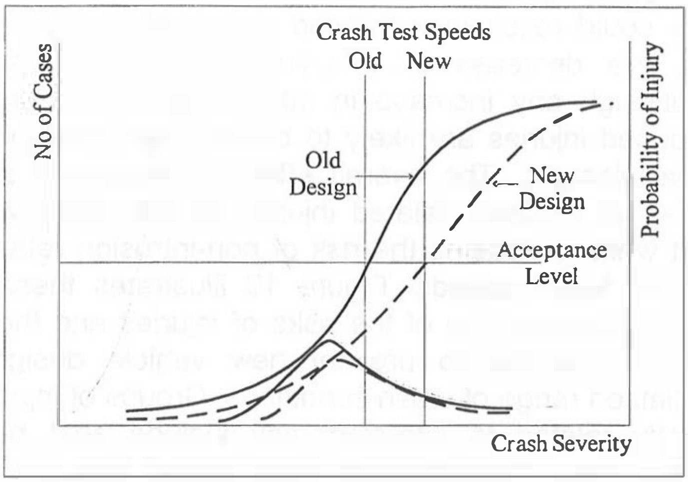
Figure 7: EES distributions for all injury levels and fatalities - Restrained drivers in frontal collisions



CCIS data 1992 - 1995

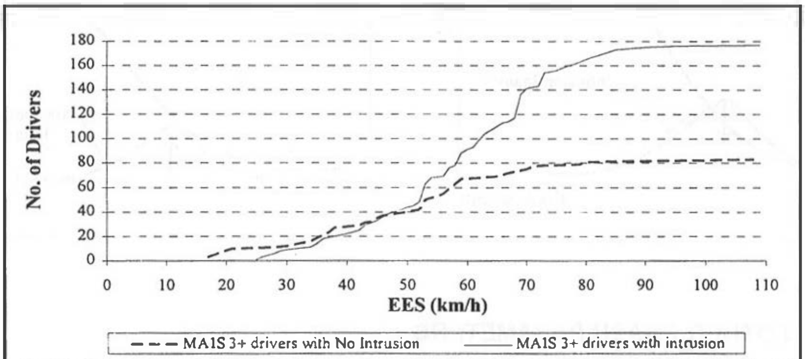
In the example illustrated the risk curve for the new design lies completely below that of the old design. The numbers of injuries are therefore reduced at all points of the crash spectrum and the new vehicle can be said to be safer than the old model.

Figure 8 : Change to higher speed crash testing with overall reduction in injury



Injuries sustained by car occupants fall into three causation groups - deceleration related, contact related and intruding contact related. These injury mechanisms can be combined for the purpose of deriving a risk function but disagreggation can allow an easier evaluation of the effects of each. Figure 9 shows the cumulative count of AIS 3+ injuries that occur in the presence of intrusion and those that occur with no intrusion. Overall 64% of drivers with AIS 3+ injuries experienced intrusion and this justifies the use of the offset deformable barrier which aims to reproduce the conditions where intrusion is sustained. However Figure 9 also shows that below 50 km/h there are as many AIS 3+ injuries sustained with as without intrusion. It indicates that both intrusion and deceleration are equally important in terms of outcome in this range.

Figure 9 : Intrusion and non-intrusion related injuries - Restrained drivers in frontal collisions

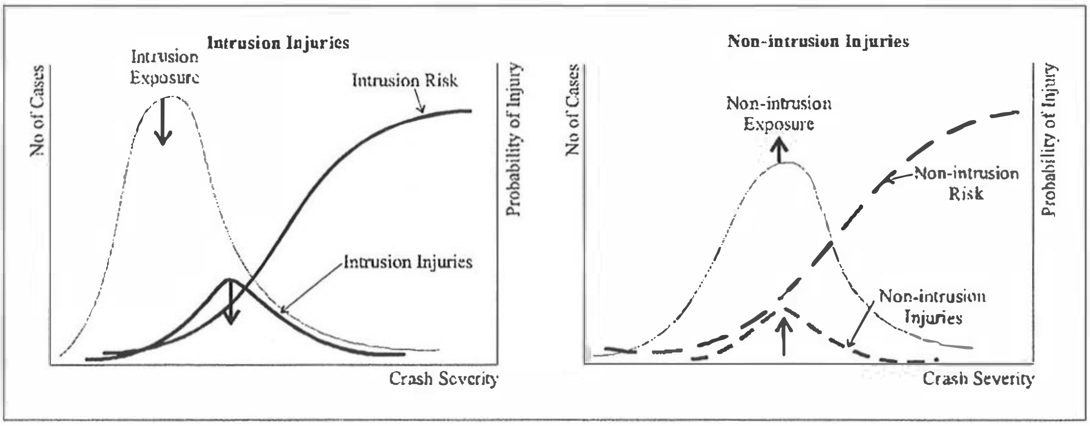


CCIS data 1983 - 1992

Improvements to vehicle structures in a car design that performs well in a higher speed crash will reduce the exposure to these conditions by reducing the number of intruding contacts. The numbers of intruding contact related injuries will therefore reduce at all speeds below that of the crash test. Since these types of injury are the most common the potential for injury reduction is reduction is the greatest. However an element of the design selected could include a stiffening of the car structure. Additionally the restraint system could be stiffened to prevent additional loads from intruding structure contact. Both of these factors could result in increased deceleration induced injuries at lower speeds. The decrease in intrusion related injuries is likely to substantially outweigh any increase in other injuries but, once achieved, deceleration induced injuries are likely to be the main component in future low intrusion car designs. The overall effect of increased stiffness is to decrease the risk of intrusion related injuries at the new crash speed so passing the test while increasing the risk of non-intrusion related injuries at the more common lower speeds. Figure 10 illustrates these effects and shows that a full understanding of the risks of injuries and the exposure to key conditions is essential to prevent new vehicle designs becoming optimised for a limited range of crash conditions. Groups of injuries which are not predominantly related to intrusion may include seat belt and child restraint related injuries. Also rear seat occupants of cars are not generally exposed to intrusion in frontal collisions.

The introduction of new types of requirement for vehicle performance may mean that old design protocols may no longer apply. The example above illustrates how a conventional response to the need to absorb higher crash energies by increasing stiffness may offset gains from intrusion reduction. New design strategies are needed to avoid this limitation in effectiveness in a cost competitive manner.

Figure 10 : Change to higher speed crash testing with changes in injury numbers

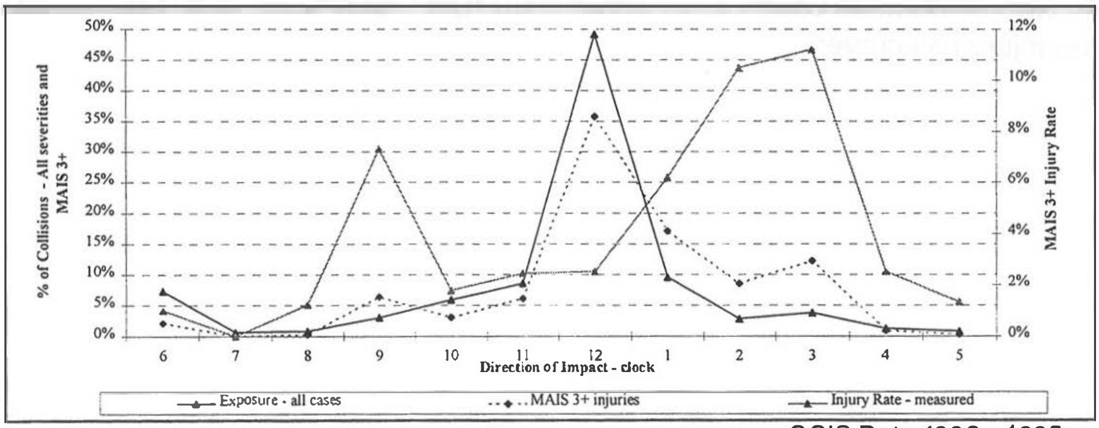


VARIATION IN OTHER CRASH PARAMETERS

Collision severity has been used as a factor to illustrate the variation of injury risk however it is not the only variable which has variation in real-world collisions and affects injury outcome. A range of parameters describing the collision, the vehicle or the occupants have a similar effect. Other examples include mass, collision direction, nature of the collision partner, gender, restraint use and casualty age. Intrusion has been shown to increase the risk of leg injury separate from the effects of collision severity. To properly understand the risks of injury associated with a vehicle design its performance must be evaluated across a range of typical conditions. The importance of each parameter must be evaluated to provide a suitable test matrix to ensure that vehicle performance is optimised for the full range of conditions experienced in real-world crashes.

IMPACT DIRECTION - Crash testing is typically conducted using perpendicular impacts - in the European front and side impact tests the barrier surfaces are parallel to the struck side. Although there may be a small degree of rotation of the applied forces they are essentially perpendicular to the surface. In the real-world there is again a considerable variation, shown in Figure 11. The straight-ahead direction 12 o'clock is the most common with 50% of all cases and 35% of all with MAIS 3+ injury. The rate of injury is measured to be 2.5% and is nearly the lowest out of all the forward directions. The injury rate shows a sensitivity to oblique directions, oblique impact directions of 1 and 2 o'clock show higher injury rates of 6% and 11%. These oblique impacts mark a transition from frontal to side collisions, 72% of the 1 o'clock impacts are to the front of the car while 85% of the 2 o'clock impacts are to the right side of the car. Occupants on the struck side in side collisions have a higher injury and fatality rate on account of the reduced opportunity for protection, particularly when the occupant is seated in the struck area. Additionally many of the cars in the sample were designed before the European side impact directive was anticipated. It is unsurprising that the injury risks in 2 and 3 o'clock impacts should be the highest. However the high injury rate for 1 o'clock impacts is less expected. This increase in injury rate is confirmed when oblique collisions involving the only front of the vehicle are considered. The injury rates of belted drivers rise from 3% to 13% in 2 o'clock impacts. Overall it can be said that collisions to the front of the vehicle are the most frequent but that the protection offered by restraints and the front structures show indications of being most effective in purely straight-ahead impacts, the systems operate less effectively even 30° away.

Figure 11 : Quantified injury - risk curves for real-world crash injury data - Impact Direction - Belted Drivers

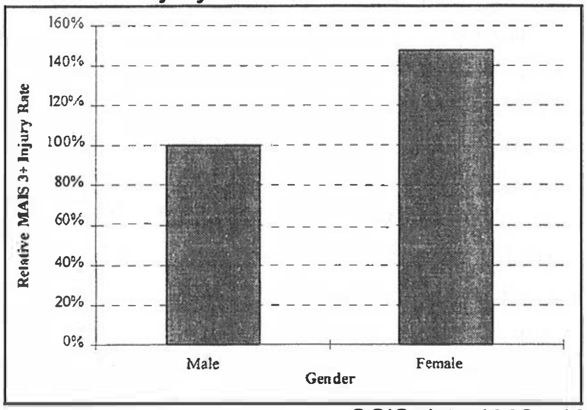


CCIS Data 1992 - 1995

The injury rates for the belted drivers in Figure 11 show a second peak for 9 o'clock impacts. Almost all of these are impacts to the far side of the car, the driver appears to be offered a low level of protection by the seat belt and other safety systems and the injury rates approach those observed amongst struck side drivers.

OCCUPANT PARAMETERS - GENDER - A variety of parameters describing the collision have been shown to relate to injury outcome, in addition characteristics of the occupants also increase injury rates. Gender is one of these characteristics, females differ from males in terms of stature, weight, injury tolerance, and in terms of the manner in which they use the vehicle. Figure 12 compares the MAIS 3+ injury rates of belted male and female drivers in frontal collisions. Females have a MAIS 3+ injury rate 48% greater than male drivers. While there is no formal requirement for crash tests to be conducted using other than 50 %ile male dummies, smaller and larger dummies are sometimes used for in-house standards. Despite this a difference in injury rates remains.

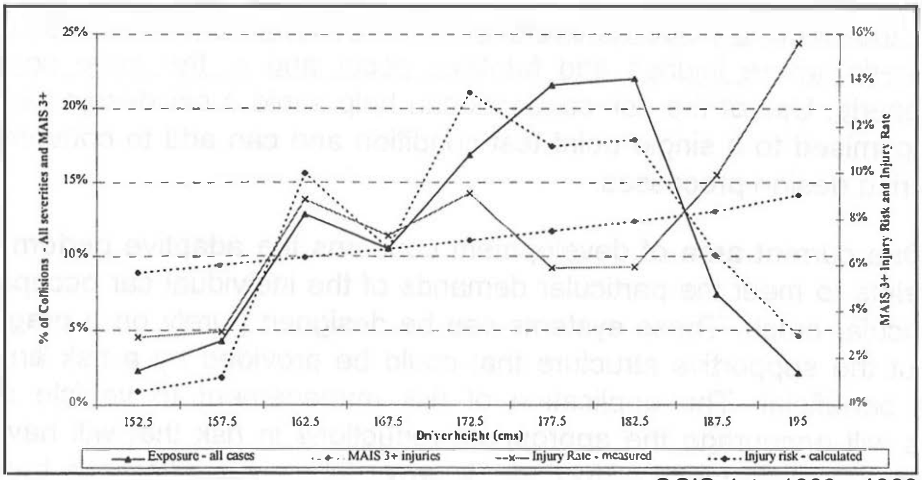
Figure 12 : Relative injury rate - male and female belted drivers



CCIS data 1992 - 1995

Not every occupant parameter clearly shows a variation in MAIS 3+ injury outcome in the real-world crash injury data. For example it might be expected that the height of belted drivers in frontal collisions would relate to injury with taller drivers being more likely to strike the steering wheel or dash. Figure 13 shows the variation observed in occupant height together with the injury rates and injury risk curves.

Figure 13 : Quantified injury - risk curves for real-world crash injury data - Occupant height



CCIS data 1983 - 1992

While the logistic regression curve indicates an increase in risk with height so that the risk rises from 6% for a driver 155 cm tall to 9% for one 190 cm, the observed injury rates do not reinforce this trend. Although not shown the corresponding graph for driver weight shows a similar pattern. It is likely that the influence of occupant height and weight is small compared to the differences between models of car; the crash parameters such as EES and mass ratio may well be more influential although the magnitude of the effects have not been compared in this analysis. These other factors may serve to mask occupant based effects. The analysis of a computer model of a dummy under controlled test conditions is expected to demonstrate the effects of varying occupant dimensions and would permit a precise evaluation of the change in injury indices.

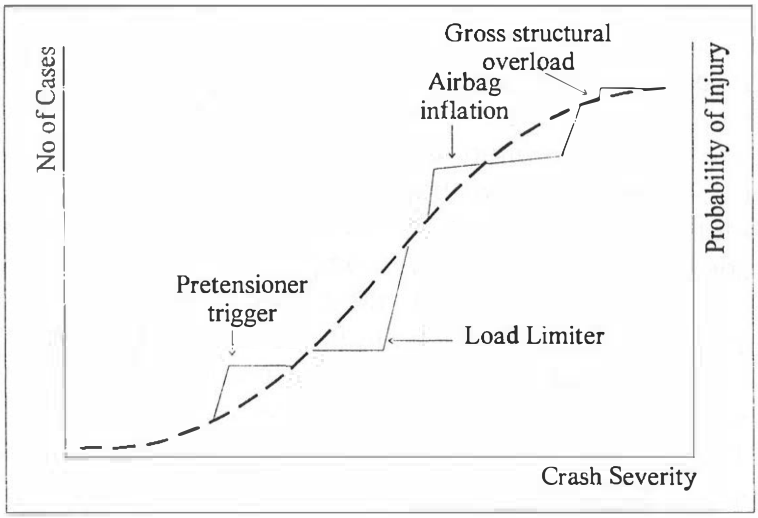
DISCUSSION

Vehicle safety design is traditionally conducted using a set of performance targets describing the response of the vehicle and dummies in a range of test conditions. There exists a set of legal requirements for the European market which are often reinforced by in-house targets. It is unusual for these test conditions to have been selected to provide a range that will ensure the safety performance of the vehicle is optimised for the complete range of crashes that occur with the complete range of occupants. Single point testing, as it has been implemented with current production vehicles, has resulted in vehicle designs which are in general markedly safer than older designs[7] [8]. This approach still has the potential to produce further improvements. However considerations of risk as illustrated in this paper, indicate that it is possible for a design of vehicle that performs well under one test condition, or a group of closely related conditions, to perform less well in the real-world. If the test conditions are at a speed significantly above the commonly occurring speeds it is possible for lower speed injuries to increase and more than equal any reduction in higher speed injuries.

An understanding of the underlying risk functions associated with the main crash parameters such as impact severity and mass ratio can provide a theoretical framework to support safety decision making. One key component involves the need to place requirements on vehicle performance both at the high speeds where injuries and fatalities occur and at the more common lower speeds. Use of the risk concepts can help avoid a car design which is highly optimised to a single point test condition and can add to conventional engineering design processes.

One current area of development concerns the adaptive performance of restraints to meet the particular demands of the individual car occupant in the particular crash. These systems can be designed purely on a pragmatic basis but the supportive structure that could be provided by a risk analysis can be beneficial. The application of risk management to vehicle safety systems will encourage the appropriate reductions in risk that will have the maximum effect on injury reduction. However there is a difference between the theoretical illustrations presented in this paper and the risk curves of real systems. The theoretical sigmoid curves obtain their shape from the variation in human response to a single event while a real-world collision involves a sequence of events intended to control risk under the crash test conditions. Pretensioners, load limiters and airbags may all deploy at different points in the crash sequence, the influence on the level of risk through the crash spectrum is not known. Figure 14 shows the injury risk curve superimposed with a series of hypothetical steps resulting from the activation of restraint components and the vehicle structure. The risk curves for a production vehicle are not published and it is not likely that many have been measured. The first step towards managing the risk is understanding the current variation of injury risk with crash parameters and an evaluation of the risk curves of individual models will be an important first step.

Figure 14 : Injury risk curve with modifications from vehicle safety systems



Much of the current discussion over injury risk, particularly that concerning the Euro-NCAP test procedures, has centred on collision speed.

This analysis has reaffirmed that speed plays a major role in the risk of fatal injury and that high speed testing is necessary to reduce fatalities. Many other collision parameters also affect injury risk, some have been examined here but a systematic evaluation is needed. In particular a number of casualty or injury groups may be sensitive to certain combinations of risk including, for example, infant - airbag interaction risks. A car design that performs well across the range of collision circumstances and for all occupants must be based on a safety strategy that takes account of these risk factors. Otherwise it is easy for vehicle design to become optimised to a single test condition and not achieve the lowest injury rates.

Management of the risk in collisions holds promise to further reduce the levels of injuries sustained by car occupants. The development of a framework to understand and measure the risk in real vehicle designs will provide a helpful first step.

CONCLUSIONS

- Improvements in vehicle safety can be obtained from consideration of the complete injury risk curves for a range of parameters.

- Crash testing under conditions that fail to reflect the complete range of collisions may result in designs that are not optimised for the whole crash population.

- High speed crash testing is necessary to reduce fatalities which occur with a median EES of 70 km/h in frontal collisions.

- The introduction of a higher speed crash test means it is likely that intrusion related injuries will decrease but the choice of less effective vehicle designs may mean deceleration induced injuries will increase.

- Both high and low speed crash testing is recommended as part of a strategy to optimise the overall crash performance of a vehicle.

- The injury risk in the crash population also depends on other collision and occupant parameters. A full assessment of the importance of these is required.

ACKNOWLEDGEMENTS

The Co-operative Crash Injury Study is managed by the Transport Research Laboratory (TRL) on behalf of the Department of Transport (Vehicle Standards and Engineering Division) who fund the project with Ford Motor Company Ltd, Rover Group Ltd, Toyota Motor Europe, Nissan and Honda. The data were collected by teams at the Vehicle Safety Research Centre at Loughborough University, the Accident Research Centre at the University of Birmingham, and from the Vehicle Inspectorate.

REFERENCES

[1] Schmid, W. A model to assess risk of injury in traffic accidents as a function of regularised impact speed. SAE paper 840864, 1984

[2] Korner, J; A method for evaluating occupant protection by correlating accident data with laboratory data. SAE 890747 1989

[3] Norin, H; Jernström, C; Koch, M; Ryrberg, S; Svensson, S. Avoiding sub-optimised occupant safety by multiple speed impact testing. Experimental Safety Vehicles Congress, 1991, Paris

[4] Norin, H; Isaksson-Hellman, I. Injury potential prediction of a safety design feature. A theoretical method based on simulations and traffic accident data. IRCOBI conference 1992, Verona

[5] Norin, H. Correlation of occupant injuries in traffic accidents and dummy responses in mathematical simulations. Accident Analysis and Prevention Vol 26, No 3, PP 277 - 286, 1994

[6] Finney, D J; Probit Analysis, Cambridge University Press, 1971, London

[7] Car Safety Rating Scale, Folksam Insurance . Stockholm 1996

[8] Choosing Safety, Department of Transport, London, 1995