THE DEVELOPMENT OF CAR SAFETY: PAST, PRESENT AND FUTURE

Adrian Hobbs

ABSTRACT

From its early beginnings, where improvements consisted of removing obvious hazards, improvements in car passive safety have developed to become one of the most effective ways of reducing road accident casualties. Accident studies identified the issues from which test procedures were developed. Knowledge and technical capability have determined the form of these tests and the tools available. Through their use in legislation and consumer information they have led to dramatic improvements and new knowledge of future problems to solve. For these tests to be effective an increasing knowledge of biomechanics is necessary and there is an urgent need for more research in this area. This paper gives the author's personal view on car safety developments and the requirements for biomechanical information to support future developments.

AUTOMOBILES, BIOMECHANICS, COMPATIBILITY, CRASHWORTHINESS, DUMMIES

FROM ITS EARLIEST DEVELOPMENTS to the sophisticated processes used today, improvements in car passive safety have provided for some of the greatest reductions in road accident casualties. It is frequently stated that the major benefits from improved passive safety have already been achieved but those deeply involved are aware that we are still only scratching the surface of the problem and that there is still much more that can be achieved. This presentation aims to show how car passive safety developments were made in the past and what is required for even greater improvements in the future.

Vehicle safety development is a multi-disciplinary subject requiring input from accident investigation, full scale and component testing, simulation modelling and car design. Essential support for this work comes from those developing anthropometric dummies and those providing biomechanical tolerance information.

The poor relation here is Biomechanics. It is relatively easy to demonstrate the benefits of crash testing to the public, policy makers and politicians. However, it is much more difficult to generate an enthusiasm for the collection of supportive biomechanical data, over a long timeframe. If further improvements in passive safety are to continue, the greater provision of new biomechanical data is essential.

PROCESSES AVAILABLE FOR IMPROVING CAR SAFETY

There are a number of driving forces available to bring about improvements in car safety. Governments may react to road accident casualty statistics by enacting legislation. Manufacturers may choose to improve the safety of the cars they build. This may be because they perceive that they will obtain a commercial advantage or avoid a commercial disadvantage by improving the safety of their products. Product liability may lead to improvements but it can also deter manufacturers from incorporating new technologies. Consumer information programmes, such as the European New Car Assessment Programme (Euro NCAP), can provide an additional incentive to manufacturers, as they perceive customer response to safety ratings (Hobbs and McDonough, 1998).

Figure 1 Little intrusion in 64 km/h offset impact with a modern car

To be effective, a consumer information programme must have credibility with the safety specialists in the car industry. It can then empower them, so that they can argue for a fair share of resources within their company and for a high level of safety to be an important goal for new designs of car.

Whatever mechanism is used to bring about greater safety, the essential tools must be available to aid the car safety engineer. Accident research can be used to identify the problems. Appropriate test procedures can be developed and these can be supported by computer simulation. To support all of this, human surrogates in the form of anthropometric dummies are required. To ensure their biofidelity, detailed biomechanical information is required. This biomechanical information also needs to include transfer functions to translate parameters measured on a dummy into injury probability for the relevant part of the human body. From this data, decisions can be made regarding the performance requirements for the tests.

THE DEVELOPMENT OF PASSIVE SAFETY IN CARS

When attention was first turned to the need to improve car safety, detailed accident studies helped to identify some obvious problems. It was relatively simple to see the major problems of the day: driver's head and chest injuries from intruded steering columns; lacerations from windscreen glass and unframed, rigidly mounted interior mirrors; occupant ejection through doors which burst open; penetrating injuries from strong projecting switch gear and head, chest and leg injuries from impacting stiff facias and parcel trays. Legislative standards were developed to remove these obvious hazards. To limit steering column intrusion, European legislation required its first crash test. This full width impact test into a rigid wall was solely concerned with preventing excessive steering column intrusion (ECE Regulation 12, 1975). In the USA, a similar test was developed using an anthropometric dummy as the device to measure the car's performance (FMVSS 208, 1972).

Once the obvious issues had been addressed, understanding how further improvements could be made became increasingly difficult. The most important breakthrough came with the understanding of how three point seat belts could effectively couple the occupant to the car, control the way the deceleration forces were fed into the occupant, help prevent secondary contact with the car's interior and prevent occupant ejection from the car. It soon became clear that, whereas improving the protection of restrained occupants was readily feasible, providing protection for the unbelted was much more difficult. As a consequence, much of the subsequent safety developments have concentrated on improving the protection of belt wearers.

Figure 2 Excessive steering column intrusion which early crash tests aimed to address

Although seat belts can help to control how the deceleration forces are fed into the occupant and can attenuate them to a degree, they cannot eliminate them. The main benefit provided by the seatbelt is the prevention of occupant contact with the car's interior. However, when passenger compartment intrusion occurs, this is not possible.

In early crash tests it was accepted that the occupant would impact the car's interior and the earliest human tolerance data was related to direct head, chest and knee contact. In the case of knee contact, the most important injury mechanism was seen to be from forces applied to the knee being transferred up the pelvis to the hip joint. This could most readily result in fracture dislocation of the hip joint or fracture of the pelvis (Wall et. al., 1976).

Before the widespread use of seatbelts and the other more recent advances in car passive safety, the number of car occupant fatalities was very large and the prevention of death was seen to be of prime importance. Consequently, test procedures concentrated on assessing the risk of life threatening injuries. This influenced the design of dummies and type of biomechanical data generated.

As the number of fatalities started to decline, so the relative importance of non-life threatening, non-reversible disabling injuries became greater. More recently, as expectations rise, less serious injuries have also become a concern. It can be expected that this reducing acceptance of road accident injuries will continue into the future.

SIDE IMPACT TEST

When in the 1970s it became clear that further significant improvements in frontal impact protection required the use of seat belts and, in the absence of belt wearing legislation the wearing rates continued to be low, research was re-directed to the second priority area, side impact.

Whereas, frontal impact protection had evolved over many years, little had previously been done to address side impact protection. Consequently, accident studies, the development of a test and its mobile deformable barrier, the design of a side impact dummy, the evaluation of human tolerance levels and the setting of performance requirements all had to be carried out. This took a prolonged period of time.

During this period technical capabilities advanced markedly. When the European Enhanced Vehicle-safety Committee (EEVC) first laid down its specification for a side impact test procedure, it was common practice to record test data plots directly onto ultra-violet sensitive paper. This strictly limited the number of data channels that could be recorded. Consequently, the number of data channels recorded on the EuroSID side impact dummy was severely limited. By the time that the test procedure was first used, both in legislation and Euro NCAP, on board digital data recording was in use with hundreds of data channels being available.

Partly because of this limitation on the number of data channels available, the number of body regions to be covered was also limited. The head, chest, abdomen and pelvis were all included but the next most important body region, the femur, was not.

OFFSET DEFORMABLE FRONTAL IMPACT TEST

With the widespread mandatory use of seat belts becoming more common in the 1980s, it became clear that frontal impact protection was worthy of further consideration. Despite some twenty years of frontal impact testing, using the full width rigid wall test, it was still the case that about two-thirds of serious and fatal car occupant casualties occurred in frontal impact accidents. A careful study of accidents showed that around two-thirds of these injuries resulted from the occupant impacting intruding parts of the passenger compartment. Of the remaining injuries, most came from contact with the interior of the passenger compartment that had not been involved with intrusion. Only a small proportion of deceleration injuries were found to have resulted from seat belt loading.

This was a very different situation from that observed by test engineers carrying out full width frontal impact crash tests. In these tests, passenger compartment intrusion had been virtually eliminated and the main concerns for the car safety engineers was the reduction of deceleration induced seat belt loads. It was clear that intrusion, the primary cause of injuries in frontal impact road accidents, was no longer a feature of the mandatory crash tests. Conversely, injuries from seat belt forces were rare in accidents but a major concern to those trying to pass crash tests.

The offset deformable barrier test was developed to address this problem by more precisely simulating the characteristics of the most commonly occurring road accidents (Hobbs, 1991). The adoption of this test in European legislation and more importantly in Euro NCAP and other consumer test programmes has resulted in a dramatic improvement in the crashworthiness of car structures. However, it is still true that cars perform less well in road accidents than they do in the crash tests. The main reason for this is their lack of compatibility with one another.

Figure 3 Intrusion problem demonstrated by an early 60 km/h offset deformable impact

FRONTAL IMPACT COMPATIBILITY

To date, all legislative and consumer testing has concentrated on providing increased protection by improving the car that the subject is travelling in. However, it has long been clear that protection is also influenced by the characteristics of the other car involved in the collision. Reducing the aggressivity of the other car and matching the characteristics of the two cars, so that they work together to optimise the protection of all their occupants is termed "Compatibility." Although little is still known about what influences side impact compatibility, recent research has shown the main factors which influence frontal impact compatibility. They are: the ability of the two frontal structures to interact well from early in the impact; the comparative stiffness of the frontal structures; the strength of the passenger compartment and deceleration pulse experienced by the passenger compartment (Edwards et. al., 2000).

It is the lack of good compatibility which is the main reason why cars which perform well in crash tests do not perform as well in road accidents. Lack of good structural interaction, early in the impact is a feature of most frontal impacts. Whereas, the difference in stiffness is primarily associated with impacts between cars of significantly different mass.

Another problem created by this lack of compatibility is related to the way it reduces the ability of the engineer to predict the outcome of an impact. This makes the task of designing for robust safety much more difficult.

Lack of good compatibility means that intrusion is still an important feature of road accidents despite it having again become much rarer in crash tests. If and when the frontal impact compatibility problems are solved, to the extent that intrusion becomes much less of a problem, the prime need will then become the control of the passenger compartment's deceleration pulse and the optimisation of the restraint systems to reduce seat belt induced injuries.

Figure 4 Over-riding of two identical cars with 100 mm ride height difference

An inevitable consequence of the reduction in intrusion has been the increase in average deceleration that the passenger compartment experiences. This results simply from the need for the car to stop more quickly in the reduced crush distance available. For those travelling in the front of cars, the benefit from reduced intrusion has been overwhelming. However for those travelling in the rear and for children in child restraints, intrusion was much less of a problem so they received much less benefit. However, they now suffer higher seat belt loads as a consequence of the passenger compartment's greater deceleration.

Understanding how the passenger compartment's deceleration influences an occupant is complex. The overall acceleration is important but the shape of the deceleration pulse is also important. Much more research is needed before we fully understand the importance of deceleration pulse shape and the extent to which it can be influenced by car design.

ANTHROPOMETRIC DUMMY DEVELOPMENT

The crash test dummies in use at any time are a product of the knowledge, the perceived needs and the technical limitations in existence at the time they were developed. Dummy response differs from that of a human, both by design and because of practical limitations. To be sure that the dummy has performed as intended in the test, it must be undamaged, to the extent that it can pass its certification tests both before and after use. Consequently, it must not break which is not the case with humans who frequently suffer bone fractures in such impacts.

There are a limited number of types of transducer which can be used with a dummy and most of these measure the response of the skeleton. There is little available to directly measure potential trauma to internal organs. It is normally necessary to estimate the probability of injury to internal organs, as well as to the human skeleton, from the response of the dummy's skeleton.

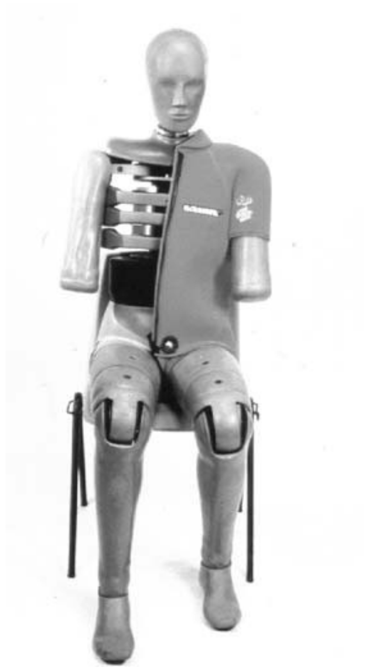

Figure 5 EuroSID I showing three ribs for chest protection assessment

The current Hybrid III frontal impact dummy was initially designed to evaluate the protection of unbelted occupants in cars equipped with airbags and with additional restraint being supplied by a knee bolster. The body regions of concern at that time were the head, the chest and the femur. Consequently, the dummy instrumentation and the supporting biomechanics were related to these circumstances. Subsequently, the dummy has become a general purpose frontal impact dummy.

Although Hybrid III is now regularly used for testing with seat belts, the shoulder and chest were not designed for this. This significantly limits the biofidelity of the dummy. More recently, instrumented lower legs have been added but no significant improvement was made to the foot and ankle. There is a pressing need for the Hybrid III dummy to be replaced to overcome these deficiencies and provide improved biofidelity. Hopefully the Thor dummy, with the advanced lower legs, will fulfil this need.

For side impact, as well as the need for improvements, there is a need for the dummy to be internationally acceptable. Unfortunately, it currently looks unlikely that the proposed WorldSID dummy will address the problems, found by Euro NCAP, from experience with both the EuroSID and ES2 dummies.

It is clear that in a side impact, there are many different load paths into the side impact dummy. Currently, only some of these are instrumented. Either by accident or by design, car manufacturers are utilising these un-instrumented load paths to obtain results that are misleading. In a few cases, Euro NCAP has added additional instrumentation in an attempt to compensate but other un-instrumented load paths still exist. To be reliable, any new side impact dummy needs to monitor all of the significant forces transmitted to the dummy.

Other dummies exist for rear impact and to simulate children, large males and small and pregnant females. In most case, these are derivatives of other dummies and are often even less sophisticated than their 50th percentile male counterparts. As demand grows to widen the scope of the protection provided, there will be a need to develop further this family of dummies. For this, a much broader range of biomechanical knowledge will be required.

BIOMECHANICS

Following the introduction of the three-point seat belt and its wider use, the greatest recent improvements in car passive safety have resulted from development of better car structures. These can now provide a much safer environment within which the car's restraint systems are able to operate, in frontal impact accidents. When in the past, occupant contact with the car's interior could not be prevented, it was important to know the body's tolerance to direct impact. As intrusion has become less of a problem, it has become increasingly important to understand how the body responds to forces, imposed by the restraint system, due to vehicle deceleration.

As time goes by, so the public acceptance of death and injury decreases and the expectations from protection systems grows. It is no longer acceptable to limit protection to the prevention of life threatening or permanently disabling injuries. Furthermore, for the future, the assessment of risk can no longer be limited to that for the average sized male. It must be extended to cover both men and women over a wide range of sizes. The need for this was forcibly demonstrated by the out-of-position problems seen with some airbags and small females.

We also live in an aging population, with the older members of the population becoming much more mobile. Consequently, their exposure to road accidents is increasing and their tolerance to injury is lower than that of younger members of the population. Although this is known qualitatively and there is a wide awareness of the problems of osteoporosis, there is little quantitative data available. This will become increasingly important as cars are developed to minimise intrusion. In a worst case situation where a light car, containing elderly occupants, is impacted at full overlap by a heavy car, intrusion may not be an issue but the limiting factor is likely to be the tolerance to seat belt loads of these elderly occupants.

FUTURE BIOMECHANICAL NEEDS

Although it is easier to generate interest in crash test programmes, the need for supportive biomechanical data cannot be overstated. Future expectations will grow and the need for a broader and more sophisticated knowledge of human tolerance will be necessary to satisfy this need. The problem is exacerbated both by the difficulty of obtaining good biomechanical data and the timescales involved in carrying out the research. Currently, much too little research is ongoing. For the future, there is a pressing need for an ongoing, long term programme of biomechanics research to provide the data that is already seen as necessary to support future needs. Such a programme could include research to provide knowledge of the following.

Figure 6 Seat belt use enabled further car passive safety developments

HEAD AND NECK: For car occupants, the almost universal adoption of frontal impact airbags has reduced the need for information about the tolerance of the head and face to hard impact. However, head impact is still a major issue for other classes of road users. Current tolerance data for the head is mainly related to forehead impact against a plane surface. Little is known about the susceptibility to skull fracture from concentrated loading along a line or at a point. For pedestrians, such loading can occur from impact with a windscreen pillar or wiper spindle. For motorcyclists and possibly cyclists a greater knowledge of injury tolerance levels for a head protected by a helmet would be useful. In recent years, work has been progressing on understanding how rotation affects brain injury but more still needs to be understood, particularly when it is combined with linear acceleration.

Although serious neck injuries are rare among car occupants, whiplash is very common. However, little is still known about what constitutes a neck strain or "whiplash" injury and the injury mechanisms leading to whiplash. For unprotected road users and for very young children, neck loading can be a serious problem. For the development of child restraints, it would be useful to know more about the ability of the very young child's neck to cope with the deceleration forces, due by the inertia of the head.

CHEST AND SHOULDER: For car occupants in frontal impacts, the prime requirement must be to gain a much greater understanding of the forces that can be sustained from seat belt loading. This may be in terms of actual seat belt force or the chest response of a dummy. This then needs to be related to the probability of both skeletal injury to the ribs and shoulder and to the chest's internal organs.

In a side impact the occupant's body is intimately involved in the impact and is potentially loaded over its whole side. Forces acting on one part of the body can be transmitted through the musculo-skeletal system to other parts of the body, so unloading them from direct forces. Of particular importance is the spine where forces into the relatively strong pelvis can be used to reduce the forces on the ribs. The extent to which this can be effective, and can be properly simulated by a dummy, requires a knowledge of the effective stiffness of the human spine under this type of loading condition.

Forces can also be transmitted through the shoulder, again reducing direct chest loading in a side impact. Although injury to the shoulder is not a major issue, the ability of the shoulder to be used to unload the chest is a concern.

ABDOMEN: Fortuitously, it is relatively rare for car occupants to suffer abdominal injuries unless they are ejected from the car or intrusion levels are very high. However, when the abdomen is loaded, the risk of a life threatening injury is very high. With no skeleton to protect it, the abdomen is very vulnerable. For unprotected road users this is a serious problem. For protective measures to be taken, a much greater knowledge of the tolerance to injury of the abdominal contents will be necessary.

For women, pregnancy poses a particular problem about which little is known. If pregnant women and their babies are to be offered protection much more knowledge would be needed about the extent of trauma that can be experienced without the pregnancy or the mother being seriously affected. Because of our the current reliance on the use of three point seat belts, improving protection may prove to be a difficult new area, about which little is known.

SPINE: Although whiplash is a well recognised consequence of a rear impact, it is much less well known that the lumbar spine is also prone to similar problems. Currently, little is known about this injury.

As stated earlier, further knowledge of spine stiffness is required for side impact protection and similar information could prove useful for frontal impact restraint development.

LOWER LIMBS: With current designs of cars, conventional restraint systems are usually incapable of preventing contact between the occupant's knees and the facia, in a frontal impact. The original concern was to protect the femur from fracture but the forces required for femur fracture were seen to be greater than those causing fracture or dislocation of the hip joint. Because of the importance of the weight bearing pelvis to mobility, a greater knowledge of the tolerance of the hip joint and the factors which affect it would be desirable. Little is known about the knee's own ability to tolerate direct loading or forces, passing through the knee joint, from loading to the upper part of the lower leg. With the type of structures present in the knee impact area, localised forces may be applied to only part of the knee. How this influences injury risk is currently un-quantified.

With the feet in contact with the car's footwell and with the driver possibly operating the foot pedals, there is no possibility of preventing foot contact with the car's interior. The foot and ankle are complex structures involving important weight bearing joints. A knowledge of their tolerance to injury and the mechanisms involved is of growing importance.

UPPER LIMBS: Historically, injuries to the upper limbs have been largely ignored. However, as other injuries are prevented, injuries to the functionally important hands can be expected to become a greater concern. The presence of airbags and the way they interact with the arms during deployment may increase the pressure to protect the hands. For this, it would be necessary to gain more knowledge.

In the future, biomechanical information for all of these body regions will have to be extended to cover males and females of a wide range of sizes and ages. As protection for the average male improves, because of current requirements, the needs of others in society increases.

CONCLUSIONS

Although much has been done in recent years to improve car occupant protection there is clearly still plenty of scope for further improvements. Improving the passive safety of cars has proved extremely beneficial and it promises to continue to do so. Further tests for frontal impact, side impact and compatibility are being studied. For the unprotected road user, much is known but little has so far been implemented. Hopefully this will change. The public demand for improved safety can be expected to increase with time, as the public acceptance of injury on the roads reduces.

If improvements are to be made, accident research will be required to identify the needs, research to develop improved test procedures will be needed and this will lead to the need for new test equipment and dummies. For success, ever more detailed data on the biomechanics of humans and their tolerance to injury will be needed.

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