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THE INTERACTION BETWEEN THE ROAD USER AND THE PHYSICAL ENVIRONMENT:
BIOMECHANICS AND THE PREVENTION OF INJURY

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The Interaction between the Road User and the Physical Environment:

Biomechanics and the Prevention of Injury

G.M. Mackay

INTRODUCTION

In the industrialised countries the growth in motor vehicle ownership has occurred over a period of roughly 80 years, and accident prevention measures have been attempted, with varying degrees of success, right from the early days of the motor car. The early and traditional approaches in accident prevention were aimed at modifying human behaviour through selection, training, legal sanctions, medical examinations leading to selection, and persuasion through propaganda.

A deeper understanding of the complexity of accident causation, and particularly the dominant, if passive, role of the physical environment has developed over the last forty years in industrialised countries, and many physical changes have been introduced by highway engineers. The improvements in road surfaces, junction design, highway alignment, street lighting and traffic management have led to the creation of a road environment which, in terms of the exposure to the risk of injury per passenger mile or per road user unit of time, is now very much lower than in previous decades. The success of highway engineering in limiting the frequency of traffic accidents has been substantial. Nevertheless, the overwhelming growth in vehicle ownership in most industrialised countries has resulted in a steady increase in accidental deaths and injuries, so that now in most of Western Europe

and North America, accidents are the fourth leading cause of death and traffic accidents alone cost something of the order of £20 per head of population annually, in measurable costs alone.

Within the last decade a relatively new approach to the control of accidental trauma has been recognised. Collisions intrinsically are bound to continue to occur at some level, regardless of the efforts made at prevention. Hence it is worth examining the actual mechanisms which generate injuries, with a view to controlling the forces and accelerations to which road users are subjected. Thus, the recognition of collision protection as a useful approach to the control of road trauma has evolved. Like many new concepts, collision protection initially has been very successful with relatively few cost penalties, and a number of examples of such measures are given below. However, in common with many other public health approaches, the reality of the consequences of a particular programme are often different from the initial predictions. Only with a thorough understanding of the technical realities and with competent field evaluation studies of remedial measures is it possible to obtain optimum benefits. Hence the study of the biomechanics of trauma and the associated aspects of crash protective design are now becoming a significant part of the measures available to health services in minimising the consequences of traffic accidents.

BIOMECHANICS AND CRASH PROTECTION

An effective strategy for implementing optimum crash protective design has three requirements; a knowledge of the aetiology of road trauma, an understanding of the limits and variability of human tolerance to impacts, and the engineering ability to design vehicle structures and components which under the complex conditions of actual accidents only apply tolerable stresses to road users. The health services have some role to play in all three of these requirements.

Aetiology of Trauma - It is a fundamental need to be able to identify specific high risk groups within the road user population, to have information on the frequencies and classes of specific injuries and specific accident types. Crash configurations, collision speeds and precise causes

of certain injuries need to be known before the priorities of crash protective measures can be established. There are particular gaps in our knowledge at the moment, for example, over the nature and long-term consequences of serious head injuries in young males, and severe lower limb injuries and associated disabilities amongst car occupants, and also our information on relatively minor injuries is incomplete. A significant proportion of certain categories of injured road users does not get included in the normal record systems so that our knowledge of the populations involved is not entirely satisfactory.

The health services could do more to improve the quality of information available on the basic epidemiology of trauma, and the need for specialised information on certain specific types of injury can only be met through the resources of the health services.

Human Tolerance to Impact - Optimum crash protective design can only be achieved if the mechanisms of specific injuries are understood. A knowledge of the biomechanics of impacts, although a relatively new field, is absolutely vital if the promises of the benefits of crash protection are to be achieved. Within the last decade quite a number of improvements have been introduced largely empirically, but the stage has now been reached where a more thorough knowledge of the subject is required. Here close collaboration between medical and engineering professions is needed where the clinical consequences of certain impacts can be translated into the physical parameters which the design engineer requires.

A fundamental aspect of biomechanics which has not yet been satisfactorily studied is the way in which human tolerance to impact varies throughout the various populations at risk. It is known that there are wide variations, factors of three or four in terms of the susceptibility to bone fracture from a given insult, for example, but the dimensions of population variability are not clearly understood nor the consequences in terms of the priorities in crash protective design. In this area carefully structured multidisciplinary research is needed, where the clinical consequences of certain types of trauma need to be related to specific collision circumstances.

The Medical Contribution to the Design Process - The first generation of crash protective design improvements was introduced by a very small number of specialists working with very incomplete information. Many measures were conceived on an entirely empirical basis, and in particular the evaluation of their effectiveness in the reality of actual accidents has been largely neglected until recently. An interesting contrast can be drawn between the thoroughness with which a new drug is tested prior to marketing, and the almost cavalier approach with which the early vehicle crash performance standards were introduced. The head restraint legislation in the United States, for example, is a cautionary tale in how a potentially very useful public health development is rendered almost entirely ineffective by ignoring the realities of human behaviour.

BIOMECHANICS AND CRASH PROTECTION

Seat Belts - Fundamental to the protection of the occupant is a restraint system which prevents him from making localised contacts with the interior, while at the same time he is coupled to the car structure, so that he can ride down on the frontal crush zone of the car, with the consequent attenuation of the forces applied by the restraint system.

Bohlin in Sweden (1) showed that seat belts, if used, would reduce the number of fatalities by approximately a half and lesser levels of injury by a rather similar amount. In order to achieve these potential benefits at least 25 governments have made seat belt use compulsory. Australia was first in this field in 1970-1 and the effects have been outstanding (2). Car occupant fatalities in Australia have been reduced by approximately 25 per cent, coincident with the change from voluntary to compulsory belt use. That effect has been maintained for eight years and acceptance of such a law by a people not renowned for a compliant acquiescence to government edicts is striking. Scandinavia has had a similar success, but for the other European countries it is too early to measure the consequences of compulsion.

In the United States three point belts have been a partial failure in the sense that at present they are used by less than a quarter of car occupants. Lap belt usage was never higher than one third, and although lap

belts are successful in stopping ejection, they do little else. Because seat belts were one of the earliest crash protective devices, they have suffered from the fact that they began life as an aftermarket addition. It is only recently that the seat belt has begun to be integrated into the car at the design stage. The legal requirements which seat belts have to meet, and the test procedures for judging compliance, have only recently been critically examined, and it appears that there are many detailed improvements needed in the laboratory procedures in order to make those procedures match more closely the conditions under which seat belts are used in the real world. Here better co-ordination between clinicians and design engineers is required in order that restraint system design matches the reality of the human population who have to use them.

Antiburst Door Latches - Despite popular mythology, being thrown from a car during a collision increases the risk of death and serious injury by a factor of from five to ten. Anti-burst latches were first introduced by the Ford Motor Company in the United States almost a decade prior to any legislative requirements. Garrett conducted field evaluation studies in 1960, and showed that door opening rates at impact were reduced from 44 per cent to 29 per cent in a sample of rural accidents (3). It took another ten years for anti-burst latches to be specified as a requirement in Europe. Research in Britain has shown that door opening rates have dropped from some 28 per cent in 1969 to 8 per cent in 1972 (4). European studies suggest that the chance of fatal injury to an unrestrained occupant is reduced by some 75 per cent if ejection does not occur. The introduction of the anti-burst latch represents, therefore, one of the most significant and unrecognised improvements in collision performance in recent years.

Steering Assemblies - The specification of the steering wheel and column is perhaps the best example of the need to continually evaluate both the legal requirements and the actual performance of designs in real life.

Current standards are supposed to specify two functions. First, the relative rearward motion of the steering assembly is controlled, as this was designated a major cause of injury in pre-1968 cars. Second, the nature of the chest contact is specified using a hard rubber body block. This simulation of a driver's chest contact is primitive, and the intention of

the original specification was to get close to the conditions of a driver wearing a lap belt. The use of lap belts is almost unknown in Europe, and with three point integral belts now specified in the United States, the original assumptions on which the current law is based are questionable.

Field accident studies in both America and Europe suggest that the present systems, especially in small cars, are not functioning as designed, and, although the anti-intrusion aspect may well have had some benefits, the nature of the chest contacts with unrestrained drivers remains unsatisfactory. In particular, the effective area over which the chest is loaded appears to be of prime importance and that parameter is not covered in current legislation.

Windscreen Glazing - Like anti-burst door latches, safety glass preceded the main development of crash performance legislation, in the case of glass by almost forty years. Recently, laminated glass has been improved significantly with the introduction of better moisture control of the interlayer, a thicker interlayer of 0.76 mm and more recently thinner glass plies. Both laboratory work and field accident studies (5) have shown that HPR laminated windscreens cause significantly fewer and less severe injuries than toughened glass windscreens. This finding is now almost universally accepted, but the relative importance of injuries from glass is still debated because of the possibility of higher levels of seat belt use in Europe.

Head Restraints - The specification of head restraints in the United States is an interesting example of the dangers of ignoring the realities of human behaviour, and of writing legal requirements which encourage ineffective or indeed dangerous design. Adjustable restraints are allowed and are fitted on the great majority of US domestic models. Both accident and survey data show that between 73 and 90 per cent of head restraints are not adjusted correctly, nearly all being in the fully down position. Only very minor benefits were found in terms of the reduction of the frequency of cervical spine injuries from police data and insurance company claims following the compulsory fitting of head restraints.

Early designs of head restraint ignored a further reality. Of injury-producing collisions only some 8 per cent are rear impacts, whereas at least

55 per cent are frontal. A rear occupant is present in some 25 per cent of impacts, and a front seat passenger in approximately 50 per cent. Some simple arithmetic shows that a head restraint will, therefore, be struck by a rear seat passenger in a frontal impact somewhat more frequently than it will be used to prevent whiplash in front seat occupants when struck from behind. Therefore, head restraints should be considered firstly as face restraints for frontal collisions. There is one proviso to add to this argument, however, which is that the symptoms of whiplash are not immediately apparent and, therefore, it is likely that an injury-only sample of collisions may well under-report neck trauma significantly, if the original data depend on police classification of the accidents very shortly after they have occurred.

Compatibility of Structures - The 30 miles per hour (48 km/h) crash into a flat, rigid barrier is a rare sort of collision in the real world. Mostly cars hit other cars either on the front or the sides, but they also hit trees, lamp posts, and commercial vehicles. If the front structure is optimised for a conventional barrier test, particularly at a speed much higher than 30 miles per hour (48 km/h), then in a car-to-car, lateral impact the bullet car is far too rigid or aggressive. Further, between cars there is a variation in mass of a factor of two for eighty per cent of the car population. In order to optimise car structures, in the future the use of deformable barriers for the specification of cars in simulated collisions will probably be necessary, with limits specified for the loads applied in various zones of the contact interface. A particular problem is the American bumper height, which in a lateral impact leads to large amounts of intrusion into the occupant sitting space by the side structure of the target car. A lower bumper would engage the floor of the target car, a naturally strong structure, and there is a further advantage in that the target car, because it is loaded below its centre of gravity, tends to rotate somewhat, and so the severity of the occupant's head contact is markedly reduced.

The demands of compatibility between cars of varying mass in several different collision configurations make car design for optimum crashworthiness an extremely complex problem. However, already the actual limitation on the performance of current restraint systems comes not from the restraints themselves, but from the loss of interior space due to crushing of the

passenger compartment. People who are killed wearing seat belts are not injured from the belts themselves, but because of crushing of the vehicle structure. Hence, the integrity of the passenger compartment, together with the basic structural properties of the front section of the car, are vital areas for improving crashworthiness in the future. The car colliding with the heavy truck is the most obvious example of incompatibility. The car versus the cyclist is another such example.

The Exterior of the Car - In Britain at present pedestrian fatalities are approximately equal in number to car occupant fatalities. If an effective occupant restraint policy, either active or passive, is enacted, then even with an increasing car population, pedestrian casualties will become relatively more important. Recent research has shown that there are real and quite marked differences in the potential for causing injuries between different car exteriors. Given these differences, there should be an optimum shape, but the problem is difficult because what may be best for an adult at one speed, for example, may not be the best for a child at another speed. Ashton has put forward some guidelines for the exterior of the car (6). The bumper, if defined as a separate structure, should be lowered away from the adult knee position. The front edges of present day bonnets are very rigid structures for pedestrians, and a smooth contour which distributes the loads up the lower leg over as broad an area as possible is to be preferred. The severity of the head contact can be controlled by the shape of the front end profile and its compliance, and if the 'wrap around distance' from the ground to the base of the windscreen is greater than 200 cm, then 85 per cent of pedestrian head contacts are likely to be on the bonnet, avoiding the hostile windscreen and the windscreen frame. The bonnet could be engineered to provide a tolerable impact condition, where the maximum amount of useful deformation needed is only of the order of 10 cm.

The compliance of the front of the car is probably even more important than the shape. Work by Pritz (7) suggests that 15 cm of compliant structure for the lower legs would increase the threshold collision speed at which fractures occur by 8 to 10 km/h. This would reduce the incidence of fractures by approximately a half. The immediate benefits from pro-pedestrian car exteriors would come not so much from reductions in fatalities

as from great savings in serious casualties. In the longer term, however, more advanced designs will give savings in the higher energy impacts as well.

Crash Helmets for Two-wheeled Vehicle Users - The most important item of equipment for reducing the severity of two-wheeler accidents is, without doubt, the crash helmet. To date the use of helmets has only been seriously considered for motorcycle and moped riders. However, some work has been done on the development of a cyclist helmet. The main factor here is that the cyclist requires very nearly the same protection as the motorcyclist because the head impact situations are quite similar.

Several studies have been performed on the effectiveness of crash helmets. These are difficult to compare not only because of the differences in exposure data but also because the design of the helmets has changed over the years. In early helmets only the top of the head was covered by a rigid shell. Later the shell was extended over the sides of the head and a shock-absorbing liner was introduced. Recently the full face integral helmet has become very popular. This development represents an extension of the protection to cover more and more of the head and face of the wearer and also an improvement of the shock-absorbing capacity of the helmet.

It appears that when using a helmet the risk of sustaining a head injury is reduced on average by 30 per cent and the risk of being killed is often reduced by 40 per cent. The type of severe head injury seen in two-wheeler accidents has changed character by the introduction of the crash helmet. Before helmets one could often see an open linear or depressed fracture of the forehead under a severely lacerated scalp, often smeared with dirt from the road and with rather localised brain damage. Fractures with helmets are more often located at the base of the skull, the brain damage is more diffuse and lacerations are less frequently seen in the scalp.

It seems reasonable to believe that crash helmets prevent laceration of the scalp to a great extent. They can also prevent skull fractures and brain damage in a significant number of impact situations. In the more severe accidents the helmets are probably less effective, and special

attention should be given to the lateral impacts common in intersection collisions. Data from some studies indicate that while injuries of all severities are more frequent in frontal impacts, injuries of higher severities dominate in the lateral impact situation. Impacts to the rear and to the top of the helmet are quite rare.

Another aspect which has not been examined very much until recently is what actually happens at head impacts. For a long time it has been taken for granted that the head usually impacts perpendicularly into the other vehicle or to the ground and is consequently subjected to linear acceleration. Standard test methods used in approval tests simulate this situation and the requirements also apply to this kind of impact. The high frequency of intersection collisions and the fact that the rider is often thrown some distance before his impact with the ground indicate that many head impacts may well be oblique rather than perpendicular in the real world, and may therefore induce angular as well as linear accelerations to the rider's head. Research in this direction is in progress in some countries. As a result of angular head accelerations one would expect tearing of the bridging veins and more diffuse brain lesions.

The extension of the protection offered by the helmet to the sides of the head as in the so-called jet type helmets seems to be a desirable development, as is also the further development seen in the full face helmets. There are, however, side effects from this which have to be taken into consideration, such as the increased weight, the hearing loss which occurs when the ears are covered and the possible build-up of carbon dioxide inside a full face helmet. However, compared to the benefits in the reduction of injury severity which follow from the use of crash helmets, the possible side effects are small, and a number of studies are in progress to solve these problems and to improve the effectiveness of crash helmets.

Visors do not appear as a significant cause of injury in themselves, and undoubtedly under some situations they prevent facial damage. There is some evidence to indicate that the heavily tinted visors cause a number of accidents, particularly at night, because of their low light transmission characteristics. Also in some countries insects are so numerous that they

can render a visor unusable after very short periods of riding.

In that injured bicycle riders predominantly have head injuries, there is a good case for the development of an acceptable, lightweight helmet for these road users.

CONCLUSIONS

The above are examples of some of the crash protective measures which have been introduced with considerable but variable benefits. Two important conclusions can be drawn. Firstly there is a need to evaluate the effectiveness of such measures, and secondly there is a need to educate the public generally about the correct use of crash protective measures, and to foster the correct attitudes which will encourage the greater adoption of crash protective design and restraint systems.

Knowledge on Effectiveness - In this area there is a great need for better co-operation between the health services and the specialised workers in the field of biomechanics. Optimum crash protective measures can only evolve if the actual consequences of such measures are monitored. This can only be achieved with structured investigations based on hospital records and the experience of general practitioners. Health services could contribute greatly by encouraging such work.

In addition, health services have provided very little input into the various organisations, both national and international, which draw up the requirements for crash protective measures. As a result the realities of human anatomy, population variability and human behaviour are often ignored and a too mechanistic view of the biological aspects of the problem is taken. A greater medical input into those areas would be of considerable value.

Health Education in Crash Protection - One of the general lessons to be learnt from the first generation of crash protective measures is that legislation is not at all effective unless it is coupled with sound health education programmes. Public response to such measures as the compulsory

use of seat belts is poor unless there is a concerted effort made to demonstrate the wisdom of such a measure and information provided on how the individual can correctly protect himself.

In this area the health services could contribute greatly with effective health education programmes on the following topics:-

1. Seat belts - their benefits, how to wear them correctly, the advantages of rear belts.
2. Child restraints - their benefits, the different types according to the child's age, the position of children in vehicles.
3. Crash helmets - their advantages, the importance of correct wearing, the extension of helmet use to cyclists.
4. Head restraints - their benefits, correct adjustment for comfort and crash protection.
5. Windscreens - the choice of glass type, benefits and care.
6. Crash protective design - the risks associated with different types of vehicles, e.g. large motorcycles, choice of features in cars, crash protection in special purpose vehicles for off-road and recreational use.

Within the health services there is also a need to provide better information and to educate general practitioners, hospital doctors, pathologists and public health administrators on the nature of biomechanics and benefits which can be obtained from crash protective measures through effective health education programmes. To this end specialised short courses in various aspects of the subject need to be developed.

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