



Mechanisms of Injury and Biomechanics: Vehicle Design and Crash Performance

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This paper reviews briefly the early evolution of the subject of the biomechanics of impacts. Some examples of rule-making of vehicle crash performance are cited to illustrate the need for evaluation of all design changes and regulations in the real world of crashes and injuries. Some background data on the relative frequencies of casualties and types of collisions are given to establish overall priorities. Mechanisms of injuries in frontal collisions for unrestrained and restrained occupants are described to illustrate the relationships between interior localized contacts and injuries to the lower limbs, the chest, and the head. Kinematics of occupants in angled, lateral, and rear collisions are reviewed together with the related injury mechanisms, and rollover crashes with and without seat belt use are mentioned. Motorcyclist and pedestrian kinematics and some of the desirable characteristics of the vehicle exterior are described together with the unfortunate consequences of the current bumper standards. In summary the paper aims to be a general review of crash kinematics and general mechanisms of injury.

Early Knowledge on the Biomechanics of Impacts

An implicit recognition of impact biomechanics exists in all of us and is engendered from an early age. Soft, deformable structures are benign; sharp, rigid objects, like kitchen knives, deserve caution. From the earliest of times, the underlying principles of impact biomechanics have been recognised: structures designed to maximize trauma are hard and concentrate loads, such as spears and clubs, while conversely, shields and armor absorb and distribute loads and protect vulnerable parts of the anatomy.

Hippocrates [1], writing around 400 BC, noted that for head injuries, "Of those who are wounded in the parts about the bone, or in the bone itself, by a fall, he who falls from a very high place upon a very hard and blunt object is in most danger of sustaining a fracture and contusion of the bone, and of having it depressed from its natural position. Whereas he that falls upon more level ground, and upon a softer object, is likely to suffer less injury in the bone, or it may not be injured at all."

Like most subjects, impact biomechanics has evolved from early observations of natural phenomena, through an experimental period, to a theoretical framework that outlines general laws and precepts. Hugh de Haven [2] is normally credited with the first insights into human tolerance of crash loads. During

World War I, he was involved in a midair collision. While convalescing, he realized that his survival was due to the maintenance of the integrity of his cockpit that, together with a safety harness, protected him from the localized contacts and catastrophic injuries that killed the other pilot. He also observed that his own serious abdominal injuries related to the buckle of his harness, causing a severe internal hemorrhage with laceration of the liver. Crash-protective design had ensured his survival rather than capricious good fortune.

In 1942 De Haven [3] analyzed the circumstances of 8 people who fell from considerable heights, 7 of whom survived. Speeds at impact ranged from 37-59 mph and the objects struck consisted of fences, a wooden roof, soft ground, and in 2 cases, the hoods of cars. Decelerations at impact were estimated and the groundwork for whole body tolerance was laid. Subsequently Snyder and coworkers [4] developed this approach into a most useful methodology for obtaining such data.

In 1941, Sir Hugh Cairns [5] published a paper on fatalities occurring among Army dispatch riders. He showed that for those who wore helmets the head injuries were relatively mild. Later work by Cairns [6] showed that following the compulsory wearing of helmets by Army motorcyclists there was a progressive fall in the death rate. He also noted that most blows on helmets were to the front and side rather than to the crown. The consequences of that observation have been reflected 30 years later in the evolution of the jet-style and full-face helmets of today and the demise of the cradle suspension inside the helmet.

John Lane [7] in Australia in 1942 noted that aircraft should be certified in two ways: they should be both airworthy and crashworthy, and so the term "crashworthiness" was born, but its application to automobile design did not begin until some 20 years later.

The experimental period of biomechanics got under way after World War II with cadaveric studies by Gurdjian [8] examining head injury and volunteer studies by Stapp [9]. The great contribution by Stapp was to show that the primary forces acting in the majority of car collisions are entirely survivable if the packaging of the human frame is satisfactory. He showed that accelerations of 30g for up to 0.5 seconds were entirely tolerable with only reversible soft tissue injuries occurring. At 45g, signs of concussion and retinal hemorrhage begin to show. These accelerations were measured on the seat of the dynamic

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sled. The accelerations experienced by the head itself were much greater.

In the 1950s, Mathewson and Severy [10] were developing the techniques of experimental crash testing with instrumented dummies and high-speed film analysis. By the mid-1960s, a body of knowledge had developed that gave insights into the general frequencies of traffic collisions and injuries, some understanding of the actual mechanisms that generate the injuries, and some means whereby the forces and accelerations applied to car occupants could be modified. What was largely missing was accurate information on the tolerance of the actual human frame to specific impact loadings, ideas of the likely benefits that could be obtained from practical changes in car design, and what the penalties would be in design terms.

In parallel with the increasing amount of experimental work on both cadavers and animals, studies of real-world trauma continued. An elegant paper by Sheldon [11] entitled "On the Natural History of Falls in Old Age" showed how the routine observations of a practicing clinician could lead to new insights into the etiology and mechanisms of injury, particularly for long bone fractures in the elderly.

Pioneering work on seat belts was conducted in Sweden where by 1960 some 50% of private cars had belts fitted. The appropriate elongation and geometrical characteristics of belt systems were evaluated experimentally by Aldman [12], who demonstrated the importance of correct anatomic positioning and dynamic properties appropriate to the deformation and geometrical characteristics of specific car designs.

The subject of biomechanics in relation to car occupant crash protection grew rapidly in the 1950s and 1960s and became institutionalized with an extraordinarily important legislative act in the United States. As a result of government hearings that illustrated the great potential of crash-protective design, in 1966 the National Highway Safety Bureau was created by an act of Congress and it initiated a set of standards controlling the performance of cars in terms of their crashworthiness. The effects of those standards have reverberated through the automotive world. They have been copied, modified, and adopted by almost every country with a significant car population and they have changed car design from a free market, styling-dominated activity to one in which certification, or passing the standards, with all the attendant engineering problems, is of prime importance in the priorities of car manufacturers.

The scientific basis of these first crash performance standards was not well founded; many of the requirements were informed guesswork only. With the benefit of hindsight, quite extraordinarily few major mistakes were made, but what has also become clear is that the subject is a most complex one. The real world of collisions contains many surprises. Common sense has the most curious property of being more correct retrospectively than prospectively, and a major gap was left as the subject became more under the control of government and industry and away from the individual efforts of the early workers.

The problem was one of evaluation. As an example, consider door latch design. Early work by the Ford Motor Company and by Garrett [13] had shown, on very unrepresentative samples of collisions, that it was statistically better to remain in a car during a collision than to be thrown out. Most people were thrown out because doors opened during the crash, and the concept of an antiburst door latch developed. Thus a problem

Table 1. Categories of fatalities.

Class	Fatalities range (%)
Car and light truck occupants	38-66
Pedestrians	16-36
Motorcyclists	10-20
Pedalcyclists	2-5
Large truck and bus occupants	2-4

was identified, a solution proposed, and the legislative machine went into action. Standards were written specifying the longitudinal and lateral strengths of door latches. The car industry, virtually worldwide, redesigned door latches to meet the new requirements, the new cars were built and sold, and the problem of ejection was then supposed to go away. It was left to the individual workers such as Huelke and associates [14] and Gussane and Bull [15] to actually look at the real world of collisions and attempt to find out if these new rules were in fact producing the benefits for which they were conceived. Systematic feedback into the legislative process did not and still does not exist.

There is a parallel to be drawn here with the drug industry. Before a new drug is marketed, it is subjected to rigorous trials, and then its performance in use is monitored for effectiveness and possible side effect. In contrast the introduction of crash-protective vehicle design measures is relatively haphazard. In most countries, until recently, there has been no systematic evaluation of design and legislative changes.

In the case of antiburst door latch design, evaluation studies in Britain on 400 crashes showed that antiburst designs reduced door opening rates in collisions from 30% to 15% [16]. Overall, car occupant deaths were reduced by 5%. Doors still continues to open in collisions however, and the detailed crash investigation studies by Mackay [16] showed that doors were opening in collisions in ways not covered by the regulations.

General Collision Frequencies

Most motorized countries have basic crash injury recording systems, almost always based on police reports. Systematic data linkage between hospital records and police systems does not exist anywhere on a large scale. Although for fatalities the system of the coroner's courts allows adequate pathological data to be linked with crash information in a few countries such as Australia and Sweden.

Serious under-reporting of minor injuries and some classes of serious injuries, especially to cyclists, motorcyclists and pedestrians, occurs in most countries using a police-based system. Fifty percent to 80% of cyclists treated in hospital never appear in the police records in Britain.

With these provisos, Table 1 gives the range for the main classes of road user fatalities in motorized countries in Europe and the United States. Britain for example has a high proportion of pedestrian deaths at 36% of total, compared to 16% in the U.S.A.

Table 2 gives the ranges of the main types of collisions in which car occupants are killed. Although frontal impacts are the majority of collision types, side impacts are important, particularly in countries with high levels of seat belt use because seat

Table 2. Collision types for car occupant fatalities.

Type	Fatalities range (%)
Frontal impact	50-60
Side impact	22-35
Rollover	8-15
Rear impact	3-5
Multiple	3-6

belts reduce deaths in frontal crashes primarily. Rollovers, rear-end collisions, and multiple collisions, which are mainly side impacts followed by rollover, also contribute significantly to the total.

These general frequencies obviously have a bearing on the overall effectiveness of crashworthiness design considerations which are now considered for the main types of collisions.

Mechanisms of Injury in Frontal Collisions

In a standard frontal collision represented by a 30 mph (50 km/hr) impact with a flat rigid barrier, most modern cars will have an overall stopping distance of approximately 2 feet (60 cm). Such a collision is similar to two cars of equal weight colliding with a closing speed of 60 mph (100 km/hr). In that latter case the actual stopping distance is usually somewhat greater than the 2 feet in the rigid barrier test, and would be about 30 inches (76 cm) because of mutual penetration of the two front structures. An approximate rule of thumb is that 1 inch of crush equates to 1 mile per hour within the middle range of crash severities.

A stopping distance of 2 feet means that from 30 mph the undeformed parts of the car, such as the passenger compartment, have an average acceleration of 15 g. In practice the decelerations are not uniform and the peak values are normally in the range of 18 g to 28 g.

An unrestrained occupant, however, experiences forces of much higher orders of magnitude. Consider the driver. As the collision develops the passenger compartment starts to slow down but the driver continues to move forward at his initial speed, closing up the interior space between him and the forward structures. Loads are applied to him sequentially through the feet from the toeboard to the knees, from the instrument panel to the chest, from the steering wheel, and to the head from the windscreen or the windscreen frame in the sun visor region.

The knee contacts occur early during this crash phase so that their localized contact velocity is low because the instrument panel is still moving forward at a significant velocity, around 20 mph (33 km/hr). Thus the knees have a low localized impact of some 10 mph (16 km/hr) and then they "ride-down" on the remaining crush of the front of the car.

The chest and head contacts occur later in the crash sequence so that their localized contact velocities are higher. Indeed for most cars the head initially is normally about 2 feet (60 cm) from the windscreen or header so that the car has already come to rest by the time the head has a specific impact, and that occurs at the full initial velocity of the car. A head striking a modern laminated windscreen at 30 mph (50 km/hr) will deform the interlayer of the glass approximately 15 cm causing it to bulge

outward. Such a condition produces an average deceleration on the head of 60 g, with a peak value of about 90 g. If however the head strikes the windscreen frame, then the stopping distance will be very much shorter, perhaps only 2 cm, being the amount which the metal of the windscreen frame deforms. That produces accelerations on the head in the range of 500 g.

Thus, no simple relationships exist between the overall crash severity and the specific forces experienced by the unrestrained driver. For a passenger the sequence of loads changes. The foot and knee contacts occur, and then the head strikes the forward structures before the chest hits the facia. That can result in major loads to the neck.

The main patterns of injuries for unrestrained occupants are thus to the knee-femur-hip complex, the chest, and the head. The lower limb injuries arise from compressive loads up from the foot and from the knee striking the lower instrument panel. Depending on the localized nature of that knee contact there may be specific fractures to the patella or a knee joint injury, or the loads may produce injury remote from that contact with fractures to the shaft or neck of the femur or dislocation of the hip joint. Modern designs of instrument panel have diminished the localized injuries by providing several inches of side-down for the knee contact.

The interaction of the chest with the steering assembly is complex. Regulations require a limit on rearward motion of the hub of the steering wheel of 5 inches (12.5 cm) measured horizontally. In addition a limit of 2500 lbs (1130 kg) is set for the permissible load on the chest measured in a 15 mph (25 km/hr) bodyblock test. There are various design solutions to these requirements usually involving some telescoping or deforming element in the shaft or hub of the steering wheel [17].

The onset of serious chest injury from in-depth crash investigations for both steering wheel contacts and from seat belt loads appears to relate to multiple rib fractures. That is associated with significant pulmonary dysfunction and risks to the great vessels in the chest. However, for other loading conditions, notably from an airbag, from an instrument panel, or from a door panel in a lateral collision, there is evidence to show that rib fracture is not an appropriate threshold for assessing injury risk. This is because the thorax has a visco-elastic response and thus exhibits different characteristics at high rates of loading. Viano and Lau [18] have proposed a viscous criterion (VC) for thoracic loading to allow for this rate dependency. At low rates of loading, deflection, leading to rib fracture at the limiting condition, is a satisfactory parameter to measure. At high rates of load, however, intrathoracic injuries occur at relatively low deflections of the rib cage. This leads to the need for more complex dummies to assess injury risk experimentally, and it raises doubts about the appropriateness of current regulatory procedures [19].

The most frequent and most serious injuries occurring to unrestrained occupants in frontal impacts are to the head. Head injuries represent a complex set of trauma to the skull, the brain, and the face occurring singly and in combinations. The mechanisms of brain injury in particular show a spectrum of conditions of extraordinary complexity. Brain injuries can occur with and without skull fracture, they can be focal or diffuse in nature, they can be predominantly vascular, with epidural or subdural hemorrhage or rupture of the bridging veins, or there can be diffuse axonal damage throughout the

entire brain mass. Gennarelli and coworkers [20] have shown how various combinations of linear and angular accelerations of varying duration lead to either focal or diffuse injuries or combinations of both. The brain exhibits different responses to motions and accelerations in the coronal and sagittal planes, with severe diffuse axonal injury (DAI) occurring primarily in lateral impacts where the head moves in the coronal plane.

It is against this background that the effectiveness of crash-worthy design must be considered. At present head injury risk is assessed experimentally using a dummy in which the resultant linear acceleration, measured at the center of gravity of the head, is the only criterion. That acceleration is the basic input into the calculation of the Head Injury Criterion (HIC) which is a time-weighted function of acceleration. Historically an HIC of 1000 is taken as the limit of head injury tolerance and that value is written into regulatory procedures worldwide.

The recent work of Gennarelli and Viano questions the validity of the HIC as an acceptable measure of head injury risk. Ultimately brain injury is probably most directly related to local shear strains occurring within the brain. The patterns of shear strain are a function of the direction, magnitude, and duration of the applied accelerations and they cannot be equated simply to one linear peak value [21].

Modern interior car design has produced yielding structures in most areas where head contacts occur. Those structures can be either of contoured metal which deforms appropriately or of plastic padding materials. One consequence is that skull fractures and related focal injuries have been reduced but diffuse trauma appears now as a relatively more important type. Indeed padding can under certain conditions of a glancing blow to the head enhance injury risk by increasing angular accelerations [22]. In general terms, however, the aims of the designer are to provide the largest amount of ride-down distance for occupant contacts consistent with all the other functions of the interior of the car.

The Restrained Occupant in the Frontal Collision

The fundamental benefit of a seat belt in a frontal crash is to prevent or diminish those specific interior contacts described above. Soon after the car starts to decelerate the occupant moves forward enough to load the seat belt. The webbing stretches allowing some forward motion yet preventing head and chest contacts, so that ideally the occupants stopping distance is actually greater than the frontal crush of the car. If the belt allows a foot of forward motion then the occupant could theoretically have a ride-down distance of 3 feet when the front structure of the car crushes 2 feet. In practice that condition is never achieved because time and hence distance is required for the seat belt load to build up, but for the 30 mph collision the forces on a restrained occupant's chest can be brought down to entirely tolerable levels, and chest contacts with the steering wheel and instrument panel are prevented.

For most interior designs a restrained occupant will still have knee contacts with the forward structures. There is clearly a tradeoff between a very stiff seat belt system limiting forward motion but generating high seat belt loads, and a softer system which gives more forward motion. Optimization of restraint design is exceedingly complex in this context because of the interaction of several variables, some of which are not well

researched. Crash severity distributions, human tolerance variation, occupant initial sitting position, occupant size and weight, and the presence or absence of pre-impact braking all have a bearing on restraint performance.

In the collision the head flexes forwards until the chin touches the sternum. Consequently the forward motion of the head of the restrained occupant is about 18 to 28 inches (46 to 72 cm) in a 30 mph collision. For convenient use the steering wheel is some 16 inches (40 cm) from the chest, and thus a head contact with the steering wheel is inevitable for the driver in a serious collision [23].

It is possible to diminish somewhat the amount of forward motion allowed by a conventional seat belt if a pre-loading device is used. A sensor detects crash-level decelerations at the front of the car. It activates a device which applies a load to the belt, thus coupling the occupant more efficiently to the car as it decelerates. Such devices may reduce head forward motion by approximately 2 inches (5 cm) as well as reducing seat belt loads by about 10% [24].

The preferred solution for the restrained driver having a head and face contact with the steering wheel is to have a supplementary airbag. In a severe collision the airbag deploys from the hub of the steering wheel and cushions the head as it arcs forward and downward [25].

Seat belts of themselves cause injuries. In the limiting condition rib and sternal fractures will occur. Abdominal injuries are also a feature of three point seat belts if the lap section is incorrectly positioned above the iliac spines of the pelvis. A phenomenon called "submarining" can occur when the pelvis rotates out from under the lap section during the collision, allowing the lap belt to load the soft organs of the abdomen. Submarining risk is diminished by careful placement of the lower anchorages of the seat belt and designing the seat cushion to limit the downward and forward motion of the buttocks [26].

Angled Collisions

An occupant in a collision always tends to move toward the position from which the principal crash force is applied. Thus, as a lateral component begins to act during a frontal collision so the occupant's trajectory alters. A crash coming from the 10 or 11 o'clock direction, 12 o'clock being head-on, results in a front seat occupant having a path angled across the interior so that the head, for example, would strike either the left side A pillar in the case of an occupant sitting on the left or the rearview mirror in the case of an occupant sitting on the right.

Great care needs to be exercised in the reconstruction of angled and intersection collisions in terms of assessing occupant trajectories. For example, in a crash in which two cars are on perpendicular paths moving at equal speeds when they strike, the resulting occupant trajectories will be roughly at 45 degrees across the compartment. If the actual contact between the two cars was such that the front of one struck the side of the other, then the pattern of the damage may give a misleading impression of the occupant's path during the crash phase.

Conventional three-point seat belts have been shown to be very effective in angled collisions. Experimental studies have shown that the diagonal section effectively restrains the torso up to angles of about 45 degrees. Even when the chest begins to come out from under the diagonal section, the lap restraint acts

effectively in diminishing lateral head excursion [27]. In this context, dummies do not give a particularly accurate representation of the actual human response because of poor biofidelity of the shoulder linkage.

Lateral Collisions

Collisions in which occupants receive injuries from the side structures of the car constitute almost a quarter of all crashes for fatal and serious injuries. For the occupant on the struck side, loads are applied directly by the door at the levels of the pelvis and chest. The armrest may produce a localized loading of the lateral abdomen.

In the case of a car-to-car impact, the direct loading of the occupant occurs from shoulder level downward, but the head may well flex laterally through the side window aperture to strike the bullet car. In a truck, the head is more exposed to severe direct loads directly on the front of the striking vehicle and, in the case of trees or poles where there is intrusion of the side of the car from door sill to roof level, the head is particularly exposed to a direct contact on that intruding object [28].

Because of the small space between the occupant and the bullet car, it is entirely possible for the occupant to receive a velocity change greater than that experienced by the car in which he is sitting. If the side structure provides negligible resistance to the bullet car before the occupant is contacted, then it is possible for the occupant to receive a velocity change that approaches the absolute impact speed of the bullet car.

That velocity change can be diminished somewhat by increasing the rigidity of the side structure of the target car, but there are severe practical constraints on that approach. A better solution can be achieved by accepting a somewhat higher velocity change on the occupant, and by positioning padding as close as possible to him or her, providing a large ride-down distance. Thus, the magnitude of the applied forces can be diminished.

For the occupant on the struck side in a side impact, a belt has negligible benefit. For an occupant on the non-struck side, however, a seat belt will retain the pelvis close to the initial sitting position, and diminish the chances of head contacts across the compartment and also reduce the interactions with an adjacent occupant, an important mechanism of injury in severe lateral collisions [28].

Mechanisms of Injury in Rear End Collisions

If a car is hit from behind, it is accelerated forward. The back of the seats therefore act against the inertial mass of the occupants. If the seat back does not deflect excessively, then the occupant is accelerated forward with the car. In the absence of any head restraints, the head tends to remain in its initial position in space and consequently it lags behind the thorax. As a result, the neck is extended over the top of the seat back and put into tension. If severe enough, that motion can generate hyperextensive injuries of the neck, which in extreme cases can cause vertebral fractures and damage to the spinal cord. Most car seats have backs that flex elastically, and as a consequence, after loading the seat in a rearward direction the occupant is then projected forward and under some conditions can experience

severe contacts with the forward structures. Those conditions for a restrained occupant can produce a forward flexion of the neck after the rearward extension, and it is that sequence of extension and flexion that is often described as a whiplash.

The purpose of head restraints is to limit the initial hyperextension by supporting the head at the same time as the back is being loaded. To do that effectively the head restraint must not only be strong enough but it must be high and close to the head to prevent relative motion developing. In design terms this presents obvious conflicts with comfort and vision requirements [29].

Occupant Kinematics in Rollover Crashes

Rollover crashes are the most random as far as the motion and contacts of the occupant are concerned. Almost every rollover is unique in that small variations in terrain and in vehicle characteristics produce vastly different vehicle kinematics. The great majority, over 90% of rollovers, occur off the roadway and there is the added complexity of striking objects while the car is in an unusual attitude.

On the other hand, field studies show that providing an occupant is not ejected and the car does not strike any rigid objects, then rollovers are one of the least injurious of crash types. This is because the kinetic energy of the car is being dissipated in small amounts over a large distance.

There is much confusion in the literature over any supposed relationship between the amount of roof deformation that occurs in rollovers and the severity of injuries to occupants. Some studies have shown a statistical relationship, but that does not imply a direct, causal link. The greater the applied load, the greater the amount of roof crush. The greater the applied load, the more severe will be the contacts made by an occupant with the interior. A stronger roof would diminish the roof deformation but would leave the forces applied to an unrestrained occupant undiminished [30].

Another area of uncertainty in rollovers is the benefit obtained from use of a seat belt. Field studies indicate quite significant benefits in general terms. Experimental studies using dummies tend to be unsatisfactory because of poor biofidelity of the shoulder and torso of current dummies. In comparison to the human frame, the torso of current dummies is far too rigid and the shoulder linkage is not adequately reproduced. As a consequence the dummy does not replicate properly the way in which real people actually move during rollovers. Current crash test dummies are only satisfactory in the limited condition of a frontal collision or a side impact.

The Kinematics of Cyclists and Motorcyclists in Collisions

Crashes involving cyclists and motorcyclists can be divided into two general classes. First there are the single vehicle events where a loss of control occurs. The rider parts company from his machine and then slides and rolls along the road surface receiving a number of blows that often generate substantial angular forces because of the oblique nature of those impacts.

The second general class of collisions involving cyclists and motorcyclists occurs when there is first a vehicle-to-vehicle collision followed by the subsequent passage of the rider along the road surface as a result of any residual velocity that he or

she may have. In this case, the closing speeds in the first collision are often high, and the rider is projected from the machine to receive his or her most injurious contacts from the other vehicle. There is a tremendous variation in the properties of the actual structures that are contacted under these conditions. The rider's head may strike almost any part of the car above the waist rail in a motorcycle-to-car collision, while his or her legs will contact the bumpers or the side panels according to the orientation of the vehicles at impact. Often the legs will receive substantial localized impacts but the rider will maintain a significant velocity so that he or she travels over the car to have a second series of contacts with the ground and any roadside objects that may be in the rider's path.

Superficially these conditions may seem to be so random that little good can be achieved by attempting to introduce crash-worthiness concepts into vehicle exterior design or motorcycle design. However, careful epidemiologic studies of the circumstances of pedestrian collisions have shown that great benefits can be obtained from improved design to car exteriors [31]. Many of those changes, relating to more compliant bumpers, recessed windshield edges, soft hoods and grills, plus improved external geometry, will benefit cyclists and motorcyclists as well as pedestrians.

Pedestrian Kinematics and Mechanisms of Injury

In global terms, pedestrians are numerically the largest single group of road users killed in traffic collisions. Although no satisfactory statistics are collected in most Asian, African, or South American countries, there are enough sources of data to suggest that traffic fatalities worldwide total some 500,000 annually and at least half of these are pedestrian [32].

Until the late 1960s, the main sources of information on pedestrian trauma were based either on police or hospital data files, but those sources were intrinsically limited in giving insight into the precise relationships between injuries to pedestrians, the relevant components of vehicles, and the associated kinematics. Several research workers, therefore, in the U.S.A., Australia, and Britain conducted detailed at-the-scene studies within 30 minutes of the occurrence of the collision, when the cars would be examined *in situ* and the environmental circumstances and vehicle damage evaluated in detail [33–35].

Field studies in general show that in some 8% of cases of pedestrian casualty collisions, either more than one pedestrian or more than one vehicle is involved. The great majority of pedestrians are injured in single-vehicle and single-pedestrian impacts. In most Western countries, studies show that some three-quarters of pedestrians are struck by cars, the remainder being trucks (14%), motorcycles (5%), and buses (4%). The involvement rate on a vehicle base varies greatly. Buses, for example, are 6 times more likely, and trucks twice as likely, to be involved in a pedestrian collision than is a private car on a yearly basis. A better measure in terms of vehicle design is the relative risk of striking a pedestrian throughout the total operating life of the vehicle [32].

On that basis, a bus is some 12 times more likely to injure a pedestrian than is a car. Other similar high-risk situations can be detected, for example, the average Manhattan taxi has a 1 in 8 chance of injuring a pedestrian in 2 years; taxis in other large cities, such as London and Paris, may well have equivalent

involvement rates. The chance of being killed also varies with the type of vehicle; only 3% of pedestrians struck by cars or taxis are killed, while for trucks the percentage killed rises from 4% for vehicles of <1.5 tons to 13% for those vehicles >4.5 tons in weight.

Ashton and associates [35] reporting on an at-the-scene study in Birmingham in the United Kingdom, noted that pedestrians were most frequently struck by the front of the vehicle, but in an asymmetrical manner. With left side of the road driving, most pedestrians are struck on their right sides by the left front corner of the car as soon as the pedestrian has moved into the road rather than when he or she is over half way across.

The most frequent type of pedestrian collision is that in which the pedestrian is struck by the front of a car. The initial contacts are from the bumper, which strikes the leg, and from the leading edge of the hood, which strikes the thigh or pelvis. The exact location of these contacts depends on the relative heights of the pedestrian and of the parts of the vehicle. The pedestrian then rotates about the leading edge until the head, shoulders, and chest strike the bonnet, the windscreen, or its frame. At high impact speeds, the pedestrian rotates about a second contact of the head or shoulders, and the legs may strike the roof. By this time, the casualty is travelling at approximately the same speed as the car.

Should there have been little or no braking during the crash phase it is possible that, at high speeds, the pedestrian may pass over the top of the car. If, however the vehicle is being braked, and this is the most frequent condition, the car slows down faster than does the pedestrian who thus continues to move forward and lands on the road in front of the vehicle. The person will finally come to rest after sliding and rolling along the road surface.

The extent and severity of the contacts on the vehicle depends on its speed and on the relative heights of the pedestrian and front structure. The initial contact results in the pedestrian being pushed forward and at the same time rotated about his or her center of gravity. He is thus not run over but run under by the front of the car.

There are thus two phases to a pedestrian collision. The first phase consists of multiple contacts with the car; the second phase is the rolling and sliding motion that occurs on the road surface. Research has shown that injury severity is strongly associated with impact speed for the first phase, but for the ground contacts there is no dependence on speed and those injuries are generally minor.

The overall relationship of vehicle exterior shape to pedestrian trauma represents one of the major areas of biomechanical research at the present time. Enough evidence exists to suggest that, in practice, different car profiles do present different risks of injury. Perhaps the most striking study that illustrates this point is one by McLean [36] who compared two groups of pedestrians, the first being struck by Volkswagen Beetles and the second by Cadillacs. The samples were standardized as far as possible with regard to other relevant variables. He concluded that there would be a 30% reduction in pedestrian fatalities in the United States if all cars that struck pedestrians had Volkswagen fronts.

At present, however, neither experimental studies nor field investigation projects are sufficiently far advanced for the ideal vehicle exterior to be specified. What may appear to be an

optimum design in terms of contour and resilience for one impact speed and one particular height of pedestrian may well produce particularly unfavorable impact conditions in different circumstances.

One unfortunate development from the pedestrian's point of view has been the promulgation of the bumper standard in the United States. This is not a safety standard at all, it is an economic standard aimed at reducing repair costs by standardizing bumper heights and specifying strength requirements in a 5 mph impact. The standard has resulted in very rigid beams across the front of cars at 20 inches (50 cm) above the ground. This corresponds to adult knee height and results in a greater incidence of disabling injuries to the knee joint, involving damage to the articulate surfaces of the joint and ligamentous injuries, than does a bumper set at a lower height [37].

Summary

This review has touched superficially on the various mechanisms of injuries to the main classes of road user casualties, and illustrated some of the desirable vehicle design characteristics which can minimize road trauma.

There is still much to be gained by better vehicle design. For occupants, enhanced performance from restraint systems, supplementary airbags, better structural integrity, and better compatibility between cars and trucks are obvious areas where known solutions are waiting to be applied.

For pedestrians there is an extensive literature outlining the characteristics of friendly vehicle exteriors; many current models of cars are exhibiting some of these properties but better agreement on an optimum specification for the car's exterior is still required.

For motorcyclists there is the promise of improved leg protection from energy absorbing fairings although substantial technical debate still surrounds these proposals.

For the clinician a more accurate appreciation of the likely injuries which occur in given collision circumstances can help in diagnosis and treatment. It is for these reasons that some understanding of vehicle design and crashworthiness is worthwhile.

Résumé

L'évolution des idées concernant la biomécanique des impacts est exposée. Quelques exemples de la performance des voitures au cours d'un accident sont donnés pour illustrer le besoin d'évaluer tout changement de "design" et de réglementation des voitures par rapport au monde "réel" des accidents et traumatismes. Quelques chiffres concernant la fréquence des lésions et les types de collisions sont données pour situer le fond du problème et exposer les priorités globales. Le mécanisme des lésions résultant des collisions de face selon que les occupants de la voiture sont ceinturés ou non sont décrits pour illustrer les rapports entre les points d'impact intérieur de la voiture et la distribution des lésions du thorax, de la tête, et des membres. Les cinétiques des occupants, avec ou sans ceinture, et les lésions qui en résultent sont décrits selon que le choc vient de face, de l'arrière, sur le côté, ou sous un angle donné, ainsi que lors des accidents avec retournement de voiture. Les cinétiques des motocyclistes et des piétons dans un accident

sont décrits en même temps que l'énumération des caractéristiques souhaitables pour la conception et réalisation de la forme des pare-chocs par rapports aux standards actuellement en vigueur. Pour résumer, le but de cet article est de faire une revue des cinétiques des accidents et des mécanismes responsables des lésions.

Resumen

Este artículo revisa brevemente la evolución inicial del tema de la biomecánica de los impactos. Se citan algunos ejemplos de la normatización sobre comportamiento del automotor en un choque para ilustrar la necesidad de evaluar los cambios en diseño y las regulaciones en el mundo real de los accidentados y el trauma. Se presentan datos sobre la incidencia relativa de muertes y de tipos de colisión para establecer prioridades globales. Se describen los mecanismos de las lesiones en las colisiones frontales en ocupantes con y sin cinturón de seguridad para ilustrar la relación entre contactos interiores localizados y lesiones de las extremidades inferiores, el tórax y la cabeza. Se revisa la cinemática de los ocupantes en colisiones angulares laterales y posteriores junto con los mecanismos de las lesiones asociadas, y se mencionan los choques con volcamiento en ocupantes con y sin cinturones de seguridad. Se describe la cinemática de motociclistas y de peatones, y algunas de las características deseables en cuanto al exterior del vehículo junto con las desafortunadas consecuencias de los actuales estándares de los "bumpers". En resumen, el artículo pretende ser una revisión general de la cinemática de los choques y de los mecanismos generales del trauma.

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