AN INTERNATIONAL REVIEW OF MOTORCYCLE CRASHWORTHINESS

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ABSTRACT

This paper summarises very briefly some aspects of trauma to motorcyclists. Three collision types are discussed, the frontal non-ejected type, the frontal ejected type and the deflected type of crash configuration. These represent the great majority of real world accidents. The optimization of the motion path of the driver is shown to be a potential means of diminishing injury exposures coupled with knee pads and energy absorbing fairings. The provision of such fairings appears to offer the most obvious advance in the medium term, but the absence of biomechanical knowledge and appropriate surrogates for the lower limbs presents a problem for the development and assessment of such designs. The high frequency of shallow angle glancing impacts suggests that leg protection is a worthwhile aim but the crash bars currently available are not effective under many circumstances. Some recommendations are made about future research priorities.

INTRODUCTION

Although the motorcycle recently celebrated its 100th birthday, a review of the machines made by the early pioneers shows a striking resemblance to those of today. The fundamental configuration of two equally sized wheels with the engine located between them, with the rider sitting astride, with the engine between his knees, and the fuel tank directly over the engine, has not changed. Radical alternatives, with armchair sitting positions and the engine located below the seat, have been attempted but with no real commercial or technical success.

Motorcycles represent between 10% and 25% of motorised road vehicles in most European countries. In many developing countries however, they represent the most common vehicle. In Thailand and Malaysia for example over 50% of powered vehicles on the roads are motorcycles. Growth rates for motorcycles in many developing countries are very high, running at 10% to 20% annually. In the USA, where the trend is towards motorcycles as a vehicle for leisure rather than daily transportation, they represent some 3.2% of registered vehicles in 1985, up from 2.5% in 1970. That growth corresponded to a doubling of the numbers of motorcycles in a 15 year period, but recently the trend has slowed to a 2% increase in the last five years.

Research in Britain shows that motorcyclists per mile travelled are approximately 20 times more likely to sustain a fatal injury than car occupants. In the USA the death rate per mile for motorcyclists is 13 times the death rate of the overall motor vehicle population. However in Britain, when the operator's age is taken into account, motorcyclists are four times more likely to be seriously injured or killed per mile than similar age car occupants. Motorcycle casualties have been a major concern in Europe and are now a major concern in USA. In Britain motorcycle fatal and serious cases constitute about 25% of highway casualties. Motorcycle research in the past has concentrated on head injury. However seriously disabling injuries involving the lower extremities are now perceived as important. A selected bibliography of field accident research studies is attached to this review.

Figure 1 illustrates the absolute numbers of motorcyclist fatalities for the United States and Figure 2 shows the fatality rate (deaths per registered motorcycle) for the last 25 years. There are likely to be very substantial differences in such death rates between one country and another, and also between different sizes of motorcycle. Also actual exposure to risk in terms of miles travelled would give a more realistic assessment of the problem, but such control data is not normally collected in any systematic way.



Figure 1





TRAUMA STUDIES AND MECHANISMS OF INJURY

The early work of Sir Hugh Cairns in 1943 on head injuries to military despatch riders showed the advantages of crash helmets. From then on there has been a significant quantity of research on the nature and frequency of head trauma with parallel experimental work on helmet design. Although current helmets are clearly not yet optimal, particularly with respect to the interior damping of helmets and to attenuating angular accelerations, a modern helmet represents a sophisticated structure, which, within the limits of acceptable dimensions, provides a crash protective system of great benefit for the motorcycle rider. The helmet until recently has been the only such system available. Within the last four years rational design of motorcycling suits has occurred (Aldman, 1981), and thus crash protection has been extended to other parts of the rider's body.

The concept of crashworthiness being incorporated into the machine itself however has not yet been adopted and this aspect is discussed in this review paper. Fundamental to a safety concept becoming practical is a knowledge of the frequency, severity and governing conditions of motorcyclists' injuries. Only with such research knowledge can practical and effective designs be developed and such knowledge of sufficient detail to be useful has not been available other than in fragmentary forms.

Injury studies have demonstrated that the lower extremities are injured frequently. For example in a US study (Hurt, 1984), where helmet use was 50%, the anatomical distribution of AIS3 or greater injuries was as follows:

Head,	neck and	face	32.3%
Chest			18.3%
Abdomen			10.5%
Upper	limbs		15.5%
Lower	limbs		23.4%
			(100%)

A feature of serious motorcyclist trauma is the multiplicity of injuries, where of hospital admissions the average motorcyclist received 2.8 injuries per casualty (Mackay, 1969).

Of different collision types, single vehicle motorcycle accidents account for some 20%, rising to 30% for fatalities. Such collision types produce extremely variable exposures to the different parts of the body as the rider leaves his machine, strikes the road surface, slides, strikes a kerb or items at the edge of the roadway, or other objects such as parked cars and even pedestrians.

With such a variety of specific contacts it is difficult to generalise about kinematics or mechanisms of injury in such collisions. For motorcycles to vehicle impacts however some general characteristics can be deduced (f.e. HUK, 1977).

Unfortunately the great majority of studies have been relatively small scale, and the results have not been sufficiently discriminating to distinguish specific exposures. This is particularly true for leg injuries. For example "frontal" impacts may well include head-on, side-swipe and oblique collisions which generate greatly different exposures for the leg.

This problem was addressed partly in studies by Hight (1976), Newman (1974) and

Langwieder (1977) and the classifications developed in that work are used below. Primarily these represent non-ejection, ejection and deflection modes to stratify the events of a motorcycle to other vehicle impact with the associated exposures to impact (Figure 3).



Figure 3

The injury patterns associated with these three types of exposure are shown in Figure 4.



Motorcycle Frontal Collisions - Non Ejected Classification

In these collisions the motorcycle usually hits the centre side area of the car so that the rider starts his ejection excursion but his forward movement is rapidly arrested by impact of his knees, chest and head with the car body. The dynamics of the motorcycle is such that during impact the rear wheel leaves the ground with a characteristic forward pitch.

Motorcycle Frontal Collisions - Ejected Classification

These collisions are initially similar to the non-ejected classification in that the speed of the motorcycle is rapidly decreased and brought to a stop. The rider initially moves forward in a seated posture. The rider then may exert some force through his arms upon the handlebar and his pelvis ramps up the gas tank which slows his pelvis. There are often thigh impacts into the sides of the gas tank during this forward excursion. At this point his upper torso rotates forward and ramps above the steering head, instrument cluster and handlebars. The hands separate from the handlebars and the thigh or lower leg often strikes the handlebars during this ejection phase. The rider becomes totally ejected and somersaults in the air prior to ground impact with his head, torso or legs. The reason the motorcycle goes into its forward pitch is because the reactive force against the front wheel at the height of the front axle is significantly below the centre of gravity height of the motorcycle. This causes a pitching moment. The riders thighs or lower legs often contact the handlebars which

moment. The riders thighs or lower legs often contact the handlebars which further increase the motorcycle pitching moment, rotation rate and the extent of motorcycle rotation during the collision. It was proposed in the 1976 Hight paper that a structured headlight extension which protruded forwards in line with the leading edge of the motorcycle would neutralise this pitch. In addition a lower extremity impact pad could be incorporated to absorb some crash energy and to initiate improved driver movement. This topic was also addressed in the 1977 and 1985 papers by Langwieder and Sporner. They concluded that a successful way to optimise the ejection path of the rider was to have a clean and early separation from the motorcycle. A controlled ejection minimises leg fractures against the handlebars and lowers the risk of serious head injuries as no or only reduced head contact to the opponent occurs. It was confirmed by crash tests that by leg entrapment on handlebar or between car and motorcycle there results a forward rotation of the rider's upper torso producing an unfavourable somersaulting rate for the rider during the ejection phase.

From other experimental crash tests (Chinn, 1984), it has been indicated that a partial overlap of the structure above the front tire should be sufficient and that it is not necessary for the structure to be in line with the leading edge of the front tyre. This forward structure will reduce the gross motorcycle pitch because after the first few inches of deformation associated with fork bending which occurs initially, the structure will make contact above the centre of gravity of the motorcycle. Such a structure would be somewhat wider than the front tyre to help deflect the motorcycle in other types of impacts such as head-on sideswipes.

Motorcycle Asymmetric Impacts - Deflected Classification

In these collisions the motorcycle rider usually tries to swerve around the other vehicle which is moving across into his path. Impact occurs between the front, side, or corner of the other vehicle and the leg of the motorcycle rider. In many cases there is only minimal impact with the motorcycle. Typical are intersection intersection collisions with left turning cars, where the driver does not see the motorcyclist. Often the car is travelling slowly but is crossing into the motorcycle's path of travel. This becomes obvious to the motorcyclist in a period of less than three seconds before impact. The operator has to make a decision to swerve left, right, brake, accelerate, or accelerate and swerve. It is interesting that most motorcyclists swerve in the direction that the car is heading. The choice of swerving towards the rear and going behind the car might eliminate some collisions altogether, but in other cases would cause impacts into the side rear quarter panels or rear corner of the car. The choice of braking is often judged by operators to be dangerous as that would slow them and place them in the path of the turning car (Figure 5).



Figure 5

Angle of Impact in the Deflected Classification

In the literature, there are a number of terms describing so called side impacts to motorcycles such as oblique, lateral and transverse. The tendency is to think of a slow moving motorcycle being struck in the side by a car moving at normal travel speeds. This concept has been illustrated in a number of motorcycle controlled collisions by Honda (1969), Bothwell (1969), Taneda (1976) and Tadokoro (1985). To better understand the mechanism of injury it is necessary to evaluate the speed and direction of both the motorcycle and the car in these asymmetric collisions where the rider's leg is impacted. This is associated with the Deflected Classification. The car's closing speed with respect to the motorcycle can be seen in Figure 5, together with the lateral speed component, with respect to the motorcycle. If one considers the motorcycle to be the reference, then the car is progressing along the relative approach path as depicted in Figure 5. The relative approach angle is 12 degrees and the lateral closing speed component is 10 feet per second (2.5 m/s).

This analysis can be compared to a naval aircraft landing on an aircraft carrier. The aircraft may have an approach angle up to 7 degrees with a vertical closing speed (decent rate) up to 24 feet per second (6 m/s). The suspension is designed to reduce the shock load and to deflect the aircraft from the glide slope to its new horizonal path post touchdown. In-depth field studies have shown that in the majority of impacts the relative approach angle of the car with respect to the motorcycle is less than 20 degrees and usually within 0 to 15 degrees. Many of the collisions where the rider's leg is impacted the motorcycle is not significantly contacted can be thought of as head-on sideswipes where the approach angle may be less than 5 degrees.

With this information it is clear that many of the experimental projects have been examining an extreme condition which does not occur frequently in actual crashes. Much of the experimental work has involved a car striking a stationary motorcycle or a motorcycle approaching a stationary car at 30 to 45 degrees. Such conditions are not common in reality and approach angles of 15 to 25 degrees would be more realistic.

Lower Extremity Injuries Associated with the Deflected Classification of Collisions

The injury mechanism and severity for the impacted leg are dependant on the individual accident dynamics and motorcycle geometry. In the case where the relative approach angle is close to zero the knee may be impacted first causing patella disruption and/or femur fracture.

Where there is a higher relative approach angle the lower leg is contacted and then driven back against the engine area. The riders may be leaning their motorcycles just prior to the assymmetric impact, and so the leg area below the knee becomes exposed and impacted. Other motorcycles with wide engines have the rider's ankles located further apart than their knees, so this lower portion of the leg becomes more exposed.

The distinguishing feature of this latter mechanism of injury is that there are two aspects to the trauma. There is first the direct blow on the leg generated by the velocity change, and secondly there is the crushing mechanism which occurs as the leg is pressed between the structures of the striking vehicle and his own machine. These injuries characteristically involve gross tissue disruption. Subsequent medical care is complex and expensive, and long term disabilities are to be expected (Mackay, 1985).

CONCEPTS IN PROTECTION

Although at first sight the relative severity of the exposure of motorcyclists in car to motorcycle collisions, and the obvious limitations of the geometry of the normal design envelope of a motorcycle appear to be extremely unfavourable to crash protective concepts, there may well be partial solutions which still offer significant benefits. In the 1960s crash bars were introduced with the hope that they would provide some protection, but neither the state of knowledge on biomechanics and leg protection, nor experience on the nature and frequency of crash circumstances, were sufficiently advanced to evaluate such systems.

A confounding factor is that the very term "crash bar" covers a variety of structures from small tubes specifically surrounding the engine, clearly only designed with the concept of minimising damage to the engine, to quite large and complex frames positioned ahead of the legs. There are obviously a number of design variables to consider for such structures, notably overall geometry, tube thickness and strength, and attachments to the motorcycle.

An example of such a crash bar is shown in Figure 6, together with an obvious improvement in performance against bending by using an insert to strengthen the tube at its position of highest stress.



Figure 6



Recently the disadvantages and benefits of conventional crash bars have been examined in real world studies with mixed results. Hurt (1984) and Mackay (1985) concluded that current crash bars provide no benefits, but Ross (1983) found that they did. What is clear is that such structures are not engineered towards effective performance in collisions and alternative approaches are necessary.

This was recognised in the experimental context in the early 1970s with the work of Bothwell at the University of Birmingham (Bothwell, 1974) and in the United States by Bartol (1975) and by Langwieder (1977). More recently it has been refined into practical proposals from TRRL (Chinn, 1984) and HUK (Danner et. al., 1985). Implicit in those recent works is a recognition of two factors: Firstly the configuration of the majority of motorcycle collisions with cars involves a substantial forward component of velocity at the level of the leg. Secondly the requirements of leg protection are to provide resistance against striking objects so that some deflection of the machine is generated and a survival space created for the legs, and in addition some attenuation is needed so that the leg can be decelerated without localised, high-energy forces being applied.

In engineering terms this results in an aerodynamic fairing fitted within the normal design envelope of current machines. Externally the structure would be as strong as practical, probably with "crash bar" like transverse components to stiffen the external skin and to provide a survival space for the leg when the machine is sliding on its side on the road surface. Internally, contoured foam would provide the knee and lower leg with "ride-down distance", using materials and criteria similar to what are currently used in cars for lower instrument panels.

The design-shape would not be unlike some of the aerodynamic racing shells

used on current competitive motorcycles. The forward edge should generally be angled slightly more than the motorcycle down tubes so that there is some upward component to help the redirection of the motorcycle when contacting a protruding bumper. If such concepts are integrated into new motorcycle design then consideration as to the width of the engine, ankle separation, width of gas tank, knee separation can be re-evaluated. Style is important but design flexibility has already been demonstrated by manufacturers locating the gas tank in different positions.

One concern expressed in some of the experimental literature is that if the lower part of the body is decelerated by energy-absorbing fairings, then when the rider leaves his machine and has a subsequent head contact with the ground, the head accelerations, measured in Part 572 dummies, in such circumstances are increased.

Generalising from a few experimental results using dummies is often not valid, particularly when the Hybrid II is used. Such a device was intended to be used only in the car occupant mode, when restrained. When ejected from a motorcycle-to-car collision with a landing on the road surface, the subsequent output readings from head and chest accelerometers are not a useful or systematic indicator of exposure to risk of real people.

Because of such experimental difficulties, and because of the absence of detailed field accident studies which can delineate usefully and accurately the important design parameters for crash performance requirements, it is perhaps not surprising that the motorcycle has not changed, from this point of view, in its first hundred years. However, transfer of biomechanical knowledge from the world of the automobile, plus an increasing understanding of the specific circumstances of actual motorcycle accidents now becoming available in the 1980s, offers an opportunity for some crash performance concepts aimed at protecting the lower limbs to be introduced. Of especial promise are the works of HUK and TRRL (ESV 1985), although clearly refining such proposals into practical, acceptable design concepts is still a current difficulty.

Restraint Systems

Early patents suggested that seat belts and other harnesses may have benefits for motorcyclists. Coupled with some energy absorbing frontal structure and a device to attenuate the upper part of the body, a seat belt could well have advantages in certain types of frontal collisions. In other crash configurations there would probably be serious and highly dangerous disadvantages.

A more practical approach is the concept of decelerating the chest with some form of chest pad. Trade-offs exist for this condition however, because of the 1 ikely increases in angular accelerations applied through the neck to the head. Such forces, augmented by a crash helmet, could well be injurious without any direct loading on the head.

A more feasible approach may be to have a crash-deploying airbag which would provide ridedown for both the head and torso. However, inflation times would have to be relatively rapid, and variability in the rider's position could well result in not intended loadings from the still-deploying airbag.

Such systems may well evolve in the future, but their development depends on a parallel development in dummy technology and in biomechanical knowledge

for those regions of the human frame which are not currently assessed with the devices of today. This is particularly the case with the lower limbs, where there is a specific need for a realistic model which will allow the designer to develop crash protective structures to agreed biomechanical criteria for the lower leg, ankle and foot.

CONCLUSIONS AND RECOMMENDATIONS

- 1) Against any criteria, in most countries the motorcycle is the most dangerous road vehicle in use.
- 2) Crash protective principles have been applied to the heads of riders of motorcycles with great success.
- 3) The lower limbs of motorcyclists are injured frequently and severely.
- 4) Crash protection engineered into motorcycle design has been inhibited by:4.1 lack of adequate, detailed accident data.
 - 4.2 lack of adequate biomechanical knowledge, particularly in relation to the lower limbs.
 - 4.3 Over-generalised attempts at the experimental level to improve crash protection, resulting in side effects which detract from the other utilities which a motorcycle has to offer.

Within the last five years however, improved accident studies have begun to produce results detailed enough to give guidance to the designer about the frequency, severity and specific nature of the circumstances of injuries to motorcyclists. What is still missing is an adequate dummy or other surrogate, either physical or mathematical, which will simulate the human frame under the complex conditions of a motorcycle collision. Further, for the leg in particular, there is inadequate knowledge about the appropriate human tolerance values to use for the various injuries, particularly when the trauma relates to soft tissues or involves complex combinations of blows and rotational forces.

To develop protection for riders of motorcycles further, the following are proposed:

- 1) Energy absorbing fairings, f.e. the type suggested by the work of Chinn et al need further evaluation. This involves a recognition that all crash performance improvements will only offer partial benefits in a proportion of collisions; however, those benefits are still probably worthwhile.
- 2) Evaluation of the concept of a high, energy absorbing structure to reduce pitch in frontal impacts and provide "ridedown" for the rider.
- 3) Reduce the potential for soft tissue injuries to the legs by smoothing the sides of the machine where the legs often make contact.
- 4) Continued evaluation of the HUK-concept "optimised motion path" with a controlled separation of the rider.
- 5) Examination of these concepts in relation to pillion passengers.

Beyond these specific developments there are more radical approaches involving energy management systems such as chest pads and crash-initiated airbags. Bringing such designs into a practical reality is combined with the problem, that adequate biomechanical surrogates need to be developed to allow for evaluation of exposures to risk and assessments of performance criteria in the more variable environment of the motorcycle collision. Automobile technology at this point in time is not directly transferable to the more complex conditions of motorcycle crash performance. This however represents a major area of work for the future.

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