## A FIELD AND LABORATORY STUDY OF THE PERFORMANCE OF PEDAL CYCLE HELMETS IN REAL ACCIDENTS.

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**Abstract.**
A study of real pedal cycle accidents was undertaken in Sydney Australia over a four month period in early 1991. Accidents of all severities in which helmets were worn were investigated. The sample sources were: accident and emergency departments, the police, the coroners courts and direct through advertising in cycling magazines and clubs. During the investigation; accident data, injury data, anthropometric data and the helmets were collected. The helmets were then examined in the laboratory for: resultant damage, impact location etc. Further, a matching helmet was tested in order to reproduce the observed damage and thus calculate the impact dynamics.

As compulsory helmet wearing for pedal cyclists became active from Jan.`91 there was a fair response. A sample of 42 cases was finally examined. In this group there was a good mixture of age groups, accident types and helmet models ( hard shell, micro shell & soft shell ). Some of the results are: The most frequently impacted region of the helmet was the frontal/temporal area ( 67 % ). There was a higher incidence of head injury AIS > =2 resulting from impact to the temporal region. There were four fatalities, three with fatal head injuries. No skull fractures were observed with non-fatally injured helmeted cases. The most frequent injury was AIS 1 injuries to the upper or lower limbs. For the group of helmets in which damage reproduction was satisfactory, the max. resultant accelerations for all helmets were between 72 and 345g, mean non-head injury 129g., mean head injury 180g. The impact velocities were between 12 and 20 km/h, mean 16.4 km/h and a mean weight corrected impact velocity of 20 km/h.

Nearly all the soft shell helmets, ie. Expanded Polystyrene, exhibited a great deal of material cracking including separation. In some cases the helmets were split into two halves or into multiple pieces. It was not possible to reproduce this damage with the test procedure.

## INTRODUCTION.

To reduce the occurrence of head injury it became mandatory from 1990-91 in most Australian states for pedal cyclists to wear a helmet.

World wide the high frequency of head injury resulting from pedal cycle accidents has been well documented: Thompson et al.(1989), Otte (1989), Sacks et al (1991) & Simpson et al. (1992). The positive conclusion of Thompson's study, and supported by Dorsch et al.(1987), was that helmet wearing could reduce the risk of head injury by 85% and brain injury by 88%. Apart from Williams (1989) there have been few studies that have examined the performance of individual pedal cycle helmets in real accidents.

There are three major types of pedal cycle helmets: Hard shell ( HS ), Micro shell ( MS ) and Soft shell ( SS ). Hard shell helmets are constructed from a beaded Expanded Polystyrene ( ESP ) foam liner with a hard plastic shell adhered to its outer surface. Micro shell helmets have a similar liner construction but have a much thiner plastic or lacquer shell. Soft shell helmets are solely the ESP liner. Some Soft shell helmets have also an inner Kevlar 'skeleton' eg. Bell Premier and Giro Air Attack.

The aim of the study was therefore to examine the performance of the current range of pedal cycle helmets and their effect in mitigating head injuries.

## METHOD.

The study consisted of three parts:
* Firstly, an investigation of pedal cycle accidents in which helmets were worn.
* Secondly, the collection and examination of these helmets.
* Thirdly, the reproduction of impact damage on equivalent helmets in order to estimate impact dynamics.

### Pedal Cycle Accident Investigation.

The study was conducted in two parts, a four week trial study followed by a sixteen week full study period between January and May 1991 in Sydney and surrounding areas. All fatals were investigated in N.S.W. To collect sufficient cases arrangements were made with: the Police, the Forensic Medicine Division of Glebe Coroner's Court and four major Sydney hospitals. The study was also promoted in pedal cycle magazines, through cycling organizations and in the general media. Cases were obtained through all these sources. Only helmet wearing cyclists who were involved in accidents, with or without injury, in which their helmet sustained a significant impact were investigated.

#### Accident Investigation Procedure.

Where possible subjects were interviewed and basic personal and anthropometric data, information about the accident and resulting injuries were recorded. With fatal cases the police cooperated by supplying accident reports and helmets. Hospital medical records were reviewed and injury details classified according to the 1990 revised Abbreviated Injury Scale (AIS). The accident site was also visited and documented.

### Laboratory Investigation.

All helmets were documented and assessed for damage. This consisted of photographing damaged areas and measurement of foam deformation, crack length etc. The general pre-crash condition of the helmets, age, applicable standards, weight etc. were also recorded. At this stage 28 of the helmets were selected for further evaluation.

#### Helmet Testing.

The helmet drop test rig consisted of a head form mounted by an adjustable system to a set of linear bearings. This system allowed the head orientation to be adjusted and secured. The bearings ran on a vertically mounted 3 metre rail. The impact surface was a flat steel plate mounted on a solid steel frame. The rig was selected to reduce the offloading of impact forces onto guide cables. Carbon paper was placed over the impact surface to mark the helmet-impact surface contact area.

Wayne State University headforms were used. These headforms were selected for their biofidelity in comparison to the magnesium alloy headforms used for standards testing; Saczalski et al (1976). Triaxial centre of gravity acceleration and impact velocity were measured.

Each helmet was matched with an identical undamaged helmet, ie. same make/model and where possible age, and fitted to the correct size headform. A test was deemed to be satisfactory if the damage on the collected helmet was reproduced on the matched helmet ie. amount of deformation and cracking/fracturing.

RESULTS.

42 cases were fully investigated. The mean age at time of accident was 27.1 years with a range from 7 to 51 years. 74% of these cases were male and 26% female. The results of these cases are presented under different catergories to enable a thorough comparison of the many variables.

It was not possible to determine how this sample fitted into the total number of possible subjects in the sampling area, the collection of accident statistics of this type being non-existent.

**Accident Details.**

Twenty six (67%) of all accidents involved another vehicle: 65% sedans, 15% utilities/vans, 4% trucks and 15% another pedal cycle. The weather was clear in 95% of the cases and the road surface, either road or cycle way, paved in all but one case.

The estimated pre-collision velocity of the cyclists were between 0 and 60 km/h and the second vehicle's between 0 and 110 km/h.

**Helmets.**

A wide range of helmet makes and models were collected, 24 different helmet types from 11 manufacturers, see Table 1. This sample appeared to correlate well with the range of helmets available at that time. 50% of the helmets collected were hard shell, 36% soft shell and 14% micro shell. All helmets conformed to set of standards eg. AS 2063, SNELL or ANSI Z90.4. Mean helmet masses were HS=468 gm., MS=258 gm. and SS=222 gm.

**TABLE 1: HELMETS: MANUFACTURERS & MODELS.**

| | |
|---|---|
| BELL: VI PRO x 3, HS, Snell<br>(USA) IMAGE x 3, MS, Snell<br>PREMIERE x 1, SS, Snell<br>SPECTRUM x 2, SS, ANSI<br>QUEST x 1, SS | GIRO: AIR ATTACK x 3, MS, Snell<br>(USA) PROLITE x 1, SS, ANSI&Snell<br><br>SAFE & SOUND: GAURDIAN x 3, HS, AS<br>(AUSTRALIA) HARTOP x 1, HS, AS |
| ROSEBANK: STACKHAT x 5, HS, AS<br>(AUSTRALIA) VENTURI x 1, SS, AS<br>GRAN PRIX x 1, HS, AS | SCOTT ASPEN: ATOM x 2, HS, AS<br>(AUSTRALIA) MAGNUM x 3, HS, AS<br>VORTEX x 1, HS, AS<br>PROLITE x 1, SS, ANSI |
| APOLLO: PEDLA x 1, HS, --<br>(AUSTRALIA) | ATOM: AIRLITE x 2, SS, ANSI, AS<br>(AUSTRALIA) CLASSIC x 1, HS, AS |
| HEADWAY: 301 x 1, HS, AS<br>(AUSTRALIA) 701 x 1, MS, AS | BRANCALE: XP7 x 1, SS, ANSI<br>(ITALY) |
| FFM: VIVO x 2, SS, AS<br>(NEW ZEALAND) | VETTA: CORSA LITE X 1, SS, ANSI<br>(ITALY) |

N.B: STANDARDS: ANSI=ANSI Z90.4, AS=AS 2063.1 or.2, SNELL=SNELL.

Impact Locations: The distribution of primary impacts is presented in Fig 1. "Location of Helmet Impacts". 67% of primary impacts were on the anterior/lateral region of the helmet ie. sites 1,2,4 & 5, skull frontal/temporal.

Helmet Damage: All helmets were in some way damaged. The most common damage was superficial abrasion. 80% of the helmets had more severe damage.

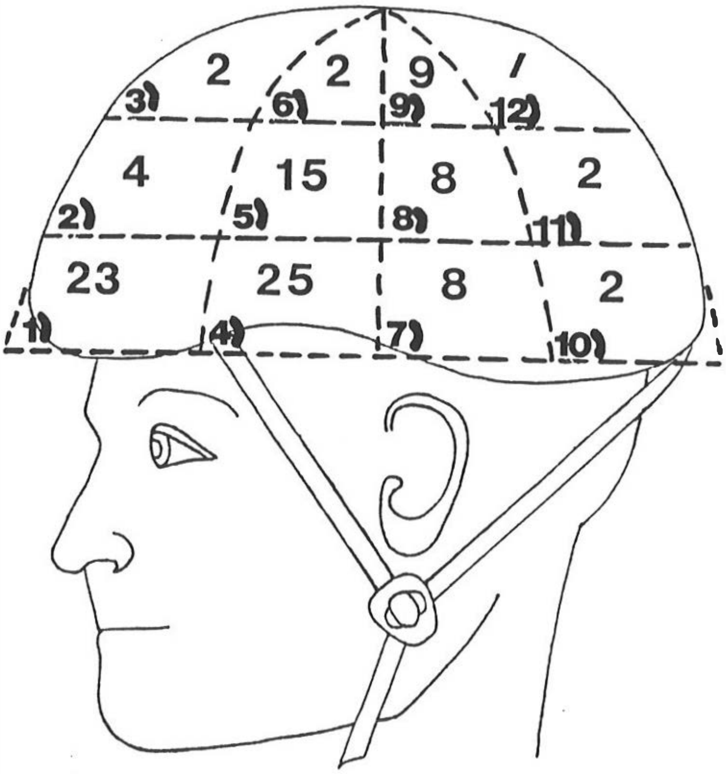


**Figure 1:** Location of Helmet Impacts.
All impacts transposed to one side, presented as %.,
Number in corner is the site. Crushed helmets and unknowns not included.
Head Injury (AIS > =2) producing impacts: 70% Site 4, 20% Site 5 & 10% Site 1

This damage was residual foam deformation (R.D.) and/or half to full thickness cracking (FTC) of the liner material, with or without separation of helmet pieces (Fig 2 & 3). This information is presented in Table 2.

**TABLE 2: HELMET DAMAGE.**

| Helmet Type | Only R.D. | F.T.C.+ R.D. | Only F.T.C. | Total |
|---|---|---|---|---|
| | no. % | no. % | no. % | no. % |
| HS | 3: 11 | 5: 18 | 5: 18 | 13: 46 |
| SS | 1: 4 | 5: 18 | 4: 14 | 10: 36 |
| MS | 0: 0 | 4: 14 | 1: 4 | 5: 18 |
| Total | 4: 15 | 14: 50 | 10: 36 | 28:100 |

N.B: This table excludes cases were there was only minimal residual deformation and two fatal cases where it was very likely that the helmets had been crushed at some stage under cars. These 28 cases were selected for further testing.

Not including the crushed helmets, 10 (36%) of the damaged helmets exhibited material separation (ie. due to a liner fracture a piece became free), 7 soft shell, 2 hard shell and 1 micro shell (sprayed on lacquer). The hard shell helmets in this group were Rosebank Stackhats that had been impacted over a thin flexible extended beam anterior to the ear.

The retention systems functioned in all cases except a fatal one, unfortunately it could not be established whether the helmet was dislodged during this accident or if it was ever correctly fastened.

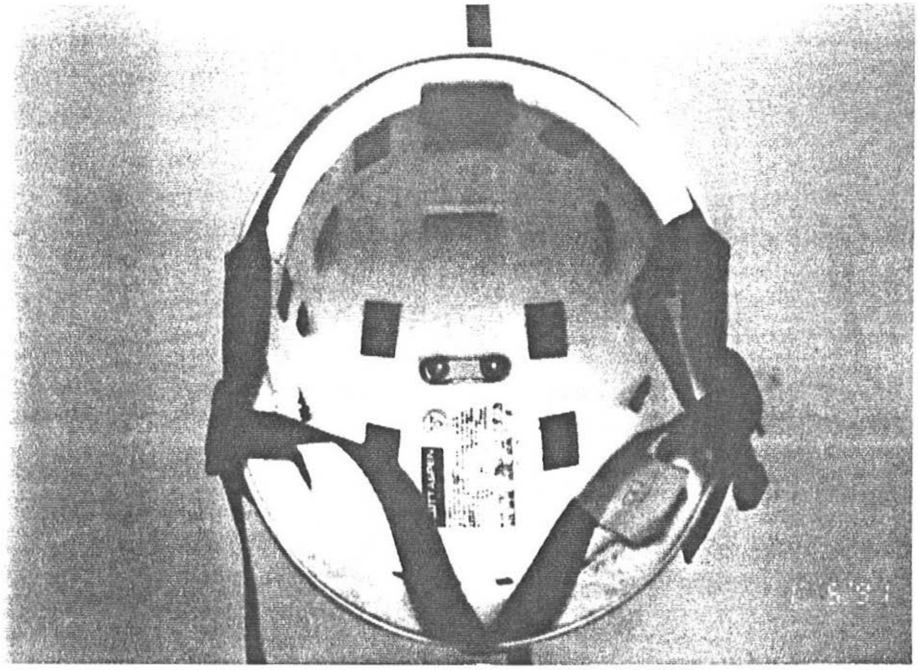

**Figure 2:** Plastic/residual deformation:
ant/lat. aspect of a HS helmet.

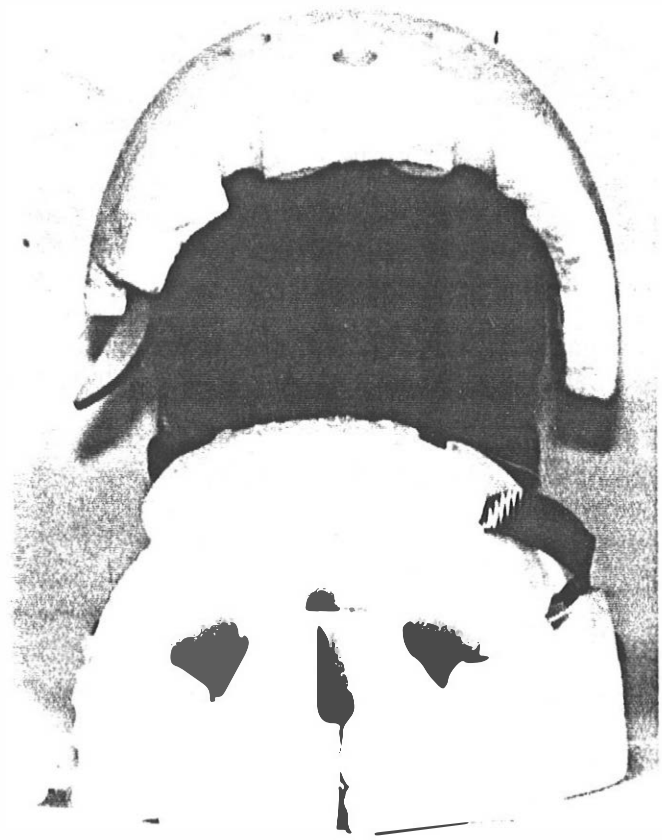

**Figure 3:** Soft shell helmet impacted ant/lat (HI, AIS=2)
front of helmet separated into 8 pieces.

The general pre-accident helmet condition was good in all cases. The mean age of helmets, ie. date of manufacture to accident, was 15.8 months, with a range from 2 to 60 months, however no trend could be established with regard to helmet age and performance.

**Injury.**

All but 3 subjects were injured in some way, ie. 39 (93%) received injuries. 17 subjects received one or more injuries of severity AIS > =2, ie. head injury and/or other injury. Thirty-one of the injured sought treatment, either through their local General Practitioner (G.P.) or through Accident and Emergency (A&E); from this group 18% were admitted to hospital.

There were four fatal accidents, however only one died solely from head injuries. Two died from multiple injuries ( in both cases the helmet was crushed either during or after the accident ) and the fourth from a fatal trunk laceration.

Nine subjects suffered non-fatal head injuries, here classified as minimum AIS=2. The non-fatal head injuries were all except one, minor AIS 2; mostly a brief loss of cosciousness for less than five minutes without resultant neurological deficit ie. Concussion. One subject was admitted to hospital with a head injury of AIS 4. Therefore only 10 subjects, including one fatal, ie. 24%, suffered head injuries that resulted from solely a blunt head impact while definitely wearing a helmet.

Other injuries included fractures of the face, limbs and pelvis, but most frequently limb and/or trunk abrasions.

**Accident Type and Injury.**

Second Vehicle involvement: Twenty six cases involved a collision with a second vehicle, however only fifteen cyclists actually impacted their heads against a vehicle part, the rest were knocked clear or flew over the bonnet. The vehicle parts impacted varied but were almost all flat with varying rigidity. Fourteen of the cases involving a collision with a second vehicle experienced a second, normally minor, impact with the road surface. Four of the 26 cases, 15%, were fatal and 10, 39%, resulted in at least one injury AIS > =2. Four of the 9 non-fatal head injuries AIS> =2 resulted from a collision with a second vehicle.

Single Vehicle Accidents: Sixteen cases did not involve a collision with a second vehicle. All head impacts were against flat rigid objects eg. road or stationary road side object. Seven (44%) resulted in at least one injury of AIS> =2, with 5, of these cases being head injury AIS> =2.

Pre-Collision Velocity and Head Injury: The majority of head injuries or other injuries AIS > =2 occurred when the cyclist was estimated as travelling over 20 km/h or the second vehicle was travelling at greater than 30 km/h (either frontal or oblique impacts). The most severe head injuries occurred in high speed accidents.

**Helmet and Head Injury.**

For the 10 subjects who sustained head injuries (AIS > =2) 6 wore hard shell and 4 soft shell helmets. This is consistent with the distribution of helmet types. Both the fatally injured subject and the most severely surviving head injured subject wore soft shell helmets, the same model FFM-VIVO, however it must be noted that in both cases the probable impact velocity was very high. All of these 10 helmets were damaged: three out of the four soft shell helmets exhibited separation of the liner into pieces, the other soft shell helmet had a kevlar 'skeleton' (Figure 4).

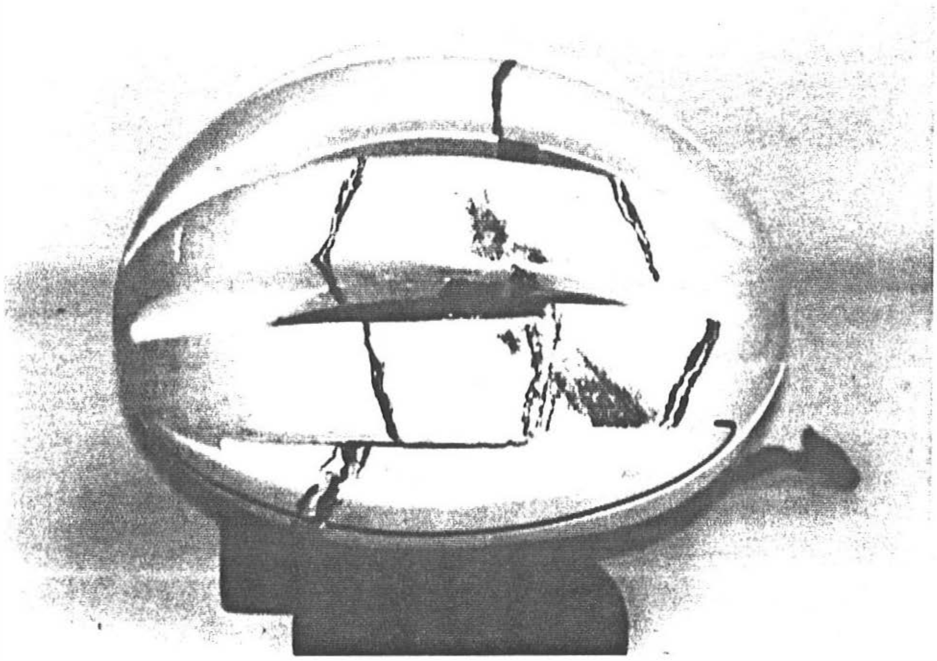

**Figure 4:** Helmet with kevlar 'skeleton'.
Without this it would have disintergrated into many separate pieces.

There was no material separation in the other helmets. The primary impact locations, for this head injury group, were all located on the anterior/lateral aspect of the helmets (Site 4). There was only a single case in which an object, front of truck, penetrated a HS helmet resulting in a lacerated scalp.

**Helmet Testing.**

A subgroup of 28 helmets was selected from the complete helmet sample. This group represented helmets in which there was significant damage, as already described. Table 3. is a summary of the results grouped into head and non head injured cases. To account for the difference between test falling mass and the subject's head-neck mass a weight corrected velocity was calculated for each case. It was assumed that the damage was related to the total kinetic impact energy. Although ESP force/deformation characteristics are strain rate dependent, it was assumed that in a velocity range of 1 m/s this would be small. Head-neck-mass was calculated as 0.081 of the total body mass (Winter 1990). Therefore the weight corrected velocity equals the measured velocity multiplied by the square root of the ratio of test mass to subject's head-neck mass.

Damage Reproduction: It was possible to reproduce similar or identical damage ie. location, severity and type (deformation or cracking) in 18 cases. Tensioning the retention system post impact failed to alter the pattern or severity of damage.

## TABLE 3: SUMMARY OF HELMET TEST RESULTS.

**Resultant C.of G. head acceleration during impact and impact velocity.**

| | Mean Peak Acc. (g) | Mean 3ms. (g) | Mean Impact Velocity. measured (km/h) | Mean Impact Velocity. wt. corrected (km/h) |
|---|---|---|---|---|
| **General** n=18 | 146 | 78 | 16 | 20 |
| **Head Injury** n=6 | 180 | 80 | 16 | 20 |
| Range | 78 - 345 | 70 - 110 | 14 - 16 | 18 - 21 |
| **Non-Head Injury** n=12 | 129 | 76 | 17 | 20 |
| Range | 72 - 217 | 51 - 86 | 12 - 18 | 16 - 24 |

No margin of error has been included in these results, an error of 20% was proposed by Williams (1989). This could increase or decrease velocity and acceleration, as could variations in mass etc.

Accurate damage reproduction was achieved for hard shell and micro-shell helmets, particularly when the damage was only liner deformation. Cracks from the rim towards the crown were also reproduced with micro-shell helmets. The extensive liner separation, or in some cases the separation of the helmet into longitudinal halves or multiple pieces, could not be reproduced with this test for any helmet.

## DISCUSSION.

The results of this study show that 75% of the possible head injury cases experienced no resulting brain injury, ie. all cases received a significant blunt head/helmet impact. Only one head injury case was admitted to hospital due to the head injury and there were no cases of skull fracture in the 9 non-fatal cases. The question that remains is whether helmet design and/or accident conditions accounted for those cases that resulted in death or head injury (Head AIS>=2).

All fatal accidents involved a collision with a motor vehicle. In the single case of solely fatal head injury the collision involved a car travelling at between 100 and 110 km/h. Therefore with regards to helmet design and effectivness we can disregard these cases, that is to say that they were out of the range of impacts that can be presently accommodated in a light weight helmet.

There was a general increase in the percentage of subjects injured or killed in accidents that involved a second vehicle compared to single vehicle accidents, 54% to 38% respectively. This trend was stronger with cars travelling at greater than 30 km/h towards the cyclist and is in agreement with the findings of Otte,D (1985&1989). Single vehicle accidents where the cyclist's pre-collision velocity was greater than 20 km/h also resulted in more severe injury.

However there was no difference between the number of head injury cases arising from accidents with or without the involvement of a second vehicle.

**Helmet Performance.**

The mean peak resultant acceleration for the group of helmets tested from head injury cases is higher than that from non head-injury cases, although not statistically significant; however the impact velocities are similar: 180 g's & 16 km/h to 129 g's & 17 km/h respectively. For both groups the mean weight corrected velocity was 20 km/h.

A further difference between the two groups is the impact site. The majority of non-fatal head injured cases were impacted at site 4., this site corresponds to the temporal region of the skull. This site received directly only 25% of the impacts and of these impacts 75% produced at least AIS 2. Williams (1989) also found that 51% of the impacts occurring below the test line were in the frontal/temporal region. The significance of this region is: Firstly, this region is generally below the test line for ANSI, SNELL and AS 2063 and therefore it does not have to meet impact testing requirements; secondly, the amount of helmet available to absorb and distribute energy is reduced close to the rim and finally; the tolerance of the head to impact at this location is reduced, both to direct loading and to radial acceleration in the coronal plane; SAE report J885 (1980) & Thibault et al (1989).

When these factors are considered and coupled with the great variability in individual tolerance to trauma, it would appear that there is a need to improve the protection offered by the helmets in this region. This can most effectively be brought about through adjustments in the positioning of the test line coupled with an increase in the area of the skull protected. Helmet aesthetics, an important factor for non-wearing, must also be considered with these changes

The separation of helmet pieces seen with soft shell helmets is a phenomenon worthy of comment. Although there did not appear to be any injuries caused directly by a helmet splitting into two or more pieces, the potential for injury would be increased if the cyclist was exposed to more than one head impact. In a number of these cases the collected helmets were split without any great amount of residual deformation, the desired mode of energy attenuation being foam deformation, Gale et al (1985). The cause of this is unknown although the relatively poor tensile strength of the ESP liner combined with helmet/skull bending is a likely factor. It appears with the addition of a shell or 'skeleton' this problem is significantly reduced with only a slight increase in helmet mass.

## CONCLUSIONS:

1) Light weight, well ventilated pedal cycle helmets are very successful in reducing the occurrence and severity of head injury resulting from blunt head trauma.
2) Injury outcome is a function of impact location as well as helmet design and impact severity.
3)The protection offered by pedal cycle helmets in the temporal region requires special consideration.
4) The standards test fall height of 1.5 metres, as opposed to 1 metre, is a safer representation of real accidents.
5) The separation/fracturing of soft shell helmets during impact is a potential problem and even greater when the cyclist is exposed to more than one head impact. Separation can be prevented by minor design modifications.

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