# ADVANCED MOTORCYCLE HELMETS

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## ABSTRACT

More than 5,000 motorcycle riders or pillion passengers are killed annually on European roads and a further 70,000 are seriously injured. In addition to the physical and emotional trauma, the financial cost of these injuries is estimated to exceed 10 billion Euros. The COST 327 European Research Action on motorcycle helmets reported that improvements in helmet design could save up to 1,000 lives per year across the European Union. Approximately 80% of motorcyclists killed on European roads sustained head impacts and in half of these cases, the head injury was the most serious.

TRL has developed with industry an advanced protective helmet which provides a higher level of protection than current helmets to BS 6658A, ECE Regulation 22-05 or Snell M2000. The helmet consists of a lightweight carbon composite shell fitted with an optimised energy absorbing liner and a low friction sacrificial outer surface. The advanced helmet is designed to reduce both linear and rotational acceleration loadings to the head.

In order to quantify the benefits of the advanced helmet, the impact response was measured during a range of impact conditions. The results were related to the AIS scale using correlation coefficients developed by TRL from an accident replication programme. It was shown that the advanced helmet could reduce injury risk by up to 20% for AIS 6 injuries and up to 70% for AIS 5 and AIS 4 injuries. The performance of the helmet during less severe impacts (corresponding to AIS 3, 2 and 1) was designed to be equivalent to current helmet designs.

Given this potential, the UK Department for Transport is collaborating with domestic and European partners in a new project to encourage the introduction of more protective motorcycle helmets. This paper describes the work to date and prospects for the future.

## INTRODUCTION

Research conducted by the COST 327 European Research Action [1] on motorcycle helmets concluded that head injury severity increased, quite remarkably, with head impact speed. More than 5,000 motorcycle riders or pillion passengers are killed annually on European roads and a further 70,000 are seriously injured. It was postulated that if helmets could be made to absorb 24% more energy then some 20% of the AIS 5-6 casualties would sustain reduced injuries of only AIS 2-4. Furthermore, an increase in helmet energy absorbing characteristics of some 30% would reduce 50% of the AIS 5/6 casualties to AIS 2-4.

Research was carried out in parallel by TRL and industry to develop a prototype of an advanced helmet design capable of satisfying both the safety performance specified by COST 327 and geometric, mass and ergonomic requirements based on current motorcycle helmets designed to BS 6658A [2] or ECE Regulation 22-05 [3].

There were two principal objectives for the new helmet (A) ultra stiff shell structure and optimised liner (B) low friction outer surface.

*A) The aim of the ultra stiff shell structure was to ensure that the outcome of a linear impact (or component thereof) was independent of the profile of the impacted surface. Thus the protection provided by the helmet corresponded to the characteristics of the liner material and thickness. The liner could then be optimised for internally induced deformation caused by the head moving into the liner. By this approach, externally induced deformation that arises, for example, by the shell of a current helmet deforming when striking a kerbstone anvil, was reduced to a negligible amount.*

*B) The aim of the low friction surface was to reduce tangential impact loads during oblique impact conditions, thus minimising the rotational accelerations imparted to the head, whilst correspondingly reducing the resultant force and, therefore, reducing the resultant linear acceleration.*

This paper describes the development programme for the new helmet and demonstrates how the COST 327 objectives were exceeded. An injury benefit analysis was conducted based on the safety performance of the new helmet. The analysis considered the distribution of injury mechanisms and severities for the riders injured on roads in Great Britain and determined the extent to which the distribution may be improved if advanced helmets had been worn. It was concluded that up to 20% of fatal rider injuries in Great Britain could be prevented. If the same proportion of injury reduction could be achieved on European roads more than 1,000 lives per year could be saved.

The advanced prototype helmets were produced using relatively expensive materials and processes. It was, therefore, important to consider the cost of such helmets if mass produced to achieve significant sales penetration. The dominant cost issues are discussed within this paper, together with new work which, it is hoped, will reduce these further to allow for greater penetration.

## HEAD INJURY MECHANISMS

A helmet is designed to protect the rider in the event of an accident by absorbing impact energy and reducing the loading imparted to the head via the helmet. In order to maximise the protection provided by a helmet, it is important to identify the mechanisms by which a head becomes injured. The term 'head injury' comprises various kinds of trauma to the skull and its contents. Usually, several different types of head injury occur simultaneously in a traffic accident. The anatomical location of the lesions and their severity determine the physiological consequences. Injuries may be divided into cranial injuries (skull fractures) and intracranial "soft tissue" injuries. Indeed, skull fracture can occur with or without soft tissue damage and vice versa.

Skull fracture occurs when the loading on the skull exceeds the strength of the bone and can be either open or closed. Skull fractures may be divided into facial, vault and basal. The most threatening form of skull fracture is basilar skull fracture. A characteristic of motorcycle accident victims is that fractures of the vault are rare among helmeted riders, but that basilar skull fractures are frequently encountered, both in helmeted and unhelmeted riders [4 and 5]. Soft tissue damage occurs, during an impact, due to high strains within the vascular and neurological tissues as a result of both linear and rotational loadings to the head.

The risk of both types of injury (skull fracture and soft tissue) can be reduced by improving the energy absorbing performance of the helmet. The advanced TRL protective helmet achieves this with a liner-shell combination of appropriate stiffness to minimise linear acceleration during high energy impacts. In addition, the outer surface of the helmet provides very low friction, so that the rotational accelerations imparted to the head are minimised.

## SPECIFICATION FOR MOTORCYCLE HELMET SHELL – LINEAR IMPACT

The objective of the new helmet was to exceed the safety performance objectives of the COST 327 European Research Action on motorcycle helmets. A target improvement in linear impact energy absorption of 75% was proposed; corresponding to impact tests at 10m/s compared with 7.5m/s for ECE Regulation 22-05.

This could be achieved, in part, by optimising the performance of the shell to be very stiff and able to resist excessive shell deformations and thus transmit loads more efficiently to the energy absorbing liner. It was proposed that the mass of the shell should not be greater than that of current designs and should be reduced, if possible. It was accepted that the thickness may need to be increased, compared with current designs (which are typically 3mm), in order to achieve the objectives. A maximum thickness of 10mm was proposed. The materials were specified such that a helmet shaped structure with double curvature could be achieved and volume production would be practicable. In addition, it would be beneficial for the structure to possess inherent damping qualities that would minimise rebound during impacts.

To meet these objectives, flat coupons tests (see below) were used to develop helmet shell materials and further full geometry tests to identify optimal liner materials. Further prototype helmet tests were completed to evaluate the performance benefits of the advanced helmet over current helmet designs.

## PERFORMANCE ASSESSMENT USING FLAT COUPONS

The impact characteristics of the shell were assessed together with consideration of temperature and moisture stability, mass, thickness and scope for production. Durability was not considered at this stage. TRL developed specific test procedures to enable the evaluation of shell structures using flat samples of shell material. The cost of manufacturing and testing flat shell samples was very much lower than for helmet shaped shell structures, therefore a greater number of potential designs could be evaluated. The dynamic loads exerted during the flat sample tests were representative of those exerted during complete helmet test, therefore it was possible to evaluate the flat shell structures for use in complete helmets.

It was important that the results from the tests on flat samples represented the performance of complete helmets, constructed with the same materials. In order to ensure this, the test procedures were representative of a falling headform test. The acceleration-history of the impactor during these flat coupon tests was related to the acceleration-history of a helmeted headform during similar impact conditions.

**Linear impact tests -** Flat shell samples measuring 120mm x 70mm were attached to a 'bed' of energy absorbing foam measuring 120mm x 70mm x 35mm using double sided adhesive tape. The foam used had energy absorbing properties similar to the Expanded Polystyrene (EPS) used in motorcycle helmets. The foam/shell specimen was attached to the base of a 2.5kg mass, with the shell facing outwards. The specimen was impacted onto a steel hemi-spherical anvil with a 25mm radius. The anvil was designed to simulate the shell-stresses developed during a helmet impact onto the ECE Regulation 22 kerbstone anvil. The impactor was fitted with a single axis accelerometer and the signal was recorded in accordance with SAE J211 (CFC1000). Tests were conducted at 5m/s, 7.5m/s and 10m/s.

**Temperature and moisture tests -** The samples were pre-conditioned for a minimum of 4 hours at -20°C, +25°C, +50°C and with moisture conditioning by means of submersion in a water bath. The samples were placed on a rigid anvil, with the shell facing upwards, and impacted with a 2.5kg mass fitted with the steel hemi-spherical impact surface as above. The impactor was fitted with a single axis accelerometer and the signal was recorded in accordance with SAE J211 (CFC1000). Tests were conducted at 7.5m/s.

**Analysis and results -** For each test the acceleration history of the impactor was recorded. By single integration of this result the velocity history was calculated and hence the rebound velocity was determined. By double integration of the acceleration result, the displacement history was calculated and this enabled the maximum dynamic displacement to be determined.

A specification was defined for the flat coupons to achieve the proposed helmet shell performance. This was considerably more advanced than that of current helmet designs, and was thought to be close to the limit of what was technically achievable. The requirements were closely met and allowed the helmet performance to be optimised within the constraints of a current helmet mass. A summary of this specification is given in the Table 1 below;

**Table 1 - Performance target for flat coupons**

| | |
|---|---|
| Size | 120mm * 70mm |
| Thickness | Maximum of 10mm |
| Mass | Maximum of 50g |
| In-plane tensile strength | Peak tensile stress will occur at the *inner surface* and will be dependant on the thickness of the structure. In the region of 250N/mm² for a 5mm thick structure or 60N/mm² for a 10mm thick structure. |
| In-plane compressive strength | Peak compressive stress will occur at the *outer surface* and will be dependant on the thickness of the structure. In the region of 250N/mm² for a 5mm thick structure or 60N/mm² for a 10mm thick structure. |
| In-plane bending stiffness | 10 times as stiff as 3mm GRP (or 5mm unreinforced polycarbonate). |
| Through-thickness compressive strength | Management of compressive forces without excessive dimpling to the outer skins. Peak compressive stresses approximately 30N/mm² at 1.5mm shell deformation. |
| Operating conditions | -20°C to +50°C with extremes of moisture |

## FLAT COUPON LINEAR IMPACT TESTS

The structural requirement for the shell structure was to transmit the impact force between the impact surface and the energy absorbing liner material, without excessive deflection or structural failure. In order to achieve this, the structure must also resist the high local contact stresses at the point of impact, without excessive local deformation.

To define acceptable levels of shell deformation, TRL investigated the impact performance of an infinitely stiff shell structure which does not deflect during impact. This was achieved by impacting samples of the energy-absorbing foam between parallel plates in accordance with the procedures used for shell evaluation discussed above. In order to transmit the impact forces to the energy absorbing liner, the maximum acceptable shell deformation was estimated to be 3mm during a 7.5m/s impact and approximately 5mm during a 10m/s impact.

The linear impact performance of the coupon structures were further analysed using the acceleration-time history and acceleration-displacement of the impactor. At 7.5m/s the peak deformation of the impactor was 18mm and at 10m/s the peak deformation of the impactor was 27mm. These results were combined with the target values for shell deformation to prescribe target displacement values of 21mm at 7.5m/s (18mm+3mm) and 32mm at 10m/s (27mm + 5mm).

In addition to impactor displacement, it was possible to evaluate the results in terms of impactor acceleration and define appropriate limits for these performance parameters. At 7.5m/s, the infinitely stiff shell achieved a peak acceleration of 200g and when tested at 10m/s the peak acceleration was 300g. The acceleration results from tests on less stiff shells were, implicitly, lower than those for the infinitely stiff shell *(except when the shell was so soft that the impactor bottomed out, hence producing a very high acceleration result)*. It was therefore proposed that the novel shell structures should achieve acceleration levels slightly lower than for the infinitely stiff shell tests. Based on this concept, the prescribed target values for peak impactor acceleration were;

*i. at least 180g during impact at 7.5m/s*
*ii. no more than 300g during impact at 10m/s*

Although a high stiffness is a fundamental requirement of the 'novel shell design', it may be an advantage for the shell to deform or yield during severe impact conditions, so that the space occupied by the thickness of the shell may be fully utilised. This characteristic was also investigated during the evaluation of the 'novel structures'.

**Test samples for linear impact tests**

The following test samples were evaluated;

1 Polycarbonate - 5mm thick
2 Polycarbonate - 10mm thick
3 Nimrod helmet shell sample - 5mm thick
4 Aluminium plate - 5mm thick
5 Carbon-sandwich (CS-01) - 4.1mm
6 Carbon-solid (CS-02) - 2.9mm
7 Carbon-experimental (CS-08) - 3.0mm

***Results for linear impact tests***

A summary of the tests data is provided in Table 2. The design values are also included.

The baseline polycarbonate and aluminium materials did not achieve the target performance values. These materials were found to have an insufficient strength to weight ratio such that when the mass criterion was met, the impact performance was not achieved, and when the thickness (and therefore strength) was increased to meet the impact performance, the mass became prohibitively high.

Three different variations of composite design were used. All three were constructed using carbon fibre composite materials. CS-01 was a sandwich construction with a syntactic foam core, CS-02 was a solid laminate and CS-08 was an experimental laminate. Both CS-01 and CS-02 achieved all the target values for mass, thickness, deformation and acceleration. CS-08 met all but the deformation target during the 10m/s test, with a deformation of 34mm compared with the target of 32mm. It was found that the performance of all the carbon structures was stable after the temperature and water conditioning.

**Table 2. Summary of test results from Carbon composite coupon structures**

| Sample | Mass [g] | Thickness [mm] | Peak Deformation [mm] | | Peak Acceleration [g] | |
|---|---|---|---|---|---|---|
| | | | 7.5 m/s | 10 m/s | 7.5 m/s | 10 m/s |
| Rigid flat plate | | | 18 | 27 | 202 | 300 |
| ***Target*** | *≤50* | *≤10* | *≤21* | *≤32* | *≥180* | *≤300* |
| PC (5.0mm) | 50 | 5 | **23** | **35** | **157** | **364** |
| PC (10mm) | **100** | 10 | 18 | 28 | 195 | 288 |
| Nimrod (5.0mm) | 45 | 4.5 | **25** | | **144** | |
| Al (5.0mm) | **117** | 5 | 18 | 26 | 204 | 293 |
| CS - 01 (4.1mm) | 40.6 | 4.8 | 21 | 30 | 200 | 298 |
| CS – 02 (2.9mm) | 36.2 | 3.0 | 20 | 32 | 210 | 242 |
| CS - 08 (3.0mm) | 39.7 | 3.0 | 21 | **34** | 193 | 293 |

Results in **bold** did **not** achieve target values

In summary, CS-01 and CS-02 achieved all the design targets and provided significantly improved performance compared to the baseline materials. These two materials were selected for testing with full-geometry helmet constructions.

## SPECIFICATION FOR MOTORCYCLE HELMET SHELL – SURFACE FRICTION

COST 327 [1] reported that reducing the tangential force during an impact by 50% may reduce the injury outcome by one AIS category. It was, therefore, agreed that the new helmet should be developed with a shell system designed to minimise surface friction. A bespoke test method was devised to assess the potential solutions for the reduction of rotational motion by measuring the effective surface friction of flat coupon test samples. The tests samples included low friction coatings and a sacrificial layer designed to peel away with very little force.

The test configuration consisted of pseudo-dynamic surface abrasion tests using flat samples of shell material. Two test methods, using the same apparatus were utilised depending on the technique presented to reduce friction. Samples that presented a surface with a low coefficient of friction were evaluated using configuration 'A'. Samples that presented a sliding-layer failure mechanism were evaluated using configuration 'B'. The results from both methods were compared directly. TRL tested three variants with three tests per variant. Figure 1 shows the apparatus used.

The samples were located in a rigid housing and positioned against the flat horizontal track surface 300mm long and 150mm wide. A normal force was applied using a pneumatic actuator to clamp the sample against the track surface. The magnitude of this load was approximately 2,000N (to simulate the typical normal force during an oblique impact test to ECE Regulation 22-05 Method A). A tangential force was subsequently applied using a pneumatic actuator to slide the track surface relative to the test sample. The stroke of the tangential actuator was 100mm. The normal and tangential loads were measured with load-cells and the acceleration of the track surface carriage was measured with an accelerometer. The instrumentation data was recorded at a rate of 10,000 samples per second and filtered in accordance with SAE J211. A filter frequency of CFC180 was chosen after careful consideration.

For configuration (A): samples measuring 25mm x 25mm and between 2mm and 25mm thick, with a 2mm radius on one edge, were mounted in a rigid sample holder and clamped against a flat carriage fitted with 80 grit aluminium oxide paper. For configuration (B): samples measuring 120mm x 70mm and between 2mm and 25mm thick were mounted on a carriage and a 80 grit aluminium oxide tool measuring 25mm x 25mm was clamped against the surface of the sample.

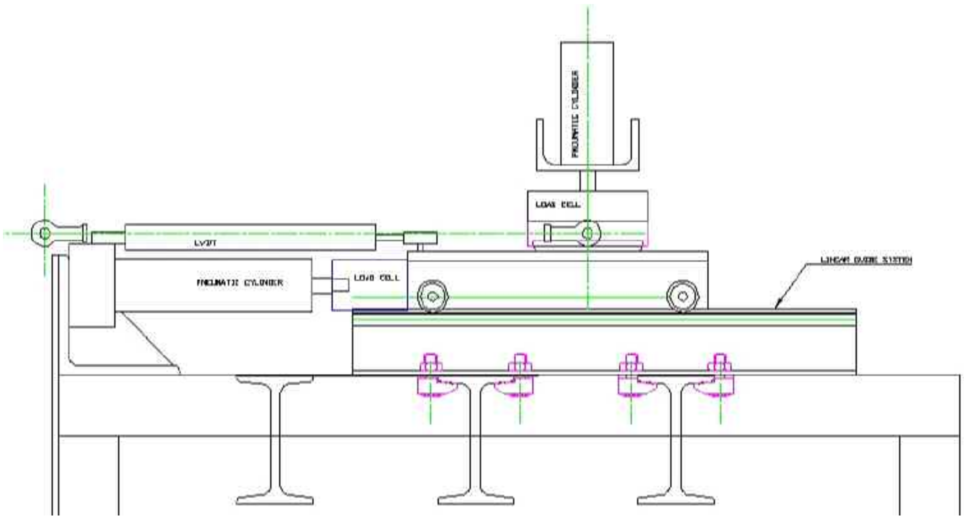


**Figure 1. Low velocity, transient, surface friction test apparatus**

**Test samples for surface friction tests**

For both configurations, the carriage was translated perpendicular to the clamping force over a minimum distance of 65mm and with a maximum speed of approximately 1.5m/s. By measuring the normal and tangential loads during the event, it was possible to calculate the effective dynamic coefficient of friction of the sample.

Three coupon samples were investigated as detailed below:

1 Polycarbonate (configuration A)
2 Carbon fibre composite with toughened epoxy matrix (configuration A)
3 Sacrificial layer (configuration B)

**Test results for surface friction tests**

A summary of the results are provided in Table 3 below. The baseline polycarbonate material achieved a peak friction of μ0.77 and a sliding friction of μ0.42. The carbon fibre material achieved significantly reduced friction values of μ0.17 peak and μ0.12 sliding, a reduction of almost 80% in peak friction. The sacrificial layer achieved the lowest values of μ0.10 peak and μ0.09 sliding, a reduction of almost 90% in peak friction. Both systems were further evaluated using full helmet shell tests.

**Table 3. Summary of test results from flat coupon structures**

| Sample | Normal force [N] | Coefficient of friction (μ) | |
|---|---|---|---|
| | | Peak | Sliding |
| Polycarbonate | 1,900 | 0.77 | 0.42 |
| Carbon fibre *(CS-01)* | 2,000 | 0.17 | 0.12 |
| Sacrificial layer | 1,900 | 0.10 | 0.09 |

## FULL GEOMETRY HELMET SHELL TESTS

Tests were conducted on full-geometry prototype helmet samples in order to develop and evaluate the linear impact and oblique impact performance as defined by ECE Regulation 22-05.

## LINEAR IMPACT DEVEOPMENT TESTS

The aim of the linear-impact development tests was to evaluate full-geometry prototype helmets with carbon shells to the laminate specification determined in flat coupon testing. The shells were fitted with Expanded Polystyrene (EPS) energy absorbing liners of different densities (25g/l and 30g/l) in order to determine the best compatibility between shell and liner. The prototype helmets were full-faced geometry construction, in size 57 (medium), and conformed to the extent of protection requirements of ECE Regulation 22-05. The impact area of the shell was profiled to closely fit the energy absorbing liner. The linear impact tests were conducted in accordance with ECE Regulation 22-05 using a rigid free-motion headform of mass 4.7kg. A total of five linear impact tests were conducted on each helmet design, with tests at 7.5m/s and 10m/s onto both the flat and kerbstone anvils with temperature conditioning at –20$^o$C, 25$^o$C and +50$^o$C.

Baseline tests were conducted on current full-faced GRP motorcycle helmets conforming to ECE Regulation 22-05. The results are shown in table 4 below. The baseline performance at 10m/s onto the kerbstone anvil (front) was 954g and onto the flat anvil (crown) was 299g. The carbon shell concept provided a significant improvement over the current motorcycle helmet design with a 10m/s kerbstone anvil (front) impact result of 235g (CS-02) and a 10m/s flat anvil (crown) result of 230g.

The results were analysed in detail to determine the best solution in terms of liner density and shell construction (solid laminate or sandwich), as described below.

**Liner Density -** During tests at 10m/s the 30g/l EPS liner achieved 235g on the front (CS-02) and 292g on the rear (CS-01) compared with 319g on the front and 890g on the rear for the 25g/l EPS liner. Based on these results, 30g/l EPS was considered to be the best solution for the main area of the energy absorbing liner. However, it was decided that the crown area should be of a lower density to compensate for the increased volume of liner that is compressed during a crown impact test due to the head geometry in this region. Evaluation of 25g/l EPS during crown impacts at 10m/s revealed a peak acceleration of 230g (CS-01) and 242g (CS-02). A 25/30g/l dual density EPS liner was therefore chosen as the best solution for the performance evaluation of the advanced helmet.

**Shell construction -** The results for the two carbon shell concepts were similar as can be seen by comparing the results for side impact onto the flat and kerb anvil: 185g and 173g respectively for the solid shell and 200g and 186g respectively for the sandwich shell. However, the solid shell had two advantages over the sandwich shell;

(1) reduced thickness, thus providing space for additional liner material
(2) potentially lower production costs.

The solid shell (CS-01) was chosen as the best solution for the performance evaluation of the advanced helmet.

**Table 4. Results from linear impact tests**

| Helmet | Liner density [g/l] | Impact velocity [m/s] | Impact site | Impact anvil | Temperature [ºC] | Peak acceleration [g] |
|---|---|---|---|---|---|---|
| CS - 01 Carbon- Solid laminate | 25 | 10 | Front | Kerb | +50 | 319 |
| | 25 | 10 | Crown | Flat | -20 | 230 |
| | 25 | 10 | Rear | Kerb | +25 | 292 |
| | 30 | 7.5 | Side R | Flat | +25 | 185 |
| | 30 | 7.5 | Side L | Kerb | +25 | 173 |
| CS - 02 Carbon- Sandwich | 30 | 10 | Front | Kerb | +50 | 235 |
| | 25 | 10 | Crown | Flat | -20 | 242 |
| | 25 | 10 | Rear | Kerb | +25 | 890 |
| | 30 | 7.5 | Side R | Flat | +25 | 200 |
| | 30 | 7.5 | Side L | Kerb | +25 | 186 |
| Baseline current | | 10 | Front | Kerb | +25 | 954 |
| | | 10 | Crown | Flat | +25 | 299 |

## FULL GEOMETRY SURFACE FRICTION DEVELOPMENT

The aim of the surface friction development tests was to develop a low friction surface coating or system to reduce the tangential forces during an oblique impact. Two systems, identified during flat coupon testing, were evaluated together with an additional hardened metallic surface as detailed below.

1. Carbon composite (toughened epoxy matrix)
2. Sacrificial layer
3. Tungsten carbide (hardened metallic surface)

The surface friction tests were conducted in accordance with ECE Regulation 22-05 using a rigid free-motion headform of mass 4.7kg impacting onto the 15° abrasive anvil at 8.5m/s. Baseline tests were conducted on current full-faced GRP motorcycle helmets conforming to ECE Regulation 22-05. A summary of the results is provided in Table 5. The carbon composite shell and tungsten carbide surface significantly improved performance during the oblique impact tests, with frictional values of μ0.42 and μ0.39 respectively, compared to the baseline value of μ0.69. However, the sacrificial layer provided the greatest improvement with a friction coefficient of μ0.16, which represented a 77% percent improvement over the baseline result. The sacrificial layer was, therefore, chosen as the best solution for the performance evaluation of the advanced helmet.

**Table 5. Results from surface friction tests**
(ECE Regulation 22-05 limit for tangential force is 3,500N)

| Helmet | Impact velocity | Impact anvil | Peak force [N] | | |
|---|---|---|---|---|---|
| | | | Normal | Tangential | Friction |
| CS-01 Carbon shell with toughened epoxy matrix | 8.5m/s | 15° abrasive | 2640 | 1118 | 0.42 |
| CS-02 Carbon shell with sacrificial layer | 8.5m/s | 15° abrasive | 2066 | 323 | 0.16 |
| CS-01 Carbon shell with Tungsten carbide layer | 8.5m/s | 15° abrasive | 3162 | 1250 | 0.39 |
| Baseline helmet Full-faced GRP to BS6658A (average) | 8.5m/s | 15° abrasive | 2874<br>2709<br>3187<br>2455<br>(2806) | 1890<br>2000<br>2060<br>1806<br>(1998) | 0.66<br>0.74<br>0.65<br>0.74<br>(0.69) |

## PERFORMANCE EVALUATION OF ADVANCED HELMET PROTOTYPE

The protection provided by the advanced helmet was assessed by comparing the impact performance of the advanced helmet with that of current motorcycle helmet designs conforming to ECE Regulation 22-05. This was achieved by performing both linear and oblique impacts with the helmets fitted with a Hybrid II headform instrumented with a nine-accelerometer array to measure linear and rotational accelerations. The linear impact tests were conducted onto the kerb and flat anvils as prescribed by ECE Regulation 22-05 with impact velocities up to 10m/s. The results from the linear tests were used to characterise the relationship between impact velocity and peak linear acceleration. The oblique impact tests were conducted onto the abrasive anvil as prescribed by ECE Regulation 22-05 (Method A) and additional tests were conducted using a variety of impact conditions established by the COST 327 replication programme, to simulate real accidents.

The results from these tests were analysed, as described below, to determine the response of both helmet designs in terms of AIS injury severity for a given impact severity. Because an impact to the head induces both linear and rotational motions, it was necessary to develop a method of assessing the performance and protection provided by the helmet with regard to both mechanisms. The GAMBIT assessment criterion was chosen for this study because it considers both linear and rotational motions and allows both impact components to be combined to give an indication of injury severity[1]. Although the COST 327 report found that the relationship between GAMBIT and AIS was low ($r^2 = 0.0751$), the replication data was reviewed and results from motorsport accident replication tests were included. This analysis produced a correlation coefficient of 0.57 ($r^2 = 0.3214$). It should be noted that the fatal cases were not included in this study. The following section describes the methodology for comparing the performance of the current and advanced helmets in terms of AIS injury outcome.

The relationship between impact velocity and peak linear acceleration, shown in Figure 2, was determined using test data from helmet tests onto rigid anvils. The advanced helmet was designed to provide protection during normal impacts up to 10m/s onto the rigid anvils compared with 7.5m/s for current helmets. The results show that the advanced helmet provides similar protection to the current helmet up to approximately 7m/s (normal impact velocity). At higher velocities the protection provided by the advanced helmet is considerably increased.

The advanced helmet was designed to provide improved protection during oblique impacts by having a very low friction outer surface. Figure 3 shows the relationship between linear and rotational accelerations for both current and advanced helmets based on the results from the ECE Regulation 22 (Method A) tests and the accident replication tests. The figure also shows a linear regression between the two parameters. It can be seen that the advanced helmet achieves

[1] The analysis needed such a relationship in order to carry out the risk of injury reduction analysis. In the absence of other combinational criteria, GAMBIT was used.

considerably lower rotational accelerations for a given linear acceleration. The results from Figure 2 and Figure 3 were combined to provide a relationship between equivalent normal impact velocity and peak rotational acceleration (Figure 4). It can be seen that the advanced helmet provides slightly improved protection up to approximately 7m/s and significant improved protection for higher impact speeds. The accident replication results, for the current helmet, were further analysed by plotting the normal impact velocity component against the peak rotational acceleration. The equation of the line of best fit was found to be $y = 1230.9x^{1.362}$. This line, as presented in Figure 4, was found to very closely agree with the rotational acceleration response curve for the current helmet and, therefore, was considered to support the validation of this methodology.

The relationship between impact velocity and GAMBIT results was determined by combining the results from Figure 2 (linear acceleration) and Figure 4 (rotational acceleration) using the equation below (see Figure 6 ).

$$GAMBIT = \sqrt{(g/250)^2 + (rad/s^2/10{,}000)^2}$$

The relationship between impact velocity and AIS (Figure 6) was determined using the results in Figure 5 and the following expression which was established from the analysis of accident replication data;

$$AIS = 2.0273Ln(GAMBIT) + 2.0933$$

The results in Figure 6 can be used to compare the performance of the current and advanced helmets in terms of AIS injury outcome. Based on this study, it was possible to estimate the injury reduction benefits of the advanced helmet for those accident types where it was considered that an improved helmet could reduce the level of head injury. The following AIS injury reductions were used for the next part of this study.

- AIS 6 injuries reduced to AIS 4
- AIS 5 and 4 injuries reduced to AIS 3
- AIS 3 remain AIS 3 *
- AIS 2 remain AIS 2 *
- AIS 1 remain AIS 1 *

** although the AIS 1, 2 and 3 levels are shown to be reduced with the advanced helmet (Figure 6), the reductions were less than one whole AIS level. And, therefore, for the purpose of this study it was considered that the advanced helmet would provide the same injury outcome for these accidents.*

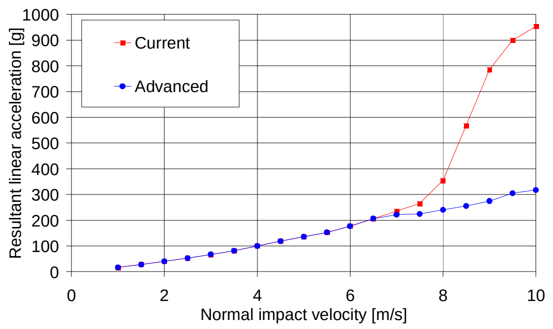


**Figure 2. Relationship between impact velocity and linear acceleration for current and advanced helmets**

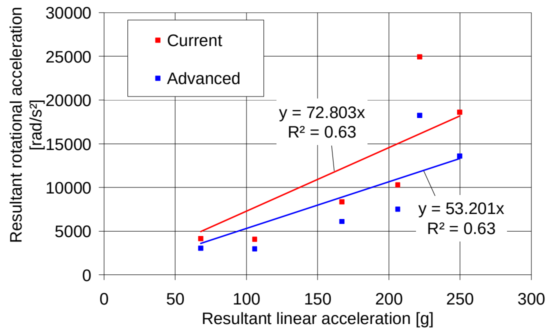


**Figure 3. Relationship between linear acceleration and rotational acceleration current and advanced helmets**

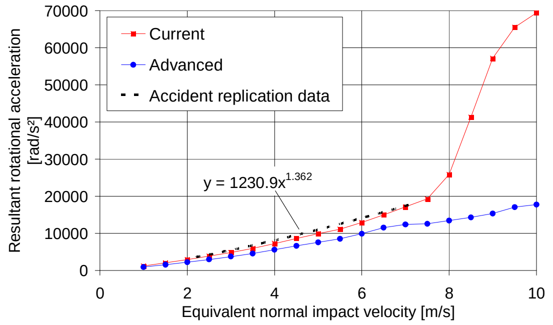


**Figure 4. Relationship between impact velocity and rotational acceleration for current and advanced helmets**

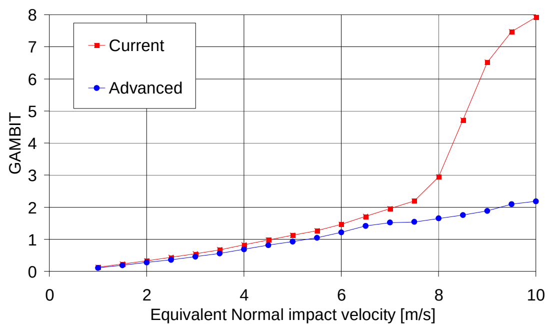


**Figure 5. Relationship between impact velocity and GAMBIT for current and advanced helmets**

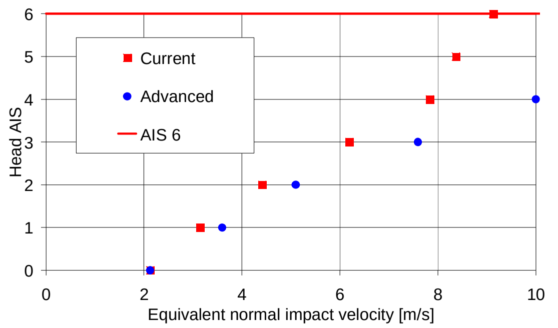


**Figure 6. Relationship between impact velocity and AIS injury severity for current and advanced helmets**

## INJURY REDUCTION ANALYSIS

### Assessment of benefits

**Number of casualties who may benefit from an improved helmet -** In order to evaluate the number of motorcyclists that may potentially benefit from an advanced helmet it was necessary to examine the national accident data. Table 6 indicates the number of Two-Wheeled Motor Vehicle (TWMV) casualties, by casualty severity, for the years 1999 to 2002 [6].

For the purposes of the cost benefit analysis the mean casualty severity values (1999-2001) were used. COST 327 [1] accident data analysis has suggested that 81.3% fatal, 67.9% serious, and 37.7% slight injured riders sustained head impacts which corresponded to 470 fatal, 4,493 serious and 7,744 slight.

**Table 6. Motorcycle casualties (1999-2001; RABG 2002 [6])**

| Casualty severity | 1999 | 2000 | 2001 | 1999-2001 (mean) |
|---|---|---|---|---|
| Fatal | 547 | 605 | 583 | 578 |
| Serious | 6,361 | 6,769 | 6,722 | 6,617 |
| Slight | 19,284 | 20,838 | 21,505 | 20,542 |

It was important to consider specifically the cases for which head was the most severely injured body region as these cases would benefit most from an improved helmet design. Based on data presented by Chinn [7], the head was the most severely injured body region in 80% of fatal and 70% of serious cases where a head impact was sustained, which corresponded to 376 fatal and 3,145 serious cases. It was estimated that the proportion of slight injuries where the head was the most severely injured body region was 60% corresponding to 4,647 cases. A summary of these results is provided in Table 7 below.

**Table 7. Annual number of motorcycle accidents where riders or pillions suffered head injuries**

| Casualty severity | All casualties (1999-2001) (A) | Casualties with head injury (B) | Casualties with head injury *and head most severely injured region* (C) |
|---|---|---|---|
| Fatal | 578 | 470 (81.3% of A) | 376 (80% of B) |
| Serious | 6,617 | 4,493 (67.9% of A) | 3,145 (70% of B) |
| Slight | 20,542 | 7,744 (37.7% of A) | 4,647 (60% of B) |

**AIS distribution of casualties who may benefit from an improved helmet -** The AIS (AAAM, 1990) distribution of those casualties whose head was the most severely injured body region was estimated by reviewing 158 cases from the COST 327 accident replication project for which detailed accident and injury data has been analysed. The AIS injury distribution is presented in Table 8, below.

**Table 8. Head AIS injury distribution for fatal, serious and slight motorcycle casualties**

| | Head AIS | | | | | | |
|---|---|---|---|---|---|---|---|
| Casualty severity | 6 | 5 | 4 | 3 | 2 | 1 | All |
| Fatal* | 33.3 % | 33.3 % | 22.2 % | 11.1 % | 0 % | 0 % | 100 % |
| Serious* | 0 % | 13.0 % | 13.0 % | 17.4 % | 56.5 % | 0 % | 100 % |
| Slight† | 0 % | 0 % | 0 % | 0 % | 12 % | 88 % | 100 % |

* based on analysis of 158 cases from COST 327

† based on COST 327 final report

The AIS distribution (Table 8) was combined with the estimated number of casualties whose head was the most severely injured body region (Table 7) to derive the data presented in Table 9 below. The numbers of slight casualties in Table 9 were distributed according to data contained within the COST 327 final report which indicated that 88% of slight injures are AIS 1 in severity; the remainder of injuries were assumed to be AIS 2 injuries.

**Table 9. AIS injury distribution for casualties with head most severely injured body region**

| | Head AIS | | | | | | |
|---|---|---|---|---|---|---|---|
| Casualty severity | 6 | 5 | 4 | 3 | 2 | 1 | All |
| Fatal | 125 | 125 | 84 | 42 | 0 | 0 | 376 |
| Serious | 0 | 409 | 409 | 547 | 1,777 | 0 | 3,145 |
| Slight | 0 | 0 | 0 | 0 | 558 | 4,089 | 4,647 |
| **All severities** | **125** | **534** | **492** | **589** | **2,335** | **4,089** | **8,167** |

Further analysis of the Cost 327 cases was made to determine whether or not the advanced helmet design would have provided improved protection to the wearer. The impact kinematics, impact type and impact mechanisms were considered, including an assessment of the linear and rotational injury potential. It was important to consider both the type and the severity of the impacts to determine which cases exceeded the protective capability of even the advanced protective helmet. Other cases involved impacts with aggressive structures or impacts through the visor that would not be protected by the advanced helmet. Table 10 presents a summary of this analysis with an estimate of the proportion of cases of each AIS severity that may have benefited from the advanced protective helmet.

**Table 10. Proportion of cases† for which an advanced helmet may provide additional protection.**

| | Head AIS | | | | | |
|---|---|---|---|---|---|---|
| Casualty severity | 6 | 5 | 4 | 3 | 2 | 1 |
| Fatal | 16.7 % | 66.7 % | 100 % | 100 % | | |
| Serious | | 100 % | 100 % | 75 % | 92 % | |
| Slight | | | | | 92 % | 40 % |

† *cases with head injury and head most severely injured region*

The values in Table 10 were combined with the values in Table 9 to provide an estimate of the number of casualties that may have had an improved injury outcome with the advanced helmet. This calculation assumes that every motorcycle rider, irrespective of factors (such as rider age, motorcycle make or model and engine capacity) is equally likely to be involved in an accident. These results are presented in Table 11.

**Table 11. Number of casualties where the head was the most severely injured body region and the accident conditions were such that an advanced helmet may have provided additional protection**

| Casualty severity | **Head AIS** | | | | | | **Total** |
|---|---|---|---|---|---|---|---|
| | 6 | 5 | 4 | 3 | 2 | 1 | |
| Fatal | 21 | 84 | 84 | 42 | | | **230** |
| Serious | | 409 | 409 | 410 | 1,635 | | **2,863** |
| Slight | | | | | 513 | 1,636 | **2,149** |
| **All severities** | **21** | **492** | **492** | **452** | **2,148** | **1,636** | **5,241** |

Thus, if all motorcycle riders wore helmets to the performance specification of the advanced helmet, there is potential to improve injury outcome for 230 fatal, 2,863 serious and 4,647 slight per annum (see Table 11). The next part of the analysis was to quantify the *magnitude* of benefit that would be afforded by the advanced helmet. A summary of this analysis is provided in Table 12 below.

**Table 12. Comparison of AIS injury outcome for current and advanced helmet designs**

| AIS current helmet | AIS advanced helmet† |
|---|---|
| 6 | 4 |
| 5 | 3 |
| 4 | 3 |
| 3 | 3 |
| 2 | 2 |
| 1 | 1 |

† AIS injury severity for those accidents where it was considered that the improved helmet may improve the injury outcome

**Assessing the injury distribution for the advanced helmet -** Using the AIS injury reduction levels presented in Figure 6 (summary in Table 12) it was possible to consider those accidents where an advanced helmet would have benefited the rider (Table 11) and determine the overall level of injury reduction. Table 13 shows the AIS distribution for both current and advanced helmets, assuming the advanced helmet had been worn for all the cases presented in Table 11. Table 14 shows the injury severity in terms of fatal, serious or slight, based on the values AIS values in Table 13. This analysis assumes that the distribution of injury severity (fatal, serious, slight) remains constant within each AIS classification for both current and advanced helmets.

The difference between the results in Table 14 and those in Table 11 represents the overall annual injury reduction that may be achieved with the advanced helmet, as shown in Table 15.

- The advanced helmet was found to have the potential of saving 94 lives and 434 serious injuries each year, approximately 20% and 7% respectively. If the same proportion of injury reduction could be achieved on European roads more than 1,000 of the 5,000 fatally injured riders and pillion passengers could be saved each year and a further 5,000 of the 70,000 serious injuries could be prevented.

**Table 13. AIS severity distribution for current and advanced helmets†**

| | AIS | | | | | | Total |
|---|---|---|---|---|---|---|---|
| AIS distribution | 6 | 5 | 4 | 3 | 2 | 1 | |
| Current helmet | 21 | 492 | 492 | 452 | 2,148 | 1,636 | 5,242 |
| Predicted Advanced helmet | 0 | 0 | 260 | 992 | 1,725 | 2,265 | 5,242 |

*† for those cases where the head was the most severely injured body region and the accident conditions were such that an advanced helmet may have provided additional protection*

**Table 14. Injury severity distribution assuming the advanced helmet had been worn†**

| | AIS | | | | | | Total |
|---|---|---|---|---|---|---|---|
| Casualty severity | 6 | 5 | 4 | 3 | 2 | 1 | |
| Fatal | 0 | 0 | 44 | 92 | 0 | 0 | 136 |
| Serious | 0 | 0 | 216 | 901 | 1313 | 0 | 2,429 |
| Slight | 0 | 0 | 0 | 0 | 412 | 2265 | 2,677 |
| **All severities** | 0 | 0 | 260 | 992 | 1,725 | 2,265 | 5,242 |

*† for those cases where the head was the most severely injured body region and the accident conditions were such that an advanced helmet may have provided additional protection*

**Table 15. Estimated annual injuries for current and advanced helmet design**

| | Current | Advanced | Reduction |
|---|---|---|---|
| Fatal | 230 | 136 | 94 |
| Serious | 2,863 | 2,429 | 434 |
| Slight | 2,149 | 2,677 | -528 |
| All | 5,242 | 5,242 | 0 |

## COSTS AND MARKET PENETRATION

The advanced helmet is produced using relatively expensive materials and processes. The cost for each prototype carbon shell was approximately £1,000 including materials, production process and autoclave time etc. It was, therefore, important to consider the key cost issues if such helmets were to be mass produced to achieve significant sales penetration.

It was estimated that if such helmets were produced in medium volume, the production costs could be reduced to approximately £200, with a corresponding minimum retail price of £300 – around £150 more than a typical current helmet.

This price would be competitive with high end market products and sales volumes of up to 10% per year may be achievable. According to the UK Department for Transport (DfT) figures, there were 760,000 licensed Two-Wheel Motor Vehicles (TWMVs) in Great Britain in 1999 [8] It was assumed that the average rider purchases a new helmet every five years, giving estimated annual helmet sales of 152,000 units. This is consistent with the number of new registrations for TWMV; 168,000 in 1999 [8] since a proportion of TWMV riders may purchase a new vehicle but already own a helmet.

If 10% of all new helmets sold conformed to the new level of performance, the fleet penetration of this new helmet would be 2% in year one, 4% in year two, 6% in year three, 8% in year four and 10% in year five (a total of 76,000 units sold by year five).

With a fleet penetration of 10%, the new helmet has the potential to save approximately 10 lives and 45 serious injuries each on roads in Great Britain. Nevertheless, it is understood that in order for future standards to be based on the performance of the new helmet, it would be desirable to significantly reduce the production costs.

## A WAY FORWORD

Given the potential performance of new helmet technology, the DfT has prompted a collaborative research effort with like-minded partners to develop the test methods that will be needed to assess new advanced helmet designs.

A partial Regulatory Impact Assessment (RIA) has been prepared for the UK DfT which suggests that a consumer information scheme might be the most practical way to encourage the supply and uptake of advanced motorcycle helmets to work towards a 20% reduction in motorcyclist fatalities.

On this basis, TRL, using their experience of Euro-NCAP and Primary NCAP, are currently developing a possible consumer information scheme for motorcycle safety helmets. Initially, interest is being sought from key stakeholders and research partners with proposals being developed for discussion in a small technical working group and with industry. Pilot assessments on a range of current and advanced helmets will be reported in a media-friendly format to complete the delivery of a ready to implement scheme. The actual tests will be based on those in Regulation 22-05, but amended as appropriate to ensure that better helmets can be identified and the objectives of the scheme achieved. Details of this and earlier related work may be found on www.mhap.info.

Further work, including physiological performance, is being taken forward in a new COST project and it is hoped that the costs of advanced helmets can be reduced through an EC 6th Framework Programme project under consideration.

## CONCLUSIONS

- An advanced prototype helmet has been developed by TRL and industry which exceeds the safety performance specified by COST 327, offering improved protection from both linear and rotational loadings to the head.

- This was achieved with a lightweight carbon composite shell fitted with an optimised high-efficiency expanded polystyrene energy absorbing liner and a low friction sacrificial shell surface.

- The advanced helmet has the potential to achieve significant safety benefits over a conventional motorcycle helmet. It was estimated that the advanced helmet has the capability to reduce AIS 6 injuries to AIS 4 and AIS 5 and 4 injuries to AIS 3.

- National accident data was analysed in conjunction with data from COST 327 and the TRL motorcycle accident replication programme. It was estimated that of the 578 motorcycle riders (or pillions) killed each year (during 1999 and 2000) 93 lives could be saved if all riders had been wearing the advanced helmet. And a further 434 of the 6,617 serious injuries could be prevented.

- If the same proportion of injury reduction could be achieved on European roads, more than 1,000 of the 5,000 fatally injured riders could be saved each year and 5,000 of the 70,000 serious injuries could be prevented.

- It was estimated that the cost of producing the advanced helmet may be in the region of £200 per helmet. Thus a minimum retail price would likely be £300 - approximately £150 more than a typical current motorcycle helmet.

- Given the potential of the new helmet technology and performance, the DfT is leading a collaborative research effort to produce the test methods that could be used to assess the protection offered by new advanced helmet designs.

- A proposal has been submitted for an EC 6th Framework Programme project to take the current work forward and minimise the cost of advanced motorcycle helmets.

## ACKNOWLEDGEMENTS

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