# Development of head protection for car occupants

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## Abstract

McLean et al. (1997) demonstrated that energy absorbing headwear for car occupants might be effective in reducing the numbers of head injuries sustained by car occupants. They estimated that the benefits were greater than the estimated benefits of padding of the upper interior of vehicles to the requirements of the US Federal Motor Vehicle Safety Standard 201. This paper will describe the development of head protection for car occupants (the RARU Headband) that would protect the head of an occupant in a crash. The development process included the testing of candidate materials, the construction of prototypes and ultimately the evaluation of the prototypes according to test methods outlined in FMVSS 201. The evaluation was made by attaching the headband to a free motion headform, and firing the headform at 24 km/h at an unpadded beam that had similar characteristics to a vehicle A-pillar, simulating a frontal collision. Three beams of varying stiffness were used to examine the protective effect of the headband over a range of impact severities. The protective effect was measured by comparing the impact severity between impacts with and without the headband present. Results showed that the headband produced marked reductions in the Head Injury Criterion value compared to the unprotected headform. In beams that produced severe impacts with the unprotected headform, that exceeded the threshold set by FMVSS 201, the headband reduced the severity to safe levels. This study showed that head impact severities can be markedly reduced for car occupants by the use of moderate amounts of head protection in frontal impacts. Further evaluation is required for other impact directions. This study was completed for the Australian Transport Safety Bureau.

## Introduction

Australian Census data shows that the average age of cars in Australia is near 10 years, and is as high as 12 years in some states (Australian Bureau of Statistics, 2001). This data indicates that the median age of vehicles is close to 9 years nationwide. The implication of this is that a new and mandatory safety standard introduced today will take approximately a decade to be prevalent in half the vehicle fleet. Safety features that are introduced as 'luxury' extras will take longer again to have any substantial presence in the car fleet. As a result current advances in occupant protection will remain unavailable for many years to the majority of road users.

In 1997, McLean et al. proposed a protective headband for car occupants in a report to the Federal Office of Road Safety. The primary aim of the report was to investigate the benefits of interior padding designed to prevent head injuries to car occupants. The report was prompted by the US National Highway Traffic Safety Administration's proposed changes to the US Federal Motor Vehicle Safety Standard (FMVSS) 201 to include a minimum level of head protection in impacts with the upper interior of the passenger compartment. The amendment requires all new cars manufactured from this year forward to have a specified level of head impact protection. This is being accomplished largely through the use of interior padding.

While noting the benefits of padding the upper interior of vehicles, McLean et al. estimated that head protection similar to a pedal cycle helmet would be more effective than vehicle padding for reducing head injuries in the event of a crash. It was proposed that a headband constructed of energy absorbing material covering the forehead and sides of the head would also provide a significant amount of head protection. The headband that was proposed would also be less cumbersome for car occupants than a pedal cycle helmet and would significantly benefit the occupants of vehicles that had no additional interior occupant protection. When the effects of the age of Australia's car fleet is considered, the development of some sort of head protection that might be worn by car occupants becomes compelling. To this end, the Australian Transport Safety Bureau commissioned a series of reports detailing the technical feasibility of some sort of protective headwear, specifically designed for car occupants (Anderson, White and McLean, 2000; Anderson et al., 2001, Anderson et al., 2002). These reports covered the selection and testing of energy absorbing materials through to the construction and testing of production prototypes. This paper summarises the findings of those reports.

## Aims

The aims of the development were to:

- Examine the feasibility of developing a protective headband for car occupants,
- Assess the performance of materials suitable for use in such a device,

- Produce a functional prototype of a protective headband for car occupants using materials selected on the basis of test results, and
- Examine the effectiveness of the headband using a standard test procedure.

### Preliminary testing

The purpose of the preliminary testing was to characterise the energy absorbing behaviour of a range of materials. The characteristic of an effective energy absorber for head protection is one that is very stiff initially in an impact but begins to plastically deform below the injury threshold, and does not allow transmitted loads to exceed the threshold. In the unloading phase of the impact, the material should return very little energy. This behaviour can be observed by plotting the force-deflection characteristic of an impact. A material that absorbs energy in this manner is said to be highly efficient.

In head injury protection, the severity of an impact is often assessed by calculating the Head Injury Criterion (HIC). HIC specifies an impact severity, beyond which the impact is thought to be unacceptably severe (HIC = 1000). The HIC valueis defined by an algorithm that operates on the acceleration that the headform experiences in the test.

For the purposes of the preliminary tests in this study, a standard headform (complying with European Enhanced Safety of Vehicles, Working Group 10) was dropped onto samples of candidate materials that were placed on a massive steel slab (Figure 1). The acceleration of the headform was measured and from this the HIC value was calculated along with the force-deflection characteristic of the material in each test.

Figure 2 summarises the preliminary testing by showing the HIC levels produced in the preliminary tests. The materials providing the best protection were rigid materials that crushed during the impact. Those materials that has a columnar structure such as cardboard honeycomb and STRANDFOAM* (Dow corporation) provided the most protection. These materials also had force deflection characteristics that were closest to an ideal material.

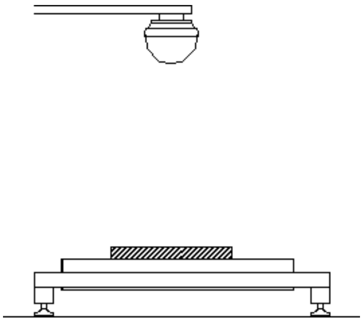

Figure 1 Schematic diagram of the rig used to assess the energy-absorbing performance of candidate materials

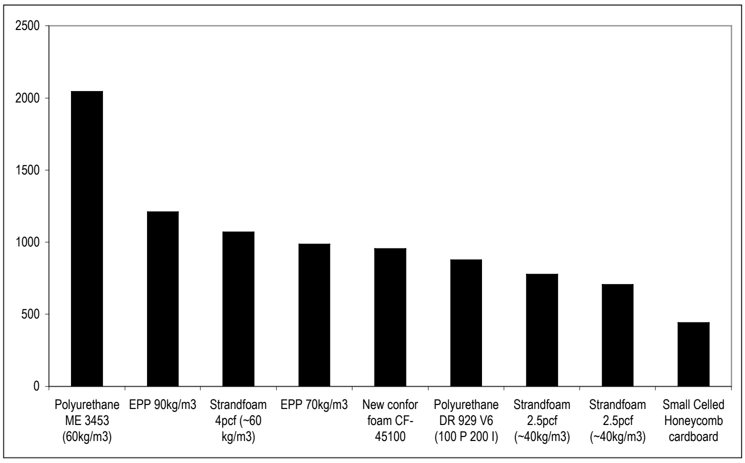

Figure 2 A comparison of HIC values across the range of materials examined

These tests were conducted on flat samples of material, whereas the headband design consists of a curved section of foam that conforms to the shape of the head. This clearly needs to be considered when assessing materials for suitability and when choosing fabrication processes. Additional considerations for material selection include durability and material costs. These considerations may preclude the use of honeycomb materials. Although the honeycomb cardboard was a highly efficient energy absorber, we could not identify any form of the material that was available, that would have been durable enough for a consumer version of the headband. STRANDFOAM* must be cut and thermoformed in the production of a component, but large distortions in fabrication reduce the effectiveness of the columnar structure of the material so that its properties revert somewhat to that of EPP from which it is made. The polyurethane grades that performed well also exhibited characteristics that may have caused durability problems. Crushable, rigid grades of polyurethane exhibit an almost friable texture. On these grounds, we chose to pursue EPP as a desirable energy absorbing material, as it was able to reduce impact severity while not presenting durability or manufacturing problems.

## Production of prototypes

The next stage in the study was to produce prototypes for further evaluation. The prototypes consisted of EPP foam, lined with a cloth fabric on the interior surface, and a vacuum formed styrene shell on the forward exterior surface (Figure 3). Two grades of EPP (70 g/l and 50 g/l) were used so that effects of material density on the results could be established. The EPP component of the headband was fabricated using a computer numerical control (CNC) machining process, in which pre-cast foam blocks of the correct density were cut to shape.The design included provision for an adjustable elastic strap for securing the headband to the head.

Figure 3 The headband is constructed from a layer of energy absorbing expanded polypropylene and a vacuum formed styrene shell

## Prototype tests

FMVSS 201 provides a method to evaluate the level of protection provided by interior padding to an occupant in the event of an impact with interior components of a vehicle during a crash. The procedure is also amenable to the evaluation of the headband. By using the procedures in FMVSS, the headband may be evaluated alongside other measures designed for occupant head protection.

FMVSS 201 stipulates the use of a free motion headform (Part 572 Subpart L) launched at a speed of 19km/h or 24km/h, depending on the structure being tested. The performance criterion of FMVSS 201 is that a modified form of the Head Injury Criterion, HIC(d), should be less than 1000. The HIC(d) calculation takes into account the fact that the free motion headform is not attached to a dummy. The modification of the HIC is an attempt to give an equivalent dummy HIC without the need for a full crash test and a complete crash test dummy.

## Impact configuration

A standardised structure was used to test the effectiveness of the headband. The structure consisted of a steel beam designed to represent an interior component of a vehicle. The steel beam comprised two lengths of mild steel (90˚ sections) and a sandwiched flat bar of mild steel. This structure formed a "T" section beam. The beam was clamped at each end.  The stiffness of the beam could be changed by varying the thickness of the flat bar of mild steel and by adjusting the distance between the end clamps (Figure 4). The Road Accident Research Unit's pedestrian legform launcher was modified to launch the free-motion headform.

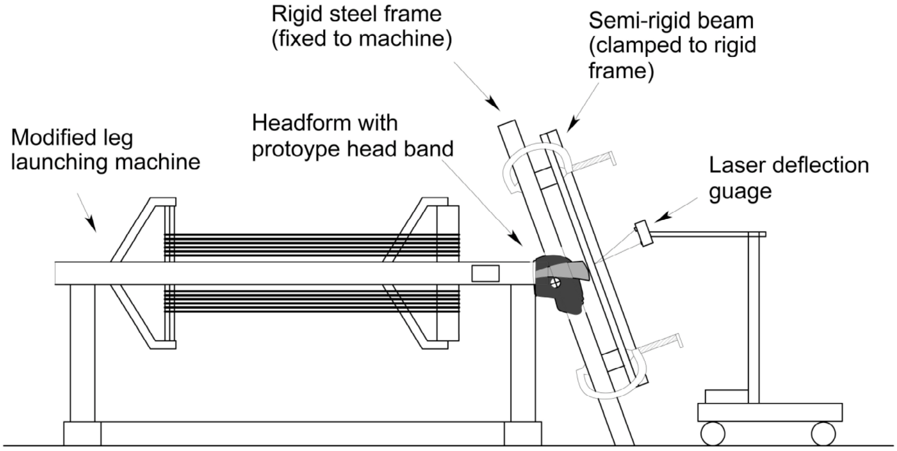

Figure 4 Experimental set-up of the launcher with headform and headband shown at the moment of impact.

## Test Measurements

The tests were designed to determine the benefit of the headband by comparing the results of impact tests between the free motion headform and the beam, made with and without the headband. The benefit can be summarised by comparing the HIC(d) values in each test. Further, a study of the force-deflection behaviour of the headband was made to explain the mechanism of protection and to identify the better performing grade of EPP.

### HEAD VELOCITY

The velocity of the headform was measured in every test using a dual-beam laser measurement system. The system consists of two laser diodes separated by a known distance, set parallel to one another and in line with two receivers. The laser receivers are connected to a counter-timer. The lasers and receivers were set so that the headform would break each of the laser beams in succession just before impact. The counter-timer recorded the interval between these events. The impact velocity was calculated by dividing the distance between the lasers by the time elapsed between the two laser signals.

### HEAD ACCELERATION

The Part 572 Subpart L free motion headform was instrumented with a critically damped Entran triaxial accelerometer. The impact acceleration was recorded using a high-speed data acquisition system sampling at 50 kilosamples per second after being filtered with a 10 kHz anti-aliasing filter. The acceleration signals were then conditioned to CFC 1000 (SAE J211 MAR95 - Instrumentation for Impact Test - Part 1 - Electronic Instrumentation). The resultant acceleration was subsequently used to calculate HIC and HIC(d).

### DYNAMIC CRUSH

The dynamic crush of the headband was measured to construct a force-deflection curve from each test. The crush in the headband was approximated by determining the difference between the displacement of the headform (assuming no significant skin displacement or headform deformation) and the displacement of the steel beam. The displacement of the beam was measured in each impact test by a laser deflection gauge (see Figure 4). The displacement of the headform during the impact was calculated by the double integration of the acceleration-time history.

### HIGH SPEED VIDEO

A high speed digital video camera captured the impact in each test. Impacts were captured at 500 frames per second. These images were used to examine the behaviour of the headband and the rotation of the headform during the test.

### TEST MATRIX

Six EPP prototype headbands were tested. Three headbands were constructed from 70 g/l EPP and three from 50 g/l EPP. Tests were conducted using three variations in the stiffness of the beam such that the unprotected headform, when fired at 24km/h, would give nominal HIC values of 2000 (Beam 1), 1500 (Beam 2) and 800 (Beam 3). Two of these HIC levels fail the requirements of FMVSS 201 and the other passes, giving a range of severities around the pass/fail criterion in the standard.

## Results

### HEAD INJURY CRITERION

Impacts which generate HIC(d) values in excess of 1000 are considered unacceptably severe and fail according to the performance criterion specified in FMVSS 201. Both densities of the expanded polypropylene prototype headband gave high levels of protection to the free motion headform as measured by HIC(d). The 70 g/l headband performed slightly better than the 50 g/l, but in all cases there was a significant reduction in HIC and HIC(d). For tests made with the beams that generated HIC(d) values in excess of 1000 in the unprotected headform, the headband produced at least a 54 percent reduction in the values of HIC(d).

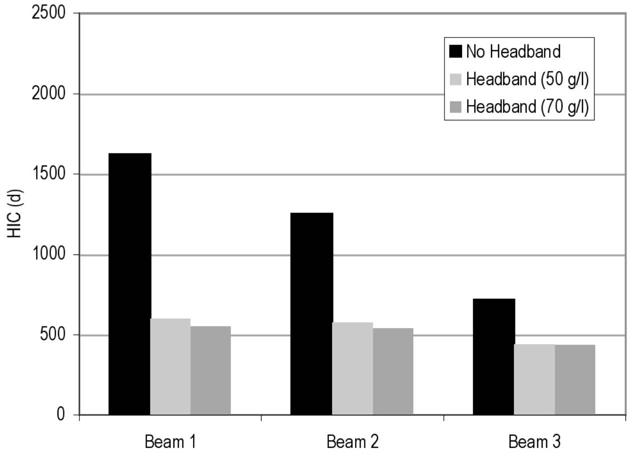

Figure 5 Chart showing the Head Injury Criterion (d) results of the tests. HIC(d) is a modified form of HIC to compensate for the free motion of the headform. The headband significantly reduced the severity of the impact as measured by HIC(d).

## HEADFORM ACCELERATION AND FORCE-DEFLECTION MEASUREMENTS

Both the 70 g/l and 50 g/l expanded polypropylene prototype headbands significantly reduced peak acceleration in all the headform impacts. Figure 6 shows that the 70 g/l headband is stiffer than the 50 g/l headband. As a result of this characteristic, the 70 g/l headband produces a higher acceleration than the 50 g/l headband in the initial stages of the impact. However, the 70 g/l headband allows the acceleration of the headform to peak at lower levels because it absorbs the energy of the impact more efficiently than the 50 g/l material. It is also able to absorb more energy before “bottoming out.”

Because the 50 g/l EPP is a lower density material, it absorbs less impact energy. Once it bottoms out, the headband can no longer absorb much energy. After this time the peak acceleration is influenced primarily by the interaction between the headform and the beam and the remaining energy of the headform. As a result the acceleration peaks higher than the 70 g/l tests.

The force-displacement curves (Figure 7) also indicate the amount of work done (or energy absorbed) by the headband in each test. The work done is the area under the force-displacement curve. On inspection, it is clear that the 70 g/l EPP headband is a more efficient energy absorber than the 50 g/l EPP headband, absorbing more energy throughout the crushing phase of the impact. (Note that due to headform rotation, these curves are only reliable in the loading phase of the force-deflection curve.)

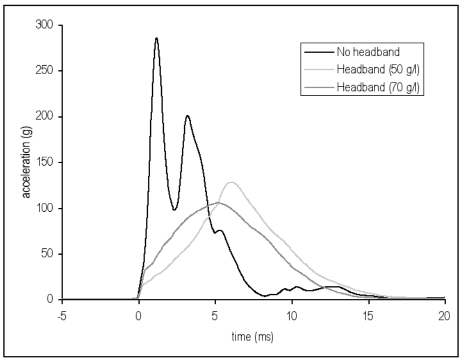

Figure 6 Headform acceleration measured in tests against Beam 2

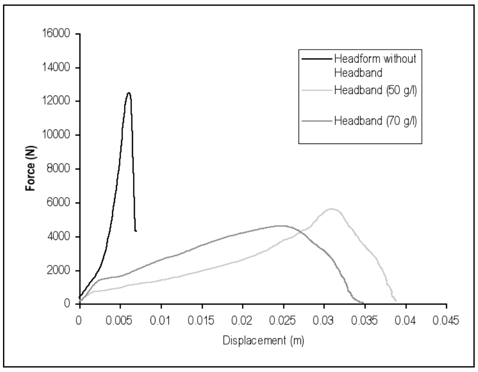

Figure 7 The force - displacement curves for the impacts with Beam 2. The deflection in the unprotected headform is included for reference.

## Discussion and conclusions

The headband prototypes provided protection to the free motion headform in all the tests conducted, to the extent that the criterion for acceptance under FMVSS 201 was satisfied. Three different levels of stiffness were tested. Two of the beam stiffnesses were such that that they failed the minimum performance criteria of the FMVSS 201 (i.e. that HIC(d) < 1000) when tested with the unprotected headform. When either of the headbands were attached to the free motion headform, the HIC(d) was reduced to acceptable levels. The headbands also reduced the peak acceleration of free motion headform considerably.

Although both the 70 g/l and 50 g/l prototype headbands surpassed the requirements of FMVSS 201, the 70 g/l prototype headband performed better than the 50 g/l in all tests. The 70 g/l prototype absorbed more energy and absorbed it more efficiently than the 50 g/l prototype.

It should be noted that the performance of the headband has only been assessed for frontal impacts through the centre of the headband. In this part of the headband the material thickness is at a maximum. In the design evaluated here, the material thickness gradually decreases around the headband to a minimum at the sides. Future design evaluation will need to consider material thickness and coverage issues and it would be of benefit to conduct side impact tests to ensure that adequate protection is provided in this impact direction. Future evaluation might also include the use of a crash test dummy in a sled or full-scale crash test. Examining the protective effects in these situations at speeds higher than those examined here would be informative for further evaluation of the headband’s protective effect. Other factors that might be considered include fitment of the headband, and the importance of correct attachment of the headband to the head.

McLean et al. (1997) estimated "that it would be more than 15 years from the time that a decision was made to require padding before half of the cars on the road in Australia provided such protection against head injury." With this in mind, it is important to consider more immediate options to protect against possible head injury in vehicle crashes. McLean et al. (1997) estimated that pedal cycle helmets could provide better protection than could be offered by interior padding. In the same study it was also estimated that a headband covering the sides of the head and the forehead, while providing half the benefits of a pedal cycle helmet, would offer more protection than interior padding.

This study documents tests and results that demonstrate the effectiveness of a headband of the sort originally proposed in 1997. The benefits of wearing a headband similar to the one evaluated in this paper would be considerable, on the basis of the results of the tests reported herein.

## Acknowledgements

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