

Protection of the unhelmeted head against blunt impact: The pedestrian and the car bonnet

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Background. In recent years, increasing attention has been paid to improving car frontal design in order to minimise pedestrian injury. Many tests have been carried out using a free-flight instrumented headform projected against the car exterior. For pedestrians and other vulnerable road users, the bonnet should act as a cushion in an impact. *Aims of this paper.* General principles of bonnet design are stated. Particular attention is given to the issue of stiffness, and new implications are drawn. *Findings.* Regarding bonnet stiffness, there is an optimum: too stiff, and the bonnet is injurious; not stiff enough, and the pedestrian's head may bottom out, i.e., strike the very stiff structures in the engine compartment. In addition, the optimum bonnet stiffness will be different for different speeds of impact. *Conclusions.* There is a need for results covering the range of speeds at which serious pedestrian injuries occur. Theory does permit scaling of HIC (Head Injury Criterion) to different speeds, however, so not all speeds will need to be tested. Similar considerations apply to headform mass.

1. Introduction

In recent years, increasing attention has been paid to improving car frontal design in order to minimise pedestrian injury. It needs to be appreciated that, for pedestrians and other vulnerable road users, the exterior of the car can and should be designed to act as a cushion to protect them from stiffer structures underneath (Figure 1). This paper will describe general principles of bonnet design so as to minimise pedestrian injury. Particular attention will be paid to stiffness, as for a given clearance distance over the stiff structures, there is an optimum, with both softer and stiffer bonnets being worse.

Head injuries are a common cause of death in pedestrians. They are usually from vehicle contact rather than ground contact. The fronts of cars are low enough that, except in the case of very young children, the pedestrian's head is not struck by the front of the vehicle, but the body rotates towards the bonnet. The head is then struck by either the bonnet or the windscreen of the vehicle.

Part of the effort towards frontal design improvement involves projecting a free-flight instrumented headform against the exterior of the car and obtaining a record of its acceleration over the milliseconds of the impact. Such tests are conducted at a specified speed. The acceleration trace is summarised by calculating the HIC (Head Injury Criterion). This is believed to reflect likely injury severity. It is based on the integration of acceleration raised to the power 2.5.

This paper is concerned with strategies for improvement that apply to a specific location on the bonnet. In addition, there may be strategies available that relate to (for example) height, length, or slope of bonnet. Also, we do not consider the problem of parts of the surface of the car that are themselves very stiff (the A pillars, for example, due to structural requirements). Technologically advanced options for improving pedestrian protection have been developed recently. Notably, pop-up bonnets are in use and have been shown to be effective (Lawrence et al., 2006). These technologies take advantage of the same design principles outlined in this paper, namely, appropriate choice of stiffness and increased clearance.

The aims of this paper are as follows. The principles for minimising the danger posed by the bonnet to pedestrians and other vulnerable road users will be stated. Particular attention will be given to bonnet stiffness. The stiffness that is optimal for the test speed (that is, the clearance distance is exactly used up in stopping the headform) will not be optimal for lower and higher speeds. At lower speeds the stiffness will be too great, and at higher speeds the stiffness will be too low. The conclusion is drawn that results need to be obtained for a range of realistic speeds. Testing is a means of obtaining those results, but sometimes a simple calculation may be sufficient. A similar conclusion applies to having a range of headform masses. The paper is organised into the following sections: General principles of bonnet design for pedestrian safety; Bonnet stiffness as a special case; Scaling of the Head Injury Criterion (HIC) to different speeds; The need for multiple conditions of testing; Conclusions and recommendations.

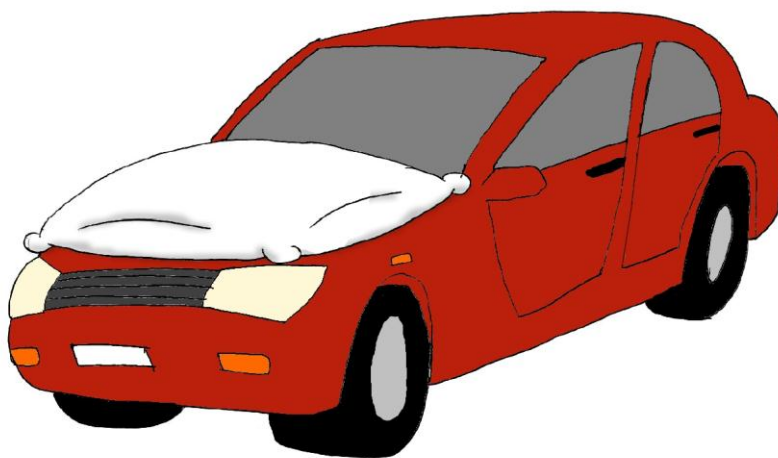


Figure 1. The bonnet should act as a cushion for the pedestrian.

2. General principles of bonnet design for pedestrian safety

We will list some general principles of bonnet design. Once they are articulated, these principles are plainly common sense: they would be expected to be valid for other vehicles striking pedestrians, for vehicles striking legs and chests, for vehicle occupants striking the interior of vehicles, and for contexts other than vehicle safety (e.g., playground, industrial, sporting, and military safety).

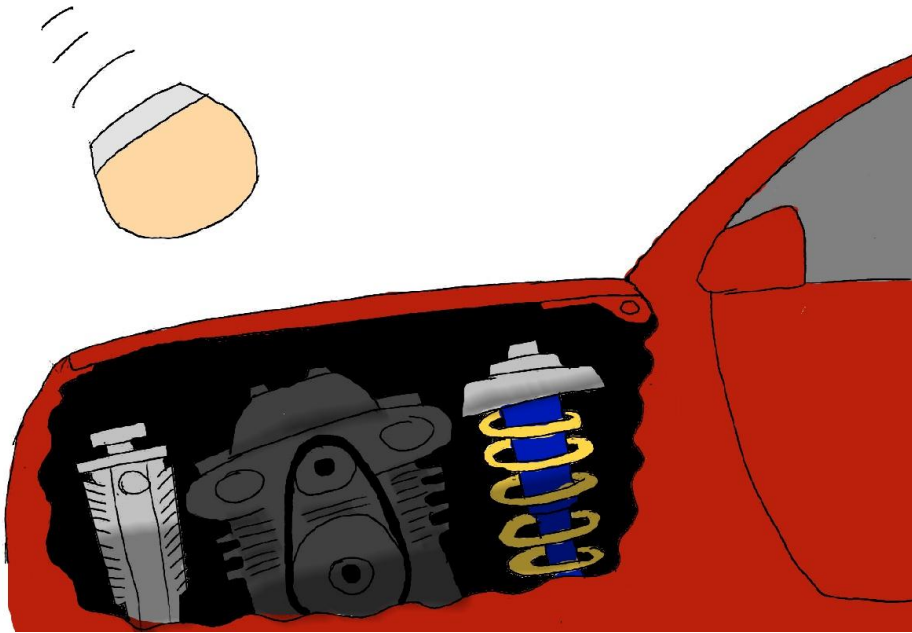


Figure 2. The source of the danger to a pedestrian's head is not so much the bonnet, but the structures underneath.

2.1 Bonnet design for pedestrian protection

Partly as a result of several years of pedestrian impact testing, general principles of bonnet design are now well understood (Figure 2).

- Projections and sharp corners and edges should be eliminated.
- There should be plenty of clearance distance between the underside of the bonnet and very stiff structures such as the engine and the suspension towers.
- The bonnet should be yielding, but not so much so that it deforms too easily and fails to prevent the pedestrian's head striking a very stiff structure. This dilemma requires some intermediate, optimal, degree of stiffness to be found.
- The very stiff structures underneath the bonnet should be made less stiff, or frangible.
- The coefficient of restitution is a quantity reflecting the proportion of its original speed that a striking object (a pedestrian, in this case) retains after an impact. This should be low: the bonnet should undergo plastic deformation, rather than elastic.
- If it is practicable to exercise some control over the shape of the acceleration pulse, the peak of this should be early rather than late in the impact. That is, the bonnet should be damped, i.e., be stiffer early in the impact (when speed is high and bonnet deflection is low) than later. On its own, the exponent 2.5 in the formula for the Head Injury Criterion (HIC) would suggest that in order for HIC to be low, the acceleration should be constant over the time the pulse lasts. However, high acceleration occurring early also disproportionately reduces the distance travelled. Thus to minimise HIC under the constraint of a given available clearance distance, acceleration should be higher early in the impact (Okamoto et al., 1994).

The principles may be common sense now, but we do not believe they were when the effect of car design on pedestrian injury was first considered. There was not the same appreciation of the distinction between the vehicle's skin --- the bonnet and other panels --- and under-skin structures, nor the same readiness to pay attention to detail in considering the position of under-skin structures relative to the skin. On the positive side, the desirability of eliminating anything sharp or projecting, and of having a low coefficient of restitution, were appreciated (Wakeland, 1962). Some years later, the account in Harris (1976) is considerably more sophisticated, with a recommendation that "Hidden components should be terminated well below bonnet level to allow depth for deformation. Examples are the engine and fittings, front suspension and the side walls of the engine compartment."

We should note that these principles indicate that regulation could attempt to control separately several dimensions of bonnet design, instead of the global performance summary represented by the Head Injury Criterion --- surface sharpness, clearances, bonnet stiffness, stiffness of under-bonnet structure, coefficient of restitution, and damping of the bonnet. We do not at present advocate this, as car companies have a great deal of expertise, and it seems reasonable to regulate overall performance and leave the method of achieving that to the vehicle designer. There may be other contexts of blunt head injury, however, in which it would be appropriate for regulations or specifications to refer directly to analogous dimensions.

2.2 Testing for consumer advice and regulatory purposes

Routine headform testing has been carried out by the European New Car Assessment Programme (EuroNCAP) and the Australasian New Car Assessment Program (ANCAP) for the last decade. Both EuroNCAP and ANCAP use the EuroNCAP pedestrian testing protocol, which specifies a series of up to 12 child and 12 adult headform tests. The tests conducted by ANCAP/EuroNCAP are conducted for consumer information purposes only. That is, this is not regulatory testing, and poor performance will not stop a vehicle from being sold.

In Europe and Japan, a pedestrian testing regulation has existed since 2005. New cars being sold in those jurisdictions must satisfy a basic level of performance in pedestrian headform tests before they are allowed to be sold. A Global Technical Regulation (GTR) on pedestrian safety began development in 2002 and was finalised in 2010. It is reasonable to assume that most major jurisdictions will align their pedestrian safety regulations with the GTR tests. The European Community have already done so. In late 2010, Vehicle Safety Standards Australia issued a Regulation Impact Statement on the adoption of the GTR as an Australian Design Rule (ADR). (However, this Statement was later retracted for reasons connected with bull bars.)

In the last five years, there have been improvements in bonnet design across most vehicles, particularly those from regions that have mandatory pedestrian testing (e.g., Europe and Japan). Ponte et al. (2007) showed that vehicles in those regions were performing better than vehicles from Australia.

Lawrence et al. (2006) demonstrated several methods for improving the pedestrian test performance of two cars: a Ford Mondeo and a Landrover Freelander. These vehicles were compared with the better-performing Honda Civic. Several design improvements were suggested, most of which involved increasing clearances and reducing the stiffness of bonnet supports. Another feature of the Honda Civic was that the stiffer structures beneath the bonnet were designed to break away --- for example, the windscreen wiper motor and the brake fluid reservoir. The features of this study illustrate the progress that was being made by one manufacturer (Honda) at the time, in contrast to manufacturers that had not considered pedestrian safety as a high priority.

Testing protocols for regulatory purposes work well, and can also have a positive influence on pedestrian safety for vehicles that are sold in countries without regulation (Ponte et al., 2007). An objective of consumer program testing is to influence the safety of vehicles, even in countries without regulation.

2.3 Trends noted in testing

Since 1997, our Impact Laboratory has conducted pedestrian head testing of 118 vehicles on behalf of ANCAP, plus tests for other clients and other purposes. Several improvements have been noted over the years.

- Beneath the bonnet. One of the most significant has been the lowering of under-bonnet components, in particular, battery terminals, suspension strut mounts, and engine components. This has been particularly evident in Japanese-manufactured vehicles.
- The side and hinges. Another significant change that has been noticed is collapsing side guards. In the past, sufficient strength and stiffness of the bonnet and guards to support the weight of people leaning on the vehicle was achieved through thickness of material and rigid support. Using better selection of materials, some manufacturers have reduced the thickness of the panelwork, reducing weight while keeping strength. Attachment of the side guards to stiff reinforced sections of the vehicle is being replaced by the use of supports or brackets that collapse or deform under impact. Typically, attachment of the bonnet to the hinges has been difficult to design safely. Years ago, testing on hinges often resulted in puncturing of the hinge screws through the bonnet top, and extremely high accelerations and HIC have been recorded. Various alternative methods of attachment have been trialled with varying levels of success in lowering HIC and acceleration, but no method is yet considered particularly safe.
- The rear of the bonnet. Wiper pivots have typically been very injurious. To combat this, some manufacturers have redesigned the wiper pivot on a frangible assembly. A change in design of the firewall has also been noted in various vehicles, where the stiff top section of the firewall that had supported the rear of the bonnet has been lowered or offset rearward to the base of the windscreen. The bonnet has then been supported by a collapsible plastic plenum. Support at the base of the windscreen has and continues to be a notable injurious area. However, a few examples have been seen of this support providing adequate support for the windscreen but yielding when impacted, giving a passable HIC result.

- The bonnet itself. Its own rigidity and strength requirements can lead the bonnet itself to be injurious, particularly the reinforcement or ribbing and at the extreme front. Some new bonnet designs have seemingly consistent stiffness characteristics across the entire bonnet, the underside reinforced sections having the same impact characteristics as the rest of the bonnet.

2.4 Comment

There is likely to be further progress in coming years as the designs of bonnets and other relevant vehicle structures are revised. In many respects, testing protocols for regulatory and consumer information purposes will be expected to work well. For stiffness of hard structures, clearance under bonnet, and coefficient of restitution, it is appropriate for regulation to encourage design in one direction:

- the softer that hard structures are, the better;
- the greater the clearance distance, the better;
- the lower the coefficient of restitution, the better.

Bonnet stiffness, however, is a special case, and this will be discussed below.

3. Bonnet stiffness as a special case

In the case of bonnet stiffness, it is not the case either that more is better or that less is better. Instead, there is an optimum: too stiff, and the bonnet is injurious; not stiff enough, and the pedestrian's head bottoms out, that is, strikes the very stiff structures in the engine compartment. The optimum stiffness succeeds in bringing the head to rest just before the very stiff structures are contacted; that is, all the clearance distance is used up. (This description is an approximation in at least two ways. Stiffness may vary with deformation distance, and stiffness may depend on speed as well as on deformation.) The stiffness that is optimal at one speed will not be optimal for other speeds.

- In particular, severity of injury at higher speeds may be very bad because of bottoming out --- especially if the bonnet is optimised for low speed impacts, i.e., is soft.
- Severity of injury at speeds lower than that for which stiffness was optimised will also be worse than necessary, as all the available clearance distance is not used.

Figure 3 illustrates this. Severity of injury is plotted on the vertical axis versus speed of impact on the horizontal axis. This is shown for bonnets of several stiffnesses (but assuming the same clearance distance is available in each case). The lines are labelled with the speed for which the stiffness is optimised.

- Consider a bonnet optimised for an impact at 40 km/h, say. At speeds of impact lower than 40 km/h, there is gradually increasing severity of injury with increasing speed, as more and more of the clearance distance is used up. At higher speeds of impact, there is sharply increasing severity of injury, as bottoming out gets worse and worse.
- The same is true for a bonnet optimised for any other speed, such as 50 km/h.
- Consequently, the lines for two bonnets of different stiffnesses will cross over.

- At low speeds, the bonnet optimised for the higher speed performs worse: it is too stiff.
- At high speeds, the bonnet optimised for the higher speed performs better: it absorbs more energy before bottoming out occurs.

No specific definition of severity is used in Figure 3, as it is intended to be valid whether severity is the Head Injury Criterion, the probability of death, or something else. Some further details of Figure 3 may be noted. (a) At speeds at which bottoming out does not occur, the lines are not very steep, and are steeper for bonnets optimised for higher impact speeds. (b) At speeds at which bottoming out does occur, the lines are steep. Lacking further knowledge, they are shown as parallel. (c) The lines are shown as straight purely for convenience.

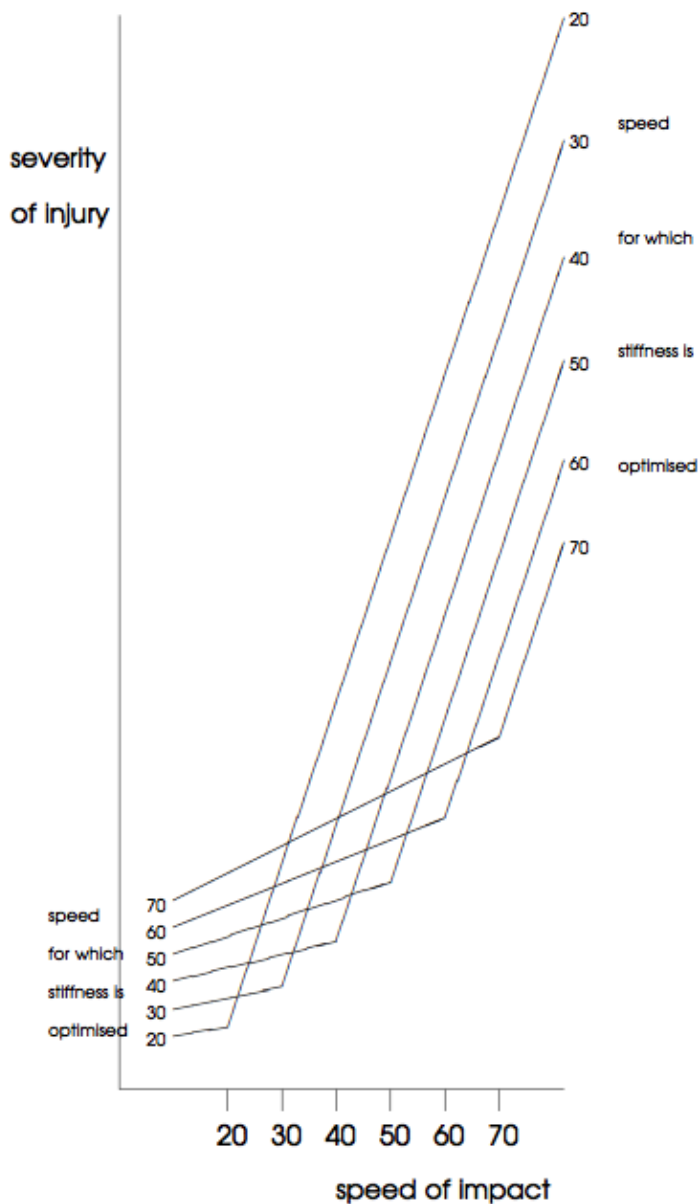


Figure 3. The relation of severity of injury to speed of impact. The six lines refer to bonnets of different design, having the same clearance distance available, but of different stiffnesses, respectively optimised for different speeds.

4. Scaling of the Head Injury Criterion (HIC) to different speeds

As shown above, the optimum bonnet stiffness depends on the speed of impact. At a faster speed, the bonnet will need to be stiffer, to absorb the impact of the head without bottoming out. At lower speeds, the bonnet can be softer (which reduces injury) without bottoming out occurring.

This trade-off suggests an approach of testing across a range of different speeds at which pedestrian crashes occur. However, there is theory that permits scaling of the Head Injury Criterion (HIC) to different speeds. Consequently, not all speeds will need to be tested. Searson et al. (2009) presented a method for scaling a HIC value obtained at one test speed to an equivalent HIC value for another test speed. The method was corroborated by real test results. According to Searson et al., HIC is proportional to speed raised to the power 2.5. The assumption behind this is that the stiffness of the bonnet is independent of the speed. If contact with a hard structure beneath the bonnet occurs (bottoming out), this method of scaling is not valid, and so it is only appropriate for speeds at which no bottoming out occurs. (It may also provide a good estimation of the result when bottoming out is minimal.)

The deflection of the bonnet can also be estimated during a test (by double integration of the acceleration measurements). Like the Head Injury Criterion, deflection can be scaled. Assuming constant stiffness of the bonnet and equating the initial kinetic energy of the headform to the energy absorbed by the bonnet during the loading phase of the impact, deflection distance is found to be proportional to speed. By measuring the distance from the outer shell of the bonnet and a harder structure beneath and making use of this proportionality, it is possible to predict the speed at which bottoming out will occur. For lower speeds, the scaling relationship for HIC may be considered valid. For higher speeds, bottoming out would occur and HIC would increase dramatically. But if bottoming out occurred in the test, scaling of HIC to a lower speed is likely to overestimate the true HIC at that speed; scaling of HIC to a higher speed is not likely to be valid, either, as performance in this range is poorly understood, and may be highly variable.

5. The need for multiple conditions of testing

It might be thought that if a location on a bonnet is poor at one speed (that is, more hostile to a pedestrian than another location on another bonnet), it will also be poor at another speed. Section 3 above shows this is not necessarily so: comparing a soft bonnet and a stiff bonnet, it is quite possible for the first to be the better at low speeds and the second to be the better at high speeds.

A single test speed means that at other speeds of impact, the bonnet may be too soft to prevent bottoming out, or else too stiff and injurious itself. Estimates of the danger posed by car exteriors need to be available for a range of realistic speeds. One means of obtaining those estimates is testing. Section 4, though, shows that testing is not always needed, and that a simple calculation may suffice. This will only be valid within a certain range of speeds, however, so would not entirely obviate the need for testing at several speeds.

This paper has discussed the speed of impact in tests because there is known to be a wide range of variation of speed in real-life impacts. There is a similar issue with headform mass: there is variation not only in the mass of pedestrians' heads but also in the proportion of the mass that is "effective" in the impact. There will tend to be greater bonnet deflection with a heavier headform, and thus HIC (the Head Injury Criterion) will tend to be lower provided bottoming out does not occur, but there will be a greater risk that bottoming out does occur. Having a single headform mass means that for a greater mass, the bonnet may be too soft to prevent bottoming out, and for a smaller mass, the bonnet may be unnecessarily stiff and injurious itself.

Testing is already carried out at several locations on any car, and the results totalled to get a result for the car as distinct from a location. It is no great step to also require results at a range of speeds and a range of headform masses, to be followed by some sort of totalling or averaging, or even weighting given a distribution of impact speeds likely in actual collisions. Another possible advantage can be noted. There are some structures (e.g., the A pillars) that are usually not tested. If testing under a range of conditions were the norm, it might extend to testing stiff structures at relatively low speeds, and give incentive for their improvement.

6. Conclusions and recommendations

A single test speed and headform mass will lead to improved pedestrian safety in those conditions. Several types of design change are available, and have been reviewed in section 2. However, an improvement achieved by making the bonnet less stiff may worsen safety at higher speeds and higher masses, and an improvement achieved by stiffening the bonnet may worsen safety at lower speeds and lower masses. Thus our chief conclusion and recommendation is that to achieve balance between these conflicts, estimates of safety performance at other speeds and headform masses are required. Furthermore, methods of calculating an average level of performance need to be developed that take into account the frequency with which different speeds and head masses occur.

The desirability of obtaining results over a range of speeds does not necessarily imply that the number of tests would be drastically increased. Firstly, when clearance distances are sufficient that bottoming out does not occur, simple calculation as described in section 4 can convert the Head Injury Criterion obtained at one speed and headform mass to other test conditions. Secondly, testing could be carried out for only some (randomly-chosen) of the combinations of conditions.

In general terms, there is a steep increase of severity with speed of striking a stiff structure beneath the bonnet. Thus the chief penalty for failing to take account of the range of real-world speeds and head masses is likely to be at high speeds and high masses. However, this is poorly understood quantitatively, and both experiment and modelling are needed to improve knowledge of what designs and materials are optimal.

Finally, we note that the principles given here apply to other large structures that the head may impact --- both in road safety contexts (e.g., the car interior), and in quite different contexts (e.g., sport, playgrounds, military).

Declaration of interest

The Centre for Automotive Safety Research, University of Adelaide, is contracted by the Australasian New Car Assessment Program to conduct pedestrian impact tests on vehicles. CASR also receives payment for pedestrian sub-system impact testing for private clients and vehicle manufacturers.

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