THE PRACTICALITIES OF PEDESTRIAN PROTECTION

Keith C. Clemo
Robert G. Davies
Motor Industry Research Association
United Kingdom
Paper Number 98-S10-P-16

ABSTRACT:

In 1991, Working Group 10 of the European Experimental Vehicles Committee (EEVC) published a set of test requirements to address pedestrian impacts against car fronts. These consisted of component tests simulating impact by the lower leg and knee joint against the bumper, the upper leg and hip against the bonnet leading edge, and child and adult heads against the bonnet top. Since then, these requirements have been set out in a draft EC Directive, which may become part of the type-approval requirements for passenger cars sold in the European Union. The same test specification already forms part of the safety assessment of selected vehicles under the Euro-NCAP initiative. For both these reasons, manufacturers are paying close attention to the performance of their vehicles in these tests.

MIRA has carried out many tests to the EEVC WG10 specification, and experience to date shows that existing models fall well short of meeting these requirements. It appears that cars will need to undergo profound changes in design to meet the required standard. This paper details the engineering problems associated with achieving standards set out in the Directive in a variety of car types, and the other aspects of vehicle design which will be affected. Some possible design strategies are also outlined.

INTRODUCTION

During the late 1980's, the European Experimental Vehicles Committee (EEVC) was charged with drafting a set of vehicle performance criteria intended to minimise serious injuries to pedestrians in impacts at up to 40 km/h. The Committee reported in 1991 [1], proposing a set of component tests representing the three most important mechanisms of injury, that is:

- lower leg against bumper
- upper leg against bonnet edge
- head against bonnet and top of wing

A draft specification based on EEVC's work [2] has been drawn up and is currently being considered by the European Commission as part of the type-approval requirements for all new cars and light commercial vehicles sold in Europe, early in the next century.

As well as possibly becoming a mandatory requirements for cars, a similar test has already been incorporated into the European New Car Assessment Programme (EuroNCAP) [3]. This is similar to NCAP initiatives in the US and elsewhere, in that it does not impose fixed performance limits, but provides consumer information on the relative safety performance of selected models. Even though it does not impose a duty on manufacturers to comply with the requirements, its effect on sales is nevertheless a powerful incentive for them to improve the standing of their vehicles in the published performance league.

It is therefore clear that, whether or not these requirements are incorporated into legislation, they will constitute one of the major challenges to automotive designers in the near future.

TEST REQUIREMENTS

Lower Leg Test

The lower leg impact test addresses soft tissue injuries to the knee joint and fractures of the adjacent bones, caused as the leg is struck by the car bumper in the first stage of pedestrian impact. It consists of an impact against the bumper by a free-flight legform impactor. This is made of two rigid segments representing the upper and lower leg, which are connected by a deformable element representing the knee joint. This deformable element is replaced for each test. The rigid segments are covered by a layer of resilient elastomeric foam, representing the cushioning effect of the flesh in the human leg. The legform, with its axis initially vertical, is propelled horizontally into the bumper at 40 km/h, as shown in Figure 1. A minimum of three separate tests is proposed at different points within a zone bounded by the corners of the bumper, these points being selected by the test authority to represent the most severe impact conditions.

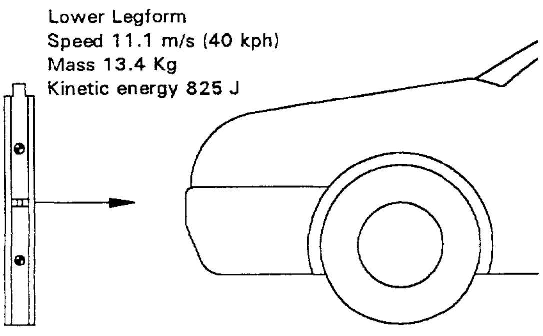

Figure 1: Lower Leg Impact Test

The legform is instrumented to record the relative dynamic shear and bending displacement of the segments during the impact, as well as the acceleration at the top of the lower leg segment.
The limits proposed by EEVC for these are as follows:

- Maximum dynamic knee shear displacement 6 mm
- Maximum dynamic bending displacement 15 degrees
- Maximum lower leg acceleration 150g

Upper Leg Test

The upper leg test addresses fracture of the femur and pelvis. It represents the second phase of the impact sequence, as the pedestrian is struck by the vehicle front after lower leg impact. In the test, the leading edge of the bonnet is struck by an impactor representing the upper leg, as shown in Figure 2. The impactor consists of a rigid mass, carrying a simply-supported beam in its impact face. The beam carries a layer of resilient elastomeric foam to simulate the leg flesh. The mass is constrained to move in a straight line during the impact, but is allowed to rotate in a vertical plane around a friction-loaded pivot. A minimum of three tests are proposed at different points along the bonnet leading edge between the corners of the vehicle, at points selected by the test authority to represent the most severe test conditions

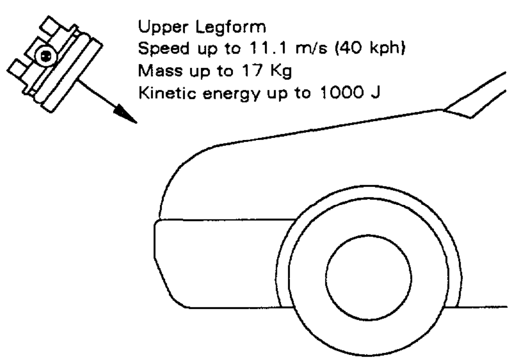

Figure 2: Upper Leg Impact Test

The impact direction relative to the ground, the mass of the impactor, and the impact velocity are all determined by the geometry of the front of the car, within the following ranges:

- Angle of impact, downwards at between 10 degrees and approximately 48 degrees to the horizontal, according to the bonnet leading edge height and the bumper lead dimensions
- Velocity, between 20 km/h and 40 km/h, according to the above dimensions
- Mass is selected to give a kinetic energy at impact between 200 J and 1050 J, according to the above dimensions and consistent with the impact velocity determined as above. Maximum 17 kg.

The effect of the vehicle dimensions on the test conditions is discussed in more detail later in this paper.

The impactor is instrumented to record the bending moment at three points along the front beam, and the compressive load at the beam's end supports. The limits proposed by EEVC for these are as follows:

- Maximum total force recorded at beam end supports 4 kN
- Maximum bending moment in beam 220 Nm

Head Impact Test

The head impact test addresses head injuries suffered as the pedestrian is pitched into the bonnet top following lower leg and/or upper leg impact. It consists of an impact at 40 km/h onto the upper surface of the car front with either of two free-flight impactors representing the head of a child or adult pedestrian, as shown in Figure 3. The child impactor has a mass of 2.5 kg and strikes points within a zone at the front of the bonnet, while the adult impactor has a mass of 4.8 kg and strikes points within a zone to the rear of the bonnet.

The front and rear boundaries of these two zones are determined according to the "wrap-around distance", that is the line described by the end of a string of given length, stretched vertically upwards from the road surface over the bumper and then longitudinally over the bonnet. For the child head impacts, the front edge of the zone lies at 1000 mm wrap-around distance and the rear edge at 1500 mm, whereas for the adult the front edge lies at 1500 mm and the rear 2100 mm. In any case, the impact zone is limited to areas forward of the windscreen lower edge. The impact direction is downwards in the vehicle's longitudinal plane, at 50 degrees to the horizontal for the child and at 65 degrees to the horizontal for the adult, reflecting the difference in stature between the two groups.

EEVC proposes a minimum of nine impacts with each impactor, at different points within the zone, again representing the most severe test conditions as judged by the test authority. For Euro-NCAP, six impacts are completed with each impactor.

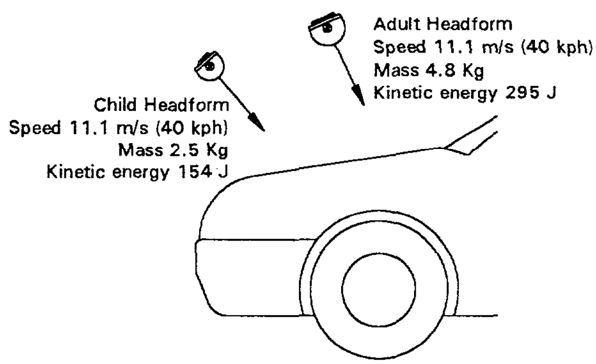

Figure 3: Headform Impact Tests

The headforms are instrumented to record the acceleration in three mutually-perpendicular axes. The injury criterion proposed by EEVC is that the Head Performance Criteria (HPC) should not exceed 1000. The HPC is determined by the following formula

$$HPC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a dt \right]^{2.5} (t_2 - t_1) \max$$

where a is the resultant acceleration of the headform as a multiple of "g", and t_1 and t_2 are any points in time (expressed in seconds) during the impact.

ENGINEERING REQUIREMENTS

In this section, the dynamics of the various impactors which are necessary to satisfy the various test criteria are considered, along with the magnitude and distribution of the impact forces which are needed to produce these dynamics. This in turn will lead to consideration of the engineering changes which may be needed in order to achieve compliance.

Lower Leg Impact Test

The draft specification imposes three sets of requirements for the bumper system design. Firstly, in order to limit the magnitude of the lower leg acceleration, as well as the inertia-based forces acting to bend and shear the knee element, sufficient crush distance must be provided for the legform to decelerate on impact and sufficient energy-dissipation to limit the change of velocity, in other words to prevent spring-back.

Secondly, to limit the bending displacement of the knee, the distribution of force over the legform must be arranged to overcome the individual segments' tendency to pitch during the impact. This might be achieved by arranging for the impact force or forces to act closer to the segments centres of gravity, or by arranging some additional resistance near the extremities of the segment, to balance that applied close to the joint.

Thirdly, to limit the *shear displacement* of the knee, it is important to avoid a concentration of loading to one side of the joint. Either the force should be spread over the whole knee area, or else the separate forces above and below should be balanced.

The amount of crush space required to meet the first of these criteria can be estimated. A half-sine deceleration pulse for the lower leg from 40 km/h to zero (no recoil) with a peak of 150 g represents a deceleration distance of 66 mm [4]. Other pulse shapes, for example square-wave may result in slightly lower deceleration distance for a given velocity change, but these are difficult to achieve in practice. On the other hand, a half-sine is typical of the pulse shape which results from a round profile impactor penetrating a flat target surface and hence meeting an increasing resistive force.

Some of the deceleration distance may be accounted for by compression of the legform's foam covering. However, in practice it is unlikely that this could contribute much to the dynamics, since the foam readily compresses on impact.

Upper Leg Impact Test

The general requirements for the upper leg are similar to the above, in that sufficient intrusion distance must be allowed to limit the impact force (as measured in the total force at the beam supports), and contact forces must be distributed over the length of the beam so as to limit the bending moment at each location.

However, for this test, the effect of the vehicle geometry insofar as it affects the severity of the test conditions must also be considered. Generally speaking, increasing the bonnet leading edge height increases the impact speed and energy, whereas increasing bumper lead reduces them. The effect of these variables on impact angle cannot be quantified, since it may have a beneficial or detrimental effect, depending on the vehicle profile.

Given the link between vehicle geometry and test conditions, it is not possible to quantify the amount of impactor deceleration distance required for a general case as in the previous section. However, it is possible to derive some broad guidelines for typical examples of various types of vehicle. Taking a typical European small saloon car (see Table 1) with a bumper height of 575 mm, a bumper lead of 125 mm and a bonnet leading edge height of 775 mm, this would result in a 13.8 kg impactor mass and a speed of 9.58 m/s, corresponding to an energy of 633 J (see Table 2). Performing a similar calculation to that in the previous section, the minimum intrusion distance for a 4 kN total load at the impactor would be 203 mm [4].

Headform Impact Test

Although a more complex relationship exists between HPC and deceleration distance, it is possible again to calculate the deceleration distance needed to just achieve the limit. Taking a half-sine deceleration pulse shape as typical, a pulse with a peak of 123 g corresponds to an HPC of 1000, and this would experience a deceleration distance of 81mm from 40 km/h with zero recoil velocity [4]. The actual penetration of the headform into the panel would, of course, depend upon the angle of the impact, and this has been evaluated for typical examples of different classes of vehicles later in this paper (see Table 2).

EFFECT ON DIFFERENT CLASSES OF VEHICLE

In order to evaluate the effect of the proposed regulation on vehicle design, MIRA has conducted a design study [4] similar to that described above based on a selection of current models in each of the following vehicle classes:

- Small saloon car
- Medium saloon car
- Executive saloon
- 4x4
- Utility (people carrier and van)

Figure 4 illustrates typical configurations for each class of vehicle in the various tests, and in particular the available impact zone and angle of impact. Four points are immediately apparent from this diagram.

The first is the way in which the adult head impact zone has been restricted on the small saloon, through being limited to the area forward of the base of the windscreen. An even more extreme situation exists in the case of the utility vehicle; indeed, it is even possible that an adult head impact zone as currently defined may not exist on some cars, due to the 1500 mm wrap-around line falling behind the bottom edge of the windscreen.

The second is the apparent difficulty in achieving a satisfactory result in the lower leg test for 4x4 class vehicles, due to the bumper contacting the legform close to the top of the upper leg segment, with no support around the knee.

The third point is the coincidence of the upper leg impact zone and the child head impact zone on high-bonneted vehicles such as the 4 x 4 and utility classes. Given the relatively high energy of the upper leg test compared with the child headform, it is clear that there will be a conflict in designing to meet the requirements of these two tests. In other words, a bonnet which has a stiffness low enough to produce an acceptable child headform deceleration may not offer the stiffness necessary to satisfy the upper leg requirements without excessive intrusion.

The fourth point is similar to the above, but concerns the situation which exists in all vehicles at the boundary between the adult and child head impact zones, that is, along the 1500 mm "wrap-around" distance line. According to the draft specification, impacts by both types of impactor are possible along the boundary line between the zones, and therefore the area close to this line must be designed to satisfy both the adult and child criteria. Since the mass of the adult headform is roughly twice that of the child, the boundary zone must be designed with crush resistance which will satisfy the child head criteria, but with additional crush depth to absorb the additional energy of the adult headform. The result of this would be to approximately double the minimum crush zone depth to around 150 mm in this area.

Figure 5 superimposes typical crush zones on the outlines of vehicles in the various classes, based upon the minimum deceleration distances derived as above.

Table 1 summarises the results of the study in terms of typical critical dimensions and Table 2 in terms of the impact energy and required minimum deceleration distance of the impactor. This again shows that the typical shape of vehicles in the 4x4 class impose very severe test conditions in the upper leg test.

IMPLICATIONS FOR VEHICLE DESIGN

Having established the minimum thickness of crush zone needed to meet the requirements, the way the impact energy can be managed must be considered, in other words, how the vehicle surface and its underlying structure can be designed to control the resistance to penetration of the impactor, and so achieve an appropriate force or deceleration level. In most cases, it may not be possible to achieve or even

Table 1: Typical Dimensions by Vehicle Category [4]

Category	Front Shape	Bumper Height mm	Bumper Lead mm	Bonnet Edge Height mm	Bonnet Angle °
Small	3 box layout passenger car	575	125	775	14
Medium	3 box layout passenger car	525	125	750	12
Executive	3 box layout passenger car	550	125	775	11
4 x 4	2 box layout all terrain	650	175	1050	9
Utility	1 box layout van	575	175	850	29

Table 2: Energy Absorption and Crush by Vehicle Category [4]

	Small	Medium	Category Executive	4 x 4	Utility
Lower leg kinetic energy J	825	825	825	825	825
Lower leg minimum deformation mm	66	66	66	66	66
Upper leg kinetic energy J	633	573	675	941	824
Upper leg minimum deformation mm	203	184	216	308	265
Child head Kinetic Energy J	154	154	154	154	154
Child head minimum deformation mm	73	72	71	70	80
Adult head Kinetic Energy J	295	295	295	295	295
Adult head minimum deformation mm	80	79	79	78	81

approximate to the half-sine wave deceleration pulse on which the minimum thickness of the crush zone was based. In that case, there is no option other than to consider a deeper zone.

In nearly all present-day cars, there are hard components which lie just below the skin of the vehicle and have been positioned there by virtue of packaging constraints. These are, of course, the points which would be chosen for impact by the testing authority as representative of the most severe impact conditions. If the necessary crush space is to be created around these points, it will generally be necessary to either move the outer surface of the car outwards, or else change the shape of the underlying mechanical components so that they lie deeper below the surface. It is recognised that the major changes to powertrain and suspension systems which will be required to create this clearance without changing the outer profile of the vehicle will need considerable lead-time, and therefore it seems more likely that early vehicles designed to offer pedestrian protection will be rather more bulbous in shape than present-day cars.

Figure 6 outlines some of the practical changes which may have to be made to a typical small saloon car in order to meet the proposed specification. These are discussed in the next section, alongside some suggestions as to the engineering features which may be adopted to overcome the problems.

Table 3 details some of the individual features which may need to be redesigned to meet the requirements, and lists some of the potentially conflicting features which will need to be resolved with the new requirements.

POSSIBLE ENGINEERING SOLUTIONS

Front Bumper

This could be made deeper in profile to support the legform either side of the knee, and could be covered with a layer of energy-absorbing material to minimise the deceleration. By extending the bumper surface vertically downwards, or providing a secondary support bar vertically below the bumper, pitching of the lower leg segment may be reduced, and hence the bending at the knee joint. However, in such cases, care must be taken to avoid creating a feature which would exacerbate ankle injuries on impact. If a vertical surface is to be created, a grille or slats may need to be provided to maintain support for the leg across the cooling air aperture.

Headlamps

It is recognised that modern headlamp units are quite heavy and rigid, and it may be difficult to design sufficient energy-dissipation into them to satisfy the proposed upper-leg criteria. Such energy-dissipation might be incorporated into the headlamp unit mountings, but this may need to be accompanied by making the units lighter. An alternative solution may be to recess the units below the surface, perhaps in conjunction with a transparent cover to maintain a smooth aerodynamic profile.

Front Crossmember and Bonnet Latch

Most modern cars incorporate an upper crossmember positioned close to the bonnet leading edge. This serves to stiffen the vehicle front end structure and generally also supports the bonnet latch, as well as supporting the radiator, cooling fan and headlamps. Where space allows, this could be moved rearwards or downwards out of the crush zone, or else could be made in lighter material which would deform when struck by the upper legform. This may in turn require a change from a single bonnet latch to a twin latch arrangement, which might also allow a lighter bonnet structure (see below).

Wing Tops

High headform acceleration caused by direct contact with the hard seam at the junction of the inner and outer wings might be avoided by adopting a "wrap-over" style of bonnet, as fitted to many present 4 x 4 models. This would also help to eliminate a similar hazard in the form of the reinforcing members running along the sides of the bonnet.

Scuttle and Windscreen Lower Edge

Under the proposed directive, the rear edge of the head impact zone lies at the lower edge of the windscreen. It is possible that an impact point may be selected which lies exactly on this line, in which case the headform would effectively contact the glass.

Bonnet

In addition to the changes suggested above, there is likely to be further development needed to avoid hard headform impacts when striking bonnet reinforcements or underlying components in the engine compartment. One possible solution would be to design a sandwich-structure bonnet which uses an energy-dissipating core material such as foam or honeycomb below a thin metal skin. An alternative solution could be an active safety system such as an airbag, or pyrotechnic devices which raise the bonnet on impact sufficiently to provide the necessary deceleration zone. This in turn would require the development of an impact detection system which would trigger the device under the appropriate conditions.

In order to avoid hard head impact against the windscreen lower edge, the bonnet might be designed so that the rear edge overhangs the lower edge of the windscreen. This feature might also help to reduce the severity of head impacts against the wiper mechanism and scuttle.

Front Suspension System

In a typical McPherson strut front suspension system, the upper mounting point of the strut lies very close to the upper surface of the bonnet, and is a rigid part of the body structure. It will therefore constitute a difficult area from the point of view of head impact. Since the tops of the suspension towers invariably lie underneath the bonnet, an energy-dissipating bonnet which is adopted to protect hard points on the top of the engine may also be used to shield these zones in a similar way.

Engine Block

Depending upon the engine layout, there may be rigid parts which lie just below the bonnet skin. These could be the casings of engine auxiliaries such as alternators, power-steering pumps etc., or the drive belt pulleys for the same. Other parts may be suitable for manufacture in energy-dissipating materials, for example covers or inlet manifolds.

CONCLUSIONS

The provision of protection for pedestrians on impact seems set to be one of the dominant driving forces of automotive design for the European market over next few years. It is likely that this will be promoted as part of the type-approval requirements for cars and light commercial vehicles, as well as under the EuroNCAP scheme, and that the requirements will be very similar to the draft specification drawn up by the EEVC.

Achieving the test requirements will not be easy, and may demand a major re-appraisal of the design of many parts of the car front end, including the bumper, bodyshell, wings and bonnet in the short term and possibly the front suspension and powertrain in the long term. Certain classes of vehicle, notably off-roaders, may present particularly difficult problems for the designer, whereas other types may be easier to accommodate.

REFERENCES

1. HARRIS, J. (EEVC Working Group 10) "A Study of Test Methods to Evaluate Pedestrian Protection for Cars" ,13th International Conference on Experimental Safety Vehicles, Paris, Nov 91, Paper No 91-S3-O-06

2. European Commission Document III/5021/96/EN, "Proposal for a European Parliament and Council Directive Relating to the Protection of Pedestrians and Other Road Users in the Event of Collision with a Motor Vehicle", February 1996

3. WILLIAMS, D.A. : "European New Car Assessment Programme (Euro-NCAP) Frontal and Side Impact Testing Protocol" Transport Research Laboratory Project Report PR/SE/249/97

4. DAVIES, R. & CLEMO, K.: MIRA Project Report No 97-456502: "Study of Research into Pedestrian Protection, Costs and Benefits", 21/8/97 (Published by European Commission Directorate General III)

Table 3: Potential Design Conflicts

Feature	Conflict
Front bumper	Resistance to light collision damage Vulnerability to bird strike etc Aerodynamic drag Number plate mounting Airbag triggering pulse Cooling air flow Approach angles Auxiliary lamps Towing eyes
Headlamps	Positioning Mounting rigidity Aerodynamic drag Scuff resistance of lens / cover Wash / wipe system Distortion in bumper impact test
Radiator	Positioning Cooling airflow Fatigue strength of mountings Damage in bumper impact test
Bonnet	Rigidity Latch strength / vehicle security Vulnerability to bird strike etc Sit-on / lean-on damage Resistance to high engine compartment temperatures Access to front of engine compartment Damage in bumper impact test
Bonnet latch	Rigidity Resistance to slamming loads Positioning Adjustment (2-latch systems) Windscreen intrusion by bonnet
Front crossmember	Body torsional rigidity Frontal offset / angled crash performance Body fatigue
Bonnet hinges	Rigidity Resistance to wind loads Windscreen intrusion by bonnet
Windscreen	Lower edge mounting
Windscreen wipers	Mounting rigidity
Powertrain	Positioning Rigidity NVH Inlet air flow Belt drives Auxiliaries
Front suspension	Upper mounting rigidity Geometry
Front bulkhead	Upper crossmember rigidity Body torsional rigidity
Cabin	Forward field of view
Vehicle (general)	Cost of collision repair (Insurance Test)

Figure 4: Typical Test Configurations by Vehicle Category
(Models shown are for illustration only)

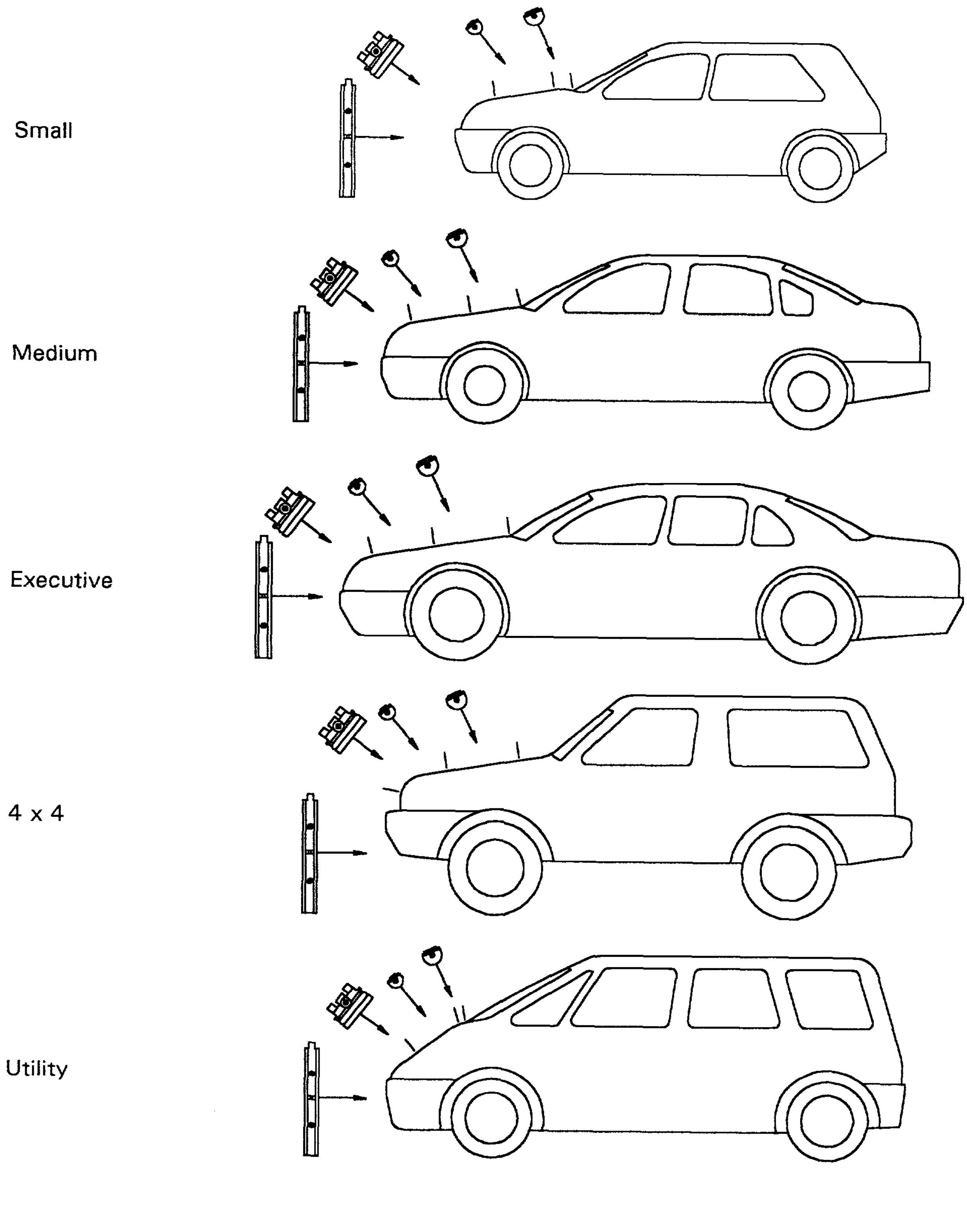

Figure 5: Typical Crush Zones by Vehicle Category
(Models shown are for illustration only)

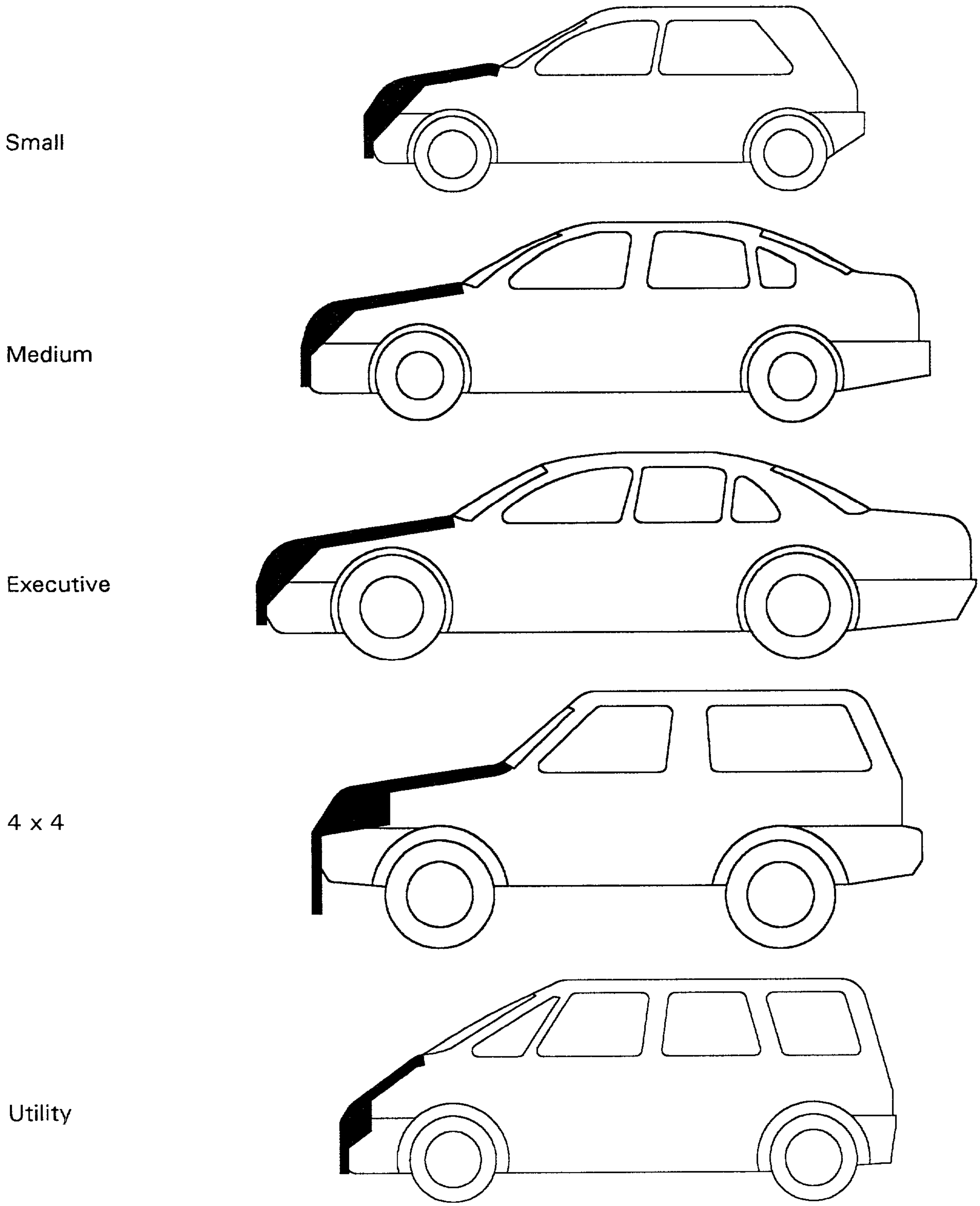

Figure 6: Practical Vehicle Design Changes