EFFECTIVENESS AND COST OF CAR FRONT END DESIGN FOR PEDESTRIAN INJURY PREVENTION AND THE PROBLEM OF CONFLICTING REQUIREMENTS

A literature review

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ABSTRACT

SWOV carried out a literature review on the subject of car front end design for pedestrian injury prevention. The review is aimed at effectiviness and cost of such design and at the problem of conflicting requirements. Such requirements are existing safety standards and common design rules on the one hand and pedestrian injury prevention solutions on the other hand.
The literature findings on these subjects are discussed, conclusions are drawn and recommendations given.

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1. INTRODUCTION

This literature review is part of a compatibility study carried out by TNO Road-Vehicles Research Institute on behalf of APR (France). The compatibility study itself forms part of an extensive research programme carried out by an international group of research institutes coordinated by EEVC-Working Group 10, established at the end of 1987. The TNO compatibility study, including this literature review was financed by the Dutch Ministry of Transport, while a substantial part of the extensive research programme was supported financially by the EEC (contract ETD/89/7750/MI/28).

Research aimed at the passive safety of pedestrians struck by cars started in the sixties, among others in the USA, Japan and Great Britain. Wakeland (1962) reported to the Fifth Stapp Conference in 1962 a study carried out on the base of accident analysis focussing on injury causation factors. The study was called "Systematic Automobile Design for Pedestrian Injury Prevention". Though he was very much in favour of design changes on behalf of pedestrians he did not neglect to point out possible conflicts of interest:

" ...Design efforts must avoid interference with functional necessities of the vehicle:

a. Free passage for cooling air and horn sound;
b. Mounting for lights, signals and license plate;
c. Sealing of interior against rain and proper run-off;
d. Parking bumper effectiveness;
e. Vehicle crash deceleration structure;
f. Parking clearance indicators;
g. Unobstructed driver vision;
h. Resistance to casual damage and ease of cleaning. ...."

He was in favour of an overall safety design of automobiles and described tests methods for assessment of the result. On the subject of effectiveness he concluded that "...No estimate can be made of how effective such design would be...." The last of his conclusions was: "...Systematic approaches to automobile design for pedestrian injury prevention are not impossible; they may only require concentrated attention and development."

In these early days many proposals for practical solutions were put forward.

One of these is found in the state-of-the-art on Vehicle Exterior Safety by Severy (1970). In this study he describes "the pedestrian inflatable bumper".
This device would be able to solve almost all known problems concerning the pedestrian-car collision, including the compatibility problems with other functional requirements. The device appears to be an airbag for pedestrians, however of substantial greater dimensions than the airbag used in the interior of cars (Figure 1). The author ends this paragraph noting that many tests are required to assess the practicality of this protective measure.

Another proposal to solve the problem was found in the report of Baird & Jones (1974), the illustration (Figure 2) speaks for itself.

Though the three examples of reports from the early sixties and seventies described above may lack a realistic approach with respect to modern car design, the problem itself was clearly defined and the aim clearly established. Now, some 20 to 30 years later, they are still valid.

In the seventies pedestrian safety soon became a separate part of the International Conferences on Experimental Safety Vehicles, organized about every two years. Numerous accident studies and experimental studies were carried out and reported to ESV. Some interesting prototypes and experimental designs were developed, mainly by the car industry, to test and show the possibilities of pedestrian-compatible front ends of cars. Some of the results were introduced in production cars.

At the beginning of the eighties the EEVC (1982) presented their final report "Pedestrian injury accidents" during the 1982 ESV-Conference at Kyoto. This report was the first coordinated international study aiming at future legislation and was based on current knowledge of accident data and accident statistics, human tolerance, design criteria, test and assessment methods. The report recommended further in-depth research on a variety of subjects, much of which has been undertaken since then.

This literature review shows that a great many valuable studies in different countries have indeed been carried out during the last 10 to 20 years both by car industry and research institutes and often supported by governments.

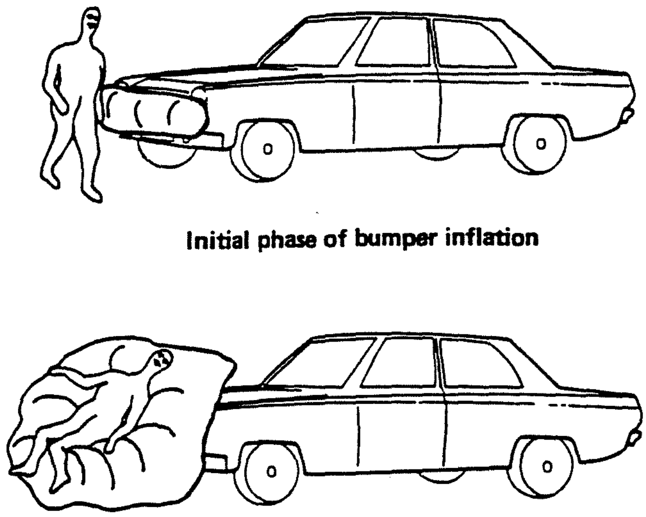

Figure 1. Inflatable design to prevent running over pedestrians

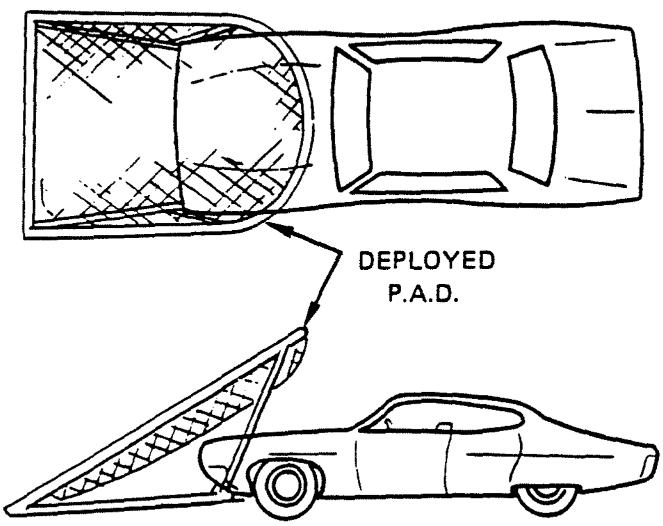

Figure 2. Preliminary concept of a deployed pedestrian arrestor device.

2. EFFECTIVENESS

The main purpose of measures regarding the front end design of cars reviewed in this report is to prevent fatalities or to reduce the frequency and severity of injuries to pedestrians. Effectiveness in this review therefore is a measure expressing the expected or actual amount of fatality and injury reduction. It is often expressed as: the (percentage) reduction of the number of fatalities, but other measures are used as well, such as:

- reduction of the number of serious injured;
- reduction of the number of injuries;
- reduction of the severity of injuries;
- reduction of the risk of permanent disability.

One of the bases for estimates of effectiveness is knowledge about injury causation factors in terms of specific parts of the car exterior. When these are known, design changes may be assessed in terms of injury reduction capability. Another approach is the comparison of different (existing or experimental) front end designs with respect to type of injury, injury severity and injury patterns in accidents. For all these purposes reliable accident and injury data are necessary, including those on the influence of collision speed, age and posture of the pedestrian and collision mode. Especially the reconstruction of collision speed is a weak part of any accident study. Experimental data are far more precise with respect to the speed, force and contacts, but because of the necessity to use human substitutes they do not provide realistic information on injury and injury severity. Estimates can only be based on incomplete knowledge of human tolerance. More or less the same is applicable to simulations using mathematical modelling.

Combined however these three methods provide sufficient insight to allow for proper assessment of effectiveness.

During the 7th International ESV Conference Stcherbatcheff (1979) from Renault reports that the increased leg protection for pedestrians provided in the Renault E.P.U.R.E (a modified production vehicle) would result in a 10% reduction of knee impact. Lower placed bumpers would even bring a 25% benefit. As far as head impact against A-pillars and upper windscreen is concerned, the E.P.U.R.E. brought down HIC-values to very reasonable levels. This could be achieved without compromising the style and aerodynamic properties of the vehicle.

In England Ashton (1980) based his estimates of effectiveness of changes in car front end design mainly on numerous accident studies, but also considering results of experimental work. To estimate the effect on the total population he used two different strategies. One strategy aimed at reducing the frequency of serious head injuries, the other at reducing the frequency of serious leg and pelvis injuries. He found that the first strategy would result in a reduction of less than 5% of the non-minor injured casualties, while the second would reduce this group with at least 25%. He therefore concluded that adoption of the second strategy, called 'the compliant front structure' was the best to use.
This strategy includes changing the stiffness of all front structures, such as bumper, leading edge and also the top surface of the bonnet and the wings to provide tolerable impacts up to 40 km/hour.
Although reduction of the stiffnesses mentioned will primarily reduce contact forces in the leg and pelvis area they have the secondary aim to reduce the impact speed of the head and also to force the head contact location to a less aggressive part of the front.

The current research activities aiming at a new EC-directive are mainly based on this strategy.

In Ashton & Mackay (1983) the strategy was again put forward and its effect on society directly compared to the benefits from the provision of passive restraints (as in the USA) or the mandated use of active restraints for occupants (as in most European countries).

In the Netherlands Huijbers & Van Kampen (1985) used a theoretical design. They saw three levels of necessary measures to master the problem.

- controlling collision speed of the car;
- controlling contact forces and decelerations;
- controlling kinematics of the pedestrian.

For the first level certain pre-crash measures are needed to reduce driving speeds. Their effect on fatalities could be very substantial (approx. 60%) and, if speed could actually be reduced to a level under 30 km/hour, even more. However the success of these measures is also dependent on change in driver behaviour and falls beyond the scope of the study on also of this review.

The second level of measures is changing the stiffness of the whole front of cars. Huijbers & Van Kampen partly based their estimates of effectiveness of pedestrian measures to cars on effectiveness of crash helmets. They 'translated' this to the protective properties of the front end of cars after stiffness reduction, considering as well the influence of collision speed and the proportion of injuries caused by ground contact. They reasoned that a fatality reduction of some 20 to 30% could be expected from the lowering of stiffness. This type of measure also brought down the number of injured with 10 to 15%.

Third level measures to influence the kinematics of pedestrians after contact mainly in order to reduce head impact speed were estimated to decrease the number of fatalities and serious injured by 10%. These measures include restyling of car front ends: altering the shape, lowering of the bumper and changing the gradients of hood and front.

The Institute of Lightweight Structures, ETH Zürich (Gaegauf et al., 1986) found for their pedestrian-activated displaceable hood impact accelerations far below the tolerable limits up to collision speeds of 40 km/hour. More about this pedestrian-compatible hood design is found in chapter 3.

In their 'written only' paper tot the 12th ESV Conference Vallee et al. (1989) of APR (France) note the huge decrease (50%) in the number of pedestrian fatalities during the last 15 years in Europe and Japan. They contribute this decrease partly to demographic factors and partly to the reduction of the most aggressive zones in cars. They forecast that further reduction of the pedestrian problem will continue independent of safety measures but will be far more influenced by primary safety measures such as on infrastructure, education and alcohol, than by secondary safety measures. They base their expectations on the low level of fatality reduction they contribute to some experimental safety vehicles already presented in the past.

In a recent paper Harris (1990) concludes that incorporating pedestrian protection features, effective at speeds up to 40 km/hour to the bumper, bonnet leading edge and bonnet top of all cars is estimated to give an annual reduction in casualties of about 6 to 10 percent of the 1205 killed by cars, and up to 30 percent of the 13000 seriously injured in Great

Britain. He also states that these savings would be worth about £ 140M per year in the UK alone. This gives a cost effective price for the proposed level of protection at about £ 70 per car.

At the end of the seventies, in a project preceding the well known UNI-CAR, the Technical University of Berlin reported that their first step to a pedestrian safety car (Kühnel & Appel, 1978) had succeeded. A decrease of 40% pedestrian fatalities was thought possible from this approach and a effectiveness-cost relation of 1,3 to 1,7 was assessed (Appel, 1980).

A few years later Appel presented the UNI-CAR and during the 9th ESV Conference a promising assessment of the expected overall effectiveness was presented (Appel et al., 1982). In this report about the softnosed UNI-CAR a overall safety gain of approximately 30% was assessed of which almost half (13%) were benefits to pedestrians and bicyclists.

An interesting study from the USA was presented by Kessler (1987) to the 11th ESV Conference. Using an impact device he compared production hoods and fenders with respect to predicted injury severity resulting from head impact. Kessler concluded amongst others that a wide variation in predicted head injury severity (ranging from 5 to 100% probability of death) was obtained among production vehicles. It demonstrated that significant injury reduction could be achieved by making all cars perform as well as the best current production cars, especially those with so called full cover hoods.

A special place has to be given to reports on the assessment of effectiveness of various experimental and research safety vehicles during the seventies and early eighties. In these reports results are often presented as a decrease in HIC values or as force and acceleration reduction. In most cases these figures apply to specific parts of the car front end and do not relate to overall effectiveness of the car design. Though these decreases are not expressed in terms of fatality reduction or injury reduction, they are of course the basis for such calculations and they show that the problem may be solved, at least partly, by proper front end design. These reports are only mentioned here and not reviewed unless specifically relevant to this report. There have been the well known Research Safety Vehicles in the USA and their counterparts in Europe, such as the

Calspan-Chrysler RSV (Kruse, 1976; Pritz, 1976); the Peugeot VSS and the VLS 104 (Echivadre & Gratadour, 1979); the Renault E.P.U.R.E. (Stcherbatcheff, 1979); the UNI-CAR from Germany (Kühnel & Appel, 1978; Wollert et al., 1983); the VW Auto 2000 (Seiffert & Grove, 1983); the British PSC-1 of TRRL and Austin Rover Group Ltd. (Hobbs et al., 1985).

Daimler Benz have reported on several occasions about their design improvements of new production vehicles. Impressive is their paper presented to the 10th ESV Conference (Stürtz, 1985). Force reductions of 10% to 30% have been established in the 124 series compared to the older 123 series in both bumper, front end, hood and fender and pillar area's.

In a recent US-publication (MacLaughlin et al., 1987) NHTSA reported that they are addressing the problem through both crash prevention and crashworthiness research activities. In the USA nearly 100.000 pedestrians are injured each year and more than 7000 killed. These fatalities represent 16% of the US national motor vehicle death toll. Part of the crashworthiness programme is the study of upper body injuries of pedestrians inflicted by vehicle front ends, also reported in (Kessler, 1987). The NHTSA authors feel that significant reductions may be possible in the numbers of serious to fatal head injuries through implementation of vehicle structurral design which depart very little from some of those currently in production. The number of thorax injuries is also substantial suggesting that significant benefit may be possible in that body region as well.

In another recent US-report (Wiechel & Guenther, 1989) the NHTSA research line is followed and the authors express their opinion that the 'harm' instrument used to determine cost to society could be improved by adding a new element considering disability. This is especially important since leg injuries, including severe knee injuries are frequent among pedestrian injuries and often cause of disablement. The authors also note that there is clearly need for more recent accident data to check the current priorities. Apart from these possible improvements they feel that the US-experience can permit a significant contribution to the international effort which is being devoted to the development of pedestrian impact test devices and procedure, though they recognise that due to variations in pedestrian impact situations and vehicle design between countries the direct applicability of their results may be limited.

3. PRACTICAL SOLUTIONS AND COST ESTIMATES

Literature on the subject of cost is very limited, probably since most known practical solutions only deal with a very small proportion of front end redesign (such as partly redesign of a vehicle headlamp) or are integral part of the structural development of new cars. However there have been made some estimates especially with regard to experimental bumper design and redesign of the existing bumper to comply both with pedestrian safety and with existing regulations.

Based on the extensive research activities regarding the Calspan Research Safety Vehicle during the last part of the seventies, the NHTSA reported about costs of the soft bumper design (Richardson, 1980). Though the bumper design did not meet the detailed requirements of the Part 581 Bumper Standard, the overall benefit might be greater than with current designs because of the increased protection to other cars in low speed collisions. The bumper complied with the performance criteria of a proposed pedestrian standard. Weight and price calculations indicated initially that there would be a 7,5 kg weight and a $65 price increase as compared to a standard bumper of a comparable car. But a more realistic comparison should reduce both weight and cost.

Herridge & Vergara (1980) from Batelle calculated costs of repair of a pedestrian-compatible bumper. They found benefits (in repair costs) with regard to car/car collisions even though the initial design did not meet all of the requirements of the bumper standard.

As shown in the previous chapter (Appel, 1980) the Technical University of Berlin has made some assessment of benefits and costs of the application of a softnosed front design, that amounted to a positive effectiveness/cost relation. Costs estimates of the UNI-CAR, another German project of the early eighties, could not be reproduced from the selected literature for this review. They amount to a total of 500 DM per car.

There are several reports on the more practical applications of available knowledge into standard vehicle design and in redesign of current vehicles. Especially examples from the German car industry are well documented such as AUDI's redesign of the hood area of their AUDI-100 (Kramer, 1979 and 1981), several examples of Daimler Benz, partly based on ESV/RSV experience (Huber, 1982), of applied knowledge to their 124 series model (Stürtz, 1985); (Grösch & Hochgeschwender, 1989).

In the report on the Peugeot VLS 104, mentioned in the previous paragraph, the following conclusions were drawn: "The results of this study indicated that a substantial reduction in pedestrian injuries is possible through straightforward modifications to production vehicles. Acceleration levels as recorded in adult and child dummy impacts were significantly reduced by the incorporation of surface-compliant materials across the front of the vehicle. The increase in surface compliance was obtained by replacing the production metal bumper system with resilient deep foam elements, using available space within the vehicle. The modified vehicle was (1) constructed of production-feasible components, (2) satisfied the 5-mph frontal barrier test portion of Part 581 Bumper Standard, and (3) offered significant weight savings."

The reports on the more recent studies from the car industry are both promising with regard to practical solutions and at the same time pessimistic with regard to its contribution towards the total pedestrian problem. This last phenomenon is reviewed in more detail in some of the next chapters.

Though there exists a clear lack of information on cost of redesign of (parts) of the car front end, there is a great amount of literature on the subject of cost of injuries, disability, treatment in hospitals and the cost for society of fatalities and injured. Most of these reports however were not directed at the problem of pedestrians but discuss traffic casualties in general. This literature was not considered for this specific literature review on cost regarding pedestrian measures.

4. CONFLICTING REQUIREMENTS

Literature concerning conflicting requirements is in nearly all cases reported by car manufacturers. The most common subject in this respect is the bumper system.

As shown in the previous chapters the USA has launched a long-term research programme during the seventies, meant to result in a new safety standard. This point of view and some of the results of research activities were presented at the 7th ESV Conference in 1979 (Daniël et al., 1979). With regard to compliance with existing Federal Motor Vehicle Safety Standards (such as Part 581 and FMVSS 208) NHTSA concluded that the required modifications were compatible. They also concluded that existing vehicles could be modified using present technology and materials.

There have been no examples found of recent publications of the American car industry on the subject of conflicting requirements. From publications already reviewed in the previous chapters it seems clear however that the American attitude is more positive towards the subject of redesign of car front ends than the attitude of several European manufacturers.

Porsche reported on the problem of conflicting requirements with regard to bumper design (Hoefs & Heinz, 1987). They stated that car manufacturers had to comply with a multitude of requirements. They specified pedestrian safety demands with respect to the following features: safety regulations, protection during accidents, operational and functional reliability, customer demands, styling and aerodynamics, production and repair costs, component weight.
They tested a variety of standard and energy absorbing bumper designs. They concluded that an energy absorbing foam bumper system seems best suited to meet pedestrian safety demands (i.e. force reduction to less than 4 kN). However, none of these systems tested met the full range of both pedestrian and other requirements. The authors concluded that a compromise is necessary in order to satisfy both. This compromise would restrict both injury reduction for the pedestrian and fulfillment of requirements from the features mentioned above.

In their paper to the 10th ESV Conference (Stürtz, 1985) Daimler Benz

expresses to be in favour of components tests as opposed to integrated (full-scale) methods mainly because of its good reproduceability and simplicity. The author suggests that the car manufacturer determines the contact zones to be valuated by component tests since he knows best where to find them. He also states that there are conflicting interests between pedestrian protection and other design characteristics without defining them properly.
The paper ends however showing some excellent design improvements of production vehicles in the 124 and 201 series as compared with the 123 series; this was already mentioned in chapter 2.

In a paper presented to the 12th ESV Conference Daimler Benz retracts somewhat from its former, more positive position with regard to the redesign of the car front end (Grösch & Heiss, 1989). As is the case in the paper of APR already mentioned in chapter 2, the authors describe the same 50% decrease of pedestrian fatalities since 1970, despite of the increase of accidents by more than 40%. The paper also describes all the good work that Daimler Benz have been carried out with regard to active and passive safety of its cars. They review the existing major bumper regulations (USA Part 581, Canada CMVSS 215 and ECE 42). Though expressing some doubt about the representativeness of these regulations, they present a table of conflicting requirements with respect to pedestrian protection. They state that all of the pedestrian friendly design features runs completely counter to both the bumper regulations and the requirements of practical use. They give a number of reasons, amongst others the more important problem of mismatch between cars, the collision against poles which requires stiff bumpers and the problem concerning the triggering air bag sensors which may result from softnosed bumpers. The authors feel that other than technical solutions should be of a higher priority, such as improvements in the traffic system, road conditions and driver education. They conclude their report stating that prevention of accidents is far better, more economic and, most of all, more humanitarian than anything else.

5. DISCUSSION

Accident statistics of nearly all European countries show that collisions against car front ends account for the majority of pedestrian casualties, fatalities as well as severe injured. Dependent on the country this accounts for 15 to 30% of all traffic casualties. The problem therefore may be regarded as a very dangerous epidemic disease for which strong measures are needed. The safest way of protecting pedestrians from these impacts is without doubt a complete separation of the two categories. In most existing traffic situations there is only limited space for the separation of traffic categories. It can be expected therefore that encounters between cars and pedestrians will remain common events for a long time to come. Assuming that society really accepts its responsibility to protect citizens against this enormous problem, other solutions are necessary.

Apart from separation of traffic categories there are other pre-crash measures to be taken that may greatly improve the situation. Among these are infrastuctural measures such as safe (protected) pedestrian crossings and traffic measures such as the reduction of driving speeds of motorized traffic. This last type of measure, if successful, may not only influence the number of accidents, but will also improve the outcome of collisions with pedestrians.

However, even if all pre-crash measures have been taken, accidents between cars and pedestrians will still occur. As with other problems in the field of traffic safety there is clearly a continuing need for crash measures. This fact is incorporated both in the long-term research strategy of the American approach (where explicitly is chosen for both strong pre-crash and crash efforts) and the European approach (where the EC-efforts are more explicitly aimed at the crash safety of pedestrians).

Since we deal with the unprotected road user having only his own body to protect himself the major part of crash improvement is to be achieved by (redesign of) the car front end. The search for this type of solution is well documented. Already in the sixties the first accident studies suggest room for improvement of car front end design. In the early seventies, after the first ESV-encounters, attention was also given to the protection of vulnerable road users through car redesign. A world-wide movement towards more compatibility had begun.

Compatibility in the field of crash safety normally means the balance between colliding structures with regard to mass, stiffness, speed etc.

Compatibility means comparable resistance against collision forces and accelerations in order to equally divide and dissipate energy. In the case of completely different structures with regard to mass and stiffness the principle of the solution is based on partial tuning of the structure, in most cases the one with the greatest mass. The local stiffness of the heavier partner should be adjusted to that of the lighter partner.

Since pedestrians have only their own bodies and clothing as means of protection, the level of force that should be encountered in collisions is directly based on human tolerance.

There is therefore an almost complete lack of balance with regard to pedestrians and cars, there is only incompatibility: Mass differences may well reach a factor 10 to 20 for adult pedestrians and even more for children. The differences in stiffness of the two colliding structures are the most troublesome bottle necks, while there are obvious considerable speed differences. It is beyond doubt that the average vehicle's structural properties are no match for the unprotected human being. They are not compatible.

Exactly the same problem of course has been apparent for vehicle occupants; they also are not compatible with the interior of cars unless some major precautions are taken. It has taken the best of 30 years now to greatly improve that situation. Not only by means of protecting devices such as seat belts, padding, head restraints and airbags, but certainly also by means of structural improvements with regard to the deceleration properties of the major colliding structures and structural strengthening of the passenger compartment. Though even there is room for improvement, the human being inside cars is 'very well off' in case of (frontal) collisions. So why could the human being colliding with the outside structure of cars not benefit as well from comparable improvements?

How do we translate these (internal) structural and protective solutions to the problem of the exterior of the car? Which part of the considerable knowledge already acquired for the protection of the human being inside cars can we use for the protection of the same human being outside cars? The mechanical principles involved are exactly the same. The human beings involved are also exactly the same.

There is one complication of course: the safety of the occupants themselves should not be impaired. This part of the problem seem to be easy solved. Because of the mass differences involved, the car will always win. That is to say that only a small part of the momentum involved will be translated tot the car; the occupants are not at risk. On the other hand the problem is far bigger because pedestrians (and cyclists for that matter) may strike almost any part of the exterior of the car front end, while occupants normally strike a well defined part of the interior. To reach a certain level of compatibility, the complete front end should be considered. There is however a practical limit to the amount of passive safety that cars could offer pedestrians. To reach realistic solutions the most important limit is the speed range for which compatibility is sought. Today we think that major improvement is feasible for collision speeds up to 40 or 50 km/hour. Moreover the pedestrian is not expected to sustain collision forces without any harm. Therefore another condition is assumed, a maximum injury severity of AIS level 2 or 3, the latter giving serious but survivable outcome for the pedestrian.

Some complaints of car manufacturers relate to the problem of conflicting interests, especially between the safety of car occupants and pedestrians. Also existing requirements on bumpers (car damage protection), practical and styling requirements on bumper and hood, aerodynamical requirements regarding the shape of the car, already ask for compromises without the need to look after the interest of pedestrians. Some of the solutions developed to fulfill aerodynamical requirements seem interesting also with regard to pedestrian protection. However, it cannot be said that all is already known about the ideal shape and stiffness of the car front end. But though more studies are needed to fill all still existing gaps of knowledge in this field, no one can honestly say that considerable improvement cannot be reached right now. Even restyling and restructuring of existing car models may improve the safety of pedestrians considerably.

When developing new models the safety requirements for pedestrians could be part of the overall safety design of the car. Even though a certain

amount of compromise will remain necessary, there is no doubt that car industry is able to fulfill reasonable requirements that will benefit car occupants as well as vulnerable road users. Some manufacturers have already begun to show the world that they take this new responsibility serious.
It is to be expected however that additional pressure from governments is needed to reach all manufacturers, giving them equal opportunities to fulfill the requirements. That is why the council of the ECE is preparing a new directive, supported by national governments and national research institutes. National governments could also stimulate this process by involving industry and research institutes in joint projects aiming at the reduction of traffic casualties.

The current activities with regard to a new European Directive will cover in principle the current range of car types. Problems however might be expected considering some recent developments: There is a tendency towards still smaller cars, especially from Japan.
Existing knowledge with regard to the first and second contact points on the front end may not apply to these smaller cars at all. The same is true for cars that do not have so called leading edges and bonnets but show a continuous, more or less straight front up to or including the windshield.

What remains is the principle common to all improvements tot the car shape and surface structure. It should be designed without sharp edges, with a local stiffness that is as close as possible tot the levels of human tolerance and a geometry and shape that result in acceptable speed differences between car and pedestrian after the first contact.

Already regulations exist that limit the possibility of exterior protrusions like the well known radiator ornaments and dangerous wheel nuts or hub caps. That, however, is not enough. Some modern front end designs appear to be more pedestrian-friendly than others. The indepth study of these differences might give new ideas for future design characteristics.

During the last ten to twenty years the problem has been investigated thoroughly and the solution seems to be focussing on several specific car parts: the bumper, the leading edge, the car hood and the windshield and its frame. That is why the current EEVC-working group and the EC are pressing hard to develop computer directed component test methods and criteria to evaluate the outcome of collisions to these parts.

Regarding some parts the opinions still differ, for instance on specific bumper requirements. There is some agreement however on the fact that bumper lead should be small, bumper height above the ground should be such that first contact is well below knee level. Of course here are some problems with regard to children whose legs are far shorter than adults'. In theory it seems very well possible to lower the stiffness of most of these parts, though there is discussion about the exact level. It may well be that the ideal level required based on human tolerance is below the level of necessary strength of the outside surfaces of cars. Some functional aspects therefore are at risk; compromises are necessary. This fact may not hamper future legislation nor the undoubtedly available creative design powers of car industry to find solutions out of their own responsibility for the safety of traffic.

These are problems that should be solved with the current knowledge on a wide variety of (new) materials and production technology. Priority should be determined with respect to such existing measures on car-damage protection to be given on one hand by bumpers, bumper requirements with respect to structural design of the car and its compatibility with other motor vehicles and on the other hand by newly developed standards in the field of pedestrian protection. Every major measure on the safety of traffic participants is ultimately a compromise. It seems however that up to now the vulnerable road user is always drawing the short straw, while the knowledge is there to make cars far more compatible with this group without compromising the safety of its occupants.

In the USA a steady flow of experimental activities, stimulated by NHTSA, culminated amongst others through the various research safety vehicles into feasible solutions or even practical designs. An example of this approach is found in one of the many reports on the Calspan/Chrysler Research Safety Vehicle (Fabian, 1980).

Pedestrian safety and occupant safety are part of the same structural design concept, in which three zones are considered: The first zone is the low resistance pedestrian and property damage zone of 255 mm, the second zone is for car to car compatibility and the third one is for high speed impact (Figure 3). Deceleration versus crush properties are also considered in three stages (Figure 4).

Another fine illustration of the feasibility of this approach is given by the Institute of Lightweight Structures, ETH Zürich (Kaeser & Gaegauf, 1986). In their report they outline an approach to a systematic design procedure for a car front, at an early stage in the design. Though clearly such design will show larger deformations under impact than a current car, they point out that requirements for normal use of the car could still be satisfied. They base their findings on knowledge of strength and energy absorbing properties of a variety of materials, including aluminum and plastic foams.

During the seventies and the early eighties most manufacturers involved in this kind of research were reporting about their respective successes. In more recent years, however, literature from the car industry on passive safety of pedestrians is changing in colour. In contrast with most of the positive results mentioned in the previous paragraphs there now seems to be the understanding that though some improvement can be reached, the problem itself can only be properly solved by means of pre-crash measures, i.c. separation of pedestrians and cars.
This position is illustrated by a recent paper of Daimler Benz (Grösch & Heiss, 1989), a manufacturer well known because of its outspoken policy regarding the whole field of active and passive safety of their cars. In this paper to the 12th ESV Conference, already reviewed in the previous paragraph, the authors explore the field of conflicting requirements for bumpers. Though reference is made to the fact that damages to the car and repair costs in minor collisions cannot simply be set off against pedestrian injuries, they also state that such economic considerations cannot be ignored because of several practical reasons. It seems clear that even Daimler Benz is retracting or trying to retract from much of what has been said and done in the past over a long period of some twenty years.

They central question seems to be: will society accept that conflicts of interest such as described above will prevail and therefore continue to accept the loss of lives, the possibility of life long disability and the enormous amount of injuries? Or will society support the idea that all traffic participants should meet in a far more compatible surrounding than the current situation.

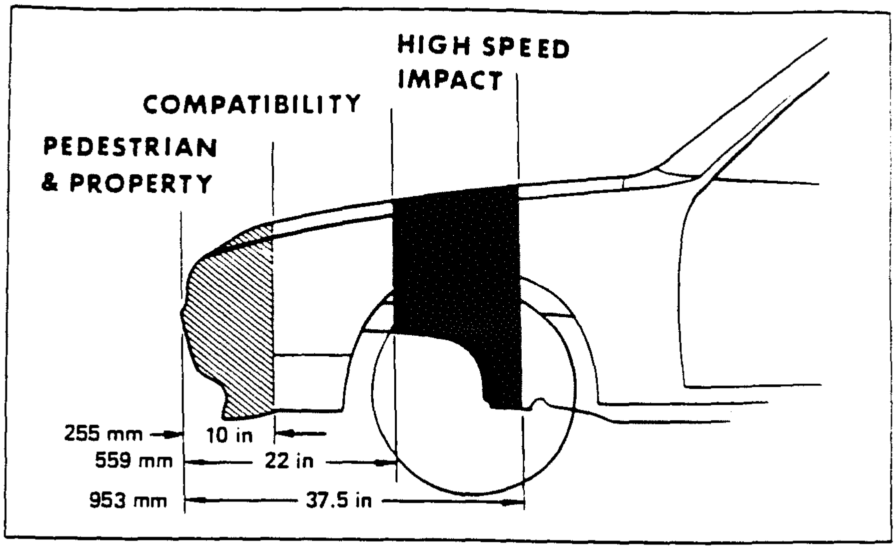

Figure 3. Front structural concept.

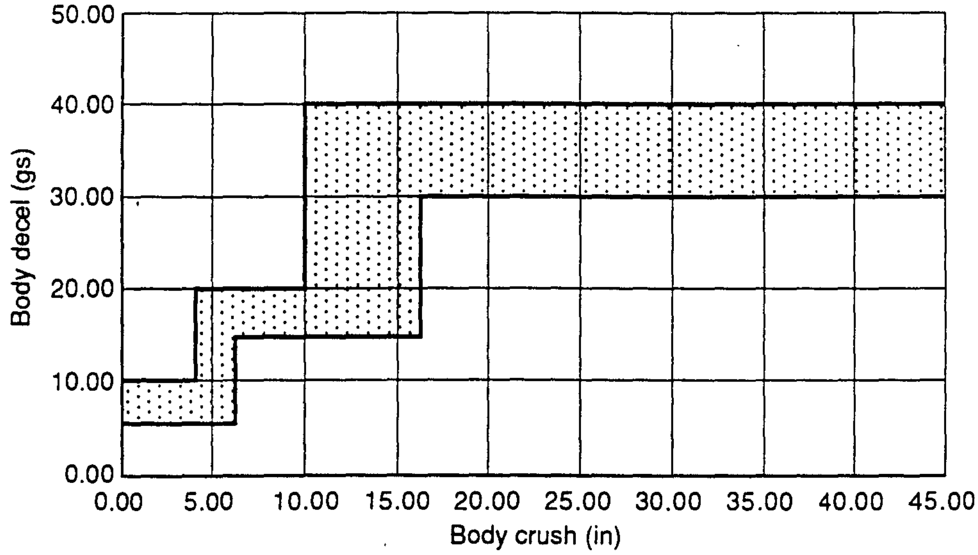

Figure 4. RSV front structure deceleration-displacement responses.

As shown, the bumper system of cars is indeed a typical example of possible conflicting interests. On one hand we know that bumper height, bumper lead and bumper stiffness have (considerable) influence on the outcome of pedestrian collisions. On the other hand there are the current requirements on bumpers and a number of more or less functional demands. The example is typical for the problem in more than one way: In the first place, current bumper requirements do not influence or are not meant to influence passive safety of car occupants. The main purpose of these requirements therefore is not to protect the car occupants against bodily harm but to protect the car owner against loss of money in case of (minor) collisions, so called parking damage. Of course such requirements are in the interest of the car owner and cannot be regarded as futilities; their existence is the result of strong negotiating between car industry, legislators and consumer organizations in the USA. In the second place there is still much room for improvement both from the point of view of occupant safety and low speed damage due to the problem of mismatch in collisions, which car industry has not been able to solve. Here we come to a major incompatibility problem. Current requirements concerning the front end structure of cars in case of (frontal) collisions force the design to be adapted to collisions with a solid (concrete) wall. In this type of collision all parts of the front structure will contribute to the proper deceleration behaviour of the car as required for instance in ECE 16 for the testing of occupant restraint systems. In reality, as accident investigation has shown, almost no collisions occur that way. Both the 90 degrees collision mode and the type of solid obstacle are not in agreement with reality. In practice therefore the problem of mismatch of colliding structures designed for passive safety of car occupants is more rule then exception. Mismatch may even occur with regard to other passenger cars due to height differences of the structures both in frontal collisions and in rear end collisions. Mismatch between cars and heavy goods vehicles and other heavy motor vehicles is an even greater problem, also regarding both front end and rear end design of those heavier vehicles. Only the part of the problem concerning low speed collision damage may be solved by redesign of the bumper area. All other problems, including both pedestrian safety and occupant safety should be part of a more integral approach.

The central problem to be tackled by both car industry and legislators, is the problem of collision-incompatibility of different structures and different categories of road users. The essence of the problem and therefore the essence of the solution is that it is literally double-sided. The structural properties of both colliding structures (either cars, car against heavier vehicle, car against obstacle and last but not least car against human structure) are involved. Only if both are also part of re-design, the possibility of a compatible solution occurs. This may well mean that a relative big part of the redesign has to be found with the heavier of the two structures, since there the 'room' for improvement is the availability of mass coupled to room for colliding structures. Without this double-sided approach even the problem of side impact, still under discussion both in the USA and EC-countries, cannot be solved properly. That problem also has its 'double' in the structural properties of the colliding front end of the car, now represented by a standard front end, comparable to, though somewhat more realistic then, the solid concrete wall 'used' for front end design. In other words, the front end of cars should also be part of the solution of the side impact.

The conclusion from this part of the discussion is that further improvement of passive safety of cars, or any other category of road vehicles for that matter, is dependent on a totally new approach. Such approach is definitely not easy to deal with. It sets new, more complex goals then ever before. It could be the most spectacular achievement of the century if both the theoretical approach and the practical applications were adapted in modern car design. At the same time it must also be clear that 100% compatibility between all different categories of road users will remain an utopia. For practical purposes a realistic approach consisting of well defined limits (speed range, collision modes, categories of road user) within which a well defined amount of compatibility (for instance the level of 'acceptable' injury severity) has to be developed and agreed upon.

In such a system the passive safety of vulnerable road users is a logical component, though not making the final solution easier to reach. However, if only pedestrian safety is added to the current range of requirements most of the knowledge is already available to make passenger cars a great deal more 'friendly' towards pedestrians (and in most cases also bicyclists) in case of collisions, than they are now. The range of possible solutions is sufficient to satisfy the individual needs of manufacturers to maintain their own character in their designs. However on the other hand some pressure from governmental sides or even from society now seems needed to maintain the level of continuing improvements in this field that started so promising in the mid-seventies.

6. CONCLUSIONS AND RECOMMENDATIONS

General

In most European countries and in the USA the proportion of pedestrian fatalities due to collisions with motor vehicles ranges from about 15% to about 30% of the respective national traffic death toll. In most countries therefore the problem is attacked by both pre-crash (accident prevention) and crash (injury prevention) strategies. This literature review is concerned with the latter strategy without denying the validity of the first.

It has been noted that while governments and other national bodies such as national research institutes are in favour of strategies aiming at car redesign (crash strategies), the position of the European car industry has changed somewhat from more or less strongly in favour of crash improvement towards strongly in favour of pre-crash measures.

Both in the US and in Europe (EC) long-term research strategies strongly supported by governments have been followed aiming at legislation in the near future. This practically means that safety requirements will be established concerning the (sub system) testing of front ends of new cars with respect to collisions with pedestrians. The European situation seems to be nearer that ultimate goal than the American.

Effectiveness and cost

From the viewpoint of cost and effectiveness the final assessments cannot be made since almost no real world experience with pedestrian injury mitigating constructions exists and therefore could not be reported.
However, effectiveness estimates based on experimental designs combined with known figures of the population at risk and the cost of medical treatment of injuries as well as the societal costs of fatalities, injured and impaired, point to a positive balance between effectiveness and cost.

Recent estimates of effectiveness of the type of car redesign currently under study of EEVC and EC range from 5% to 10% less fatalities. There are also estimates of reductions regarding non-fatal injuries. Reduction of up to 30% of the number of seriously injured is thought possible.

Conflicting requirements

The fears of car manufacturers that occupant safety may be impaired by the new requirements on pedestrian safety are at least theoretically unfounded. Mass differences between cars and pedestrians as well as the possibilities to make far better use of available crush distances in both current and new car design guarantee that occupant safety will not be impaired.

One of the grounds for manufacturers opposed against the proposed new requirements is their concern that these may conflict with existing requirements. The most frequently found examples of this conflict focus on bumper regulations. These existing requirements aim at the reduction of damage and damage repair cost in minor (low speed) collisions. There is found evidence that it is indeed difficult to combine the two sets of regulations, especially when all detailed requirements of the current bumper regulations have to be met as well as future pedestrian requirements. Some compromise between the two sets of requirements could therefore be expected, probably resulting in the lowering of the level of damage protection of the current bumper requirements. There is also found ample evidence however that application of new materials, both lightweight aluminum and various other kinds of energy absorbing material will solve most of these problems, even without taking away the characteristics of individual car design. There is also found evidence that such new designs will improve the outcome of car to car collisions, especially in case of side impacts with regard to the overall damage.

Recommendations

The European situation differs from the American with respect to accident situation and vehicle characteristics, but the offer of the US to make use of their still growing experience, based on their ongoing pedestrian research programme, should be accepted.

It is recommended also that both research institutes and car manufacturers stimulated by their respective governments, preferably coordinated by existing international bodies (such as EC, EEVC, ESV), combine forces and pave the road for still further improvement of car design. Countries with car industry may also stimulate joint national projects combining efforts of both industry and research institutes, in order to achieve nationally set goals with regard to traffic casualty reduction.

This is also necessary in view of the still existing amount of crash-incompatibility between motor vehicles of the same type and between different types of road user.

To solve this overall incompatibility problem the approach will have to change from a redesign aiming at isolated incompatibility problems (such as the car-pedestrian problem; the car side collision problem; the car frontal collision problem; the car-heavy goods vehicle problem; etc) to a coordinated integral approach. It should be realized that incompatibility is always a two-sided problem. Solutions concerning only one of these sides (such as seems the case with side-impact redesign) might be sub-optimal. In case of the car-pedestrian problem the possibilities of changing the crash behaviour of the pedestrian seem minimal. Therefore car front end redesign, taking into account the human tolerance levels of the human body, is the only way available as far as crash measures are concerned. Some improvement of the safety of pedestrians may be expected of thicker clothing and head protection but these means might not be very popular, although application of the same type of solution for many different sports is normally accepted by all concerned.
This might mean that apart from redesign of the car front end some attention should be focussed on the (self) protection of pedestrians through other injury protection means.

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