PEDESTRIAN IMPACT PRIORITIES USING REAL-WORLD CRASH DATA AND HARM

Brian Fildes[1], Hampton Clay Gabler[2], Dietmar Otte[3], Astrid Linder[1] and Laurie Sparke[4]

[1]. Monash University Accident Research Centre, Victoria, Australia.
[2]. Rowan University, Glassboro, New Jersey, USA
[3]. Medical University Hannover Accident Research Unit, Hannover, Germany
[4]. Holden Innovation, Victoria, Australia

ABSTRACT

A study was undertaken to assess the crash types, behaviour and injuries associated with vehicle and pedestrian crashes and the priorities for vehicle design optimisation based on reduced societal Harm. Data from the Australian fatal file and the University of Hannover was analysed for the types of pedestrian crashes with cars, pre-crash pedestrian behaviours, injuries sustained and contact sources of these injuries. The Harm associated with these outcomes was then ranked to provide priorities for vehicle design aimed at increased pedestrian protection.

KEYWORDS – Pedestrians, Accident Analysis, Injury Severity, Optimization Methods, Vehicles, Injuries (Harm).

PEDESTRIAN CASUALTIES are relatively common and severe types of road crashes. Figures published in ETSC (1999) report the number of pedestrian deaths in 14-EU Countries in 1996 to be 16% overall but with some individual country rates as high as 28%. Fitzharris and Fildes (2002) reported that pedestrian impacts in Australia between 1994 and 1998 accounted for 18% of all crash-related fatalities and 12% of all serious injury casualties. Crandall et al (2002) reporting on more recent crashes claimed that vehicle and pedestrian collisions are responsible for more than one-third of all traffic-related deaths and injuries worldwide. Pedestrian crashes are more frequent in urban areas (OECD 1998) and commonly involve children and the elderly (Fildes et al, 1994, OECD 1998). The behavioural causes of pedestrian crashes are many and varied including speeding vehicles, risk taking, non-compliance with right-of-way, lack of information processing, alcohol, infrastructural problems and parked vehicles (OECD 1998). Limited cognitive processing abilities of the elderly have also been shown to contribute to the behavioural issues surrounding pedestrian crashes (Oxley 2000).

It has long been recognised that vehicle design plays a major role in determining the injury severity of pedestrian crashes with cars (World Health Organization 2004). EEVC (2002) noted that the most common forms of injury to pedestrians include head injury caused by the bonnet, and upper and lower leg injuries from contact with the front of the car, notably the bumper and leading edge of the bonnet. They note differences in injuries and injury severity by year of manufacture of the car and age of the pedestrian. EEVC (2002) cite an analysis by Foret-Bruno and Faverjon (1998) that proposed that auto manufacturers should focus on child and adult head injury and lower leg and knee injuries as priority issues for increased pedestrian protection in vehicle design.

Consequently, the EEVC Working Group 17 for pedestrian safety in Europe developed a component test procedure for specifying pedestrian protection levels for cars that requires compliance with a dynamic head, knee and lower leg test (EEVC 2002). The World Health Organization (2004) argued that if motor vehicles were required to pass these tests, the annual numbers of deaths and serious injuries to pedestrians in Europe would decline by around 20%. To date, though, this component test has not been mandated, instead relying on an agreement with the auto manufacturers in Europe to improve the pedestrian friendliness of their vehicles. EuroNCAP and Australian NCAP have adopted this test procedure, though, for use in their comparative performance tests of vehicle makes and models. They claim that only one vehicle model so far has met the 80% level of protection demanded. It is understood that the Europeans are considering introducing such a test soon.

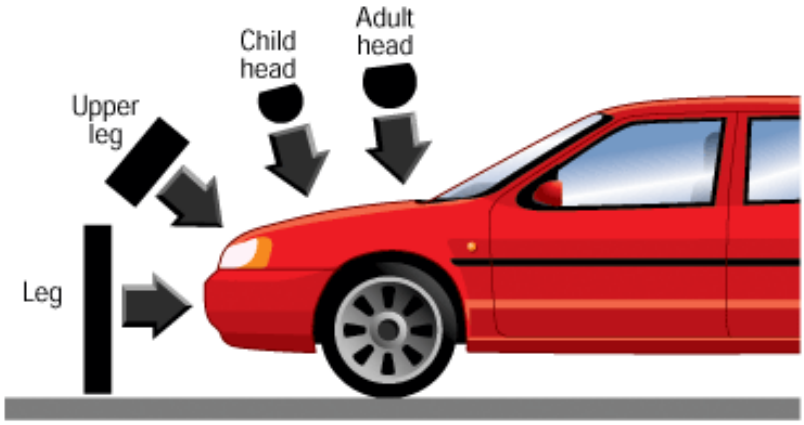

Figure 1: The EEVC test procedure diagram

There have been a number of concerns raised as to whether the EEVC procedure is a comprehensive test for all pedestrian crashes and whether it is likely to provide optimal pedestrian protection. Foret-Bruno and Faverjon (cited in EEVC 2002) questioned whether the EEVC test procedure would address a significant proportion of pedestrian injuries when impacted by a modern car and argued for further research studies to focus on these issues. There is, though, claims that the component test is able to replicate some real world injury patterns (Anderson et al, 2003) and leads to relevant design options (Edwards & Green, 1999; Kalliske & Friesen, 2001).

The Commission of the European Communities (EES 2003) have since pronounced a directive relating to the level of protection required for pedestrians and other vulnerable road users in the event of a collision with a motor vehicle (Directive 70/156/EEC). This directive which was to take effect from 1 January 2004 and specifies a number of modified tests and criteria, agreed to with the European, Japanese and Korean automobile manufacturers. These are different to those specified by EEVC Working Group 17 (EEVC 2002). What is required is a full detailed analysis of pedestrian crash types, the injuries sustained and contact sources to judge the suitability of these component test procedure.

Physical measures such as HIC have come under some criticism for use in assessing head injury reductions in pedestrian crashes. Authors such as Kleiven and Juntikka (2003) have noted HIC only addresses the resultant translational acceleration and duration of the impulse and that no consideration is given to the direction of the impulse or rotational acceleration components. They argued of the need for further safety developments in this area to be driven by more sensitive tools such as validated biomechanical computer programs involving FE models of the human head. Otte (1999) and Bosma et al (2001) also called for better methods of simulating pedestrian kinematics and injury mechanisms in pedestrian crashes through the use of computer modelling and optimisation procedures.

Harm and Pedestrian Crashes

Daniel (1982) reported on the role of the vehicle front end in pedestrian impacts with both adults and children for 1970s and earlier vehicles using data from the Pedestrian Injury Causation study and the Fatal Accident Reporting System in the USA. He undertook an analysis using "total societal cost or harm" measures, which is undefined. He reported that injuries to the head, chest, abdomen and legs contributed to the "societal cost of pedestrian accidents" and that adults, aged above 10 years, sustained over 70% of the Harm, even though children comprised 40% to 50% of the crash victims in his databases. He also noted that 48% of the Harm occurred in crashes 40km/h or lower. While these findings relate to a very old population of American-design vehicles (presumably mainly passenger cars), the analysis is very important in helping to determine priorities for the front-end design of cars to improve protection in pedestrian crashes.

Given the age and older design of the vehicles analysed by Daniel (1982), it was considered important to undertake a similar analysis of more recent European-design cars as part of an

international collaboration program aimed at improving car design[1], The study set out to determine the priorities for vehicle design in addressing the most frequent pedestrian injuries and Harm for adults and children. A detailed analysis was undertaken of in-depth crash data to identify priorities for improved pedestrian protection through vehicle design. A number of research questions were examined during the course of this analysis:

- Does the distribution of injuries and Harm differ between children and adults?
- What is the effect of impact speed on these distributions?
- How does Harm differ for low and high impact speeds?
- What are the sources of injuries and Harm to adult and child pedestrians?
- Do countermeasure priorities vary for child and adult pedestrians?

METHOD

A statistical analysis was undertaken of over 2100 pedestrian impacts involving both children and adults using real world crash data. A number of independent variables were examined including pedestrian age, gender, pre-impact movement, darting-out behaviour, impact speed, impact location on car, and injury severity. Dependent variables included injury frequency, severity and Harm (the latter defined as injury frequency by AIS by cost to society).

Two databases were used in this analysis. First, the fatal file in Australia 1997 to 1999 was used to describe the extent of fatal pedestrian injury occurring across all Australian states and territories. The Australian Transport Safety Bureau routinely collects these data from coroner's records across all states for all deaths occurring on Australian roads. The analysis focussed on years 1997 to 1999 and involved 838 fatally injured pedestrians. More than 95% of fatal pedestrian crashes were subjected to an autopsy.

Second, the in-depth database comprising 2134 cases of real world crash data collected by the Medical University of Hannover (MUH) from 1973 to 2000. It comprised a representative sample of in-depth crash investigations of pedestrian collisions with minor, severe and fatal injury severities that occur in the Lower Saxony region of Germany. While the majority of cases were older vehicles, there were still considerable numbers of cases involving post 1995 cars and vans (light trucks were excluded from the database). Among these data, there were no cases of MAIS 0 and 192 cases where the injured pedestrian sustained an MAIS 4+ injury. The Hannover dataset was partitioned into two sets; children defined as height ≤150cm (674 cases) and adults >150cm (1441 cases) and separate analyses were conducted on each of these datasets.

Harm & Injury Mitigation

Harm is a metric for quantifying injury costs from road trauma. It is a function of the number of injuries sustained, expressed in terms of community costs. The Harm method adopted here comprised the systematic approach outlined in detail in Monash University Accident Research Centre (1992).

This approach is more suited for use in computing likely benefits of countermeasures where there are no global estimates of the likely improvements but where there are results reported on the expected specific body region injury reductions. Many publications on the likely effectiveness of new regulations, for instance, show specific test results for particular body region and contact source benefits (eg; Fildes, Digges, Les and Tingvall, 2001). The method also allows one to identify priorities for optimising for vehicle design as reported in Fildes, Gabler, Fitzharris and Morris, 2000) based on the expected overall benefit from a series of individual body region and seating position estimates. A computer spreadsheet was developed for making the detailed Harm calculations by body region, similar to that used in the previous study (Fildes et al, 2000).

[1] This data analysis was conducted as part of the "Pedestrian Safety Research: A Collaborative Research Program" conducted at the Monash University Accident Research Centre, involving a partnership between MUARC, MH-Hannover (Germany), Rowan University (USA), Wayne State University (USA), INRETS (France), Chalmers University (Sweden), Toyota (Japan) and Holden (Australia).

RESULTS

Fatal File

The results of the analysis of the fatal file in Australia are shown in Table 1. The majority of pedestrian killed in the fatal file (96%) sustained at least one injury of AIS 4+ severity. Head and chest injuries alone of AIS 4+ severity accounted for 20% and 16% of fatal injuries respectively and 39% in combination. Major lower limb injuries by themselves were primarily judged as fatal in only 1% of cases and 7% in combination with head and thoracic injuries. Only 4.1% of those fatally injured sustained an MAIS <4.

Table 1: Distribution of AIS4+ injuries to different combinations of body regions of 839 fatally injured pedestrians in ATSB fatal file, 1997-1999.

Fatal injury	No.	%	Fatal Injury	No.	%
Head & chest	178	21%	Chest, abdomen & lower ext.	5	0.5%
Head	168	20%	Chest, abdomen & spine	4	0.5%
Head, chest & abdomen	77	9%	Abdomen & lower ext.	4	0.5%
Chest	73	9%	Head, chest, abd., spine & lower	4	0.5%
Chest & abdomen	44	5%	Spine	3	0.4%
Head, chest & spine	19	2%	Head, abdomen & spine	3	0.4%
Head & abdomen	17	2%	Head, chest, spine & lower ext.	2	0.2%
Head, chest, abdomen & spine	15	2%	Head, neck, chest & spine	1	0.1%
Chest & lower extremity	14	2%	Head & neck	1	0.1%
Head & spine	12	1%	Head, neck & chest	1	0.1%
Head, chest, abd. & lower ext.	9	1%	Head, neck, chest & abdomen	1	0.1%
Head, chest & lower ext.	9	1%	Head, abdomen & lower	1	0.1%
Head & lower ext.	9	1%	Chest, spine & lower ext.	1	0.1%
Abdomen	7	1%			
Chest & spine	7	1%	No AIS code	113	13%
Lower extremity	7	1%	No severe injury (AIS<4)	30	4%

MUH In-Depth Data

A number of findings of relevance for car design were identified from this analysis, shown in Figures 2 to 5. Most pedestrians in the dataset suffered MAIS 0 or 1 injuries. Head and face regions accounted for a sizeable proportion of serious injuries comprising 29% to children and 28% to adults, while lower leg and foot injuries were particularly noteworthy for children (35% c.f. 13%). Thoracic injury accounted for 26% of adult and 19% of children's injuries. Pedestrian injuries were most commonly associated with contact with the front of the car (roughly equal between left, front and right side of the vehicle) and two-thirds from impacts over 40km/h (not shown). As shown in Figure 5, more than half of child contacts occurred from darting out behaviour, most noticeable from behind parked cars, important for showing the majority type of child impacts from real world data and the implications for vehicle design.

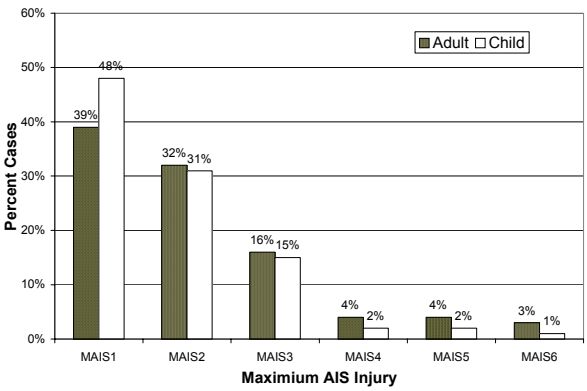

Fig 2: MAIS Injuries by pedestrian age

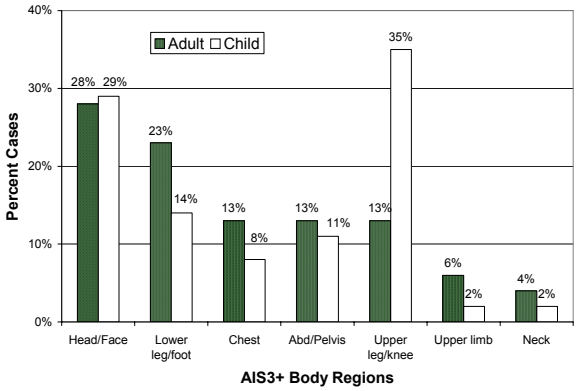

Fig 3: AIS3+ injuries by pedestrian age

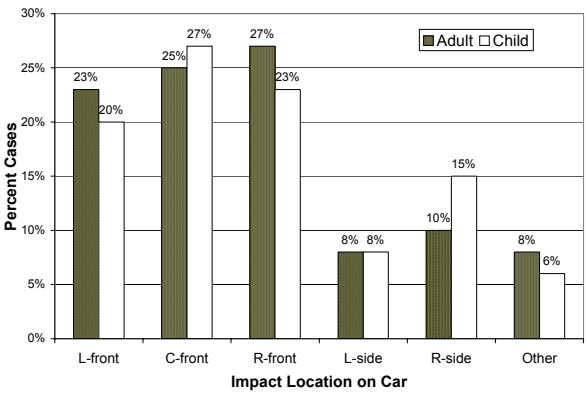

Fig 4: Impact location by pedestrian age

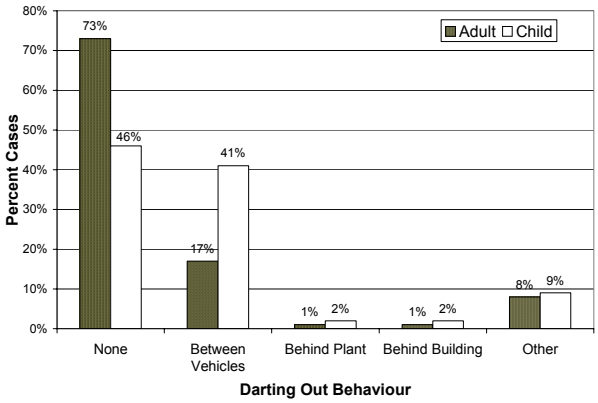

Fig 5: Darting Out by pedestrian age

The Effect of Impact Severity

Figures 6 shows the effect of impact severity by crash speed for all pedestrians where 70% of the crashes occurred below 40km/h, while two-thirds of the Harm occurred for the 30% of cases above 40km/h. The probability of a fatality in Figure 7 rises dramatically for impact severities above 40km/h.

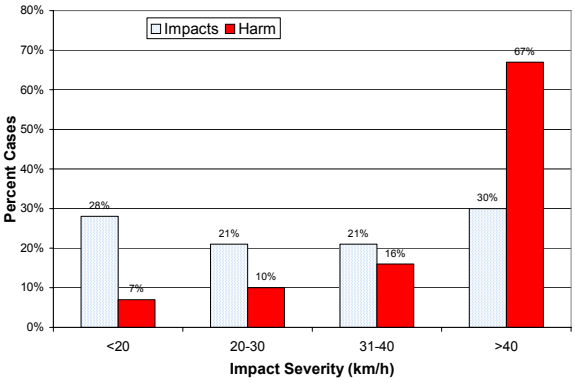

Fig 6: Cases and Harm by crash severity

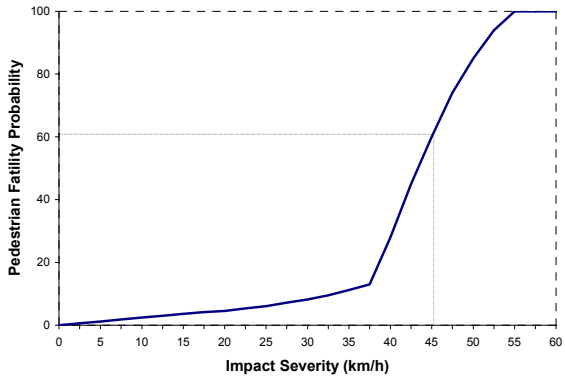

Fig 7: Fatality probability by impact severity

Figures 8 and 9 show the disproportionate amount of Harm associated with head and neck injuries in high-speed pedestrian impacts. Severe lower limb injuries were relatively frequent and harmful in low-speed crashes; they are substantially less of concern in higher impact severities. Thoracic injuries (chest and abdominal/pelvic) injuries and Harm accounted for up to 36% of serious injuries and around 20% of Harm in these data.

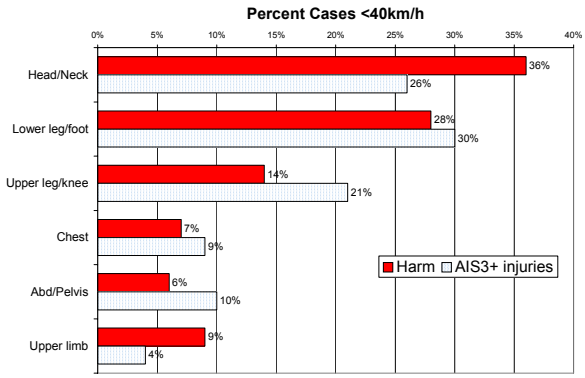

Fig 8: Serious Injuries and Harm for impacts <40km/h

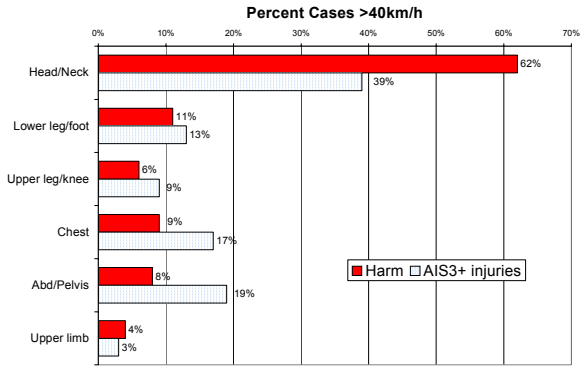

Fig 9: Serious Injuries and Harm for impacts >40km/h

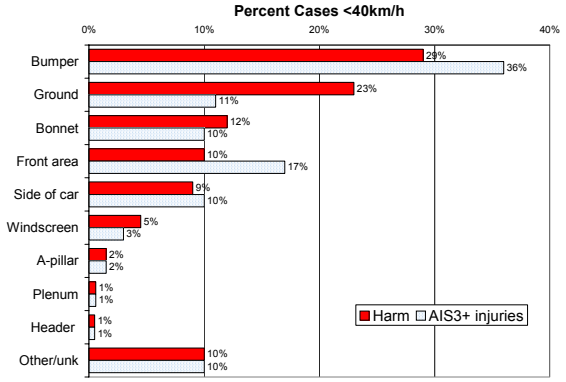

Fig 10: Contacts for impacts <40km/h

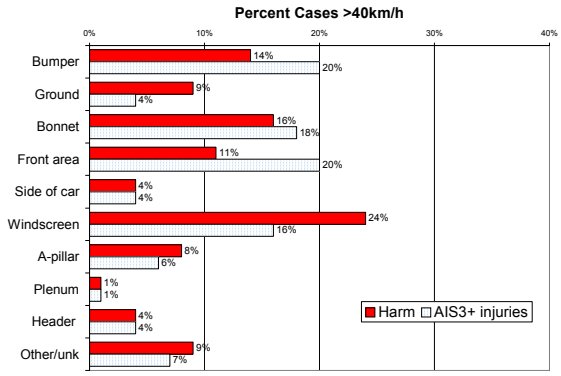

Fig 11: Contacts for impacts >40km/h

The percent of Harm and AIS3+ injuries by contact source and impact severity are shown in Figures 10 and 11. Front area refers to the grille, lights, and leading edge of the bonnet, ground means all injury-causing parts of the road, windscreen is the glass plane, roof and bottom frames, and the A-pillar is separated if there is no contact with the glass windscreen. For low-speed crashes, two-thirds of the serious injuries and half the Harm occurred from contact with the front of the car. The ground was involved in 11percent of severe injuries but one-quarter of the Harm. In higher speed crashes above 40km/h, the windscreen and A-pillar areas featured more highly in both frequency and Harm from the resultant occupant trajectory further towards the passenger compartment. Ground contacts were less frequent and associated with less pedestrian Harm.

Countermeasure Priorities for Children and Adults

The final four figures (12 to 15) show the priorities for reducing Harm for adults and children in pedestrian crashes as well as the top 10-body region and contact source combinations for both adults and children.

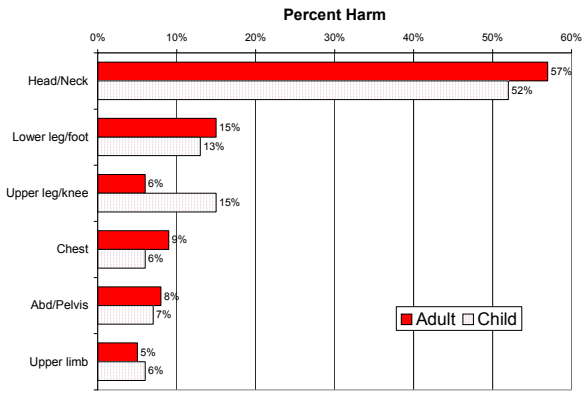

Fig 12: Harm priorities – adults and children

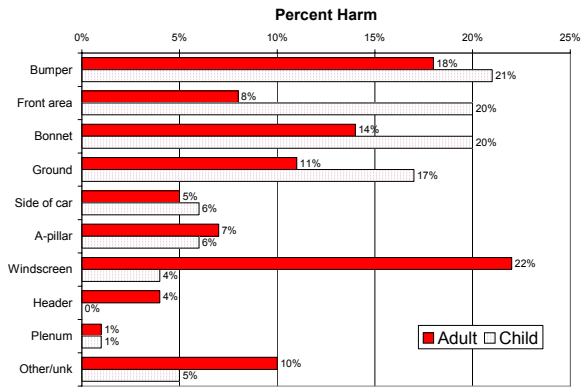

Fig 13: Harm contacts – adults and children

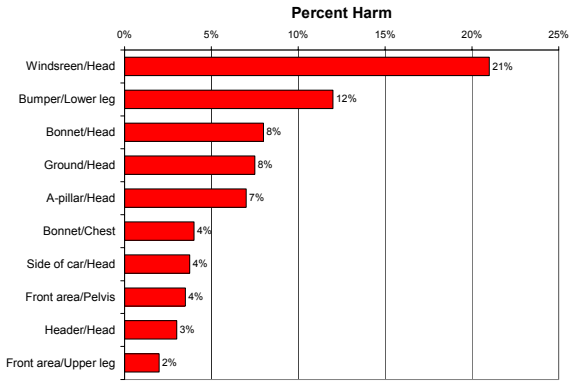

Fig 14: Top 10 priorities – Adults

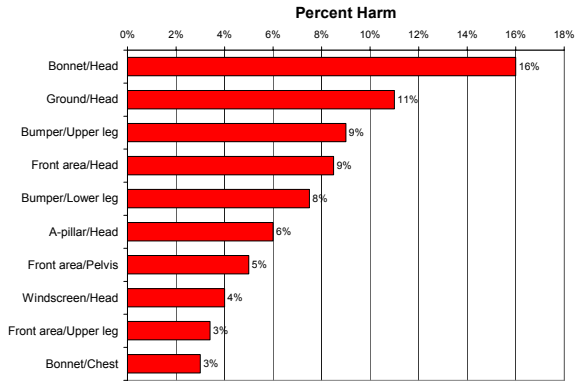

Fig 15: Top 10 priorities - Children

Head injury Harm clearly predominates over all other body region Harm among both adult and child pedestrians in these data. The most frequent sources of serious injury for adults included the windscreen, the bumper, the bonnet and the ground, while for children, the bumper, front area, the bonnet and the ground predominated. The top-10 body region and contact source priorities varied between adults and children, but commonly involved bonnet/head, ground/head, windscreen/head, bumper/lower leg and A-pillar/head combinations. The top-10 priority body region by contact source combinations for both adults and children captured over 70 percent of the total Harm for both these pedestrian groups.

DISCUSSION

Pedestrian impacts account for a sizeable amount of occupant Harm in most developed countries and an even greater amount in developing countries. The collaborative pedestrian research program at the Monash University Accident Research Centre, involving a number of partners from Europe, USA and Australia, attempts to identify priority impact types and solutions for use in car design based on real-world collisions. The data analysis is a first step in the program towards optimal car design solutions to minimise pedestrian Harm.

From the analysis of the fatal file in Australia, half of all pedestrian deaths were from AIS4+ injuries to the head, chest or in combination. Somewhat surprising was the proportion of pedestrian fatalities (17%) that involved a torso (chest, spine and abdomen) injury alone. For the most part, initiatives to reduce injuries among pedestrians have overlooked this body region, preferring to concentrate on the head and lower extremities. Clearly, the current focus on the head and lower extremities is important based on the analyses reported here but at the same time, the apparent disregard for serious torso injuries in these solutions needs to be addressed. This may be particularly true among young children and in SUV vehicles where the chest and abdomen are more likely to receive a primary strike in a pedestrian collision. The analysis of the substantial in-depth database at the Medical School of the University of Hannover set out to examine a number of research questions outlined earlier in the paper. The findings from this analysis will discuss each of these separately.

Adult and Child Pedestrian Injuries & Harm

Of some solace was the fact that 71% of adult injuries and 80% of child injuries were MAIS 2 or less among these real world cases. Serious head injuries did feature highly, however, among those sustaining a severe injury for both adults and child pedestrians and severe upper legs and knee injuries to children. The chest and abdomen, and the lower leg and foot, were severely injured in around one-quarter of those sustaining an AIS3+ injury. Compared with the findings of Daniel (1982), there were similar proportions of head Harm but considerably more lower extremity Harm in the data used in this analysis, compared to the earlier USA data. This could reflect differences in vehicle design between the older US population and more recent European cars or may indicate differences in the Harm measures used (Daniel 1982, did not explain what comprised his total societal cost metric). Nevertheless, the significant proportion of Harm to the head and neck regions (almost 40% in both studies) confirm the need to provide better head protection in front-end vehicle designs. The implication for lower limb injury though is less clear from these two studies.

Clearly, adults and children experience different injury patterns in pedestrian crashes in both this study and that reported by Daniel (1982) and this need to be taken into account in vehicle design. The smaller stature of children means that they are likely to be more exposed to the front components of the vehicle and their impact trajectories are probably quite different to adults. While not plotted here, children and older adults were over-represented in pedestrian crashes among these cases when controlling for exposure, a finding that has been previously reported (Fildes et al, 2001).

Influence of Impact Severity

Impact severity has a significant influence on the outcome to both children and adults in a pedestrian crash (Daniel, 1982; and Otte & Pohlemann, 1998 presented similar results). Data presented here showed a rapid increase in the likelihood of a fatality for impacts above 35 to 40km/h with a 100% probability above 55km/h. In addition, for all age groups, 70% of impacts were less than 40km/h and they accounted for one-third of the total Harm, while the 30% of impacts above 40km/h attracted two-thirds of the pedestrian Harm. Lower limb injuries were more predominant at lower

speed impacts while head and neck injuries, especially among adults, increased considerably at impact severities above 40km/h.

Impact severity also interacted with the type of injury or level of Harm as well as the source of these injuries, discussed further below. Well-targeted vehicle design initiatives offer promise to reduce Harm in pedestrian crashes, through improved design of the front of the vehicle and should be a priority for automobile manufacturers. However, it is also clear that there will be limits to what these improvements can deliver. High-speed impacts apply a level of violence to vulnerable pedestrians that is biomechanically unsustainable and therefore additional traffic control measures to reduce travel speed are also important in high pedestrian areas.

Adult and Child Harm Sources

The source of injury to both adults and children is important when considering how to improve vehicle design to reduce pedestrian injuries. The data analysed here showed different contact sources for pedestrian Harm for both children and adults and low and high speed collisions. At low speeds (<40km/h), the bumper, the bonnet, the front and the side of the car were major sources of injuries and Harm, whereas at higher impact speeds, the windscreen and its surround and the A-pillar also featured more highly. The windscreen, in particular, accounted for around one-quarter of all Harm in impact severities above 40km/h.

Children seemed more vulnerable to injury and Harm from contact with the bumper, front area and bonnet (not to forget the ground). These results were similar to those reported by Daniel (1982). For adults, the windscreen, bumper and bonnet were major sources of injury and Harm. The side of the car has been overlooked in the EEVC component test procedure, yet this source was involved in up to 10% of injuries and Harm especially in low severity impacts. This needs to be re-examined to ensure more forgiving structures in these regions.

Interestingly, the ground was associated with 23% of all Harm in low speed crashes and about 10% of all Harm in high-speed impacts (Daniel reported 15% of Harm from the road for all severities). The efficacy of restraining the struck pedestrian on the bonnet area of the car might be worth further examination in reducing Harm in pedestrian crashes. One possibility might be to simply change the pedestrian's trajectory to reduce the probability of the pedestrian "bouncing-off" the front of the car and then impacting the ground.

Impact Location and Pre-Crash Behaviour

Impact location for these pedestrian crashes showed some interesting findings. Across the front of the car, the impact zone was approximately equally distributed across the centre of the bonnet and the left- and right-side front areas. In around 18% of adult and 23% of child impacts, the initial impact point was to the left- or right-side of the car, not the front. This illustrates the importance of not disregarding the side wings in designing for improved protection as well as questioning the logic of a regulation test dictated by a single impact to the centre-front of the vehicle.

The pre-crash behaviour of the pedestrian also adds some further insights into these collisions. Darting out from behind a vehicle, plant or building was noted in over half of child and one-quarter of adult pedestrian impacts. As these were all left-hand drive vehicles, it would be expected that most dart-out collisions would impact the right side of the car (from the near curb side of the road). While not shown here, right-side impacts indeed did feature in around 50% of these crashes, although interestingly, 40% impacted the left side of the car. Thus, it is dangerous to assume too much from these findings.

Countermeasure Priorities

The Harm and injury findings show that vehicle design countermeasure priorities do differ between adult and child pedestrian crashes. The top-10 body region/contact source analysis revealed a stronger focus on the bumper, front and immediate bonnet region of the car for children and the windscreen, its surround, the A-pillar and the rear bonnet regions for adults. Holding et al (2001) proposed a pre-sensing airbag to mitigate against pedestrian injuries while Fredriksson et al (2001) proposed a bonnet lift from the rear after a leg-to-bonnet impact. The side wings of the car, especially when struck from the front edges and from the sides should also be target areas for improvement, although this seems to have generally been overlooked in discussions of likely countermeasures.

Addressing these regions would take into account up to 75% of pedestrian Harm involving severe injuries to the head and lower limbs. However, up to 15% of this Harm does involve the thorax, which is a life-threatening injury to some people, particularly the aged, and should not be overlooked.

It should be noted that the outcome and consequence of injury differs markedly between young and older pedestrians. Moreover, older people have been shown to be over-involved in serious pedestrian crashes in a number of international studies (Oxley & Fildes, 1999; Henary et al, 2003). Thus, there is a case for ensuring that any impact with a pedestrian occurs at much slower speeds. McLean et al (1994) and Yang et al (2001) argued that reducing travel speeds by as little as 5km/h would have a significant impact on both the number of pedestrian crashes and their severity in high pedestrian areas. Levy et al (1998) further reported that the introduction of pedestrian safety zones had a significant influence on reducing pedestrian injuries in defined zones. While not necessarily related to vehicle design, there is a case for improved traffic engineering and management strategies to also reduce pedestrian impact Harm.

Limitations of this Study

Extensive in-depth pedestrian crash databases are not freely available for conducting analyses such as these. It is necessary, therefore, to assume that these results are indicative of pedestrian crashes that occur in other western countries around the world. These data were collected over a period of 27 years during which time there have been significant changes in vehicle design. It would have been desirable therefore to have only looked at pedestrian crashes involving post-1995 or 1997 vehicles but this would have reduced the size of database considerably. Thus, the applicability of these findings to modern vehicles remains somewhat questionable. A repeat of this analysis using recent vehicles only, is clearly warranted when sufficient data are available to conduct this analysis.

Finally, the societal injury costs used in the Harm analysis were based on a combination of USA and Australian human capital estimates, which are traditionally, lower than alternative Willingness-To-Pay figures. Future investigation should examine a range of different cost information form other countries like Germany and UK.

Vehicle Dependence

As noted in the method section, the real world pedestrian findings collected by the Medical University of Hannover have focussed on car and van collisions only and have not addressed injuries from light trucks, such as Volkswagen T5, etc. This is more typical of Europe than North American fleets, presumably behind some of the differences reported earlier by Daniel (1982). There is no doubt that the injury and contact patterns observed in these data may not typically represent countries with a higher proportion of SUV vehicles. Indeed, studies by Liu (2001) illustrate the different injury consequences for high front vehicles such as SUVs. These effects need to be taken into account by vehicle designers when addressing improved pedestrian protection.

Future Research

As noted earlier, this analysis was the first stage in an international collaborative research program and intended to provide direction for future research aimed at improving pedestrian protection in optimising vehicle design. Future research effort will be directed towards validating existing computer models and undertaking relevant crash tests as required to further enhance pedestrian protection. It is expected that these data and procedures will be made available for all vehicle manufacturers to use in their on-going attempts to reduce pedestrian Harm from vehicle impacts.

CONCLUSIONS

This analysis was undertaken to provide direction for optimising vehicle design for pedestrian protection based on a minimal Harm outcome and a number of important findings are apparent from these data and subsequent discussion.

- The analyses of Harm by body region and contact source show the importance of focussing attention on various vehicle collisions, components and structures to provide maximum benefits.
- As 70% of the Harm occurred at impact speeds below 40km/h with a high likelihood of survival, it would seem important to address these injuries as a matter of high priority.

- The focus should be on preventing or mitigating head, leg and chest and abdominal injuries from contacts with the bumper, bonnet, front regions and side wings.
- The windscreen and surrounds and the A-pillar are more of a priority for high-speed impacts.
- Improved methods of capturing the pedestrian and mitigating contacts with the ground would seem to be warranted, given the high number of these high severity contacts, especially at lower speeds.
- In addition to vehicle design improvements, traffic engineering and management initiatives such as reduced travel speed are also important for minimising crash opportunities and impact severity.

These data provide a sound basis for modelling pedestrian impacts and optimising vehicle design improvements to ensure minimal Harm outcomes and to provide additional insights for pedestrian impact regulation.

Acknowledgments

The authors acknowledge the co-operation and contribution to the study from all the partners in the Collaborative Pedestrian Research Program, namely members of the Medical University of Hannover, Alana DeSimone, Mechanical Engineering at Rowan University, New Jersey, Professor King Yang, Wayne State University, Detroit, Dr. Dominique Cesari, INRETS in France, Dr. Jikuang Yang and Dr. Rikard Fredriksson, Chalmers University in Sweden, Dr. Miki Kazuo, Toyota Japan, and staff at Holden Innovation and the Monash University Accident Research Centre in Australia.

REFERENCES

Anderson R, McLean AJ, Streeter L, Ponte G, Sommariva M, Lindsay T & Wundersitz L (2003). Severity and type of pedestrian injuries related to vehicle impact locations and results of sub-system impact reconstructions, Proc. IRCOBI conference, Lisbon, Portugal.

Bosma F, Gaalman H & Souren W. (2001). Closure and trim design for pedestrian impact, Enhanced Safety of Vehicles conference, Amsterdam, The Netherlands.

Crandall JR, Bhalla KS & Madely J (2002). Designing road vehicles for pedestrian protection, **Brit. Med. Journal, 324:** 1145-1148.

Edwards KJ & Green JF. (1999). Analysis of the inter-relationship of pedestrian leg and pelvis injuries, Proc. IRCOBI conference, Sitges, Spain.

EEVC (1998). **Safety of Vulnerable Road Users**, Scientific Expert Group on the Safety of Vulnerable Road Users (RS7), Doc. 68074, Organisation for Economic Co-operation and Development, www.oecd.org/dataoecd/24/4/2103492

EEVC (2002). Improved Test Methods to Evaluate Pedestrian Protection Afforded by Passenger Cars, EEVC Working Group 17 Report, European Enhanced Vehicle-Safety Committee, Brussels, www.eevc.org

EES (2003). Directive of the European Parliament and of the Council relating to the protection of pedestriansand other vulnerable road users in the event of a collision with a motor vehicle, Directive 70/156/EEC, Brussels, http://europa.eu.int/documents/comm/index_en.htm

ETSC (1999). **Safety of Pedestrians and Cyclists in Urban Areas**, Report, ISBN 09-76024-08-1, European Transport Safety Council, Brussels, www.etsc.be/rep.htm

Fildes BN, Corben B, Kent S, Oxlet JA, Le T & Ryan P (1994). **Older Road User Crashes**, Research Report No. 61, Monash University Accident Research Centre, Clayton, Australia.

Fildes BF, Gabler HC, Fitzharris M & Morris AP. (2000). Determining side impact priorities using real-world crash data and Harm, Proc. IRCOBI conference, Montpellier, France.

Fildes BN, Digges K, Les M & Tingvall C. (2001). Benefits of a 64km/h offset crash test in Australia, Proc. IRCOBI conference, Isle of Man.

Fitzharris M & Fildes BN (2002). An analysis of pedestrian crashes in Australia, Occasional Report, Monash University Accident Research Centre, Clayton, Australia (in press).

Fredriksson R, Håland Y & Yang J. (2001). Evaluation of a new pedestrian head injury protection system with a sensor in the bumper and lifting of the bonnet's rear part, Enhanced Safety of Vehicles conference, Amsterdam, The Netherlands.

Henary B, Crandall J, Bhalla K, Mock N & Roudsari B. (2003). Child and adult pedestrian impact: the influence of vehicle type on injury severity, Proc. AAAM conference, Lisbon, Portugal.

Holding P, Chinn B & Happian-Smith J. (2001). Pedestrian protection – an evaluation of an airbag system through modelling and testing, Proc. Enhanced Safety of Vehicles conference, Amsterdam, The Netherlands.

Kalliske I & Friesen F. (2001). Improvements to pedestrian protection as exemplified on a standard-sized car, Proc. Enhanced Safety of Vehicles conference, Amsterdam, The Netherlands.

Kleiven S & Juntikka R. (2003). Optimization of single skin surfaces for head injury prevention – a comparison of optima calculated for global versus local injury thresholds, Proc. AAAM conference, Lisbon, Portugal.

Kramlich T, Langwieder K, Lang D & Wolfram H. (2001). Accident characteristics in car-to-pedestrian impacts, Proc. AAAM conference, Lisbon, Portugal.

Levy M, Vegega M, Cleven A & Blomberg R. (1998). Field test of a pedestrian safety zone program for older pedestrians, Proc. AAAM conference, Charlottesville, VA.

Liu X. (2001). Car-to-pedestrian collisions: effects of vehicle front structure on injury risks and development of child mathematical models, PhD Thesis, Chalmers University, Sweden.

McLean AJ, Anderson R, Farmer M, Lee B & Brooks C. (1994). Vehicle travel speeds and the influence of fatal pedestrian collisions, Paper presented at the 1994 Road Safety Research & Enforcement conference, Melbourne, Australia.

Monash University Accident Research Centre (1992). **Feasibility of Occupant Protection Measures**, Report CR100, Federal Office of Road Safety (now Australian Transport Safety Bureau), Department of Transport and Regional Services, Canberra, Australia.

Otte, D. & Pohlemann, T. (1998): Analysis and load assessment of secondary impact on the road for grown-up pedestrians after car collisions, Proc. IRCOBI, Isle of Man, UK

Otte D. (1999). Severity and mechanism of head impacts in car-to-pedestrian accidents, Proc. IRCOBI conference, Sitges, Spain.

Oxley JA (2000). **Age Differences in Road Crossing Behaviour**, Unpublished PhD Thesis, Monash University Accident Research Centre, Clayton, Australia.

Teresiński G & Madro R. (2003). A comparison of mechanisms of ankle, knee, pelvis and neck injuries in pedestrian and cyclists according to the direction of impact and type of vehicle, Proc. AAAM conference, Lisbon, Portugal.

World Health Organisation (2004). **World Report on Road Traffic Injury Prevention**, ISBN 92 4 156260 9, World Health Organisation, Geneva, www.who.int/features/2004/road_safety/en/

Yang J. Liu X. Lővsund P, Tingvall C, Lie A, Larsson P & Lekander T. (2001). Speed limit in the city area and improvement of vehicle front design for pedestrian impact protection – computer simulation study, Proc. AAAM conference, Lisbon, Portugal.