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ROAD SAFETY POLICY PAPER

PEDESTRIAN CRASH RISK AND INJURY OUTCOMES AND THEIR RELATIONSHIP WITH VEHICLE DESIGN

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PEDESTRIAN CRASH RISK AND INJURY OUTCOMES AND THEIR RELATIONSHIP WITH VEHICLE DESIGN

1.0 Background

There is now a significant body of research that can inform government and motoring club policy development and advocacy on pedestrian crash risk and injury outcomes and their relationship with vehicle design. This document aims to synthesise the range of research outputs into a cohesive and comprehensive message, taking into account all available research knowledge through a review of past VSRG research outcomes as well as other research published internationally in the context of the local research and associated issues. This document is available as a ready and concise reference on the current state of research knowledge and provides an interpretation of the research evidence and the implications the research may have on road safety policy and strategy development in the area of safer vehicles, so that government agencies and motoring clubs may respond in a rapid and informed way to requests from within agency, from government and from the public.

Scope

This document focuses on the effects of vehicle design on pedestrian outcome. The main factors associated with the type and severity of pedestrian injury also include crash (e.g. impact speed, angle, etc.) and pedestrian (e.g. age, height and weight) factors. Pedestrian and crash factors which interact with vehicle design in determining injury outcome are discussed in this document. Environmental and behavioural effects on pedestrian injury outcome, which are largely independent of vehicle design, are not within the scope of this document. In addition this document does not discuss the causes of pedestrian crashes. Influencing factors have been identified using real word data and crash test simulations. Details of the main datasets used in these studies are presented in the appendices.

Unless otherwise stated:

- injuries and fatalities are solely referring to pedestrian injuries and fatalities produced by vehicle-pedestrian collisions,
- bonnet and hood are interchangeable words describing the same vehicle body part ,
- windshield and windscreen are interchangeable words describing the same vehicle body part, and
- confidence intervals for estimates obtained from (logistic) regression refer to 95% confidence intervals.

The document begins with the current trends in Australia and New Zealand for vehicle market groups, pedestrian crashes and severity of those crashes and follows with the types of injuries produced from pedestrian crashes with a focus on the injury differences by vehicle type. It then synthesises this information with the current knowledge on pedestrian protection within vehicles and the associated limitations imposed by vehicle safety technology, level of development and vehicle design.

Definitions

50th percentile male	Average male, 50% of the male population is smaller
A-pillar	The most forward car structure joining bonnet/fender area and the roof. Also the side member of the windshield frame/
Abbreviated Injury Scale	Single injury tanking with a scale of 1 to 6 representing 'threat to life' associated with a traumatic injury. 1= minor, 2=moderate, 3=serious, 4=severe, 5=critical, 6=unsurvivable (see appendix)
Primary safety	Pre-crash or active safety
Secondary Safety	In-crash or passive safety
Wrap around distance	Measured from the ground surface up around the car contour to a selected point

2.0 Pedestrian Crash Rates in Australia and New Zealand

In 2012, pedestrian fatalities accounted for 13% of Australian and 11% of New Zealand road fatalities; both are lower than the global figure of around 19% (ITF 2014). Australian pedestrian fatalities are declining (Table 1); from 1990, the decline has been at a greater rate than for vehicle occupancy fatalities (63% c.f. 51% for Australia), most likely due to vehicle fleet increasing at a greater rate than the pedestrian population (ibid). However, amongst older Australians and New Zealanders, pedestrian fatalities pose a particular risk. Population adjusted pedestrian fatalities were distributed at frequencies of more than double most other age grouping (0-14, 15-24 and 25-64) for pedestrians 65 and over in 2011/2012 (**Figure 1**).

Table 1 : Road fatalities by road user group (ITF 2014)

						2013Percent change from	
Australia	1990	2000	2010	2012†	2013‡	2012†	2000
Pedestrians	420	287	170	169	157	-7.1	-45.3
%	18	16	13	13	13		
Total	2,331	1,817	1,353	1,299	1,196	7.9	-34.2
New Zealand							
Pedestrians	104	35	35	31	33	6.5	-5.7
%	14	8	9	11	11		
Total	729	462	375	284	308	8.5	-33.3

†2011 NZ, ‡2012 NZ

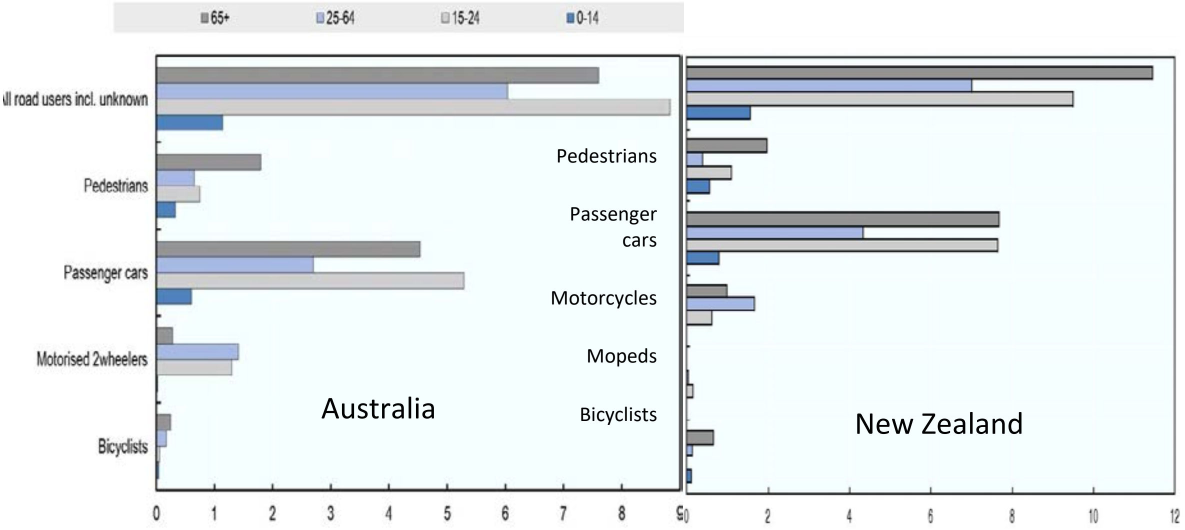


Figure 1

Road death rate by age and road user group fatalities per 100,000 population, Austrlia 2012 New Zealand 2011 (2014)

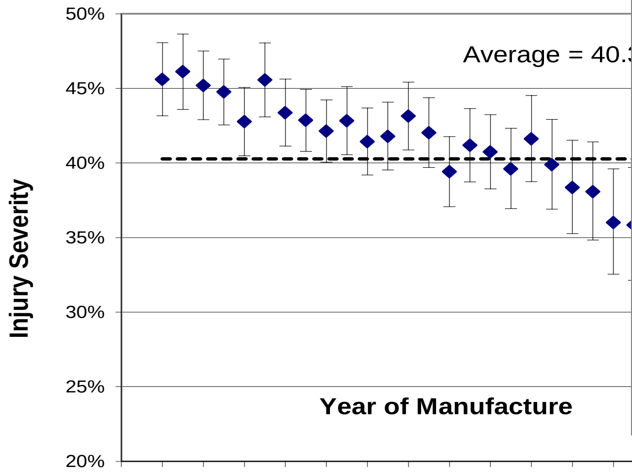
In 1993, 12% of road crash hospital admissions were pedestrians (Cairney 2000). Increased crash risk was observed in Australia if the pedestrian is male, intoxicated, elderly or a child (ibid).

Cariney (2000) described trends in pedestrian crash types in Australian jurisdictions. The most frequently observed pedestrian crash type (>40%) was observed to be a near side vehicle hit from the right. Furthermore about a third of pedestrian crashes were reported as 'far side- hit from left'. 7-14% of pedestrian crashes occurred when the pedestrian emerged from behind a vehicle. In rural areas, there are fewer of these types and more of the 'walking with/against traffic' types. At least a third occurred at intersections across the jurisdictions and over 90% occurred in urban areas. It was of interest that 7% of pedestrian crashes involved reversing vehicles. Reversing vehicles are typical of low speed run-over types of crashes.

Low speed vehicle run-over (LSVRO) crashes represent a unique pedestrian injury type in Australia. An average of 7 child fatalities and 60 seriously injured children per year were produced over 2001-2010 (BITRE 2012), predominantly: in rural areas, involving parent drivers, reversing movements, head injuries, SUVs and children who are male and under 2. They are probably under-reported in Australia given the difficulties in defining, identifying and coding these crash types. They may occur in a traffic or non-traffic area. Although infrequent compared with other pedestrian mortalities, they were considered in 1996 to represent the largest cause of death after pool drowning for children aged 1-4 (Griffin, Watt et al. 2011).

3.0 Pedestrian Crash Severity in Australia and New Zealand

Keall et al (2012) characterised the probability of fatal or serious injury given an injury from a vehicle-pedestrian collision for the Australian and New Zealand passenger vehicle fleet over 1982 to 2010. The following three figures display the overall, and by market group, decreasing trends.



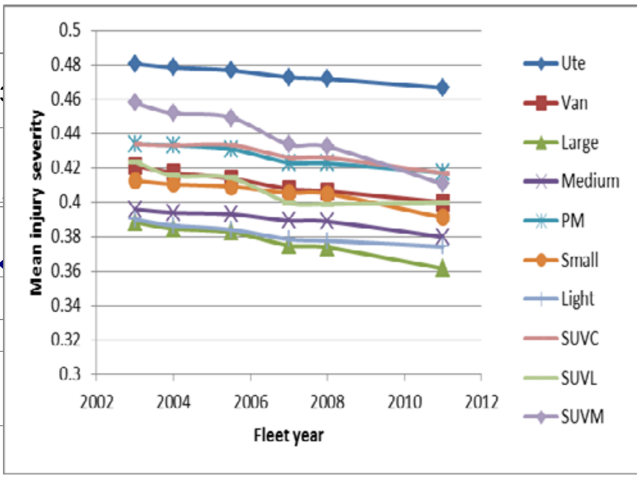


Figure 2

ANZ Pedestrian injury severity rating (probability of fatal or serious injury given an injury occurred) by year of manufacture of vehicles 1982 to 2010 with 95% confidence intervals (Keall, D'Elia et al. 2012)

Figure 3

NZ Pedestrian injury severity rating (probability of fatal or serious injury given an injury occurred) by market group of vehicle and fleet year (Keall, D'Elia et al. 2012)

Utilities and medium SUVs were the vehicle market group with the highest risk of severe pedestrian injuries in both countries.

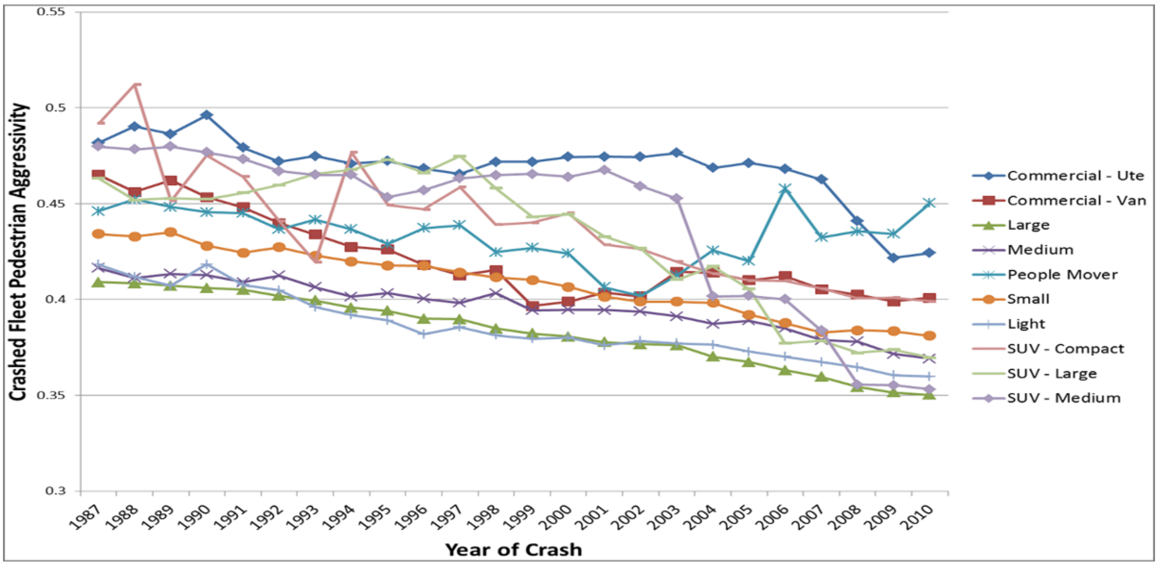


Figure 4

Average Australian fleet aggressivity by market group and year of crash 1987-2010 (Keall, D'Elia et al. 2012)

4.0 Market group composition of the Australian and New Zealand Registered Fleet

Keall et al. (2012) also presented current, past and projected market group distributions of passenger vehicles for Australia and New Zealand. The trend of growing market sectors of flatter fronted and more pedestrian aggressive vehicles (SUVs and commercials) is highlighted in **Figure 5** and in **Figure 6**.

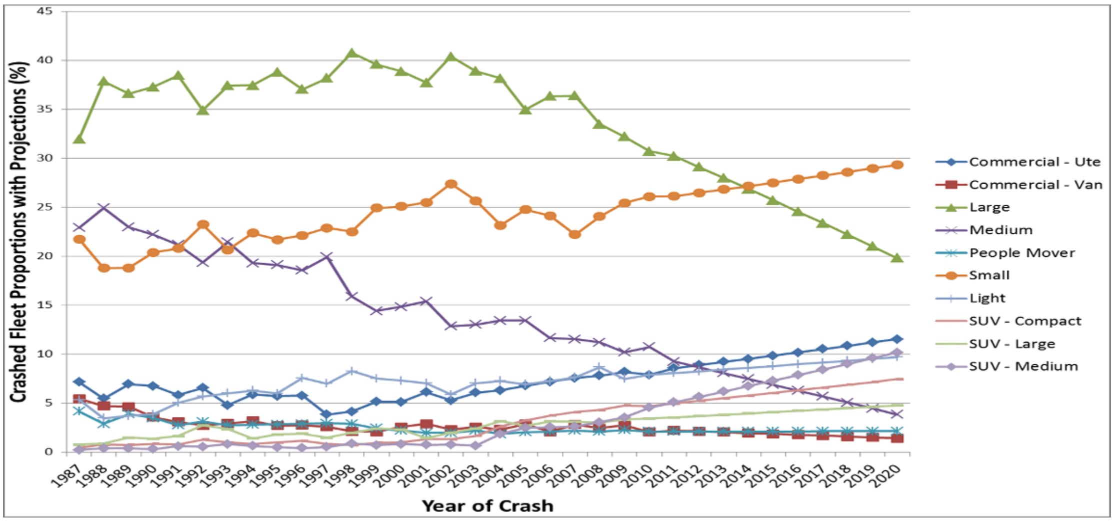


Figure 5

Australian fleet composition by market group including forecasts 1987-2020 (Keall, D'Elia et al. 2012)

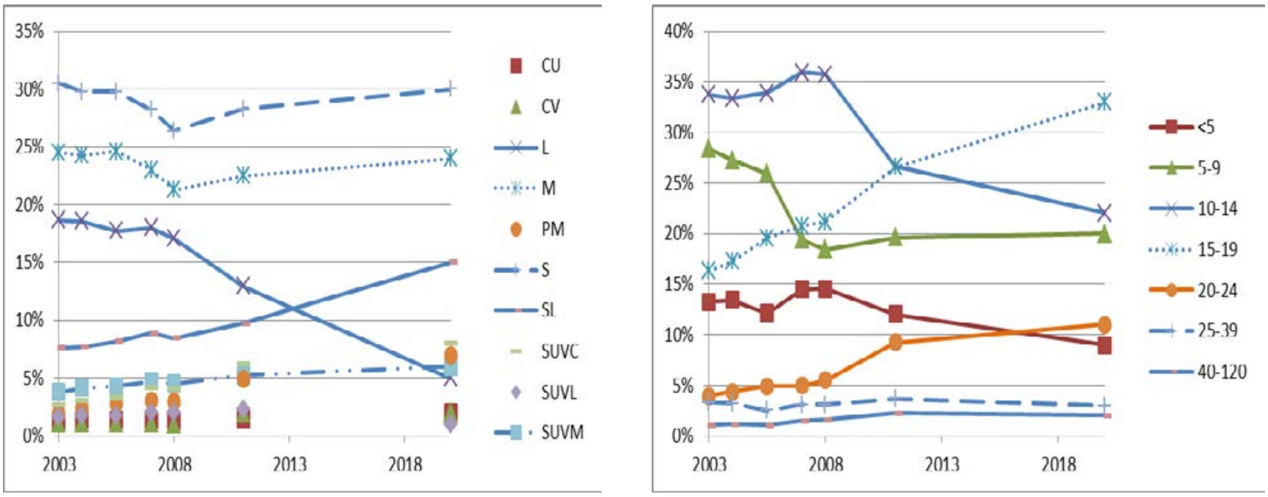


Figure 6
Composition of NZ fleet by Market group, with projected potential "business as usual" composition in the year 2020 (Keall, D'Elia et al. 2012)

Figure 7
Composition of NZ fleet by vehicle age, with projected potential "business as usual" composition in the year 2020 (Keall, D'Elia et al. 2012)

Vehicles over 20 years old present a very different vehicle profile in terms of stiffness, geometry and mass (**Figure 7**). The New Zealand fleet (current and projected into the future) has and will continue to have significant proportions of these older vehicles. The follow on effect is that the counter measures addressing current vehicle geometry will have a reduced impact on New Zealand pedestrian fatalities.

5.0 Typical pedestrian Injuries

5.1 Effect of Pedestrian

Impact with the vehicle is the main contributor to pedestrian serious injuries; the ground causes less than 20% of serious injuries (Zhang, Cao et al. 2008, Fredriksson, Rosén et al. 2010). However, another study found 43% of the most serious injuries could be ascribed to secondary ground impact (Neal-Sturgess, Carter et al. 2007). Impact with the vehicle is usually with the pedestrian presented side-on, whether injuries are fatal or not: 72-89% of pedestrians have been found to be struck laterally (Jarrett 1998, Yang, Yao et al. 2005, Neal-Sturgess, Carter et al. 2007, Fredriksson, Rosén et al. 2010) with percentages as high as 87%-98% for child pedestrians (Yang, Yao et al. 2005, Yao, Yang et al. 2007). The majority of pedestrians do not attempt any avoidance manoeuvre (Jarrett 1998), although children are more likely to be running (Yang, Yao et al. 2005, Yao, Yang et al. 2007).

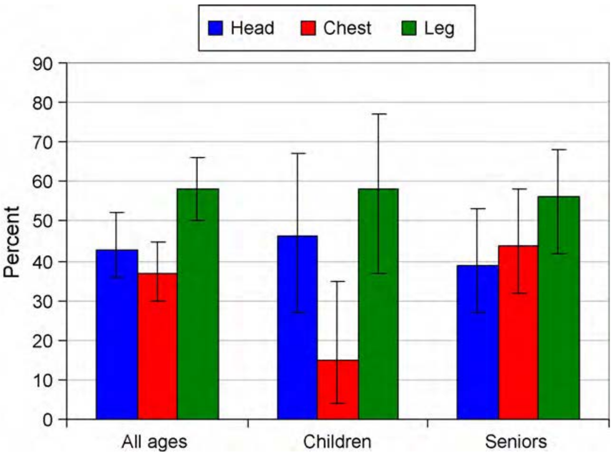


Figure 8
Proportion of severely injured pedestrians with severe injury to different body regions, GIDAS data 1999-2008 (Fredriksson, Rosén et al. 2010)

The head and lower extremities are the most commonly injured body regions (Mizuno 2005, Neal-Sturgess, Carter et al. 2007) for both adults and children (Yang, Yao et al. 2005, Yao, Yang et al. 2007) (**Figure 8**). Roudsari et al. (2004), using the PCDS data, found greater proportions of head and lower extremity principal injuries in children and lesser proportions of thorax and abdomen.

Fatal pedestrian injuries most commonly result from impact to the head (Mizuno and Kajzer 1999, Hardy, Lawrence et al. 2007) when considering only single causes. However, head, chest, and pelvis polytrauma have been reported as the most common overall cause of fatality (Mallory, Fredriksson et al. 2012). Lower extremity injuries have often caused long term disability.

Injury patterns and severity have been found to differ with age, speed and height. *Gender* differences have rarely been identified (Zhang, Cao et al. 2008), but Richards and Carroll 2012 did find that men aged 26-45 had a significantly greater risk of head fracture, and men under 65 had a significantly greater risk of intracranial injury. Over the past 20 years the average pedestrian has become older, taller and heavier. The remainder of this section summarises recent differences in injury patterns and severity associated with age, height and weight.

Corrected for vehicle type (truck c.f. car), speed and pedestrian age; pedestrian height, weight and BMI have been negatively associated with risk of severe injury or death ($p<0.05$) (Teft 2013). Corrected for vehicle geometry, speed and pedestrian age, and limiting the study to only adults over 1.5m, *height and weight* have been differentially associated with risk of severe injury or death ($p<0.05$)(Zhang, Cao et al. 2008): specifically shorter pedestrians (<161 cm c.f. 161-175 cm) were associated with an 81% reduced risk of serious head injury[1] and heavier (>90 c.f. 61-90 kg) pedestrians were associated with an increased risk of whole body[2] and lower extremity[3] serious injuries. This is in line with trajectory models based on height and with the concept of an increased pedestrian inertia resulting in larger impact forces and more serious injuries (at first impact to the lower extremities).

Pedestrian age and injury/mortality have been associated through logistic regression with findings of triple the mortality rate and 2-3 times the risk of serious injury[4] for adults than for children (Henary, Crandall et al. 2003) and more than three times the mortality rate for the elderly than for adults (Neal-Sturgess, Carter et al. 2007). Support for age related risk was also found via over-representation of the elderly in fatal and serious injury collisions and of children in the less serious (AIS 2+) cases for the German GIDAS data(Jarrett 1998, Mizuno 2005, Fredriksson, Rosén et al. 2010), however these tendencies may be explained in part by differences in exposure as children were found to be involved at higher frequencies in lower speed impacts(Mizuno 2005).

With adjustment for vehicle type and impact speed, no age association was found significant by Henary et al. (2003), however when including only adults over 1.5m and correcting for vehicle geometry, pedestrian gender, height and mass, pedestrians aged 65 and above were associated with more than double the risk of serious injuries overall and to the lower extremities[5] and 23.8 times the risk of serious injuries to the torso[6] (Zhang, Cao et al. 2008). There were no significant findings regarding increase to the risk of head injuries. This suggested to the authors that reduced long bone strength due to age related osteoporosis may be the cause and recommended further investigation. However, increased risk of head injuries have been found for the elderly in the form of intracranial injuries, postulated to be caused by the effects of increased impact motion of a reduced brain size within the skull and the increased head rotation at impact due to weaker neck muscles (Richards and Carroll 2012). Intracranial injuries were of concern due to their association with longer hospital stays and rotational impacts which have been found to be poorly considered by impact test procedures (Hardy, Lawrence et al. 2007).

Age related risk has been found to interact with impact speed. Yao (2007) found at 30 km/h, a child had a 23% risk of an AIS≥2 head injury, whereas significant age related risk increases were not found at other speeds.

Higher risk of severe injury or death has been found for elderly pedestrians at fixed speeds from 24-100 km/h (Teft 2013). Teft (2013) found with US 2007-2009 crash data, the average adjusted, standardized risk of severe injury for a 70-year-old pedestrian struck at any given speed was approximately equal to the average risk for a 30-year-old struck by a vehicle travelling 18.5 km/h faster (95% CI: 10.9–25.9 km/h). The average risk of death for a 70-year-old pedestrian struck at any given speed was approximately equal to the average

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[1] (OR=0.19 (0.043,0.86), n=5)

[2] (OR 4.26 (1.49-12.19))

[3] (OR 3.03 (1.24-7.41))

[4] (OR=2.81 based on SSI, CI:1.56-5.06, not adjusted for vehicle type nor speed)

[5] (OR of 2.24 (0.94-5.36) and 2.44 (1.15-5.18) respectively

[6] (5.0-114.2. $p<0.0005$)

risk for a 30-year-old pedestrian struck by a vehicle travelling 19 kph faster (95% CI: 11.4–26.6 km/h). In addition, Mizuno (2005) found that children are injured at lower impact speeds than adults.

The mechanisms explaining age related injury pattern differences are further explored in the section addressing the effects of vehicles.

In summary;

- the most frequent serious pedestrian injuries are to the head and lower extremities;
- lower extremity injuries are positioned higher in the body for children;
- fatal injuries are mostly likely to include head injuries and injuries to the torso are next likely to be fatal;
- older pedestrian outcomes are more severe and less likely to be head injuries;
- children have worse outcomes at lower speeds than adults but are less likely to sustain head injuries,
- shorter and less heavy adults have better outcomes and increased speed increases the risk of injury at a greater rate for older pedestrians than for adults.

5.2 Effect of Driver and Environment

Vehicle design countermeasures implemented to improve pedestrian outcomes will likely have better efficacy under specific environmental and driver behaviour conditions. For example, driver alert and brake assist systems depend upon driver response; and environmental conditions will determine visibility, impact speed and impact angle, thus direct the forces and trajectories of the impacting body to the passive countermeasures. Although pedestrian and driver behaviour and environmental factors are beyond the scope of this document, the interaction with vehicle design and the crash factors which they influence will be discussed in following sections.

When considering countermeasure efficacies it will be useful to consider that

- almost half of pedestrian collisions occur while the vehicle *is on a straight path* and 30% while turning (Jarrett 1998);
- the majority of drivers were *not able to perform an avoidance manoeuvre* (Jarrett 1998);
- almost two thirds of U.S. pedestrian related crashes and 76% of all pedestrian fatalities occur away from *intersections* (Wang and Kockelman 2013);
- pedestrian injury/fatality counts rise with traffic volumes, shares of arterial streets lacking transit, share of land zoned for neighbourhood, commercial and mixed residential/neighbourhood commercial uses, numbers of residents and (resident) workers, and share of persons living in poverty (Weir, Weintraub et al. 2009);
- many built environment, transport system, and traveller attributes (such as land use types, network intensity, transit supply, and demographic characteristics) in the vicinity of intersections are strong predictors of pedestrian activity but have rather small effects on collision frequency (after controlling for exposure)(Miranda-Moreno, Morency et al. 2011);
- the ground itself was found to be a significant (but lesser than the vehicle itself) contributor to serious head injuries in a UK study based on 2000-2010 crash data: 46% of pedestrian head injuries graded AIS≥2 and 39% graded AIS≥3 were attributed to impacting the ground after the vehicle impact (Badea-Romero and Lenard 2013) and
- amongst US and German data, serious injuries to the head and face were more frequently attributable to the environment than any other region (Mallory, Fredriksson et al. 2012).

5.3 Vehicle Effects

In addition to pedestrian factors, vehicle front geometry, stiffness and speed influence injury severity (Yao, Yang et al. 2007).

5.3.1 Speed

Because collision energy increases proportionally to the square of impact speed, impact speed has been found to be the most important factor in determining the severity of pedestrian injuries with mostly minor injuries sustained at impacts below 20km/h and mostly fatal outcomes at speeds in excess of 45 km/h (Waltz, Hoefliger et al. 1983, Wood 1991, Anderson, McClean et al. 1997, Otte 2001, Lefler and Gabler 2002). Increased fatalities have been observed with an increase in speed limit : 23.5% in ≤40 km/h zones and 39.4% >64 km/h zones (Ballesteros, Dischinger et al. 2004). Zhang (2008) also found an increased risk of serious injury with increasing impact speed when corrected for pedestrian height, weight and age and vehicle geometry in assessing adult pedestrian cases greater than 1.5 m in height.[7] For every 5 km/h increase in impact speed, the severity of pedestrian injury has been found to increase by 3.4 units on the ISS scale ($p<0.01$) and the risk of mortality increased by 4% ($p<0.01$) (Henary, Crandall et al. 2003). More recently, corrected for pedestrian height, weight and age and vehicle type (truck c.f. car), risk of severe injury was found to increase approximately linearly with impact speed for speeds between 40 km/h and 66 km/h, with an average increase of 3.1 percentage points[8] for each 1.6 km/h increase in impact speed for speeds within this range (Teft 2013). Corrected for pedestrian height, weight and age and vehicle type (truck v car), risk of death increased approximately linearly with impact speed for speeds between 52.3 km/h and 77.2 km/h, with an average increase of 3.2 percentage points[9] for each 1.6 km/h increase in impact speed for speeds within this range (Teft 2013).

The trend was also significant for serious injuries by body region (head, torso and lower extremity). Lower extremity injuries were the least affected (~5x) by speed increases[10] and torso injuries were most affected (~53x) by impact speed and speed[11] and the risk of head injuries were found to increase by about 33 times[12] (Zhang, Cao et al. 2008).

The serious injury (AIS 3+) risks from pedestrian-passenger vehicle collisions by three broad injury types, at various speeds (**Figure 9**), showed the highest risk at 50 km/hr for serious leg injuries, followed by head and chest: 17%, 13% and 11% respectively[13] (Fredriksson, Rosén et al. 2010).

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[7] The odds ratios of whole body MAIS ≥3 was evaluated at 8.59 (4.17-17.68) and 335 (38-2,921) respectively for 22-55 km/h and >55km/hr impact speed ranges referenced against a 0-24 km/h range.

[8] (95% confidence interval [CI]: 2.5–3.8)

[9] (95% CI: 2.4–4.0)

[10] $OR_{22\text{-}55}$=3.9 (2.1-7.4) and $OR_{>55}$=21.2 (7.3-61.9)

[11] increases with $OR_{22\text{-}55}$=82.0 (9.3-725.9) and $OR_{>55}$=4,342 (300-62,815)

[12] with $OR_{22\text{-}55}$=7.0 (2.4-20.2) and $OR_{>55}$=230 (48-1,100)

[13] Leg (17%: CI, 12–23%), head (13%: CI, 9–18%) and chest: (11%: CI, 8–15%)

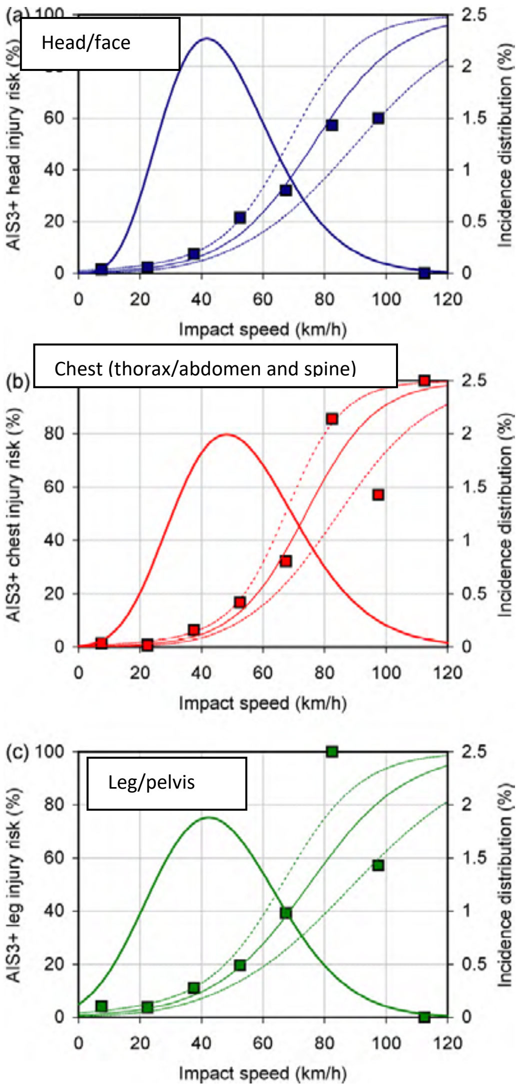

Figure 9

AIS3+ injury risk (left axis) and incidence (right axis) as functions of car impact speed, GIDAS data 1999-2008 (Fredriksson, Rosén et al. 2010).

Ligament knee injuries were found to be more likely at impact speeds around 20-30 km/h and leg fractures at around 40 km/h (Matsui 2005).

Fredriksson (2010) also summarised impact speed by injury mechanism (**Figure 10**), and found that impact speeds in the glassed windshield area were similar to those in the framed area. Head impacts to the windshield have also been found to be at greater speed than to the bonnet (Fredriksson 2011).

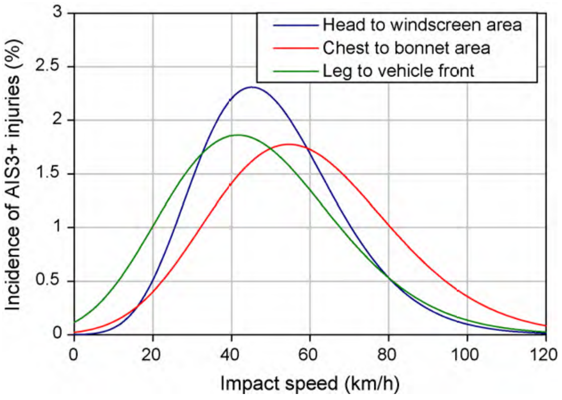

Figure 10

Vehicle impact speed distributions of AIS3+ GIDAS data 1999-2008 (Fredriksson, Rosén et al. 2010)

5.3.2 Mass

The large difference between vehicle and pedestrian masses has led to the general belief that curb weight does not determine injury severity (Roudsari, Mock et al. 2004). Lefler et al. (2002) postulated that vehicle geometry rather than mass may be the key factor responsible for their observed higher pedestrian fatalities from collisions with large vans and LTVS given that minivans, which have similar frontal geometry, produced fatality rates identical to passenger cars (**Figure 11**). Indeed, fatality risk has been demonstrated independent of vehicle weight for vehicles up to 1.4t, however the risk was found to rise with curb weight thereafter (Mizuno and Kajzer 1999) and Ballesteros (2004) found vehicle curb weight to be strongly associated with curb weight. This association may also be attributed to the vehicle geometry of SUVs and large vans, rather than their mass given the established correlation of vehicle mass with stiffness and frontal geometry (Joksch 2000).

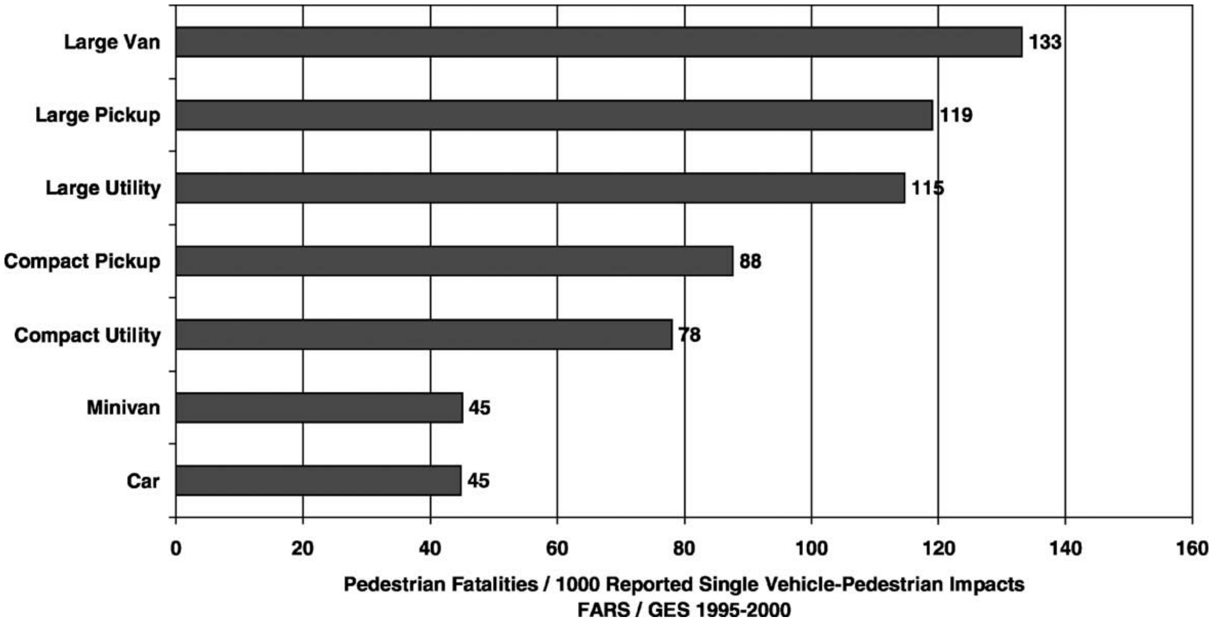

Figure 11

Pedestrian risk by vehicle type, FARS, GES data 1995-2000 (Lefler and Gabler 2002)

5.3.3 Components

Mallory et al (2012) and Mizuno (2005)[14] examined injury severity by vehicle component and found the *bumper*[15] to be responsible for the highest percentage of serious injuries and disability. The *windshield*[16] was responsible for the next highest percentage of serious injuries and disability. *Bonnet surface and leading edge* contact were found to be responsible for serious injuries to body regions (chest (54%), head (18% adult, 42% child), abdomen (69%), and pelvis (60% adult 72% child)). 93% of AIS≥2 injuries sourced to the bumper were leg injuries, 65% sourced to the windshield and A-frame were head injuries and 31, 24 and 13 % sourced to the hood surface and leading edge were chest and abdomen, head and pelvis injuries (Mizuno 2005). Overall 85% of adult and 83% of child serious injuries were sourced directly to vehicle components; only 9% of adult and 12% of child injuries were attributed to road surface contact (Mizuno 2005).

Differences in stature lead to differences in frequently injured areas for children. In contrast to adult head serious injuries, child head injuries more commonly arise from impacts with the hood than from the windshield and pelvis serious injuries arising from contact with the hood are more frequent in children than in adults.

In support of the findings above by Mallory (2006) and Mizuno (2005), the most frequent serious injury (AIS 3+) passenger car-pedestrian mechanisms were found by Fredriksson et

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[14] Percentages are for AIS≥2 injuries from this study:

[15] 62% of adult and 55% of leg injuries were sourced to the bumper .

[16] 56% of adult and 23% of child head injuries were sourced to the windshield and A frame

al. (2010) for all ages to be leg to front end (44%), head to windscreen (25%, with 52% of these hitting impacting glass and 39% impacting the A-pillars), chest to bonnet (15%) and chest to windscreen. Also in agreement, the second most frequent mechanism was found to be different for children than for seniors and adults: head-to-bonnet occurred with greater frequency than head-to-windscreen (Roudsari, Mock et al. 2004, Fredriksson, Rosén et al. 2010). The most common mechanism for fatalities was head-to windshield, followed by thorax to hood/windshield (Fredriksson, Rosén et al. 2010). One study on vehicles manufactured in 2000 or later even found that no fatally injured adult pedestrian head injuries were caused by any part of the car forward of the base of the windscreen (Richards, Cookson et al. 2009).

In addition , chest to bonnet serious injury outcomes were found to increase with age and brain injuries were more frequently observed from head-to-windscreen collisions in the glassed than in the framed windshield area (most likely due to differing translational or rotational loading) (Fredriksson, Rosén et al. 2010) .

The AIS levels of lower extremity and head, but not chest, injuries were found to be associated with impact region; the *hood-edge* was found to be associated with more severe *lower extremity* injuries (Helmer, Ebner et al. 2010); *head injuries* from the windshield frame were associated with a greater fatality risk than those from the windshield itself (Neal-Sturgess, Carter et al. 2007, Richards, Cookson et al. 2009); and head injuries caused by car front structures were found more severe than those caused by secondary ground impact (Yang, Yao et al. 2005).

5.3.4 Type (Geometry and stiffness)

The discussion above has outlined differences in injury severity patterns related to pedestrian factors and speed on impact with various passenger vehicle components. The main points on pedestrian injuries were summarised at the end of Section 5.1. Section 5.3.3 above places bumpers and windshields, particularly the A-pillars, as the primary contact point in the cases of the two most frequent serious injury types. However, bonnets are the primary contact point for the majority of torso injuries and torso injuries have also been observed as a large contributor to fatalities especially in the elderly. Bonnets are also the primary impact point for heads of children. Much research has gone into making bumpers, bonnets and less so windshields safer to pedestrians.

This section examines the interactions of speed and pedestrian collision factors with vehicle design. For example, in the case of the injury most likely to cause fatalities, head injuries, the head impact conditions such as impact speed, timing and angle and wrap around distance are dependent upon vehicle geometry and stiffness which produce a different trajectory and injury outcome for adults and children (Yang, Yao et al. 2005). Furthermore literature has shown that apart from the impact velocity, vehicle front end design is the most important factor in determining pedestrian kinematics (Kausalyah, Shasthri et al. 2014). Another example of the part that a vehicle’s geometry plays in pedestrian injury is in the visibility allowed by the design (Paulozzi 2005). Put simply, studies have shown that different vehicle market groups produce different pedestrian injury patterns and severity. Studies have focussed primarily on comparisons of passenger cars and SUVs and light commercial vehicles.

5.3.4.1 Passenger cars[17]

The typical trajectory for a person colliding with a passenger vehicle front involves initial bumper contact to the lower extremities (upper thigh/pelvis for child), below their centre of gravity; followed by body rotation and pelvis/upper leg (pelvis/chest for child) contact with the leading edge of the bonnet, the head/thorax colliding with the bonnet or windscreen (bonnet for child) and then the “wrap and carry” until the vehicle stops, whereupon, the pedestrian then contacts the ground (Roudsari, Mock et al. 2004, Hardy, Lawrence et al. 2007). Bumpers and rounded aerodynamic designs provide a protective effect for the first two impact points, and crush space provides for bonnet impacts. Windshields themselves, however, offer no additional protective features over lamination. The windshield-to-head impact is not only the least protected mechanism but also the most likely injury to cause fatalities.

5.3.4.2 SUV, Pick-up trucks and vans

Most studies combine SUVs and pick-up trucks due to their similar geometry and mass. Some go further and include light commercial vans. These combinations of vehicle types are typically called light truck vehicles or LTVs. In the US studies a ‘van’ may resemble an Australian station wagon.

A typical SUV has an empty mass from 1.00 to 3.25 tonnes, an average bumper height of 560 mm (typically 470-655), an engine volume of 1.8 to 6.6 litres and an engine power of 48 to 430 kW (Hoogvelt, de Vries et al. 2004). Hoogvelt et al (2004) found that almost all mid and large size passenger cars will sit within these ranges, except for bumper height, which is typically 20% higher in The Netherlands on an SUV. In fact, the entire SUV front end is blunter, higher and stiffer and shaped significantly different than a passenger car, thus the geometry rather than the mass difference (considering the pedestrian-vehicle disparity) is the most significant cause of injury outcome differences between LTVs and cars.

As discussed earlier, SUVs and LTVs are increasing in proportion in the Australian and New Zealand vehicle fleets. In addition, over time standard passenger vehicle geometry has greatly changed. These phenomena have been observed also in Europe and the US. Average vehicle geometry was observed to have changed as much as 26% between the late 80’s and the late 90s in one US data set (Jarrett 1998) with respect to bumper height, hood height, bumper lead, hood length and lead angle. The result of these changes put greater differences between the average vehicles of passenger cars and LTV market groups and greater differences within pedestrian injuries produced by these vehicle types. **Figure 12** displays typical frontal geometry for four vehicle types.

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[17] Most studies exclude SUV, MPV, pick-up trucks (utilities) and vans from this vehicle group.

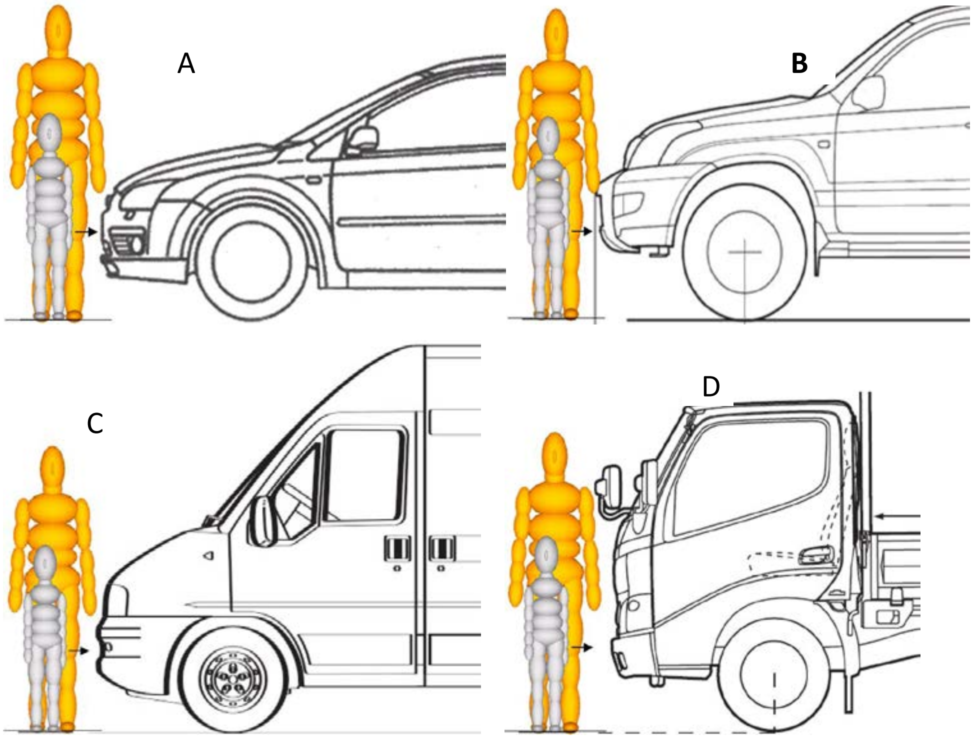

Figure 12

Vehicle front gemetry compared laterally with adult and child. A: passenger car, B SUV, C: MPV D: goods van or truck (Hardy, Lawrence et al. 2007)

The typical trajectory for a person colliding with a SUV or LTV vehicle front involves initial bumper contact with the upper leg (pelvis/chest for child), above their centre of gravity; such that “wrap and carry” and rotational movement are less likely, and forward projection followed by being over-run by the vehicle is more likely (Roudsari, Mock et al. 2004) (Simms and Wood 2006, Hardy, Lawrence et al. 2007). The head is more likely to make contact with the bonnet top (bonnet leading edge for a child) than with the windshield and at a lower impact velocity due to the reduced rotation, an event which is expected to be more pronounced in taller SUVs (Kerrigan, Arregui-Dalmases et al. 2012) (Hardy, Lawrence et al. 2007). Loads sustained by the pelvis are expected to be substantially higher, and contact with the stiff engine structures are expected to contribute to head injuries (Simms and Wood 2006).

Children have a greater chance of being hit above their centre of gravity and thus being run over (Roudsari, Mock et al. 2004). With larger SUVs, a child’s head is expected to impact with the grill or near vertical part of the bonnet and the body will not rotate onto the top of the vehicle, and thus sustain a higher velocity and more horizontal impact to a stiffer surface (Hardy, Lawrence et al. 2007). A taller child may experience no primary head impact or a low velocity contact (Hardy, Lawrence et al. 2007). A smaller child may benefit from a reduced load to the head if primary impact is below the stiffer structures of the bonnet leading edge (Liu and Yang 2003).

More detailed differences in pedestrian trajectories are shown in **Figure 13** (Simms and Wood 2006) and for head impact in Table 2 .

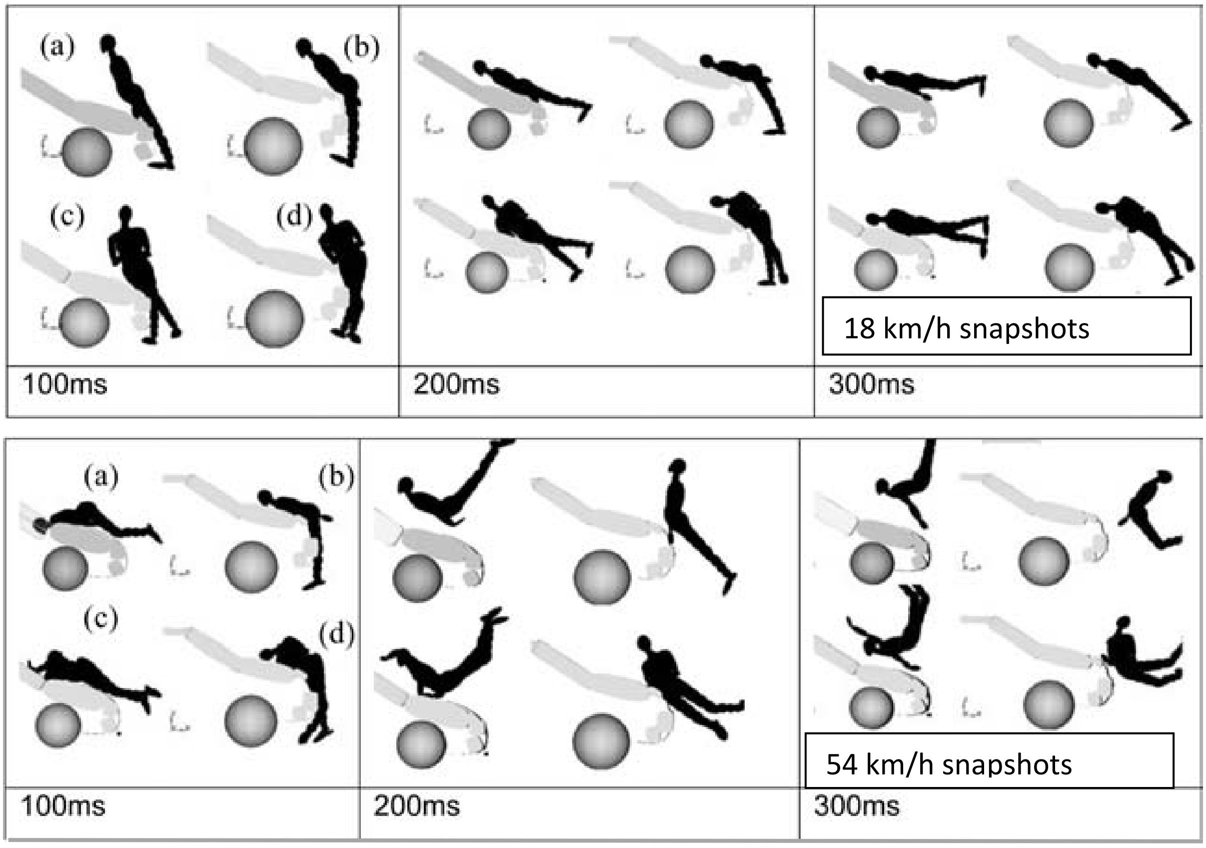

Figure 13
18 km/h and 54 km/h impact snapshots for a) a pedestrian facing a car, b) a pedestrian facing an SUV, c) a pedestrian sideways to the car, and d) a pedestrian sidways to the SUV at 100m intervals (Simms and Wood 2006)

Table 2 : Adult and child pedestrian head impact velocities and angles for 40 km/h vehicle impacts (average ±1SD) (Mizuno, 2003 within (Hardy, Lawrence et al. 2007))

Pedestrian	Shape corridor	Impact velocity (km/h)			Impact angle (degrees)		
		Bonnet	Windscreen	BLE/Grille	Bonnet	Windscreen	BLE/Grille
Adult	Sedan	+ 30.4 +/- 7.2	35.2 +/- 6.8	nc	66.0 +/- 14.0	38.4 +/- 10.9	nc
	SUV	30.8 +/- 8.8	nc	nc	76.7 +/- 22.2	nc	nc
	One box	nc	29.6 +/- 3.2	nc	nc	47.3 +/- 9.6	nc
Child	Sedan	+ 30.0 +/- 4.0	nc	nc	66.0 +/- 6.3	nc	nc
	SUV	27.2 +/- 1.6	nc	32.0 +/- 3.6	59.2 +/- 2.6	nc	22.5 +/- 4.2
	One box	27.6 +/- 0.8	nc	nc 33.2 +/- 3.2	49.8 +/- 1.8	nc	17.4 +/- 6.1

One box= Flat fronted trucks/vans
nc: no contact

The head is the most frequently seriously injured body part in both LTVs and cars, however the next ranked body part is lower extremities for cars and torso for LTVs (Hu and Klinich 2012) (**Figure 14**). The responsible component is most frequently the bonnet and leading edge in LTVs and the windshield and bumper for cars (**Figure 15**).

SUVs may not offer bumper protection against initial point of impact, knee, femur and pelvis injuries, particularly if fitted with a bull-bar. Femur injuries are more likely than knee and tibia injuries due to the increased bumper height (Matsui 2005). Furthermore, the abdomen (head if child) is more vulnerable when it impacts the stiffer bonnet leading edge, a more rounded geometry here offers better protection of vital organs.

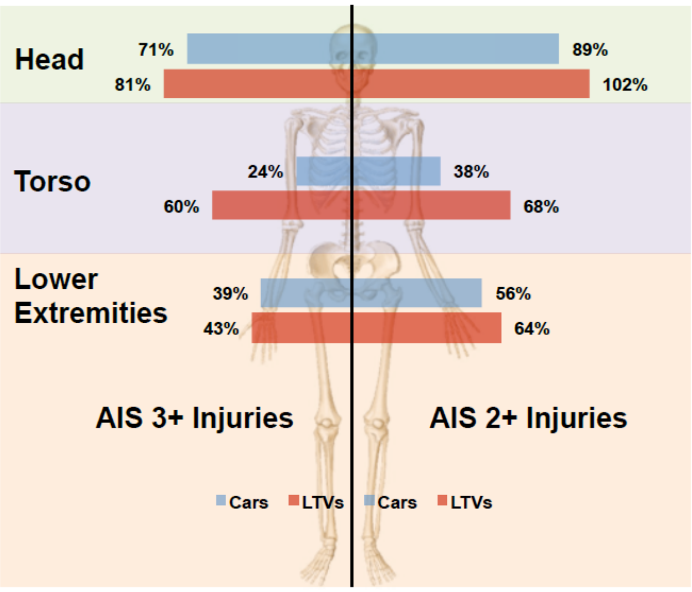

Figure 14
Distribution of pedestrian injuries by vehicle type (Longhitano, Henary et al. 2005)

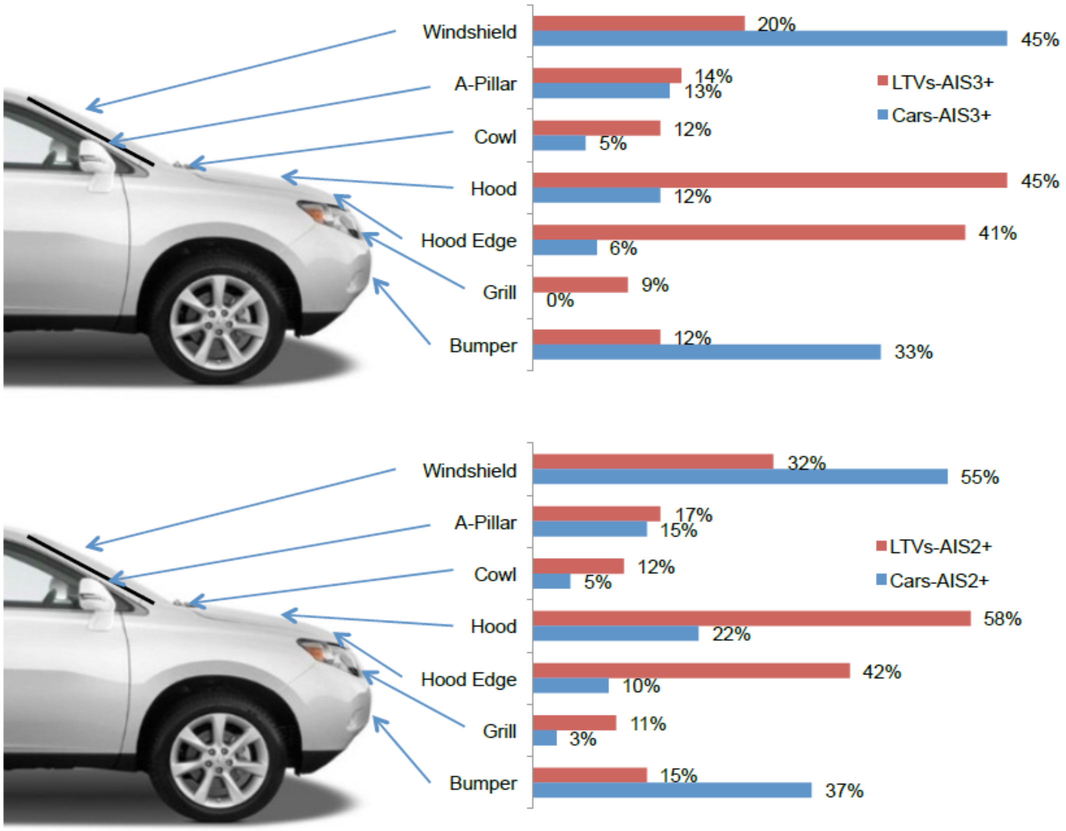

Figure 15
Sources of pedestrian injuries by vehicle type (Longhitano, Henary et al. 2005)

Hoogvelt et al (2004) found SUVs to be significantly more aggressive against vulnerable road users through a logistic regression corrected for mass and gender: The odds of an SUV pedestrian involved collision was found to be double that of passenger cars[18]. Pedestrians hit by LTVs (SUV + utilities + light trucks) demonstrated greater injury frequencies at higher MAIS (**Figure 16**) and after 1997, had a greater chance (2-3 times) of death than when struck by a passenger car (Lefler and Gabler 2002, Ballesteros, Dischinger et al. 2004). Utilities were found to yield 1.3 times the odds of a pedestrian fatality when compared with large passenger cars (Table 3). The SUV (c.f. passenger car) risk was found to be greatest amongst under 8 year olds (Starnes and Longthorne 2003). Furthermore, Hoogvelt (2004) contrasted 13% fatalities when hit by a van with 5% when hit by a car.

The risk of non-fatal adult moderate and serious injuries (ISS ≥9 and ISS≥15 or AIS≥4 respectively) have also been found to be greater for LTVs than for vans or passenger cars (Henary, Crandall et al. 2003, Ballesteros, Dischinger et al. 2004, Roudsari, Mock et al. 2004), even after adjustment for pedestrian age and vehicle speed (Table 3).

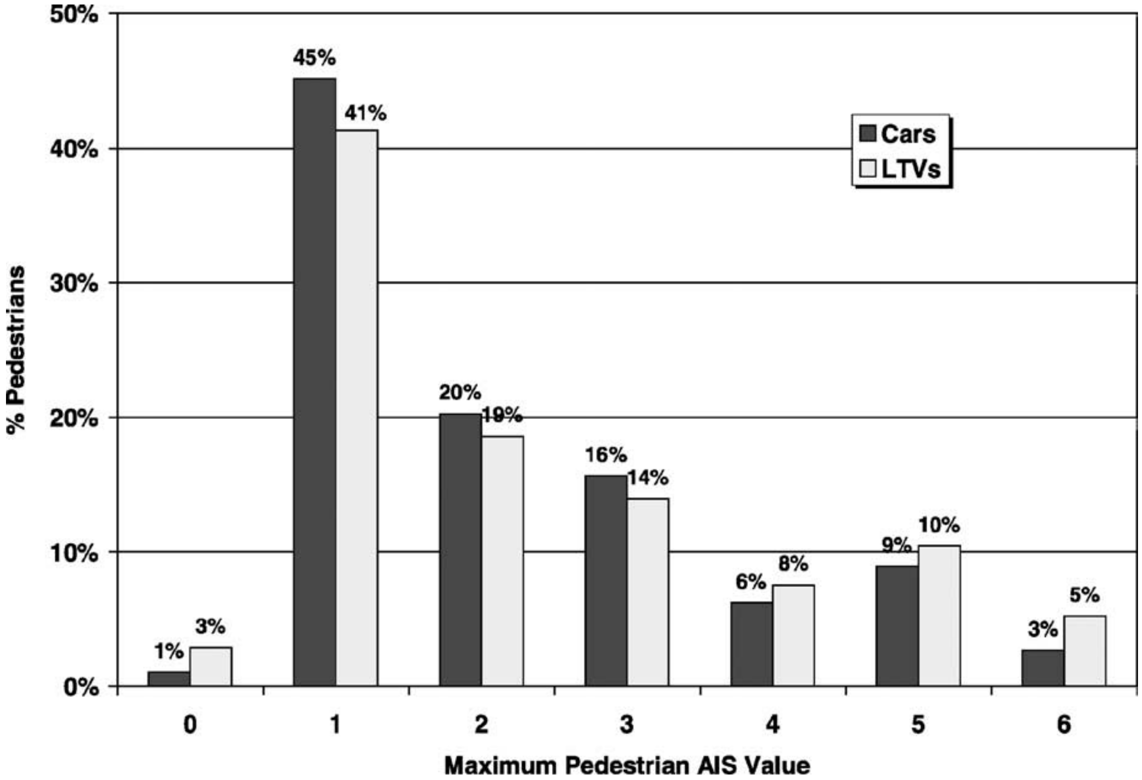

Figure 16

Frequency of MAIS value by vehicle type, PCDS data 1994-1998 (Lefler and Gabler 2002)

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[18] (95% CI 0.96,4.17)

Table 3 : Effect of Vehicle type: Age adjusted odds ratios of serious injuries or mortality

		Definitions			Age Adjusted Odds Ratios			
					SUV/LTV to passenger car		Van to Passenger Car	
year	First author	Low weight vehicle	low speed	Serious injury	serious injuries	fatalities	serious injuries	fatalities
2003	Henary‡	no weight adjustment	<=30 km/hr impact speed	ISS>16	1.31 (0.88-1.94)	1.40 (0.84-2.34)		
2004	Roudsari†	no weight adjustment	<=30 km/hr impact speed	ISS>16	2.1 (p=0.021)	3.4 (1.5- 7.8) 4.0 (1.5-11.1) weight adjusted	1.6 (0.8-3.6,p=0.207)	0.57 (p=0.42)
				AIS≥4	2.9 (1.4,6.3) p=0.004		3.0 (1.3,7.3) p=0.01	
2004	Ballesteros**	<1.45t	<48 km/h speed zone	ISS≥16	1.15 (0.86-1.55)	1.32 (0.92 - 1.87)	1.63 (1.10-2.42)	1.30 (0.78-2.15)

						Injury or death
2014	D'Elia#	No weight adjustment	≤50 km/hr	MAIS≥1	Light	1.06 (0.86-1.30)
					Small	1.13 (1.00-1.28)
					Medium	1.02 (0.88-1.19)
					Large (reference)	
					People Movers	1.29 (0.90-1.84)
					SUV compact	1.13 (0.88-1.46)
					SUV Medium	1.20 (0.88-1.64)
					SUV Large	0.91 (0.69-1.19)
					Van	1.17 (0.87-1.57)
					Utility	1.29 (1.05-1.57)

‡ LTV group includes vans #Reference is Large passenger car

† Speed adjusted as ordinal variable

** weight and speed adjusted as 3 speed zone bands: 40, 48-56 and >64 km/hr

Table 4 : Effect of Vehicle type at low speeds: Age adjusted odds ratios of serious injuries, mortality and risk of serious injury to body regions

		Low Speed Age Adjusted Odds Ratios; SUV/LTV to passenger car									
		SUV/LTV to passenger car						Van to passenger car			
year	**First author**	serious	fatal	Brain trauma	Abdominal	Thoracic	Below Knee	Brain Trauma	Abdominal	Thoracic	Below Knee
2003	Henary ‡	3.34 (1.35-8.29)	1.87 (0.95-3.68)	1.99 (1.22-3.24)		6.69 (2.71-16.53)					
2004	Ballesteros**	no sig interaction	no sig interaction	1.97 (1.08-3.59)	2.51 (1.20-5.27)	2.00 (1.08-3.72)	0.39 (0.28-0.54)	2.45 (1.27-4.73)	3.00 (1.35-6.68)	2.42 (1.22-4.79)	0.52 (0.34-0.80)

Table 5 : Effect of Vehicle type in body regions: Age and speed adjusted odds ratios of serious injuries and mortality and risk of serious injury

			Head, face or Neck Injury	**Thoracic Injury**	**Pelvis and lower extremity Injury**
			Injury or death	Injury or death	Injury or death
2014	D'Elia#	Light	1.20 (0.94-1.53)	1.04 (0.74-1.45)	0.88 (0.70-1.10)
		Small	1.27 (1.10-1.47)	1.01 (0.83-1.23)	0.93 (0.81-1.06)
		Medium	1.17 (0.98-1.39)	1.08 (0.85-1.37)	0.85 (0.72-1.00)
		Large (reference)			
		People Movers	1.54 (1.04-2.28)	1.43 (0.85-2.41)	1.06 (0.73-1.55)
		SUV compact	1.11 (0.82-1.50)	0.93 (0.61-1.43)	0.94 (0.71-1.24)
		SUV Medium	1.09 (0.76-1.56)	1.00 (0.60-1.65)	0.81 (0.58-1.14)
		SUV Large	1.45 (1.07-1.95)	1.74 (1.21-2.52)	0.81 (0.60-1.09)
		Van)	1.65 (1.20-2.27)	1.53 (1.01-2.31)	0.73 (0.82-1.02)
		Utility	1.54 (1.23-1.92)	1.26 (0.93-1.70)	1.08 (0.87-1.33)

‡ LTV group includes vans, torso not thoracic

** weight adjusted

Literature has also shown that pedestrian head and chest serious injuries were more likely outcomes, and lower extremity serious injuries less likely outcomes, from collisions with LTVs than with cars (Figure 17) (Ballesteros, Dischinger et al. 2004) (Lefler and Gabler 2002, Roudsari, Mock et al. 2004, Longhitano, Henary et al. 2005). Lefler (2002) demonstrated this trend for any given speed up to 60 km/h. D'Elia (2015) also found similar trends for head and chest injuries from large SUVs, vans and utilities in his comparisons with outcomes from large cars. However, the evidence was weak for thoracic injury odds ratios from utility comparisons. D'Elia included pelvic injuries in his "lower extremity" group so observed no evidence of differences in odds of injury for this region (at p=0.05). Rousardi et al. (2004) found that the injury pattern differed for their 114 cases of child pedestrian data: thorax and abdomen proportions remained higher but lower extremity injuries were higher in child-to-LTV collisions. Table 4 and Table 5 summarise the logistic regression odds ratios for different body regions published in these studies.

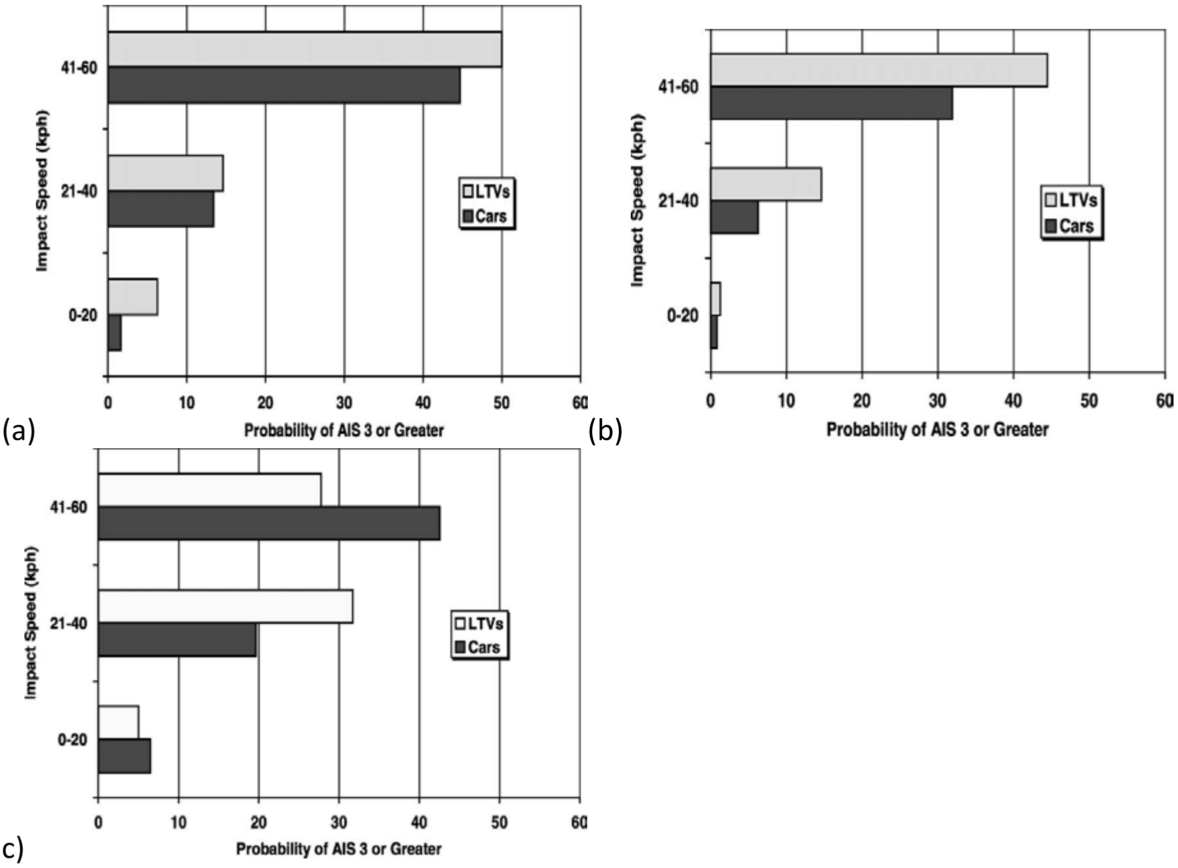

Figure 17

Probability of serious injury AIS of 3 or greater a)head b) chest c)lower extremity, PCDS data 1994-1998 (Lefler and Gabler 2002)

Zhang (2008) studied the injury risk associated with vehicle front geometry and body region adjusted for speed and pedestrian height, age and weight in adults less than 1.5 metres tall. Vehicles with a shorter RHOD (rear hood opening distances) were more likely to invoke a trajectory that involved head-to-windshield impact; they were more likely to be sedans than SUVs. Shorter rear hood opening distances (0-170 cm c.f. 171-200 cm) contributed to 4.30 times the risk of MAIS 3+ head injury[19] . Vehicles with a larger ground to front/top transition point height were generally more vertically aligned, providing a shorter wrap around distance and thus invoked an increased impact force of the torso to the bonnet/bonnet leading edge; they were more likely to be SUVs than sedans. Larger ground to front/top transition point heights (>100 cm c.f. 0-75 cm) produced 20 times increased risks of AIS 3+ torso injuries[20]. These results supported the findings of the previously listed studies (above) with respect to higher torso injuries in SUVs; in addition the results were able to pinpoint which features of the vehicle types were responsible for the risk. Other crash test dummy testing has supported the finding of higher head injuries risks in vehicles with shorter RHOD (Kerrigan, Arregui-Dalmases et al. 2012).

It has been demonstrated that greater proportions of head injuries result when the head makes contact with the ground after the primary impact and that this scenario is almost certain for pedestrians of various sizes colliding with SUV's irrespective of their front-end profile at speeds of 40 km/h (Gupta and Yang 2013). At lower speeds, lower front end profiles and taller pedestrians were found to have reduced head to ground secondary impacts. It was found that the secondary ground head impacts from SUVs were not improved by using pop-up bonnets (ibid).

Vans were found to produce greater frequencies of abdominal and fewer below knee injuries than passenger cars, but generally the same injury patterns as for SUVs and Pick-up trucks (Ballesteros, Dischinger et al. 2004). D'Elia (2015) found sound evidence of a higher magnitude risk of head injuries for people movers than for large cars; this result may be due to the blunter bonnet geometry producing a shorter wrap-around time, and hence greater impact speed to the windshield.

5.3.4.3 Small Medium and Light Cars and Electric Vehicles

D'Elia (2015) also found evidence of an increased risk for injuries from small cars, which was found in Table 5 to be from head injuries which may result from greater windscreen contact from the shorter wrap around time that a small car offers. Odds ratios of similar magnitude (although not significant) were found for risk for medium and light cars.

Electric vehicles are said to pose an increased risk pedestrian collision due to pedestrians being unable to hear them approaching and being unable to estimate the speed of their approach, although tyre noise may be able to replace engine noise as the source of vehicle perception by the pedestrian.. A recent study has found that the crash risks to pedestrians of quiet (electric) vehicles are higher only for less dangerous crashes because noise emission

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[19] (OR_{RHOD}=4.30, CI: 1.33-13.79)

[20] (OR_{FTTPH} 20.8, CI:2.3-187.9)

differences were only found to be significant in low speed phases where severe injury risk is low, and in high acceleration phases where crash risk is low (Johannsen and Muller 2013).

In addition electric cars and vans have the freedom to locate the drive train in other parts of the body, leaving the potential for pedestrian impact optimised vehicle fronts (Fredriksson 2011, Pozo De Dios, Alba et al. 2013).

5.3.5 Speed and Type

Some crash data studies have found that SUVs and pick-up trucks (Pus) tended to have their pedestrian collisions in higher speed zones , with almost double the passenger car collision rates in speed zones >64 km/h (Ballesteros, Dischinger et al. 2004) and more than triple on 80 km/h roads (Hoogvelt, de Vries et al. 2004). However this trend was not found to be true for the PCDS data (Henary, Crandall et al. 2003) where the mean impact speed was similar: 29.3±19.8 for passenger cars and 26.3±21.1 for LTVs.

The impact velocities of human body regions depend on the vehicle's shape and injury risk depends on vehicle impact velocity, impact location and stiffness of the vehicle structure at the impact location. Stronger associations of vehicle type and risk of serious pedestrian injury have been found at slower impact speeds when averaged adjusted for speed (Henary, Crandall et al. 2003). In addition, significantly different risks of serious injury to body regions were found to be significant by vehicle type when analysed at low speeds (Ballesteros, Dischinger et al. 2004) (Henary, Crandall et al. 2003). It was postulated that a threshold above which the occurrence of injuries is independent of vehicle type exists where speed is the prime determinant of injury severity (Ballesteros, Dischinger et al. 2004). Low speed severe injury risks for body regions and vehicle type are presented in Table 4.

5.3.6 Visibility and Type

A 2011 pedestrian crash study from the US found that pedestrians were obscured from drivers' views in 13% of all pedestrian involvements and in 17% of pedestrian deaths (Jermakian and Zuby 2011). Ogawa et al. (2013) identified pedestrian visibility as an important factor for avoiding pedestrian accidents and identified parameters related to vehicle design that affect the ability of a driver to see a pedestrian: Angle of Hindrance at Driver's side (AHD), Angle of View at Driver's side (AVD), Angle of Hindrance at Passengers side (AHP) and Angle of View and Passenger's side (AVP) (**Figure 18**). Their findings included that a pedestrian accident is more likely to occur when the angle of hindrance due to the A-pillar is larger and also when the horizontal angle of view is smaller. They found that optimization of parameters in visibility indices and pedestrian head protection could lead to the decrease in the number of pedestrian accidents, particularly when the vehicle was straight–going and when the pedestrian was hit by the vehicle body. Pedestrian sensing technology could aid in preventing collisions related to decreased visibility due to vehicle design.

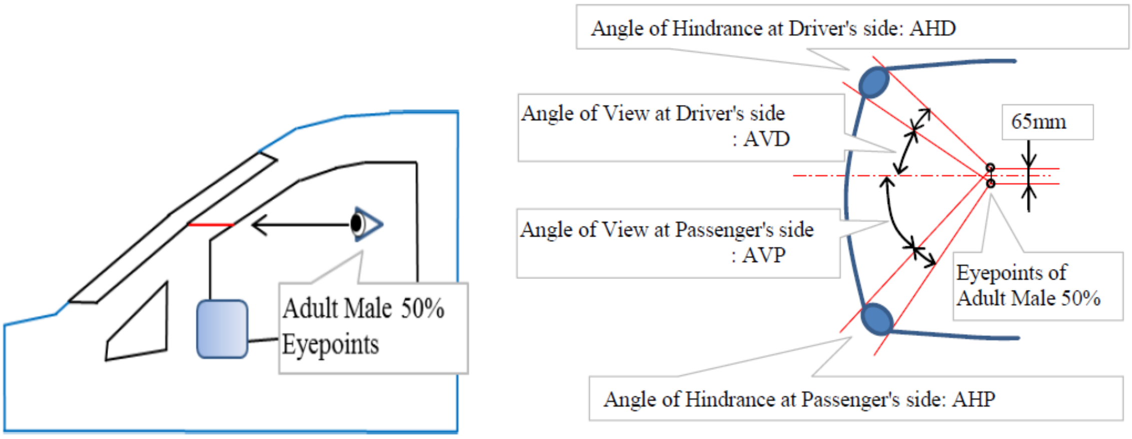

Figure 18

Definitions of Visibility parameters: side and top view (Ogawa, Chen et al. 2013)

Rear and side visibility of pedestrians is the most important design issue related to vehicle type, contributing to low speed run-over crashes. It has already been stated that theses crashes are more typically involving larger vehicles like trucks and SUVs which have longer rear sight distance (distance from rear of vehicle to 5-ft 1 inch person) and larger side blind zones. However, when a pedestrian is immediately behind the rear bumper, collisions have been found to be 40% more likely regardless of vehicle type because the region is typically not visible to a 50th percentile male driver (Mazzae and Garrott 2011). Paine et al. (2003) have also found that some of the vehicles with the worst rear visibility were sedans.

In 2003 IAG assessed 100 vehicles[21] for rear visibility on the criteria of the rear visible distance depth and width and the presence of reversing aids such as sensors and cameras. The worst vehicle did not allow a 2 year old child to be seen 15m behind the rear of a vehicle (Paine, Macbeth et al. 2003). Design factors found to influence visibility were:

i) high rear windows
ii) high boot lid
iii) rear mounted spare tyres
iv) rear head restraints
v) rear mounted brake lights
vi) rear mounted wipers
vii) rear spoilers.

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[21] Listed in appendix

5.3.7 Vehicle Effect Summary

In summary:

- Increased risk of Injury severity and fatalities are associated with increased speed,
- increased speeds have the largest effect on torso injury severity, and the largest effect on the elderly (c.f. adults),
- at 50 km/h, lower extremity serious injuries are more likely than torso or head injuries,
- bumpers are the first impact point and cause the highest percentage of serious injuries and disability, injuring primarily the lower extremities , but may cause injuries higher up the body (femur and pelvis in adult and torso and head in children) if the vehicle is an SUV or truck, and may offer no protection if the vehicle is fitted with a bullbar,
- bonnet surface and leading edge impacts are primarily responsible for fatal and serious adult torso and child head injuries in passenger vehicles and adult head injuries in SUVs and vans,
- torso injuries are more prevalent than head injuries when the vehicle is an SUV and the reverse is true for passenger cars,
- windshields, particularly the A-pillars are responsible for adult head injuries, which are more often fatal,
- over recent years, vehicle front geometry has become more blunt, with one cause being the increase in popularity of SUVs and utilities,
- geometry rather than mass of vehicle is the key factor explaining the injury risk differences observed for SUVs and vans when compared with passenger vehicles, however the effect of vehicle type appears only to be significant to speeds up to, whereupon speed has the most influence on pedestrian outcome,
- SUVs have a greater risk of collision with a pedestrian and a greater chance of producing a more severe injury or fatality than a passenger car, and
- vehicle design and frontal geometry contributes to the risk of a pedestrian collision through reduced pedestrian visibility.

6.0 Limitations of Vehicle safety Testing

There have been many investigations into the ability of national safety standards testing to evaluate safety. Correlation between EuroNCAP ratings and both real world pedestrian injury and pedestrian injury countermeasures have been established (Pator 2005, Strandoth, Rizzi et al. 2011, Searson, Anderson et al. 2014) , however, limitations to vehicle safety standards evaluations have also been identified.

Deficiencies have been found in the bio fidelity of body-form to model the human body, particularly in the effect of shoulder stiffness offering more protection to the head-to-bonnet impacts than would a human shoulder which is expected to make evaluation of pop-up hoods or windshield airbags difficult (Hardy, Lawrence et al. 2007).

Head injury testing has ignored rotational loading which has been found to be an important contributor to brain injury (Fredriksson 2011). The HIC (head injury criterion) is used in assessment of pedestrian regulations and is based on linear acceleration and limited to fractures and brain injuries associated to linear loading. The cumulative strain damage measure (CSDM) and other measures not listed here incorporate injuries from rotational loading and may be a useful addition to HIC in vehicle safety testing.

Also debated is the speed at which vehicle design safety is tested. Currently standards are generally placed at 40 km/h impact speed in the belief that it is a reasonable upper speed typical of injury producing pedestrian crashes (Mizuno 2005). Hardy (2007) suggested that new protections systems such as deployable and active systems may offer protection at speeds up to 50 km/h and thus require testing standards at higher speeds.

With respect to vehicle type, differences in geometry cannot be properly evaluated by isolated component tests and torso injuries, which were found to differ in risk by vehicle type, are not considered by current (2012) impact tests (Hu and Klinich 2012). Torso injuries are of particular interest because they are more frequent in the growing older pedestrian population. Vehicle design and testing in general has focussed on the bumper; and vehicle testing of the bonnet has focussed on injuries to the head (through head- form testing), however given that seriously disabling or fatal injuries to the pelvis, abdomen and thorax commonly result from the bonnet, (and fatal head injuries more commonly result from the windshield,) vehicle countermeasure bonnet design and testing are important for non-head regions, especially with respect to the ignored roundness of the bonnet, and the stringent bonnet leading edge to upper leg-form testing. Hardy (2007) recommended increasing the scope of vehicles included in pedestrian safety testing from passenger vehicles less than 2.5 tons to include more flatter fronted models (light commercial vehicles) and in doing so, also recommended changes to test procedures to reflect the different wrap-around distance, head-form start area and head-form impact angles of these vehicles. Hardy also recommended new bonnet edge test procedures for vehicles with a high bonnet leading edge.

In 2012, pedestrian safety testing did not include the rapidly growing market of active safety technology (Hu and Klinich 2012). Hardy (2007) recommended the development of standards for brake assist systems. It has also been recommended that integrated systems be evaluated as a whole rather than by their separate parts (Hu and Klinich 2012). And in evaluating integrated systems it was recommended that full dummy testing be used rather than body component forms (Fredriksson, Shin et al. 2011).

7.0 Vehicle designs for Pedestrian Protection

Passive safety designs offer protection to specific pedestrian body parts from specific vehicle components. Pedestrian outcome can be improved by prolonging the duration of each impact through

- reducing contact stiffness and
- increasing crush depth

at locations as determined by the vehicle type and pedestrian height (Hu and Klinich 2012).

Pedestrian height has been shown a significant factor in studies of adult versus child injury outcome benefits associated with pop-up hoods and windshield airbags. Bonnet and windshield countermeasures have been shown to have little benefits to children (Hu and Klinich 2012) because of differences in trajectory after impact.

Recommendations and mandates from road safety authorities have led to manufacturers reducing vehicle body stiffness to create a protecting crush depth at bumpers, bonnet leading edges and bonnet tops; and they have also lead to more curve to bonnets and bull bar removals from SUVs (Simms and Wood 2006). Furthermore, passive, deployable, impact sensing systems such as pop-up bonnets and windshield airbags have been developed.

Deployable systems are dependent upon the accuracy and reliability of the sensor system used to ensure that risk of injury is not increased by the safety system. Further discussion of active systems sensor technology follows in Section 8.

7.1 Bumper Design Counter measures

The bumper is usually the first point of contact and as a result lower extremity injuries are reduced primarily by reduced stiffness, however this is constrained by its function in protecting the vehicle in low-speed object or vehicle impacts, by its composition and by its depth which has generally reduced from that of vehicles styled 40 years ago (**Figure 19**). The smoother front-end increases the impact contact area which in turn reduces the lower-extremity injury risk, however it also affects the amount of the bending in the knee (Hu and Klinich 2012). Functional stiffness is maintained by positioning an extra lower stiffener below the bumper, which has a protective effect on the knee by sacrificing the tibia, which if fractured is easier to heal than the knee (Fredriksson 2011).

Bumper materials used to absorb energy include foam inside a moulded plastic outer shell. The energy absorption of such materials has been found to reduce the tibia fracture risk of centre impacts but not for bumper side impacts where the foam is thinner (Matsui, Hitosugi et al. 2011).

Loading location and bumper height, rather than bumper stiffness, influence the bending and shear to the knee area (Matsui 2005). Additional support in the form of a vertically larger bumper, bumper airbags and fixed or deployable lower stiffeners reduce knee bending (Schuster 2006), however a fixed lower stiffener will reduce bumper clearance and deployable stiffeners and bumper airbags are costly and rely on the efficacy of the sensing system. The functionality constraint of bumpers has meant that in order to continue improving energy absorption in bumpers after materials, shape and positional optimisation has been achieved, deployable systems are required. Future developments will be needed to overcome cost, sensor efficacy and clearance issues.

Older pedestrians benefit the most from bumper countermeasures. It was discussed earlier that older pedestrians face greater proportions of lower extremity injuries than do adults due to their frailer bone structure.

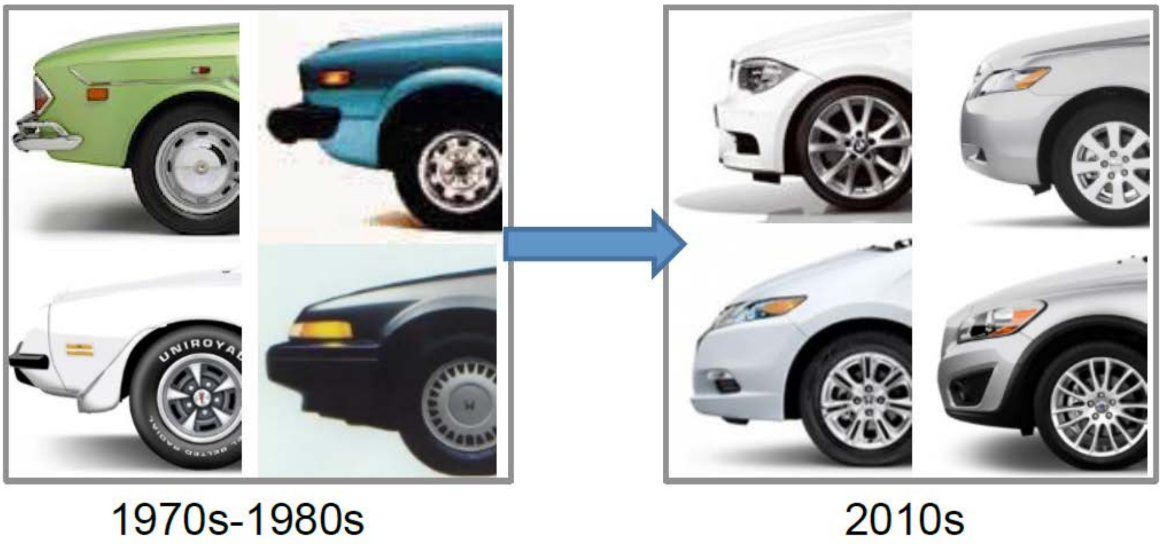


Figure 19
Change in vehicle bumper syle (Hu and Klinich 2012)

7.1.1 Bumper Air Bag

Bumper airbags are designed for both pedestrian and vehicle impact energy absorption. As they need to inflate before impact, sensing of the impending collision must be made before impact. In order to be useful for pedestrians, the sensor used must be able to detect pedestrians and not just approaching vehicles and objects; and the airbag must be positioned such that protection against colliding vehicles is not made to the detriment of potential pedestrian outcomes.

Assuming effective sensor activation, dampened bumper airbags have been shown to reduce neck bend and body rotation and thus improve the retention of the pedestrian on the bonnet (Holding, Chinn et al. 2001). If a pedestrian is retained on the bonnet, they are less likely to be hit by another vehicle or suffer a severe ground impact injury (Pipkorn, Fredriksson et al. 2007).

Increased risk of lower extremity injuries, produced by the flatter, higher fronts of SUVs, has been found to be reduced by the use of deployable airbags. The results of leg form testing at 40 km/h in SUVs showed that reductions to knee bending angle, knee shearing displacement and tibia acceleration were possible with the fitment of below bumper 134 litre airbags (Pipkorn, Fredriksson et al. 2007). Torso injury tests were devised using side impact dummies to evaluate the protective effect of a bonnet leading edge airbag (Fredriksson, Flinke et al. 2007) in SUVs. The study found the airbag not to be sensitive to the bonnet leading edge stiffness. It also found that (AIS≥3) injury risk loadings were reduced when using the airbag by 42% to 97%, so that large risk reductions were estimated for the chest and abdomen and pelvis.

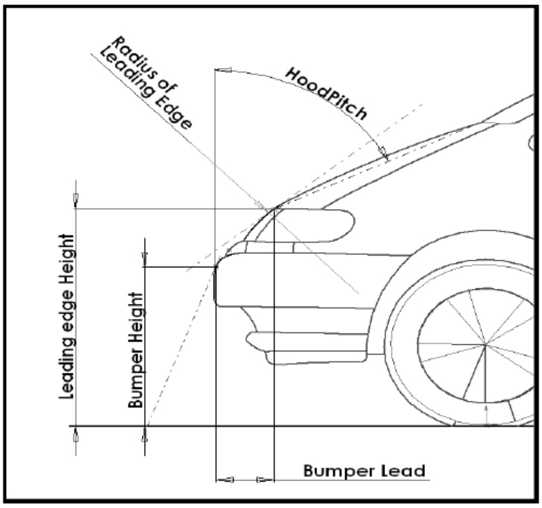
7.2 Bonnet Design Countermeasures

The bonnet an the area likely to collide with the pedestrian head or torso so bonnet design countermeasures are a good place to start to increase pedestrian safety especially when considering fatalities are more likely to result from head and torso injuries than from other body parts. Furthermore, given the different trajectory path for pedestrians colliding with SUVs, countermeasures for the bonnet and bonnet leading edge are more critical in SUVs than windshield airbags. The reverse would be true for passenger cars.

7.2.1 Leading Edge/ front-end geometry

Figure 20 shows that modern car designs have a more aerodynamic shape which is less protruding than in the 1970's, so pose reduced risk of pelvis and thigh injuries than previously. The optimum leading edge design for the best lower-extremity injury outcome was described by Snedeker (2005) as:

- A low leading-edge height <750mm (sedan)
- A large hood-edge radius >250 mm (SUV, Van)
- A moderate bumper lead >150 mm (Van) and
- A high bumper edge >490 mm (SUV, Van, Sedan)



	Sedan		SUV		Van / A-Box	
	Class Avg.	STD	Class Avg.	STD	Class Avg.	STD
Model Year	1996	2.9	1998	1.4	1997	1.7
BH	500	20	640	30	580	60
BL	140	20	140	50	160	60
LEH	740	50	1020	90	860	130
Rad. LE	230	130	410	370	730	530
Hood Pitch	79	1.5	80	2.9	65	4.5

Figure 20
Average geometric characteristics of vehicle types (Snedeker, Waltz et al. 2005)

Snedeker also found that a rounder hood improved outcomes of moderate leading-edge height (750-850 mm) because the roundness affects the pelvis/thigh contact speed. The flatter bonnet styles of cars prior to the 1980s, which somewhat resemble current SUV front profiles, were also associated with greater proportions of torso injuries (Hu and Klinich 2012).

Kausalyah et al. (2014) used simulations to optimise the vehicle front-end geometry for both adult and child. They found that front-end designs optimised for 6-year old children were unsafe for adults and vice-versa. Their optimised design not only avoided run-over scenarios but also minimised HIC values for both the adult 50th percentile male and the 6-year old child pedestrian. Their optimisation program can also be altered to suit any targeted bias. Their optimised design is as follows:

Windshield angle	40°
Bumper length	10 mm
Bumper Centre Height	435 mm
Hood Leading Edge	150 mm
Hood Length	782 mm
Hood Angle	11°
Hood Edge Height	839 mm

WSα (Degrees)	Windshield Angle
BL	Bumper Lead
BCH	Bumper Centre Height
HLE	Hood Leading Edge
HL	Hood Length
Hα (Degrees)	Hood Angle
HEH	Hood Edge Height

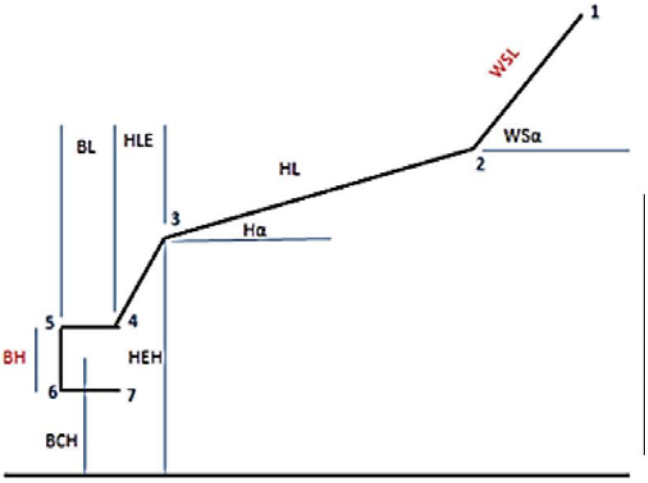


Figure 21
Front end design parameters and profile shape(Kausalyah, Shasthri et al. 2014)

The stiffness of the leading edge is limited by the hood latch, lamp housing and rigid edge support (Hardy, Lawrence et al. 2007). Room for improvement to stiffness of these features has been found through

- A downward latch design (Kalliske and Friesen 2001),
- Deformable lamp housing (Hardy, Lawrence et al. 2007) (Lucas 2000) and
- Moving the front hood edge rearward (Hardy, Lawrence et al. 2007).

Deployable airbags have been proposed for SUV front hood edges to mitigate thorax injuries caused by their higher front ends (Fredriksson, Flinke et al. 2007).

The trends in safety regulation testing have led to design developments being more focussed on bumper than on bonnet improvements.

7.2.2 Bonnet stiffness and under-hood space

Severity of head injuries may be reduced by improvements to stiffness and crush zone of the relatively compliant sheet metal bonnet and laminated glass windshield area. As with the bonnet leading edge, the energy absorption of the bonnet is limited by underlying rigid structures such as the engine and reinforced edge, and the least energy absorbent region of the windshield area is the rigid A-frame, which is essential for support. In the areas where a crush zone[22] is impossible and stiffness reduction impractical, deployable countermeasures offer the only measure for improved energy absorption.

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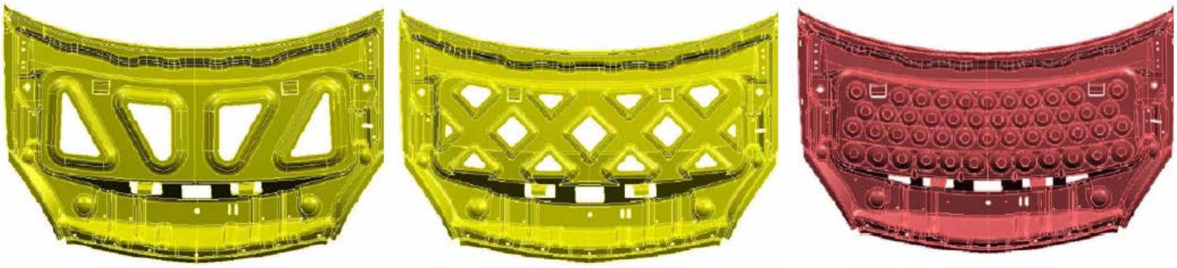
[22] Deformation distances of 60-70 mm can be sufficient to achieve the acceptable standards in HIC Okamato, M., A. Akiyama, K. Nagatomi and T. Tsuruga (1994). *Concept of hood design for possible reduction in head injury*. The 14th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Munich,

Vehicle type/geometry is not the sole determinant of the bonnet impact position; impact speed, angle and position as well as pedestrian height and weight will have influence. This means that energy absorption must be possible in all regions of the bonnet regardless of which engine components lie beneath. As a result effort has gone into energy absorbing bonnet designs such as those with multi-joint hinges (Kerkeling, Schaefer et al. 2005), sandwich designs which improve child injury outcomes (Liu, Xia et al. 2009, Shojaeefard, Najibi et al. 2014) and hybrid hoods with thermoplastic wire structure (Belingardi, Scattina et al. 2009).

A typical bonnet is constructed of a strong inner body and a stylish aerodynamic upper body. The strength is needed for durability, closing endurance, misuse and crash performance. It may be composed of steel, HPPC (a thermoplastic composite material capable of superior impact absorption) and foam composites and include materials such as shock absorbing glue between inner and outer panels (Shojaeefard, Najibi et al. 2014).



(a) Traditional Design (b) Increased Rib Design (c) Multi Cone Design

(d) Sandwich Design (e) Hybrid Design Concept (f) Wire Hybrid Concept

Figure 22

Different hood designs for improving pedestrian head protection (a) to (c) are from Kerkeling et al. (2005), (d) is from Lui et al. (2009) and (e) to (f) are from Belingardi et al. (2009).

Germany., however a 100 mm under-hood space reduced skull fracture-related and brain-related injury criteria at 40 km/h impact velocities Fredriksson, R., L. Zhang and J. Bovenkerk (2009). *Influence of deployable hood systems on finite element modelled brain response for vulnerable road users*" International Journal of Vehicle safety **4**(1): 29-44. .

Shojaeefard et al. (2014) proposed four inner structures with more efficient energy absorption than the usual inner structure which has ‘hard points’. Their suggestions avoided extra deformation of the hood whilst maintaining impact absorption and torsional latch strength, without the addition of significant extra weight (at most 12.7% heavier hood). The advantages claimed included improved pedestrian safety and hood strength and reduced required gap between hood and engine. The efficacies of these designs are still constrained by the limited under-hood clearance, and once energy absorption has been optimised by hood design, deployable countermeasures again offer the only way to further improve pedestrian safety. In the interests of pedestrian safety, bonnet heights have been increasing in recent years to expand the crush space (Takahashi, Miyazaki et al. 2013). Satisfactory linear and rotational head impact test results were found using an under-hood distance of 100mm at 40 km/h head impact speeds (Fredriksson, Zhang et al. 2009). Furthermore, a 20 mm decrease in under-hood distance was comparable to a 10 km/h increment in speed with regards to head and brain impact loading (ibid).

To improve bonnet fronts for child impacts, Yao (2007) suggested that bonnet designs be improved with smooth edges and energy absorbing materials, and unevenly structured hood surfaces, such as hood rims and air intakes on the hood, avoided. Yang et al. (2005) concurred that child injury severities could be improved with improved car frontal design.

7.2.3 Pop-up bonnets

Vehicle style and practical designs may prohibit a raised bonnet height to create a sufficiently large crush space, so Pop-up Bonnet systems were developed as a pedestrian protection technology for vehicles with a narrow space between the inside surface of the hood and the rigid parts in the engine compartment. As the main pedestrian head injury to bonnet assessment is made with the Head injury Criterion (HIC) test, the aim of these systems is to reduce the HIC by creating a greater space by lifting the bonnet before the pedestrian head comes in contact with it. Lifting the bonnet has the advantage over a deployable bonnet airbag in that it is no longer sensitive to the problems of correct positioning.

Pop-up bonnets include a sensor in the bumper, an electronic control unit (ECU) that judges whether to operate the actuator, a bonnet actuator that lifts the bonnet, and a hinge release mechanism. When a sudden (pedestrian) impact is sensed through impact of ‘leg to bumper’, the rear of the hood is raised 50-120 mm, (within 60 milliseconds of the first leg-to-front 40 km/h impact, and 40 ms at 60 km/h), to present an additional crush space permitting additional energy absorption and reducing head and torso injuries (Oh, Kang et al. 2008, Inomata, Iwai et al. 2009, Huang and Yang 2010). The timing is dependent on the pedestrian height so efficacy for both children and adults is complex. Some designs may be difficult to apply to low engine hood vehicles such as sports cars, however some compact configuration designs with collapsible actuators have been developed (Inomata, Iwai et al. 2009).

Reversible hood actuator systems require more activation time than contact sensors provide so need to use collision warning sensors, but they have the advantages of being re-deployable after false activation.

The main issues with pop-up bonnets are related to the sensors and the actuators (Takahashi, Miyazaki et al. 2013). Bumper sensors must be able to detect the pedestrian leg across the entire vehicle front. Takahashi et al (2013) addressed this problem with a design that uses the concept of effective mass and is able to sense the difference between a 6 year old and an adult. Effectively, this works on the principle that a body will collapse onto the hood when hit whereas a pole is fixed in the ground so will collapse to the front of a vehicle. This means that the pedestrian will be in contact with the upper bumper for a longer time so that a pressure chamber across the top of the entire vehicle front bumper will enable sensors to detect the energy absorption characteristics regardless of the lateral position. Fiat achieved their bumper sensor sensitivity with the use of piezoelectric polymers (Zanella, Butera et al. 2002). An issue with actuators is to maintain the popped up height throughout the absorption of energy at the time of impact. Takahashi et al (2013) addressed this with a micro gas generator activated rod which pushes the bonnet down with the head impact, helping to absorb impact energy regardless of the impact position on the bonnet.

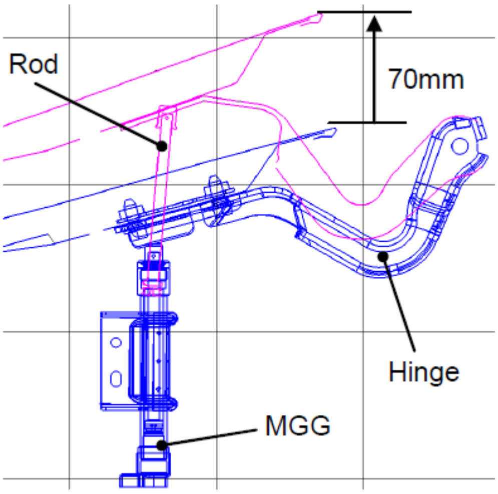


Figure 23
Actuator lift up height (Takahashi, Miyazaki et al. 2013)

There will be some impacts where a pop-up bonnet offers little or no benefit with respect to head injury; when the shoulder hits the bonnet before the head impact, the decrease in head impact velocity associated with energy absorption from the pop-up hood can be compensated by the increased velocity encountered by the earlier impact caused by the lifted bonnet and in addition the shoulder impact may compromise the crush space prior to head impact to the bonnet insert {Fredriksson, 2011 #170.

Pop-up bonnets need to activate early enough for children and short adults and long enough for tall adults.

Pop-up hood (Inomata et al. 2009) Windshield airbag (Kuehn et al. 2005)

Figure 24

Deployable passive windshield and hood safety devices

Pop-up bonnets are available on the Australian Honda Legend and the Citroen C6 (Road Safety Committee 2008) and are in production in Jaguar, Citroen, Honda, BMW, Mercedes Benz, Cadillac, Nissan and Porsche models.

7.3 Windshield Design Counter measures

Laminated glass, which has improved energy absorption over regular glass because of its multi-layer nature, is fairly compliant during crashes. The type of laminated glass used in windshields can improve pedestrian outcomes through greater efficiency in energy absorption (Pinecki, Fontaine et al. 2011). If a non-porous material is substituted in the inter-layer more energy absorption is offered (Xu and Li 2011).

7.3.1 Windshield Airbags

The increased injury risk and severity of the windshield frame compared with the glassed areas has already been noted in this report, along with the fact that the stiffness of the A frame and cowl cannot be compromised as it functions not only to hold the glass in place but also has a role in occupant protection. The U-shaped windshield airbag (**Figure 24**) fills the gap between the windshield frame and pop-up bonnet, covering the A-pillars, so that energy is absorbed prior to impact with the stiff frame. However reliability may be compromised by complexity.

This technology has now been developed for production vehicles and has been available since 2012 in the Volvo V40 (Jakobsson, Broberg et al. 2013). Sensors in the bumper are able to discriminate pedestrians from objects at speeds between 20 and 50 km/h. The sensors input the control unit to activate the pedestrian airbag and to release the hood hinge. The airbag raises the hood rear by 10 cm by releasing the hood hinge in a controlled limited way. The airbag inflates in a few milliseconds and stays fully inflated for 300 milliseconds covering about one third of the windscreen and part of the A-pillars.

A pop-up alternative to the windshield airbag has also been explored: a dampened flexible protective panel (Road Safety Committee 2008).

Windshield airbags have the fault that if falsely deployed may obstruct vision and cause crashes, so are constrained to the lower windshield and A-pillars (and roof edge in very small cars) to a maximum size needed which allows visibility to driver.

If the air bag can be extended 200 mm higher that the current standard of 2.1 m, the percentage of pedestrians addressed is raised from 60 to 90% of severely injured (Fredriksson 2011). Windshield airbags have recently been associated with 42% HIC, 60% neck compression and 30% neck moment reductions (Bovenkerk and Sahr 2009).

7.4 Integration of passive Countermeasures

Integrated passive countermeasures have been established as effective at reducing pedestrian injury and can be enhanced with the use of pre-crash sensors. Combined bumper and bonnet airbags integrated with pedestrian sensors deployed in 40 km/h and 48 km/hr speed zones have been shown through simulations to reduce adult (50th percentile) pedestrian injuries in SUV and saloon passenger cars. At 40 km/h impact speeds reductions found were as follows: Head Injury Criteria (HIC) by a factor of 5, chest acceleration by 49% (40 km/h), pelvis acceleration by 12%, knee lateral acceleration by 71% and in saloon cars only, knee lateral angle by 40% (Holding, Chinn et al. 2001). The protective effect was reduced when impact speeds were raised to 48 km/h; with average injury criteria 30-40% higher (Holding, Chinn et al. 2001).

Integrated passive designs interact with one another; for example a lower (height) bumper will potentially increase the head impact speed and a pop-up bonnet can have a negative effect if no windshield airbag is present (Hu and Klinich 2012) (Hamacher, Eckstein et al. 2011). Fredrikkson et al. (2011) used full 50th and 90th percentile male dummy models to study chest injuries in integrated pop-up bonnet and windshield airbag systems in medium and large cars. They found that the countermeasures did not reduce chest loading and that pop-up bonnets, which were designed to minimise HIC, needed further redesign to reduce chest loading.

7.5 Vehicle Design Countermeasures Summary

- Vehicle front end designs have become more aerodynamic over time; rounder hoods have improved pelvis/thigh outcomes, however shallower and smoother bumpers have increased the amount of bending in the knee.
- Generally the front end geometry can be optimised for both adult and pedestrian protection.
- Bumper design currently has design features which:
  - protect the knee by sacrificing the tibia, and
  - centrally (but not at edges) protect the tibia by the use of materials which improve the energy absorption , but
  - are constrained by the functionality required for vehicle to vehicle collisions and the effectiveness of collision sensors.
- Bonnet design currently has design features which:
  - make use of materials, design and layering to improve energy absorption,
  - improve the energy absorption of traditionally rigid parts such as latch, wiper engines and lamp housing, and
  - position components to minimise pedestrian injury; e.g. front hood edge moved rearward and increase the crush zone with higher hoods, but
  - are constrained by functionality and style (which limits crush depth).
- Windshield design currently has design features which:
  - make use of materials, such as laminated glass to improve energy absorption, and
  - are constrained by functionality of the rigid A-pillars.
- Windshield, Hood and bumper passive safety designs offer additional protection to pedestrians over that optimised by vehicle design and constrained by vehicle functionality; in general they must:
  - consider both adult and child trajectories,
  - be correctly positioned (airbags only) so that the do more good than harm,
  - allow for continued driver visibility, especially if falsely deployed,
  - minimise false deployment,
  - activate at the right time and stay deployed for the required protective time and
  - consider integrated effects.
- Improved hood and bumper design will most benefit older pedestrians.
- Deployable systems increase the time spent on the vehicle and thus reduce the severity of ground injuries and the likelihood of being hit by another vehicle.
- Deployable systems are particularly beneficial in SUV vehicles.
- Bonnet and windshield safety design has not been as progressive as bumper design and has not been developed using full dummy models to enable minimisation of torso injuries.
- Pop-up bonnets and windshield leg-form sensors need to
  - be able to distinguish human from object,
  - detect over the entire bumper width,
  - detect over a range of impact speeds
  - deploy early enough for children and short adults and
  - provide sufficient time for the deployable action.

8.0 Visibility Counter-measures and Pedestrian Sensors

8.1 Pedestrian sensors

Pedestrian sensing devices on motor vehicles which work under the full range of EMC, speed, light and weather conditions are still under development. They need to be able to distinguish pedestrians of all sizes from objects and track them over time in a way that will enable sufficient braking time and distance. To maximise the working ranges, a variety of sensor technology is employed, including radar and stereo vision (Matsui, Han et al. 2011). Combining the information from several different and disparate devices is called *sensor fusion.* If the information is redundant it may be used to eliminate false positive which are still a problem in high pedestrian areas (Cairney 2000).

The two main *camera* sensor types are CMOS and CCD. They recognise pedestrians, with high resolution, from their contour and their expected movements. Depth can be measured if cameras are used in stereo, however, speed cannot be measured with camera sensors.

Infrared sensors have been found able to differentiate pedestrians from incident and reflective solar light, and radar sensors are reliable for pedestrian movement detection (Holding, Chinn et al. 2001). Different radar sensors are useful for long range early prediction and shorter range tracking (McCarthy and Simmons 2005). Monocular infra-red cameras for night time pedestrian detection are in development (Liu, Zhuang et al. 2013). The range, cost[23] and limitations of various sensor technologies have been summarised in literature {Lemmen, 2013 #202}(McCarthy and Simmons 2005).

McCarthy (2005) also evaluated High Resolution *RADAR* (HRH) which is a short range radar operating in the 24 GHz ISM band. It was found to perform well with velocity vectors parallel to the vehicle, however there was a tendency for false deployment for near miss scenarios with the pedestrian velocity at an oblique angle to the vehicle. Apart from the scenario with pedestrians amongst vehicles parked at the side of the road, performance over a variety of simplified test scenarios was judged good to excellent, accurately tracking the pedestrian and reliably predicting the point of impact and activating the protective system at the appropriate time.

In general RADAR technology has inferior resolution to image based devices, but can complement the high resolution of camera technology in sensor fusion. For example, Toyota uses the sensor fusion of millimetre band/wave radar (30-300 GHz) combined with camera technology to accomplish early detection of pedestrians quickly crossing the road (Hayashi, Inomata et al. 2013) At night the system uses near infrared projectors to enhance camera detection. As a result high deceleration rate AEBS was installed in the Lexus LS 2012 model.

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[23] This table has been included in the appendices.

Photonic Mixing Devices (PMD) sensors capture grey-scale and distance information of pedestrian shape and posture with near infrared (850nm) technology, acting with perception up to several metres.

Light Detection and Ranging (LIDAR) uses short laser pulses to measure the distance to a pedestrian

Actual sensors work with a less than 180° field of view. However, sensor systems have been found robust to the field of view with respect to pedestrian fatalities: a decreased fatality rate from 44% to 40% and serious injury rate from 33% to 27% were associated with a decrease from 180° to 40° in an autonomous braking pedestrian sensor system (Rosén, Källhammer et al. 2010).

Sensors which provide only a warning (audible, visual or vibration) have the disadvantage of providing a distraction at a time when the driver is already dealing with a danger (Saad, Hjalmdahl et al. 2005); sensors teamed with an appropriate automated response help reduce the danger without the additional cognitive workload burden for the driver.

Forward looking pedestrian sensors may alert the driver to a collision, or may be incorporated with passive deployable systems or with BAS or autonomous braking systems to enhance or automate (respectively) the braking process (Hardy, Lawrence et al. 2007). Rearward sensors and cameras can aid with prevention of low-speed reversing collisions.

With improvement in reliability, integration with passive and active systems may allow for earlier detection and greatly enhance the performances of the systems (McCarthy and Simmons 2005). For example, pop-up bonnets are generally deployed by bumper contact sensors and some (reversible hood actuator) Pop-up hoods require more activation time than contact sensors provide (Fredriksson 2011).

Integrated with a collision warning system (which warns and prepares the vehicle for a collision), pedestrian sensors have been costed at up to $8,000 (Cairney, Imberger et al. 2010).

8.2 Pedestrian visibility Counter measures

8.2.1 Low speed run-over crashes

Visibility of pedestrians to drivers is a known contributing factor to a pedestrian-vehicle collision, especially in the case of ‘low speed run-over’ crashes. Added technology may compensate for vehicle designs with poor or limited vehicle visibility (such as side and rear view from vans and SUVs). Sensors and reversing cameras may prove helpful in reducing these kinds of collisions especially when SUVs are involved given their extra height and diminished rear vision capability; Fildes et al. (2014) have identified the need for research in this area with a feasibility study.

Some manufacturers have included front and rear sensors which after sensing an on-path object will to trigger autonomous braking (BITRE 2012), however, reversing cameras still suffer from several limitations.

- Reversing sensors alone are currently not sufficiently sensitive to detect some small, narrow and moving objects (such as small children playing behind a car) (Mazzae and Garrott 2006) (Fildes, Newstead et al. 2014), nor to excessive reversing speeds (Llaneras, Green et al. 2005).
- Studies have found that drivers typically turn off ultrasonic/microwave parking sensor due to perceived poor reliability (Mazzae and Garrott 2006).
- Sensors typically work to distances of 1.5m at 3 km/h speeds whereas the rear visibility distances may begin at best at 3 m or 19 m in passenger cars (Paine, Macbeth et al. 2003).
- Longer sensor working distances and narrow driveways have been associated with excessive false positives.
- Sensors have been found ineffective at speeds greater than 5 km/h (Paine, Macbeth et al. 2003).

Paine (2003) recommended that cameras and sensors be used together. Back-up cameras may display passively on a centre console mount or may be combined with sensor-based alerts. The camera display is for the area directly behind the vehicle. Future developments may include mirror based camera displays which activate when vehicle is in reverse (Paine, Macbeth et al. 2003).

8.2.2 Enhanced Night Vision

A 2011 pedestrian crash study from the US found that the majority of pedestrian involvements happened in daylight (57%) but the majority of pedestrian deaths occurred at night (75%) (Jermakian and Zuby 2011). Pedestrians are also at higher risk of vehicle collisions at night, and enhanced night vision systems help reduce this risk by making pedestrians more visible to drivers at night. This is particularly useful for older drivers who are more sensitive to light conditions when trying to make out objects on path. Night vision enhancement of pedestrians has been estimated to double detection distance (from 40 m) (Cairney, Imberger et al. 2010).

Near infra-red and far-infrared (FIR) sensors are able to create an image that differentiates objects from the environment at night on a centrally mounted display in a heads-up or heads-down configuration (Cairney, Imberger et al. 2010). FIR sensors work better than NIR sensors at enhancing the visibility of pedestrians, but it is at the cost of a less realistic and translatable image (ibid.). The display can be enhanced by radar.

Infra-red technology fitment availability is limited to high-end vehicles as standard or as an option at a cost of about $3,000 (ibid.). As a retrofit in cars and motorcycles, it can be rented from about $60 per week (ibid.) from Vissacon (http://www.vissacon.com.au). Infra-red detectors are available in vehicles manufactured by Cadillac, Lexus, BMW, Audi, Honda, Mercedes and Toyota (Fredriksson 2011).

8.3 Vehicle visibility Countermeasures

Improving the conspicuity of vehicles to pedestrian may be achieved by running lights (DRLs) during the day, which in theory would when viewed from the front, in low-light conditions contrast with the background, however, it has been shown to be of no advantage in the higher levels of illuminations typical over much of Australia, over much of the year (Cairney 2000).

Improving conspicuity of vehicles may also be achieved through audible signals. It has been recommended that noise making equipment be fitted to electric wheelchairs, golf carts, Segways or silent, electric or hybrid cars, which operate more quietly than vehicles fully powered by combustion engines, to enable pedestrians to hear them coming and gauge their speed (Zegeer and Bushell 2012).

9.0 Active Crash Avoidance Technology

Speed has been identified in this report as a significant contributor to the risk of pedestrian injuries and death. In addition to decreased speed limits and enforcement in high pedestrian regions, traffic speed reduction can be achieved through calming measures such as speed bumps, lane narrowing, and changes in roadway curvature (Teft 2013). Speed limits in areas with high frequency car-to-pedestrian collisions have been recommended at 40 km/h (Peng, Chen et al. 2012) after findings of 50% (AIS≥2 and AIS≥3) serious head injury risks at impact speeds of 38.9 and 54.4 km/h respectively. Yao (2007) recommended 30 km/h limits around schools, residential and commercial areas after findings of AIS≥2 child head injury risk increasing sharply at speeds >30 km/h.

In addition to speed limit reduction, impact speed may be reduced with technology. Active safety features are designed to improve collision avoidance principally through alerts and/or speed reduction through brake-assist or autonomous braking systems. They reduce severity or prevent all pedestrian injuries regardless of the specific body region, and regardless of whether caused by primary vehicle or secondary ground impact. As such they protect all pedestrian types in all vehicle types and thus provide the potential to prevent all pedestrian injuries.

It is important to also point out that ground injuries cannot be prevented by passive systems of protection and vehicle design. Also, a greater proportion of pedestrian injuries are caused by ground impacts arising from LTV collisions than from passenger cars (Hu and Klinich 2012). Speed reduction, potentially through the use of active systems, is thus essential for preventing (or reducing the injury outcome from) ground impacts, particularly when the colliding vehicle is an LTV.

Passive countermeasures and safety testing focus on lower extremity and head injuries; more focus on active countermeasures which reduce torso injury is therefore needed. LTVs contribute more to torso injuries than passenger cars and that torso injuries may be a significant contributor to death, so speed reduction, through active systems is particularly relevant in SUVs.

Speed reduction through active safety systems will also be a greater benefit to reducing injury severity in the elderly and in children; the elderly because of frailty, and children because of the poor protection offered them through passive systems based on adult trajectory. Furthermore torso injuries, which are largely ignored in pedestrian safety testing and hence overlooked in passive safety countermeasures, are more frequent than head injuries in the elderly and in children.

Initially the potential collision must be sensed, and most recent developments have been involved in the technology associated with sensing to attempt to widen the speed and environmental ranges of accuracy in active systems. If successful in detecting pedestrians in the three most common crash scenarios (straight/crossing, straight/in-line and turning/crossing), it has been predicted for the USA that as many as 65% of pedestrian involvements and 58% of pedestrian fatalities in single-vehicle crashes could be mitigated (Jermakian and Zuby 2011).

9.1 Brake Assist Systems

Most drivers do not make the full use of the braking system available to them. Brake assist systems (BAS) aim to improve drivers' braking performance in emergency situations by detecting the situation and increasing the chance that fast, efficient braking is achieved (Breuer, Faulhaber et al. 2007). The fast efficient braking should be the maximum achievable braking rate or braking which causes full cycling of the Anti-lock Braking system (Badea-Romero, Paez et al. 2013). The ABS will prevent wheel lock during BAS activation.

BAS will reduce pedestrian collisions in which the driver has reacted quickly but not with sufficient vigour, because BAS only activates if an emergency situation is detected through an unusual high brake pedal speed, and BAS is only effective if the driver has not maximised the braking capacity of the vehicle (**Figure 25**).

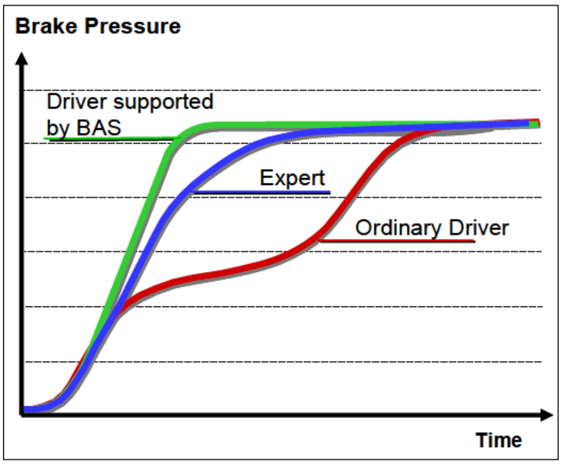


Figure 25
Illustration of typical brake pressure build-up in an emergency situation for ordinary drivers, expert drivers and drivers supported by BAS (Breuer, Faulhaber et al. 2007)

BAS+ABS have been found to generally reduce pedestrian injury; more so when the driver was unable to brake to the full stroke (e.g. due to time and space) (Badea-Romero, Paez et al. 2013). Increases to injury were found when the BAS only made small reductions to impact speed; in these cases, impact speed was less relevant factor and deployable devices would have benefit (ibid). **Figure 26** shows that reductions to the ISP (a head injury index) of up to 50% corresponded with low reductions in impact velocity, suggesting that vehicle frontal design and pedestrian factors are important at lower speeds.

BAS is currently in production and has proven pedestrian protection: e.g. analysis of German crash data demonstrated a reduction in severe pedestrian crashes involving Mercedes Benz vehicles on standard BAS fitment compared with similar vehicles (Breuer, Faulhaber et al. 2007).

BAS are standard on a wide range of Australian and New Zealand vehicles including the full range of Mercedes-Benz vehicles since 1997 (Cairney, Imberger et al. 2010). A list of those available in 2008 may be found in the appendices. BAS were mandated in new vehicles in Europe in 2008.

BAS systems have claimed to reduce stopping distance by up to 45% on dry roads (Breuer, Faulhaber et al. 2007) and to reduce impact speeds by 5 to 7 km/h (Barrios, Aparacio et al. 2009).

Figure 25 shows that

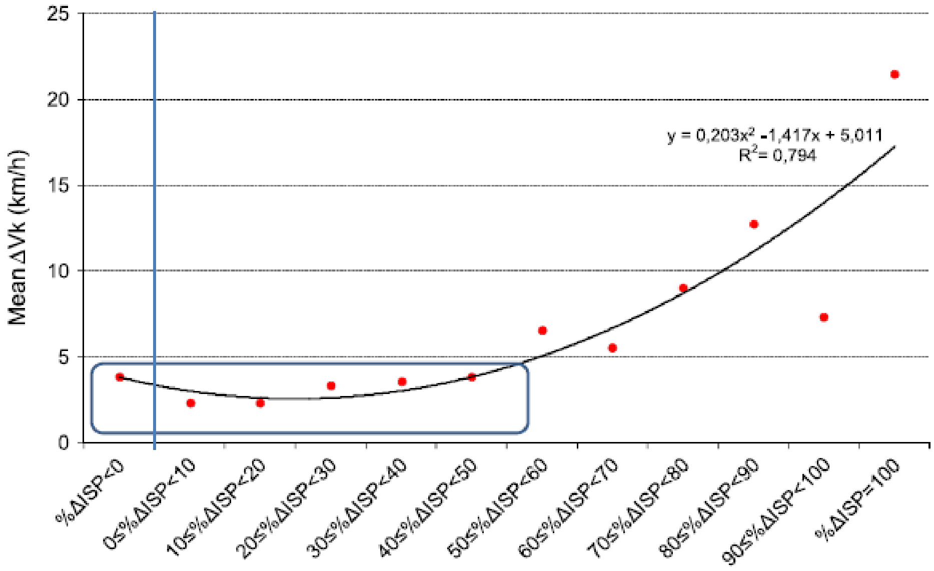


Figure 26

Mean Collision Speed BAS reduction by the rate of ISP variation (Badea-Romero, Paez et al. 2013)

9.2 Autonomous Emergency Braking Systems (AEBS) or PBAS

The BAS relies on a driver braking actions, so would not activate in all situations; initiation is estimated in only 50% of pedestrian collisions due to drivers' poor observed brake responses (Hannawald and Kauer 2004). Pre-emptive brake assist systems (PBAS) will detect when a collision is imminent using a collision warning system, and in response initiate the BAS functions in support of driver braking, or automatically if driver does not respond (Cairney, Imberger et al. 2010). The area immediately in front of the vehicle is continuously monitored with short and long range radar and cameras, each detection system complementing the deficiencies of the other. Thus autonomous emergency braking systems offer wider pedestrian protection, which is possibly double that of BAS alone (Section 11.0).

For example, in Mercedes-Benz systems, the warning system starts with an audible and visual alert 2.6 seconds before calculated impact; then if there has been no driver reaction after 1 second, autonomous partial braking is activated; and then after another second, if there is no driver intervention of swerving or full-braking, then full autonomous braking is activated (Breuer, Faulhaber et al. 2007).

AEBS do not aim to avoid collisions but to reduce the force of the collision through reduction in impact speed. Thus braking is conservative, and may start at deceleration rates as low as 2.5 m/s^2 and end with a shorter higher 5.9 m/s^2 burst (Road Safety Committee 2008). They also may be supplemented by a reduction in engine power, which has the potential to reduce impact speeds by up to 15 km/h (Matsui, Han et al. 2011). There are claims that the systems will stop vehicles travelling at 25km/h or reduce speeds by up to 40 km/h and thus completely prevent a low speed pedestrian collisions (Fredriksson 2011, Hayashi, Inomata et al. 2013). More than 50% reductions in speed using vision sensors has also been claimed (Barrios, Aparacio et al. 2009). Because AEBS reduce speed they have the potential to yield large reductions in chest, head and brain loading.

The ability of AEBS to reduce speeds is not only limited by the capabilities of the sensors but also by reduced road friction and the brake timing and force determined by the algorithms employed. Hayashi et al. (2013) have designed algorithms to induce braking which aims to not interfere with driver actions and to reduce the chance of driver dependence on the system.

Mercedes, Benz Volvo and Toyota are amongst the manufacturers with vehicles in Australia with standard or optional AEBS (e.g. MB S-Class and Lexus LS). A list of makes and models available with PBAS in 2008 may be found in the appendices.

9.3 Intelligent speed Adaption

Intelligent Speed Adaption (ISA) assists compliance with speed limits either by warning the driver or by actively slowing the vehicle control systems. This technology suffers from driver acceptability issues especially in higher speed ranges (Cairney, Imberger et al. 2010), when the speed limit is advisory, and when falsely (not) activated by on-board maps which are not up to date. They may also not reflect temporal speed limit changes due to road works, school zones or the weather. It is most effective at controlling speeds in free-flowing traffic conditions, specifically in 30-50 km/h ranges in the control of momentary excesses, approach speeds to curves, intersections and roundabouts and car-following behaviour (Ma and Andréasson 2005).

There are three forms of ISA available in Australia; all are able to determine whether the vehicle is driving over the speed limit by an interaction with a vehicle GPS (Cairney, Imberger et al. 2010). Advisory systems provide an auditory warning of exceeded speed limit. Supportive systems initiate limiting of the speed but may be overridden. Limiting/Mandatory systems limit the speed but cannot be overridden. An example of a Supportive ISA device is the in-vehicle speed limiter which produces a counter-force in the accelerator pedal when the speed limit coded into a digital map using the GPS system is reached (Ma and Andréasson 2005). This speed limiter may be over-ridden with force by the driver with the extra force required acting as a deterrent to speeding.

ISA has established effectiveness through a correlation between the reduction of free flow speed and variance and the diminishing probability of pedestrian collision and risk of death (Ma and Andréasson 2005).

ISA may is available in Australia as an option within navigation systems and as a dedicated ISA system (SpeedAlert and Speedshield) (Cairney, Imberger et al. 2010). The cost of ISA is not limited to the in-vehicle cost (approximately $3000 in new vehicles for supportive ISA), as government infrastructure is also necessary to create, update and disseminate the digital map databases in real time (Cairney, Imberger et al. 2010). The Victorian government has estimated the cost of producing a speed limit map at $3 million (Road Safety Committee 2008). Retrofit is possible but not feasible on a cost basis.

The effectiveness for ISA to reduce pedestrian injuries is limited in that it only helps to keep vehicles travelling at speed limits and to reduce speeds on approach to intersections, etc. ISA systems do not directly help the driver to see and react to potential pedestrian impacts, however studies have shown that ISA is associated with greater awareness of the presence of pedestrians (perhaps because the distraction of having to look at the speedometer is removed) (Cairney, Imberger et al. 2010).

9.4 Vehicle to Pedestrian Wi-Fi based communications

These systems, which consist of both a vehicle device and pedestrian hand held device allow vehicles to inform the pedestrian of their approach using greater than 1 Hz Wi-Fi. A study which assumes the network connection had already been established, demonstrated an effective risk calculation and hazard alarm was possible with 400m of coverage (Anaya, Merdrignac et al. 2014). The 'app' was limited by 100m of coverage if the signal was intercepted by another human being.

9.5 Electronic Stability Control

ESC is not being considered a potential countermeasure in this document. The regression results from a meta-analysis, controlled for driver characteristics, showed that fatal light vehicle crashes involving pedestrians increased with ESC fitment (Hoye 2011). No ESC effect was found in non-fatal pedestrian crashes. The Reasons supplied for this result included that ESC-equipped drivers may at times drive less carefully than other drivers.

10.0 Integrated Systems

An active sensing/braking system such as autonomous braking is expected to reduce the impact speed, which has two effects which work against each other: reduced car front pitch which makes the pedestrian impact more rearward; and reduced impact speed which reduces sliding making the pedestrian impact more forward (Fredriksson and Roudsari 2012). The resultant position from these two effects may place the pedestrian in an area not protected by passive countermeasures. Passive systems by design work optimally (or only) at impact speeds less than 40 km/h, so if active braking countermeasures reduced a high impact speed to one less than 40 km/h, then an integrated passive/active system will enhance the passive system. If the impact speed was already expected to be less than 40 km/h, further speed reductions imposed by the active system may position the pedestrian away from the passive system, or may merely provide no significant further protection than already provided by reduced impact speed.

Integrated systems can use the collision warning sensors to deploy airbags and pop-up bonnet countermeasures that would otherwise have to be activated by contact sensors. This allows for inclusion of technology that needs ‘more notice’ to be effective such as reversible actuator pop-up hoods and front edge deployables. Front edge countermeasures are of specific benefit to SUVs.

Fredrikkson et al. (2012) studied the integration of hypothetical centre fitted, all weather, all light conditions, forward looking pedestrian sensors which activated autonomous braking one second prior to predicted impact; with a passive countermeasure designed to mitigate head injuries from the bonnet, the A-pillars and the remaining windshield area up to a 2.1 m wrap around distance. The effectiveness of the integrated system at real crash data (GIDAS) impact speeds was evaluated at 50 % (95% CI: 30-70) more effective than sensors with a 180° field of vision alone and 90% (95% CI: 50-150) more effective than the passive countermeasure alone at decreasing AIS ≥3 head injuries.

Fredrikkson et al (2012) studied lateral pedestrian primary impacts to medium and large sedans fitted with AEBS, windshield airbags and pop-up bonnets using full body dummies. AEBS was modelled to reduce the speed by 10 km/h and pitch rotate the vehicle with a 1.0 g deceleration. They found that the change in impact speed produced by the AEBS altered the impact position. The results by impact configurations described by impact locations by the body region studied and grouped by the pre- impact speed are presented in **Figure 26** and show the success of the integrated system. AIS≥3 linear loading head injury risk (determined from risk curves) was decreased most by the passive countermeasures, however when determined for combined linear and rotational loading, passive restraints were less efficient, particularly for the lower windshield impacts. From **Figure 26** it can be deduced that the increases in measurements observed in integrated systems over AEBS alone are because the effectiveness of the deployable countermeasures have been compromised by a change in impact location. It is thus also possible that if countermeasures are optimised to work in an integrated system (and at higher speeds) then further improvements in pedestrian safety are possible than those measured in this study. Fredrikkson found that although passive deployable systems were designed to reduce HIC at 40 km/h, they showed potential to offer protection at higher speeds for of other body parts within an integrated system.

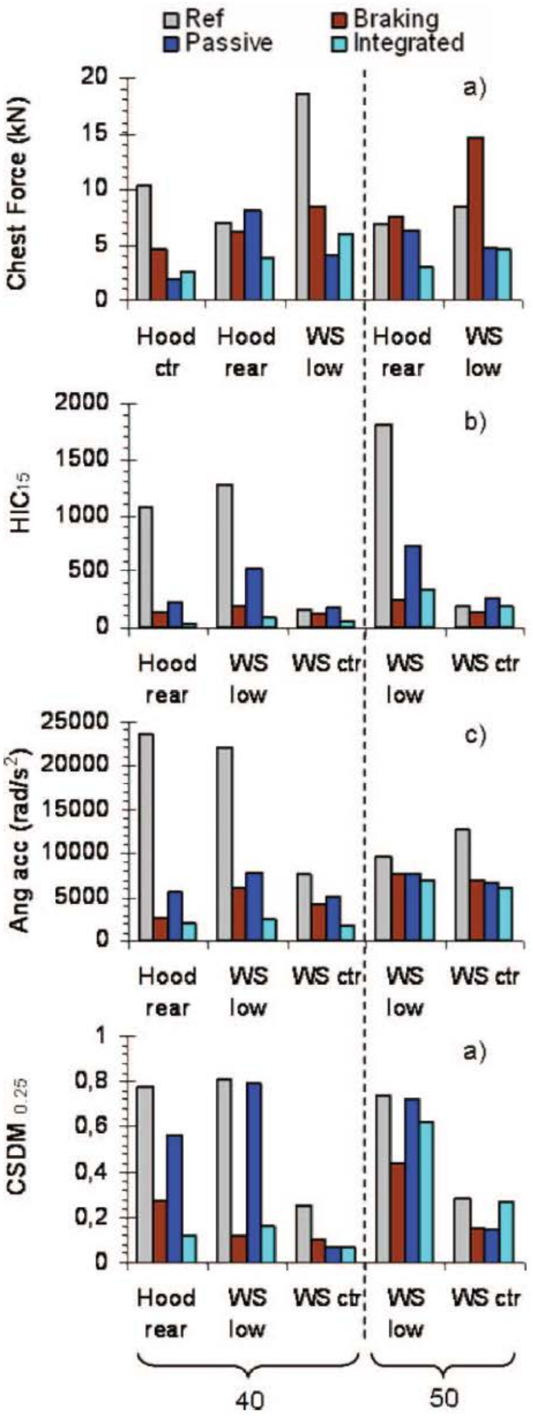


Figure 27
Peak values recorded I the simulations a) chest force, b) HIC_{15}, c) andgular deceleration, and d) $CSDM_{0.25}$ (Fredriksson, Shin et al. 2011)

Badea-Romero (2013) found, when simulating crash characteristics from real crash data, that the head impact point with BAS was not very far from the location without BAS and the stiffness at the impact point was similar, although sometimes stiffer with BAS. Velocity reduction had a more significant influence on injury when impact velocity reductions were great, and compensated for the stiffer surface, but when velocity reductions (from BAS) were small, they still found ISP (probability of suffering a AIS≥3 head injury) reduction rates to 50% suggesting the important interplay of vehicle design and pedestrian factors and providing evidence that value can be added with integrated passive deployable systems. In support, adding BAS to a set of secondary safety measures was found to boost the reduction in seriously injured pedestrians from 10% to 14.3% and fatalities from 6.3 to 11.1% (Hannawald and Kauer 2004).

Jermakian and Zuby (2011) noted that such systems as above would need to function in low-light conditions and at speeds above 64 km/h to prevent a large proportion of pedestrian fatalities. Optimal speeds for secondary systems would be the most common impact speeds: 45 km/h for head-windshield and 50-55 km/h for chest to hood/windshield (Fredriksson 2011). Protection is offered via the AEBS at speeds greater than these.

11.0 Estimates of Injury and Crash Benefits from Countermeasures

Based on these results, it is estimated that secondary safety systems for vulnerable road users, such as improved frontal design, pop-up bonnets and external airbags, have the scope to provide benefits at higher speeds to up to 54% of pedestrians and pedal cyclists with AIS AIS ≥2 head injuries and up to 61% with AIS ≥3 head injuries (Badea-Romero and Lenard 2013).

Fredriksson et al (2010) identified five high frequency severe injury mechanisms and offered 73% (95% CI, 65–81%) in potential AIS ≥3 vehicle-induced injury savings using suggested counter measures, with the acknowledgement that higher speeds will decrease their effects. Fredriksson also suggested combinations of counter measures, to cover the differences in protection needed for differently aged pedestrians, and that the counter measures are optimised at the median impact speeds (Table 6) or at the current test speeds.

Table 6 : accumulated frequency of addressed pedestrians for different injury mechanisms and countermeasures (Fredriksson, Rosén et al. 2010)

Impact type	Potential serious injury reduction (cumulative)	Counter measure	Optimum vehicle speed for counter measure to work
Leg to front end	34% (26,43)	Pedestrian bumper	41 km/hr
Head to bonnet	37% (29,46)	Pedestrian bumper and pedestrian bonnet	45 km/hr
Chest to bonnet	44% (36-53)	Pedestrian bumper and pedestrian bonnet with design to improve chest impact injuries	55 km/hr
Head to windscreen	63% (54-71)	Pedestrian bumper plus windscreen protection	Not estimated
Chest to windscreen	73% (65-81)	Pedestrian bumper and windscreen protection with design to improve chest impact injuries	55 km/hr

Fredrikkson et al. (2001, 2012) estimated that combined windscreen and bonnet passive countermeasures on passenger cars to be 34% (CI:23-46) effective at reducing AIS≥3 head injuries to AIS≥2 head injuries. In addition they found a 20% reduction in the cumulative strain brain damage measure (which considers also rotational loading) and a 58%HIC. Pop-up bonnet fitment was found able to save between 32.8% and 83.6% (95% confidence) of pedestrians than otherwise would have died (Oh, Kang et al. 2008).

Active and integrated systems also have had crash and injury reductions associated with them Table 7 and Table 8). The calculated injury reductions refer to pedestrian injuries from pedestrian collisions and are dependent upon estimates of pedestrian approach, pedestrian visibility (e.g. Day versus night, obstructed views, degrees of sensor view), range of detection and brake force and timing applied.

Table 7 : Speed and injury reductions estimated to be possible with BAS systems

Study	Reduction in serious injuries	Other reductions
(Badea-Romero, Paez et al. 2013)	33% cases had ISP reduction of <10% 4% cases –ISP increase	12.7% cases, collision avoided Speed reductions: <5 km/h- 55% cases 5-10 km/h -25% cases
(Lawrence, Hardy et al. 2006)	10% fatal and serious cases	
(Page, Foret-Bruno et al. 2005)		10-12% of fatalities

Table 8 : Speed and injury reductions estimated to be possible with AEBS or integrated protection systems

Study	Technology	Reduction in serious injuries	Other reductions
(Rosén, Källhammer et al. 2010)	AEBS	27%	40% fatality <20 km/h speed reduction
(Fredriksson, Shin et al. 2011, Fredriksson and Roudsari 2012)	AEBS (no SUV)	44% (34-53) AIS≥3 head	20% chest force 82% Head Injury Criteria (HIC)
	AEBS + Pop-up hood + windshield airbag (no SUV)	64%(CI:53-74) AIS≥3 head	56% CSDM 85% HIC
(Edwards, Nathanson et al. 2014)	Current 2013 AEBS	4%	6% fatality
	Second generation 2018 AEBS	9%	14% fatality
Reductions in this study are based on a denominator of all UK passenger vehicle crash casualties- not just pedestrian casualties	Best technically feasible AEBS-2023+	14%	20% fatality

12.0 Policy recommendations

The summaries presented in Table 9 and Table 10 may be combined to determine which passive countermeasures and passenger car and SUV vehicle designs will be most effective at reducing specific injury types for adults, children and the elderly. Table 6 offers possible injury reductions for these countermeasures.

All injuries may be reduced if the collision is avoided altogether or if speed is reduced: AEBS and to a lesser extent BAS and ITS have been demonstrated effective at collision mitigation and speed reduction. Table 7 and 8 offers possible injury reductions for these countermeasures, separately or as an integrated system.

It is important in applying these crash and injury savings to consider the following about injury risk, severity and location.

- Head injuries and torso injuries are more likely to be fatal than low extremity injuries which are more likely to incur severe disability.
- lower extremity and head injuries are the more frequent than torso injuries in adults hit by passenger cars
- increased speed have the largest effect on torso injury severity and the largest effect on the elderly
- torso injuries are more common than head injuries in *SUV c*ollisions
- torso injuries are more common in the *elderly* than in adults
- Injury outcomes generally are worse for taller and *the elderly*
- Flatter geometry rather than vehicle mass explains the increased injury risks observed for *SUV* over passenger cars, up to a fixed speed, after which speed is a more important factor than geometry.
- *SUVs* have greater collision and injury severity risk than passenger cars

Table 9 : Summary of injury type and vehicle impact points for adults, children and SUVs

Injury Type	Usual Vehicle Impact Source (Adult)	Usual Vehicle Impact Source (Child)	Usual Vehicle Impact Source (SUV or Van)
Head	Windshield (especially A-frame) bonnet being the next most frequent source	bonnet	bonnet or bumper in adult bumper child
Torso	bonnet surface or leading edge	bumper	Bumper/bonnet leading edge
Lower Extremities	bumper	Bumper- but injuries tend to be higher up the body, e.g. femur and pelvis	bumper -but injuries tend to be higher up the body, e.g. femur and pelvis

Table 10 : Summary of vehicle component and pedestrian countermeasures

		Countermeasures		
Impact Site	Constraints	Design	Deployable	Who benefits most
Bumper	Must protect against vehicle to object/vehicle collisions Pre-crash sensing technology developments	Optimised frontal geometry Energy absorbing materials and design Lower stiffener , remove bullbar	Airbag	Elderly and children
Bonnet LE	Contains rigid parts such as lamp housing and latches	Optimised frontal geometry Rounder design Rigid parts have energy absorption		Elderly and children
Bonnet surface	Has rigid parts beneath and may not have sufficient crush space due to styling Safety testing focus on HIC not torso	Optimised frontal geometry Energy absorbing materials and design	Pop-up bonnet	Elderly and children
Lower Windshield and A-frame	Must protect occupant from rollover and must provide maximum visibility Safety testing focus on HIC not torso or rotational head loading	Laminated glass structure	Airbag	Adults

Bonnet and windshield safety testing has focussed on minimising head injury using head-form testing. As a result countermeasure development has not been strong in the area of torso protection and in particular studies into the effect on the torso within a whole body simulation on integrated systems have been few. Given that seriously disabling or fatal injuries to the pelvis, abdomen and thorax commonly result from bonnets vehicle countermeasure design and testing are important. As a result, adult torso protection offered by pop-up bonnets is likely to be currently sub-optimal, particularly if used within an integrated system, where trajectory is altered by the autonomous speed reduction. For children the focus on head injury criterion in the testing of pop-up bonnets is more appropriate. Development of pop-up bonnets or other torso countermeasures will have great benefits for the elderly and for those colliding with SUV vehicles. In addition they have the potential to further protect children and short adults against head injury.

Head-form testing using linear forces has also meant that rotational forces and whole body protective effects have largely been ignored. Thus the protection offered to the head by windshield airbags and pop-up bonnets may also be sub-optimal, especially within integrated systems.

Thus passive countermeasures within integrated systems still have more potential to reduce injury severity. The potential to work at higher speeds and over a greater range of vehicle types is yet to be fully explored.

Active countermeasures are limited by their sensor systems, which are constantly under development and offer great potential for pedestrian safety improvements.

12.0 References

AAAM (2008). *The Abreviated Injury Scale (AIS) 2005 -Update 2008*. Barringron, IL USA, Association for Advancement of Automotive Medicine.

Anaya, J. J., P. Merdrignac, O. Shagdar, F. Nashashibi and J. Naranjo (2014). *Vehicle to pedestrian communications for protection of vulnerable road users*. IEEE Intelligent Vehicles symposium, Michigan, United states.

Anderson, R. W. G., A. J. McClean, M. J. B. Farmer, B. H. Lee and C. G. Brooks (1997). *Vehicle travel speeds and the incidence of fatal pedestrian crashes*" Accident Analysis and Prevention **29**(5): 667-674.

Badea-Romero, A. and J. Lenard (2013). *Source of head injury for pedestrians and pedal cylclists: Striking vehicle or road?*" Accident Analysis and Prevention **50**: 1140-1150.

Badea-Romero, A., F. J. Paez, A. Furones, J. M. Barrios and J. L. de-Miguel (2013). *Assessing the benefit of brake assist system for pedestrian injury mitigatio through real-world accident investigarions*" Safety Science **53**: 193-201.

Ballesteros, M. F., P. C. Dischinger and P. Langenberg (2004). *Pedestrian injuries and vehicle type in Maryland, 1995–1999*" Accident Analysis and Prevention **36**(1): 73-81.

Barrios, J. M., A. Aparacio, M. A. Merino, J. L. Miguel, A. Olona, S. Modrego, F. J. Paez, A. Furones, A. Badea and J. M. Martin (2009). *Evaluation of the effectiveness of pedestrian protection systems through in-depth accident investigation, reconstruction and simultion*. The 21st International Technical Conferenc on the Enhanced Safety of Vehicles (ESV), Stuttgart, Germany.

Belingardi, G., A. Scattina and E. Gobetto (2009). *Developments of an hybrid hood to improve pedestrian safety in case of vehicle impact*. The 21st International Technical Conference on the Enhanced safety of Vehicles (ESV), Stuttgart, Germany.

BITRE (2012). *Child pedestrian safety 'driveway deaths' and 'low-speed vehicle run-overs', Australia 2001-2010*. Canberra, Bureau of Infrastructure Transport and Regional Economics.

Bovenkerk, J. and C. Sahr (2009). *New modular assesment methods for pedestrian protection in the event of head impacts in the windscreen area*. The 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV), Stuttgart, Germany.

Breuer, J. J., A. Faulhaber, P. Frank and S. Gleissner (2007). *Real world safety benefits of brake assist systems*. The 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV) Lyon, France.

Cairney, P. (2000). *Pedestrian and cyclist safety - recent developments*. A. T. Research, Austroads. **AP-R155**.

Cairney, P., K. Imberger, K. Walsh and T. Styles (2010). *Reviewing ITS Technologies and Road Safetyt Opportunities* Austroads. **AP-T157/20**.

D'Elia, A. and S. Newstead (2015). *Pedestrian injury outcome as a function of vehicle market group in Victoria, Australia*" Traffic Injury Prevention.

Edwards, M. J., A. Nathanson and M. Wisch (2014). *Estimate of the potential benefit for Europe of fitting Autonomous Emergency Braking (AEB) systems for pedestrian protection to passenger cars*" Traffic Injury Prevention **15**(sup1): S173-S182.

Fildes, B., S. Newstead, M. Keall and L. Budd (2014). *Camear effectiveness and backover collisions with pedestrians: A feasibility study*. Monash University Accident Centre, Monash University Injury Research Institute. **321**.

Fredriksson, R. (2011). "Priorities and potential of pedestrian protection."

Fredriksson, R., E. Flinke, O. Bostrom and K. Backman (2007). *Injury mitigation in SUV-to-pedestrian impacts*. The 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Lyon, France.

Fredriksson, R., E. Rosén and A. Kullgren (2010). *Priorities of pedestrian protection—A real-life study of severe injuries and car sources*" Accident Analysis and Prevention **42**(6): 1672-1681.

Fredriksson, R. and B. S. Roudsari (2012). *Integrated pedestrian countermeasures-potential of head injury reduction combining passive and active countermeasures*" Safety Science **50**(3): 400-407.

Fredriksson, R., J. Shin and C. D. Untaroiu (2011). *Potential of pedestrian protection systems- A parameter study using finite element models of pedestrian dummy and generic passenger vehicles*" Traffic Injury Prevention **12**(4): 398-411.

Fredriksson, R., L. Zhang and J. Bovenkerk (2009). *Influence of deployable hood systems on finite element modelled brain response for vulnerable road users*" International Journal of Vehicle safety **4**(1): 29-44.

Griffin, B., K. Watt, B. Wallis, L. Shields and R. Kimble (2011). *Pediatric low speed vehicle run-over fatalities in Queensland*" Injury Prevention **17**: 10-13.

Gupta, V. and K. H. Yang (2013). *Effect of vehicle fron end profiles leading to pedestrian secondary head impact to ground*" Stapp Car crash Journal **57**: 139-155.

Hamacher, M., L. Eckstein, M. Kuhn and T. Hummel (2011). *Assessment of active and passive technical measures for pedestrian protection at the vehicle front*. The 22nd International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, D.C.

Hannawald, L. and F. Kauer (2004). *Equal effectiveness study on pedestrian protection*. Dresden, Germany, Technische Universitat Dresden.

Hardy, B. J., G. J. L. Lawrence, I. M. Knight, I. C. P. Simmons, J. A. Carroll, G. Coley and R. S. Barlett (2007). *A study of possible future developments of methods to protect pedestrians and other vulnerable road users*, Transport Research Laboratories. **UPR/VE/061/07**.

Hayashi, H., R. Inomata, R. Fujishiro, Y. Ouchi, K. Suzuki and T. Nanami (2013). *Development of pre-crash safety systems with pedestrian collision avoidance test*. The 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV) Seoul, Republic of Korea.

Helmer, T., A. Ebner, R. R. Samaha, P. Scullion and R. Kates (2010). *Injury risk to specific body regions of pedestrians in frontal vehicle crashes modeled by empirical in-depth accident data*" Stapp Car Crash J **54**: 93-117.

Henary, B. Y., J. Crandall, K. Bhalla, C. N. Mock and B. S. Roudsari (2003). *Child and adult pedestrian impact: the influence of vehicle type on severity*. Association for the advancement of automotive Medicine 47th Annual Conference, Lisbon, Portugal, Barrington, USA: Association for the Advancement of Automotive Medicine.

Holding, P. N., B. P. Chinn and J. Happian-Smith (2001). *Pedestrian protection - an evaluation of an airbag system through modelling and testing*. The 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV) Amsterdam, The Netherlands.

Hoogvelt, R. B. J., Y. W. R. de Vries, D. Margarites, E. van den Tillaart, H. van de Burgwal and E. Willemsen (2004). *Impact of sport utility vehicles on traffic safety and the environment in The Netherlands.*, Delft, The Netherlands: TNO Automotive. **04.OR.SA.065.1/RH.**

Hoye, A. (2011). *The effects of electronic stability control on crashes _ An update*" Accident Analysis and Prevention **43**(3): 1148-1159.

Hu, J. and K. Klinich (2012). *Towards designing pedestrian friendly vehicles*. Michigan, University of Michigan Transportation Research Institute. **UMTRI-2012-19**.

Huang, S. and J. Yang (2010). *Optimization of a reversible hood for protecting a pedestrian's head during car collisions*" Accident Analysis and Prevention **42**(4): 1136-1143.

Inomata, Y., N. Iwai, Y. Maeda, S. Kobayashi, H. Okuyama and N. Takahashi (2009). *The development of the pop-up engine hood for pedestrian head protection*. The 21st International Technical Conference on the Enhanced Safety of Vehicles (ESV), Stuttgart, Germany.

ITF (2014). *Road Safety Annual Report 2014*. I. T. Forum, International Traffic Safety Data and Analysis Group.

Jakobsson, L., T. Broberg, H. Karlsson, R. Fredriksson, N. Graberg, C. Gullander and M. Lindman (2013). *Pedestrian airbag technology- a production system*. The 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV) Seoul, Republic of Korea.

Jarrett, K. L., Saul, R.A. (1998). *Pedestrian injury-analysis of the PCDS field collision data*. The 16th International Technical Conference on the Enhanced Safety of Vehicles (ESV) Windsor, Canada.

Jermakian, J. S. and D. S. Zuby (2011). *Primary pedestrian crash scenarios: factors relevant to the design of pedestrian detection systems*. Arlington, VA, Insurance Institute for Highway Safety.

Johannsen, H. and G. Muller (2013). *Effects of low noise emissions of electrical vehicles for pedestrian accident risks*. The 23rd International Technical Conference on the Enhanced safety of Vehicles (ESV), Seoul, Republic of Korea, National Highway Traffic Safety Administration.

Joksch, H. C. (2000). *Vehicle design versus aggressivity*, US Department of Transportation. **DOT HS 809 194**.

Kalliske, I. and F. Friesen (2001). *Improvements to pedestrian protection as exlemplified on a stard-sized car*. The 17th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Amsterdam, The Netherlands.

Kausalyah, V., S. Shasthri, K. A. Abdullah, M. M. Idres, Q. H. Shah and S. V. Wong (2014). *Optimisation of vehicle front-end geometry for adult and pediatric pedestrian protection*" International Journal of crashworthiness **19**(2): 153-160.

Keall, M., A. D'Elia, S. Newstead and W. Watson (2012). *Retrospective and projected future impact of characteristics of the New Zealand and Australian vehicle fleet on pedestrian injury*. Monash University Monash University Accident research Institute.

Kerkeling, C., J. Schaefer and G. Thompson (2005). *Structural hood and hinge concepts for pedestrian protection*. The 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, D.C.

Kerrigan, J., C. Arregui-Dalmases and J. Crandall (2012). *Pedestrian head impact dynamics: comparison of dummy and PMHS in small sedan and large SUV impacts*" International Journal of Crashworthiness **17**(3): 243-258.

Lawrence, G. J. L., B. J. Hardy, J. A. Carroll, W. M. S. Donaldson, C. Visvikis and D. A. Peel (2006). *A study on the feasibility of measures relating to the protection of pedestrians and other vulnerable road users- Final*. UK, Transport Research Laboratory. **UPR/VE/045/06**.

Lefler, D. E. and H. C. Gabler (2002). *The fatality and injury risk of light truck impacts with pedestrians in the United States*" Accident Analysis and Prevention **36**(2): 295-304.

Liu, Q., Y. Xia and Q. Zhou (2009). *Friction Effects in Pedestrian Headform Impacts with Engine Hoods*" Tsinghua Science & Technology **14**(5): 631-638.

Liu, Q., J. Zhuang and J. Ma (2013). *Robust and fast pedestrian detection method for far-infrared automotive driving assist systems*" Infrared Physics and Technology **60**: 288-299.

Liu, X. and J. Yang (2003). *Effects of vehicle impact velocity and front-end structure on dynamic responses of child pedestrians*" Traffic Injury Prevention **4**: 337-344.

Llaneras, R. E., C. A. Green, R. J. Kiefer, W. J. Chundrlik Jr, O. D. Altan and J. P. Singer (2005). *Design and evaluation of a prototype rear obstacle detection and driver warning system*" Human Factors **47**(1): 199-215.

Longhitano, D., B. Y. Henary, K. Bhalla, J. Ivarsson and J. Crandall (2005). *Influence of body type on pedestrian injury distribution*" SAE International(2005-01-1876).

Lucas (2000). *Flexible lamp mounting*" USA patent application US6190030. 1999-02-18.

Ma, X. and I. Andréasson (2005). *Predicting the effect of various ISA penetration grades on pedestrian safety by simulation*" Accident Analysis and Prevention **37**(6): 1162-1169.

Mallory, A., R. Fredriksson, E. Rosen and B. Donnelly (2012). *Pedestrian Injuries by source: serious and disabling injuries in US and European cases*" Annals of Advances in Automotive Medicine **56**: 13-24.

Matsui, Y. (2005). *Effects of vehicle bumper height and impact velocity on the type of lower extremity injury in vehicle-pedestrian accidents*" Accident Analysis and Prevention **37**(4): 633-640.

Matsui, Y., Y. Han and K. Mizuno (2011). *Performance of collision damage mitigation braking systems and their effects on human injury in the event of car-to-pedestrian accidents*" Stapp Car Crash J **55**: 461-478.

Matsui, Y., M. Hitosugi and K. Mizuno (2011). *Severity of vehicle bumper location in vehicle-to-pedestrian impact accidents*" Forensic Science International **212**(1-3): 205-209.

Mazzae, E. N. and W. R. Garrott (2006). *Experimental evaluation of the performance of available backover prevention technologies*. Washington, D.C., National Highway Traffic Safety Administration. **DOT HS 810 634**.

Mazzae, E. N. and W. R. Garrott (2011). *Vehicle rearview image field of view and quality meaurement*. Washington, D.C., National Highway Traffic Safety Administration. **DOT HS 811 512**.

McCarthy, M. and I. C. P. Simmons (2005). *Active pedestrian protection*. The 19th International Technical Conference on the Enhanced safety of Vehicles (ESV), Washington, D.C.

Miranda-Moreno, L., L. Morency and A. El-Geneidy (2011). *The link between built environment, pedestrian activity and pedestrian-vehicle collision occurrence at signalised intersections*" Accident Analysis and Prevention **43**(5): 1624-1634.

Mizuno, K. and J. Kajzer (1999). *Compatibility problems in frontal, side, single car collisions and car-to-pedestrian accidents in Japan*" Accident Analysis and Prevention **31**(4): 381-391.

Mizuno, Y. (2005). *Summary of IHRA Pedestrian Safety WG activities (2005) proporsed test methods to evaluate pedestrian protection afforded by passenger cars*. The 19th International Technical Conference on hte Enhanced Safety of Vehicles (ESV), Washington, D.C.

Neal-Sturgess, C., E. Carter, R. Hardy, R. Cuerden, C. Gullander and J. Yang (2007). *APROSYS European in-depth pedestrian database*. The 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Lyon, France.

Ogawa, S., Q. Chen, K. Kawaguchi, T. Narikawa, M. Yoshimura and S. Lihua (2013). *The effect of visibility and pedestrian protection performance on pedestrian accidents*. The 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV) Seoul, Republic of Korea,.

Oh, C., Y.-s. Kang and W. Kim (2008). *Assessing the safety benefits of an advanced vehicular technology for protecting pedestrians*" Accident Analysis and Prevention **40**(3): 935-942.

Okamato, M., A. Akiyama, K. Nagatomi and T. Tsuruga (1994). *Concept of hood design for possible reduction in head injury*. The 14th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Munich, Germany.

Otte, D. (2001). *Severity and mechanism of head impacts in vehicle to pedestrian accidents*. IRCOBI Conference, Isle of Man.

Page, Y., J. Foret-Bruno and S. Cuny (2005). *Are expected and observed effectiveness of emergency brake assist in preventin road injury accidents consitent?* The 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, D.C.

Paine, M., A. Macbeth and M. Henderson (2003). *The danger to young pedestrians from reversing motor vehicles*. The 18th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, D.C.

Pator, C. (2005). *The correlation between pedestrian injury severity in real-life crashes and Euro NCAP pedestrian rest results*. Germany, Federal Highway Institute. **13-0308**.

Paulozzi, L. J. (2005). *United States pedestrian fatality rates by vehicle type*" Injury Prevention **11**: 232-236.

Peng, Y., Y. Chen, J. Yang, D. Otte and R. Willenger (2012). *A study of pedestrian and bicyclist exposure to head injury in passenger car collisions based on accident data and simulations*" Safety Science **50**: 1749-1759.

Pinecki, C., L. Fontaine, C. Adalian, C. Jeanneau and R. Zeitouni (2011). *Pedestrian Protection - Physical and numerical analysis of the protection offered by the windscreen*. The 22nd International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, D.C.

Pipkorn, B., R. Fredriksson and J. Olsson (2007). *Bumper bag for SUV to passenger vehicle compatability and pedestrian protection*. The 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Stuttgart, Germany.

Pozo De Dios, E., J. Alba, O. Cisneros, M. Avalle, A. Scattina, A. Esnaola and G. Pochettino (2013). *Optimising vehicle structure architectures for light trucks*. The 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV) Seoul, Republic of Korea.

Richards, D. and J. A. Carroll (2012). *Relationship between types of head injury and age of pedestrian*" Accident Analysis and Prevention **47**: 16-23.

Richards, D., R. Cookson, R. Cuerden and G. Davies (2009). *The causes of pedestrians' head injuries following collisions with cars registered in 2000 or later* The 21st International Technical Conference on the Enhanced Safety of Vehicles Conference, Stuttgart, Germany.

Road Safety Committee (2008). *Inquiry into vehicle safety*. Melbourne, Road safety Committee, Parliament of Victoria.

Rosén, E., J.-E. Källhammer, D. Eriksson, M. Nentwich, R. Fredriksson and K. Smith (2010). *Pedestrian injury mitigation by autonomous braking*" Accident Analysis and Prevention **42**(6): 1949-1957.

Roudsari, B. S., C. N. Mock, R. Kaufman, D. Grossman, B. Y. Henary and J. Crandall (2004). *Pedestrian Crashes: higher injury severity and mortality rate for light truck vehicles compared with passenger vehicles*" Injury Prevention **10**: 154-158.

Saad, F., M. Hjalmdahl, J. Canas, M. Alonso, P. Garayo, L. Macchi, F. Nathan, L. Ojeda, V. Papakostopoulos, M. Panou and E. Bekiaris (2005). *Literature Review of Behavioural Effects*, INRETS. **WP1_2_1**.

Schuster, P. J. (2006). *Current trends in bumper design for pedestrian impact*. Warrendale, PA., Society of Automotive Engineers. **SAE2006-01-0464**.

Searson, D. J., R. W. G. Anderson and T. P. Hutchinson (2014). *Integrated assesment of pedestrian head impact protection in testing secondary safety and autonomous emergency braking*" Accident Analysis and Prevention **63**: 1-8.

Shojaeefard, M. H., A. Najibi and M. R. Ahmadabadi (2014). *Pedestrian safety investigation of the new inner structure of the hood to mitigare the impact injury of the head*" Thin-walled Structures **77**: 77-85.

Simms, C. K. and D. P. Wood (2006). *Pedestrian risk from cars and sport utility vehicles- a comparative analytical study*" Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering **220**: 1085.

Snedeker, J. G., F. H. Waltz, M. H. Huser, C. Lanz and G. Schroeder (2005). *Assessing femur and pelvis injury risk in car-pedestrian collisions: comparison of full body PMTO impacr and a human body finite element model*. The 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington, DC.

Starnes, M. and A. Longthorne (2003). *Child pedestrian fatality rates by striking vehicle body type: a comparison of passenger cars, sports utility vehicles, pickups, and vans*. Washington, USA, National Center for Statistics and Analysis. **DOT HS 809 640**.

Strandoth, J., M. Rizzi, S. Sternlund, A. Lie and C. Tingvall (2011). *The correlation between pedestrian injury severity in real -life crashes and Euro NCAP pedestrian rest results*" Traffic Injury Prevention **12**(6): 604-613.

Takahashi, H., H. Miyazaki, S. Narita, T. Shamoto and Y. Mase (2013). *Development of pop-up hood system for pedestrian protection*. The 23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV) Seoul, Republic of Korea.

Teft, B. (2013). *Impact speed and a pedestrian's risk of severe injury or death*" Accident Analysis and Prevention **50**: 871-878.

Waltz, F. H., M. Hoefliger and W. Fehlmann (1983). *Speed limit reduction from 60 to 50 km/h and pedestrian injuries*. 27th Stapp Car Crash Conference, San Dieago.

Wang, Y. and K. M. Kockelman (2013). *A Poisson-lognormal conditional-autoregressive model for multivariate spatial analysis of pedestrian crash counts across neighborhoods*" Accident Analysis and Prevention **60**: 71-84.

Weir, M., J. Weintraub, E. Humphreys, E. Seto and R. Bhatia (2009). *A are-level model of vehicle-pedestrian injury collisions with implications for land use and transportation planning*" Accident Analysis and Prevention **41**: 137-145.

Wood, D. P. (1991). Pedestrian impact, injury and accident causation. Automotive engineering and litigation. G. A. Peters and B. J. Peters. New York, John Wiley. **4**.

Xu, J. and Y. B. Li (2011). *Automotive windshield- pedestrian head impact: Energy absorption capability of interlayer material*" International Journal of Automotive Technology **12**(5): 687-695.

Yang, J., J. Yao and D. Otte (2005). *Correlation of different impact conditions to the injury severity of pedestrians in real world accidents*. The 19th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Washington D.C., U.S. DOT National Highway Traffic Safety Administration

Yao, J., J. Yang and D. Otte (2007). *Head injuries in child pedestrian accidents- in-depth case analysis and reconstructions*" Traffic Injury Prevention **8**: 94-100.

Zanella, A., F. Butera, E. Gobetto and C. Rierche (2002). *Smart bumper for pedestrian protection*" Smart Materials Bulletin **2002**(7): 7-9.

Zegeer, C. V. and M. Bushell (2012). *Pedestrian crash trends and the potential countermeasures from around the world*" Accident Analysis and Prevention **44**: 3-11.

Zhang, G., L. Cao, J. Hu and K. Yang (2008). *A field data analysis of risk factors affecting the injury risks in vehicle-to-pedestrian crashes*" Annu. Proc. Assoc. Adv. Automot. Med. **52**: 199-214.

13.0 Appendices

13.1 Appendix 1: Pedestrian Vehicle Crash Data Sets:

data country	data region	data years	vehicle types	Cases	Example Papers
USA	PCDS:6 major cities	1994-1998	passenger cars, LTV (SUV+ light truck), vans <=4.5t	552 Ped	Jarrett (1998), Henary (2003), Zhang (2008) Roudsari (2004) Lefler(2002)
USA	Maryland	1995-1999	passenger cars, (SUV+ utilities/pick-up trucks), vans	2,942 Ped	Ballesteros (2004)
USA	Fatality Analysis Reporting System FARS	1992-2001 2005-2009		Match to crashes	Starnes (2003) Lefler (2002) Jermakian (2011)
USA	National Automotive sampling System General Estimates system NASS GES	1992-2001 2005-2009	passenger cars, (SUV+ utilities/pick-up trucks), vans All vehicles	6,679 ped 10,079 ped	Starnes (2003) Lefler (2002) Jermakian (2011)
Japan, Germany, USA and Australia	International Harmonised Research Activities Pedestrian Safety Working Group –IHRA Pedestrian Accident Data Set	1985-2000		1605	Mizuno (2005)
Netherlands	Dutch National Accident Database	1/2001 to 8/2002	SUVs and passenger cars	1,788 veh	Hoogvelt (2004)
Netherlands	TNO Automattive In-depth Accident database	4/02 to 11/02	SUVs	32 crashes	Hoogvelt (2004)
Germany	GIDAS: German in depth accident study Dresden, Hanover and rural surrounds	1999-2008 2000-2012	passenger cars and vans (MPV) and excluding SUVs	1030	Fredrikson (2010) Edwards (2014)
Australia	Vic 2001-2010	2001-2010			(D'Elia and Newstead 2015)
Europe	European in depth Pedestrian database APROSYS	1997-2001 2013		63 ped	Carter (2008) Neasl-Sturgess (2007)
Spain	3 cities	2002-2006	Passenger, MPV, SUV, utility	139	Badea-Romero (2013)
United Kingdom	OTS-Nottingham and Maidenhead	2000-2010	Passenger		Edwards (2014)

13.2 Appendix 2: The Abbreviated Injury Scale: (AAAM 2008)

The Abbreviated Injury Scale (AIS) incorporates current medical terminology providing an internationally accepted tool for ranking injury severity. The AIS© is an anatomically based, consensus derived, global severity scoring system that classifies an individual injury by body region according to its relative severity on a 6 point scale. The AIS© 2005 Update 2008 is protected by copyright, and both individual use and site licenses can be purchased.

What is the Abbreviated Injury Scale (AIS)?

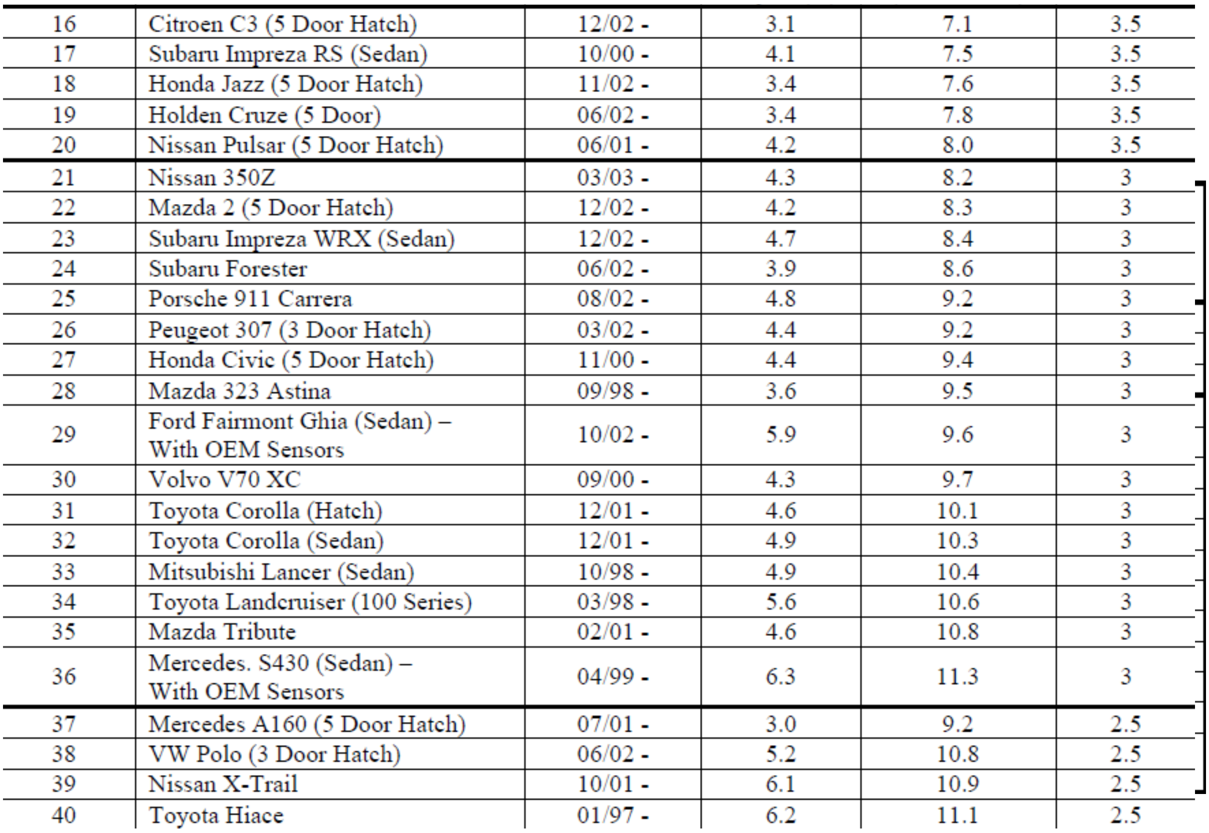
The Abbreviated Injury Scale (AIS©) is an anatomically based, consensus derived, global severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale (1=minor, 2= moderate, 3=serious, 4=severe, 5=critical and 6=maximal). AIS© is the basis for the Injury Severity Score (ISS) calculation of the multiply injured patient.

The AIS provides standardized terminology to describe injuries and ranks injuries by severity. Current AIS users include, health organizations for clinical trauma management, outcome evaluation and for case mix adjustment purposes; motor vehicle crash investigators to identify mechanism of injury and improve vehicle design; and researchers for epidemiological studies and systems development, all of which may influence public policy (laws and regulations).

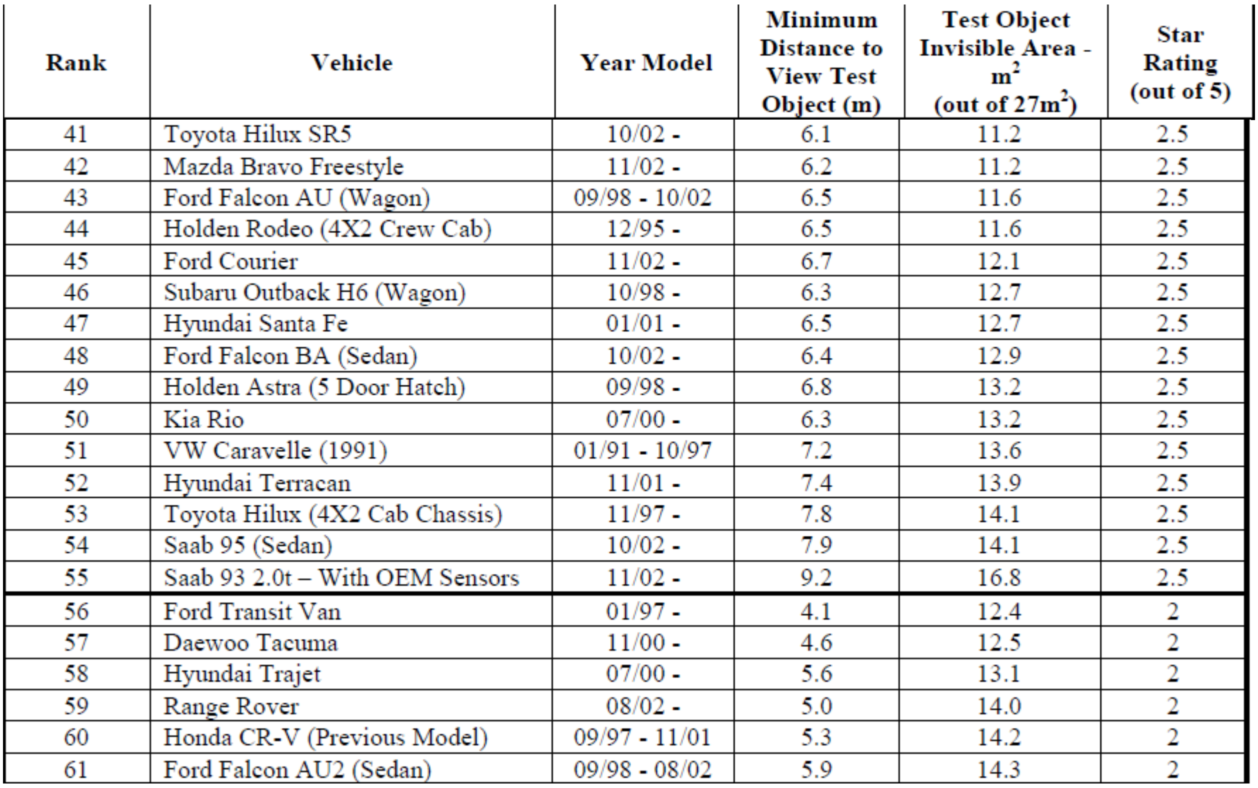
Some users are interested in its standardized injury descriptor capabilities; some are interested only in its injury severity assessment; and some in both. The AIS Uses and Techniques course allows people to learn how to correctly code injuries according to established rules and guidelines, which increases inter-rater reliability worldwide.

Health and research records of all types may be coded in a prospective manner. AIS codes may be assigned using algorithms that map other commonly used disease and injury codes — such as the WHO-originated International Classification of Diseases. Some of these maps have been programmed into trauma registry and medical record software, and may be proprietary tools. Some others have been made available by the original developers.

(AAAM 2008)



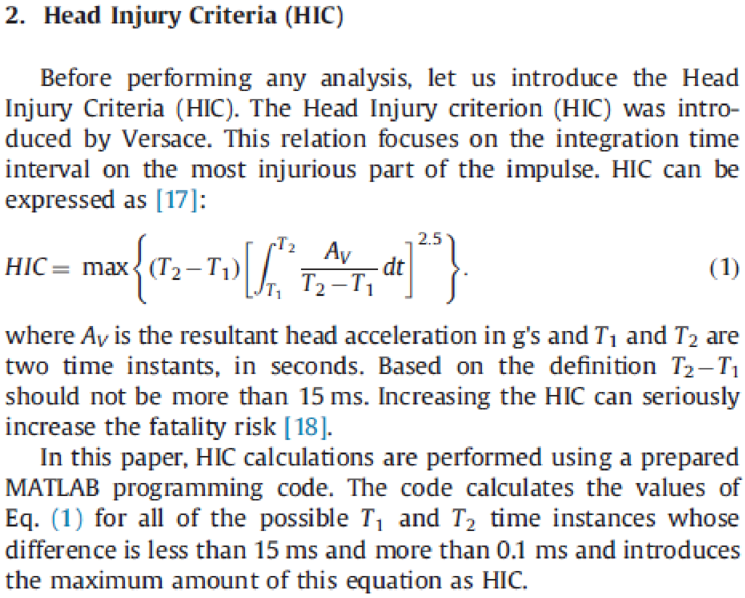
16	Citroen C3 (5 Door Hatch)	12/02 -	3.1	7.1	3.5
17	Subaru Impreza RS (Sedan)	10/00 -	4.1	7.5	3.5
18	Honda Jazz (5 Door Hatch)	11/02 -	3.4	7.6	3.5
19	Holden Cruze (5 Door)	06/02 -	3.4	7.8	3.5
20	Nissan Pulsar (5 Door Hatch)	06/01 -	4.2	8.0	3.5
21	Nissan 350Z	03/03 -	4.3	8.2	3
22	Mazda 2 (5 Door Hatch)	12/02 -	4.2	8.3	3
23	Subaru Impreza WRX (Sedan)	12/02 -	4.7	8.4	3
24	Subaru Forester	06/02 -	3.9	8.6	3
25	Porsche 911 Carrera	08/02 -	4.8	9.2	3
26	Peugeot 307 (3 Door Hatch)	03/02 -	4.4	9.2	3
27	Honda Civic (5 Door Hatch)	11/00 -	4.4	9.4	3
28	Mazda 323 Astina	09/98 -	3.6	9.5	3
29	Ford Fairmont Ghia (Sedan) – With OEM Sensors	10/02 -	5.9	9.6	3
30	Volvo V70 XC	09/00 -	4.3	9.7	3
31	Toyota Corolla (Hatch)	12/01 -	4.6	10.1	3
32	Toyota Corolla (Sedan)	12/01 -	4.9	10.3	3
33	Mitsubishi Lancer (Sedan)	10/98 -	4.9	10.4	3
34	Toyota Landcruiser (100 Series)	03/98 -	5.6	10.6	3
35	Mazda Tribute	02/01 -	4.6	10.8	3
36	Mercedes. S430 (Sedan) – With OEM Sensors	04/99 -	6.3	11.3	3
37	Mercedes A160 (5 Door Hatch)	07/01 -	3.0	9.2	2.5
38	VW Polo (3 Door Hatch)	06/02 -	5.2	10.8	2.5
39	Nissan X-Trail	10/01 -	6.1	10.9	2.5
40	Toyota Hiace	01/97 -	6.2	11.1	2.5



Rank	Vehicle	Year Model	Minimum Distance to View Test Object (m)	Test Object Invisible Area - m^2 (out of $27m^2$)	Star Rating (out of 5)
41	Toyota Hilux SR5	10/02 -	6.1	11.2	2.5
42	Mazda Bravo Freestyle	11/02 -	6.2	11.2	2.5
43	Ford Falcon AU (Wagon)	09/98 - 10/02	6.5	11.6	2.5
44	Holden Rodeo (4X2 Crew Cab)	12/95 -	6.5	11.6	2.5
45	Ford Courier	11/02 -	6.7	12.1	2.5
46	Subaru Outback H6 (Wagon)	10/98 -	6.3	12.7	2.5
47	Hyundai Santa Fe	01/01 -	6.5	12.7	2.5
48	Ford Falcon BA (Sedan)	10/02 -	6.4	12.9	2.5
49	Holden Astra (5 Door Hatch)	09/98 -	6.8	13.2	2.5
50	Kia Rio	07/00 -	6.3	13.2	2.5
51	VW Caravelle (1991)	01/91 - 10/97	7.2	13.6	2.5
52	Hyundai Terracan	11/01 -	7.4	13.9	2.5
53	Toyota Hilux (4X2 Cab Chassis)	11/97 -	7.8	14.1	2.5
54	Saab 95 (Sedan)	10/02 -	7.9	14.1	2.5
55	Saab 93 2.0t – With OEM Sensors	11/02 -	9.2	16.8	2.5
56	Ford Transit Van	01/97 -	4.1	12.4	2
57	Daewoo Tacuma	11/00 -	4.6	12.5	2
58	Hyundai Trajet	07/00 -	5.6	13.1	2
59	Range Rover	08/02 -	5.0	14.0	2
60	Honda CR-V (Previous Model)	09/97 - 11/01	5.3	14.2	2
61	Ford Falcon AU2 (Sedan)	09/98 - 08/02	5.9	14.3	2

Rank	Vehicle	Year Model	Minimum Distance to View Test Object (m)	Test Object Invisible Area - m^2 (out of $27m^2$)	Star Rating (out of 5)
62	Toyota Landcruiser (80 Series)	01/93 - 02/98	7.9	15.1	2
63	Toyota Camry (2000 - Sedan)	08/97 - 09/02	7.7	15.4	2
64	Holden Vectra (Sedan)	08/99 -	8.3	16.6	2
65	Holden Commodore Ute (VU)	12/00 -	9.3	16.7	2
66	Mitsubsihi Magna (Sedan)	08/00 -	9.7	17.5	2
67	Subaru Liberty GX (Sedan)	03/99 -	5.1	15.3	1.5
68	Nissan Pulsar (Sedan)	06/00 -	6.7	15.7	1.5
69	VW Caravelle (2002)	11/97 -	5.8	16.0	1.5
70	Toyota Camry (2002 - No Spoiler)	09/02 -	6.7	16.1	1.5
71	Toyota RAV4 (5 Door)	06/00 -	7.9	16.7	1.5
72	Subaru Liberty RX (Sedan)	03/99 -	5.2	16.7	1.5
73	Mazda Premacy	02/01 -	4.6	17.1	1.5
74	VW Golf (5 Door Hatch)	10/98 -	4.0	17.1	1.5
75	Ford Focus (Sedan - Ghia)	10/02 -	9.8	18.2	1.5
76	Jaguar S-Type R (Sedan) – With OEM Sensors	11/00 -	7.7	18.8	1.5
77	Mercedes C-Class (Sedan)	08/01 -	10.6	19.0	1.5
78	Holden Commodore VY (Sedan)	09/02 -	11.5	21.2	1.5
79	Toyota Camry (2002 - Spoiler)	09/02 -	11.8	21.3	1.5
80	Toyota Tarago	06/00 -	9.0	18.1	1
81	BMW 320i Wagon	06/02 -	4.9	18.1	1
82	Audi Allroad	02/01 -	6.1	18.4	1
83	Honda Odyssey	03/00 -	5.5	18.5	1
84	Hyundai Accent (3 Door Hatch)	06/00 -	7.2	18.8	1
85	Toyota RAV4 (3 Door)	06/00 -	5.5	18.8	1
86	BMW X5 (3.0L)	10/00 -	10.2	19.9	1
87	Audi A4 Avant (5 Door Wagon)	09/02 -	8.9	20.0	1
88	Nissan Patrol	04/00 -	6.4	20.1	1
89	Toyota Avensis	12/01 -	8.5	20.7	1
90	Kia Carnival	09/99 -	9.3	20.7	1
91	Holden Commodore (VS ute)	03/95 - 12/00	10.5	20.8	1
92	Mazda 6 (Sedan)	09/02 -	10.3	21.5	1
93	VW Passat	05/01 -	7.5	21.6	1
94	Holden Commodore Ute (VY - SS)	10/02 -	12.6	22.7	1
95	Ford Explorer	11/01 -	10.8	22.8	0.5
96	Hyundai Elantra (5 Door Hatch)	10/00 -	10.6	22.9	0.5
97	Honda CR-V (Current Model)	12/01 -	9.6	23.5	0.5
98	BMW 325ti (3 Door Coupe)	02/02 -	12.6	23.9	0.5
99	Holden Combo	09/02 -	12.2	25.0	0.5
100	Holden Commodore (VX Wagon)	09/97 - 09/02	13.2	25.1	0.5
101	Mitsubishi Pajero	05/02 -	11.1	25.4	0.5
102	Mazda MPV	08/99 -	13.7	26.4	0.5
103	Holden Commodore (VX Sedan)	09/97 - 09/02	16.8	27.0	0
104	Land Rover Discovery	02/02 -	20.9	27.0	0
105	Toyota Prado	06/96 -	15.6	27.0	0

13.4 Appendix 4: Head Injury Criterion (Shojaeefard, Najibi et al. 2014)



2. Head Injury Criteria (HIC)

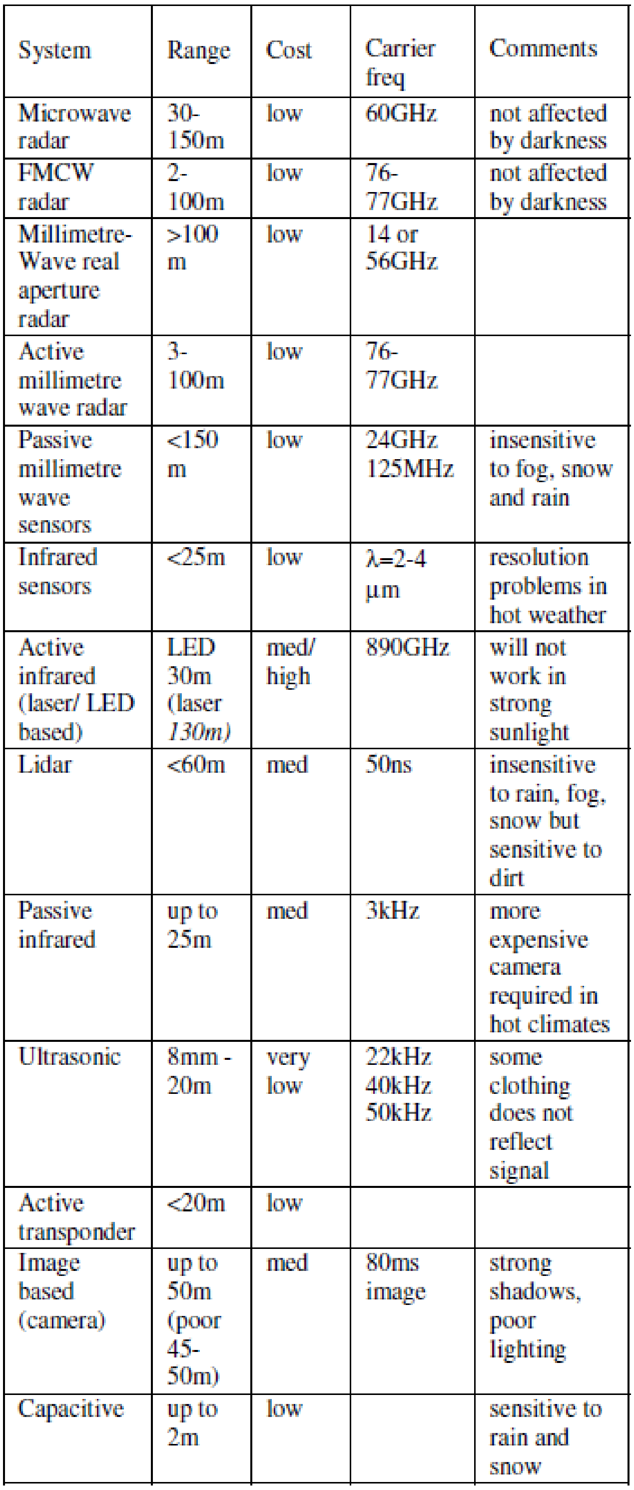
Before performing any analysis, let us introduce the Head Injury Criteria (HIC). The Head Injury criterion (HIC) was introduced by Versace. This relation focuses on the integration time interval on the most injurious part of the impulse. HIC can be expressed as [17]:

$$HIC = \max\left\{(T_2 - T_1)\left[\int_{T_1}^{T_2} \frac{A_V}{T_2 - T_1}\, dt\right]^{2.5}\right\}. \quad (1)$$

where A_V is the resultant head acceleration in g's and T_1 and T_2 are two time instants, in seconds. Based on the definition $T_2 - T_1$ should not be more than 15 ms. Increasing the HIC can seriously increase the fatality risk [18].

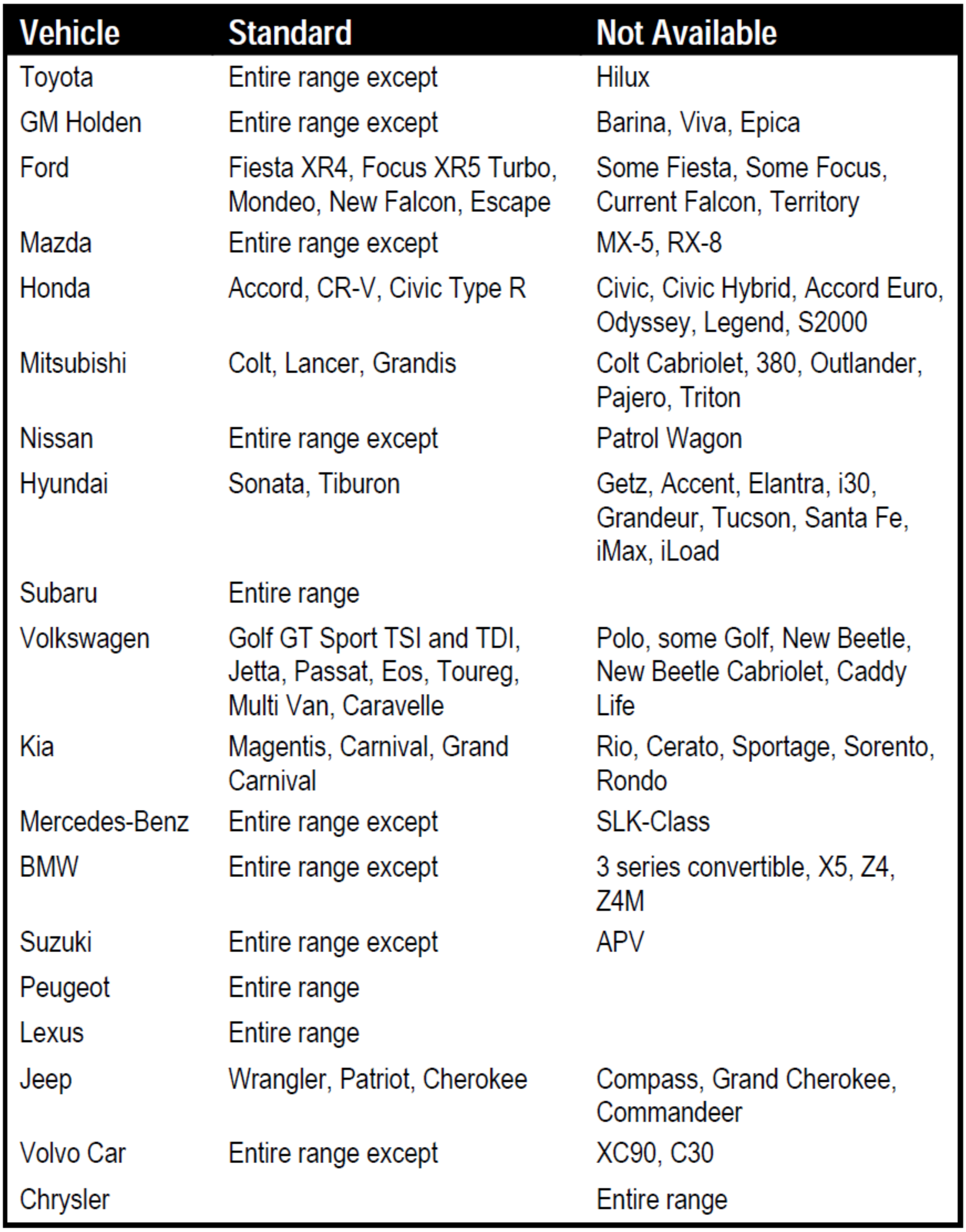
In this paper, HIC calculations are performed using a prepared MATLAB programming code. The code calculates the values of Eq. (1) for all of the possible T_1 and T_2 time instances whose difference is less than 15 ms and more than 0.1 ms and introduces the maximum amount of this equation as HIC.

13.5 Appendix 5: Summary of sensors used for detecting pedestrians (McCarthy and Simmons 2005)



System	Range	Cost	Carrier freq	Comments
Microwave radar	30-150m	low	60GHz	not affected by darkness
FMCW radar	2-100m	low	76-77GHz	not affected by darkness
Millimetre-Wave real aperture radar	>100 m	low	14 or 56GHz	
Active millimetre wave radar	3-100m	low	76-77GHz	
Passive millimetre wave sensors	<150 m	low	24GHz 125MHz	insensitive to fog, snow and rain
Infrared sensors	<25m	low	λ=2-4 µm	resolution problems in hot weather
Active infrared (laser/ LED based)	LED 30m (laser *130m)*	med/ high	890GHz	will not work in strong sunlight
Lidar	<60m	med	50ns	insensitive to rain, fog, snow but sensitive to dirt
Passive infrared	up to 25m	med	3kHz	more expensive camera required in hot climates
Ultrasonic	8mm - 20m	very low	22kHz 40kHz 50kHz	some clothing does not reflect signal
Active transponder	<20m	low		
Image based (camera)	up to 50m (poor 45-50m)	med	80ms image	strong shadows, poor lighting
Capacitive	up to 2m	low		sensitive to rain and snow

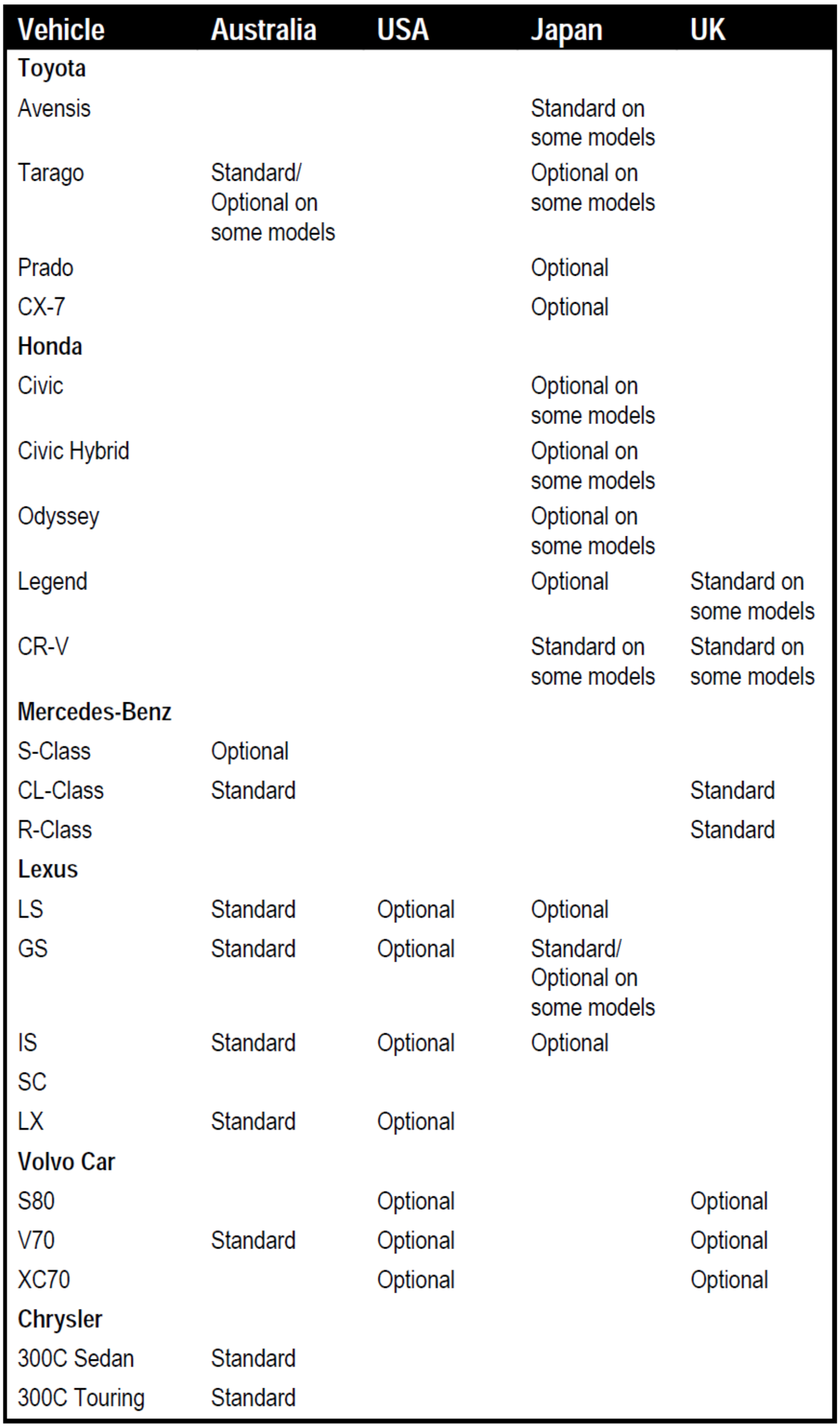
13.6 Appendix 6: Vehicles available in 2008 with BAS (Road Safety Committee 2008)



Vehicle	Standard	Not Available
Toyota	Entire range except	Hilux
GM Holden	Entire range except	Barina, Viva, Epica
Ford	Fiesta XR4, Focus XR5 Turbo, Mondeo, New Falcon, Escape	Some Fiesta, Some Focus, Current Falcon, Territory
Mazda	Entire range except	MX-5, RX-8
Honda	Accord, CR-V, Civic Type R	Civic, Civic Hybrid, Accord Euro, Odyssey, Legend, S2000
Mitsubishi	Colt, Lancer, Grandis	Colt Cabriolet, 380, Outlander, Pajero, Triton
Nissan	Entire range except	Patrol Wagon
Hyundai	Sonata, Tiburon	Getz, Accent, Elantra, i30, Grandeur, Tucson, Santa Fe, iMax, iLoad
Subaru	Entire range	
Volkswagen	Golf GT Sport TSI and TDI, Jetta, Passat, Eos, Toureg, Multi Van, Caravelle	Polo, some Golf, New Beetle, New Beetle Cabriolet, Caddy Life
Kia	Magentis, Carnival, Grand Carnival	Rio, Cerato, Sportage, Sorento, Rondo
Mercedes-Benz	Entire range except	SLK-Class
BMW	Entire range except	3 series convertible, X5, Z4, Z4M
Suzuki	Entire range except	APV
Peugeot	Entire range	
Lexus	Entire range	
Jeep	Wrangler, Patriot, Cherokee	Compass, Grand Cherokee, Commandeer
Volvo Car	Entire range except	XC90, C30
Chrysler		Entire range

Source: Manufacturers' Websites, April 2008.

13.7 Appendix 7: Vehicles available in 2008 with pre-emptive BAS (Road Safety Committee 2008)



Vehicle	Australia	USA	Japan	UK
Toyota				
Avensis			Standard on some models	
Tarago	Standard/ Optional on some models		Optional on some models	
Prado			Optional	
CX-7			Optional	
Honda				
Civic			Optional on some models	
Civic Hybrid			Optional on some models	
Odyssey			Optional on some models	
Legend			Optional	Standard on some models
CR-V			Standard on some models	Standard on some models
Mercedes-Benz				
S-Class	Optional			
CL-Class	Standard			Standard
R-Class				Standard
Lexus				
LS	Standard	Optional	Optional	
GS	Standard	Optional	Standard/ Optional on some models	
IS	Standard	Optional	Optional	
SC				
LX	Standard	Optional		
Volvo Car				
S80		Optional		Optional
V70	Standard	Optional		Optional
XC70		Optional		Optional
Chrysler				
300C Sedan	Standard			
300C Touring	Standard			

Source: Manufacturers' Websites, April 2008 and *Japanese New Car Assessment Program, New Car Assessment*, Table of Safety Performance Comparison by Model, 2007.