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Proposed vehicle impact speed - severe injury probability relationships for selected crash types

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Abstract

Speed is recognised as a key contributor to crash likelihood and severity, and to road safety performance in general. Its fundamental role has been recognised by making Safe Speeds one of the four pillars of the Safe System. In this context, impact speeds above which humans are likely to sustain fatal injuries have been accepted as a reference in many Safe System infrastructure policy and planning discussions. To date, there have been no proposed relationships for impact speeds above which humans are likely to sustain fatal or serious (severe) injury, a more relevant Safe System measure.

A research project on Safe System intersection design required a critical review of published literature on the relationship between impact speed and probability of injury. This has led to a number of questions being raised about the origins, accuracy and appropriateness of the currently accepted impact speed–fatality probability relationships (Wramborg 2005) in many policy documents. The literature review identified alternative, more recent and more precise relationships derived from the US crash reconstruction databases (NASS/CDS).

The paper proposes for discussion a set of alternative relationships between vehicle impact speed and probability of MAIS3+ (fatal and serious) injury for selected common crash types. Proposed Safe System critical impact speed values are also proposed for use in road infrastructure assessment. The paper presents the methodology and assumptions used in developing these relationships. It identifies further research needed to confirm and refine these relationships. Such relationships would form valuable inputs into future road safety policies in Australia and New Zealand.

Introduction

Speed is recognised as a key contributor to crash likelihood and severity, and thus, to overall road safety performance. Its fundamental role has been recognised by making Safe Speeds one of the four pillars of the Safe System, and is given a focus in many policy documents including the National Road Safety Strategy 2011-2020 (Australian Transport Council 2011). Since the late 1990s, impact speeds above which humans are likely to sustain fatal injuries have been adopted in many Safe System infrastructure policy and planning discussions. Since then, there has been no revision of these in the context of the actual Safe System objective of minimising the risk of fatal or severe injury.

In an Austroads project on safer intersections, Jurewicz, Tofler and Makwasha (2015) reviewed recent research on this subject raising questions about appropriateness of the existing impact speed–fatality probability relationships as basis for future road safety strategies. Alternative relationships, based on probability of a fatal or serious injury outcome given vehicle impact speed, have been proposed on the basis of more recent research carried out in the US. Further discussion and refinement of these relationships is needed in order to fully address the local demands of the Safe System implementation. One relationship worthy of refinement includes the nature of the vehicle fleet and mix of vehicles on the road.

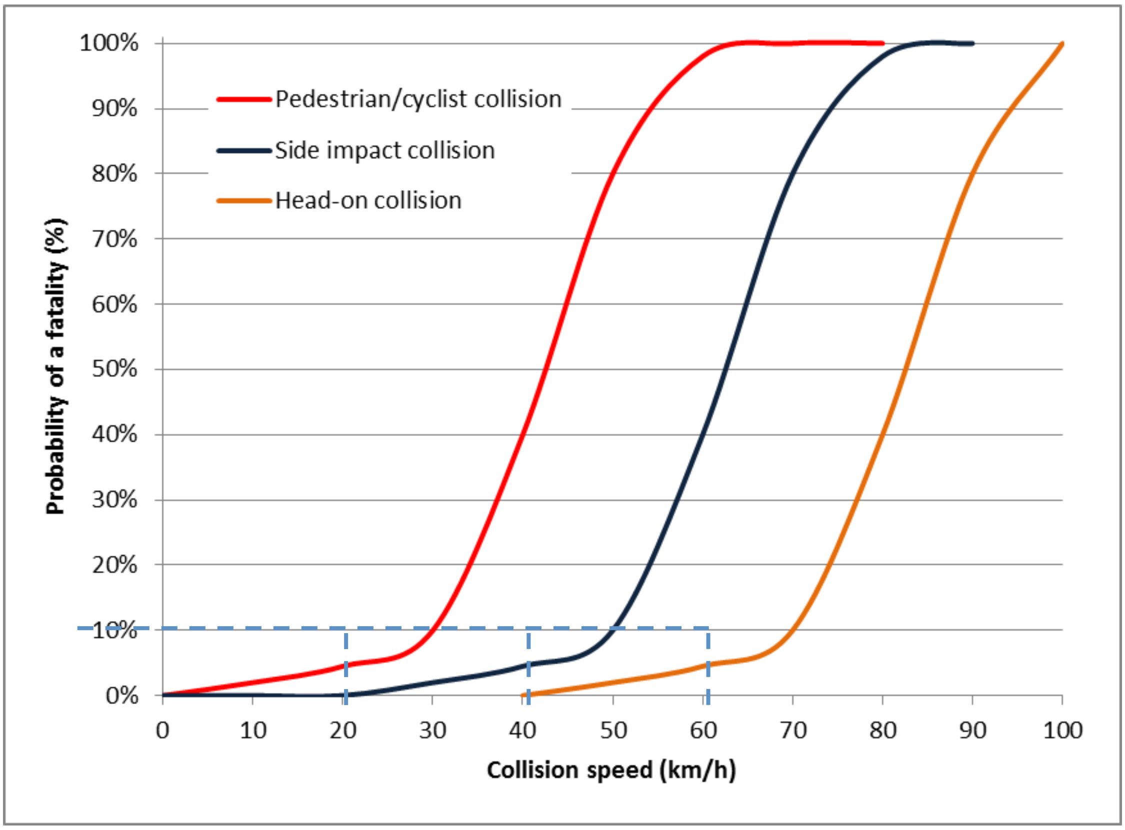
Review of existing relationships

The role of speed in crash likelihood has been confirmed through numerous studies. For example, Nilsson (2004) and then Elvik (2013) demonstrated that lower mean traffic speeds in response to speed limit reduction result in reduced likelihood of casualty crashes. Kloeden (2001, 2002) presented relationships demonstrating that the likelihood of driver involvement in a casualty crash increased with his or her speed over the speed limit. Much of this body of research points to the fact that even small speed reductions can lead to considerable reductions in road trauma.

Severity of crash outcomes in response to speed has also been well researched. Studies by Elvik and others, e.g. Elvik (2013), showed that fatal crashes decline more substantially with the same amount of mean speed reduction than all injury crashes. In other words, severity of crashes decreases with reduced mean speed.

One model in particular has been adopted in Australia and New Zealand to illustrate the effect of impact speeds on severity of selected crash types. Wramborg (2005) proposed the three impact speed–fatality probability relationships as shown in Figure 1.

Figure 1. Wramborg's model for fatality probability vs. vehicle collision speeds



Source: based on Wramborg (2005).

These relationships assume that the conflicting vehicles have equal mass and speed. According to these probability curves, there is a 10% chance of fatality outcome when vehicles impact at the following speeds:

- 30 km/h in pedestrian/cyclist crashes
- 50 km/h in side impact collisions
- 70 km/h in head-on collisions.

These speed thresholds were also noted earlier in a conference paper by Tingvall and Haworth (1999). Much of the Safe System infrastructure discussion to date has been based around these thresholds. They are often quoted as the maximum or 'survivable' impact speeds which can be tolerated in relation to intersection design, pedestrian activity areas, or provision of medians.

There are several important issues which limit the applicability of Wramborg's curves. The first issue is that Wramborg's curves only provide information about the probability of fatal injury. As minimisation of both fatal and serious injuries is the key concern of the Safe System vision, any advice on Safe System infrastructure should reference probability of types of severe injury.

The second issue is that little is known about the source of these relationships. The Wramborg (2005) conference paper did not provide any research references or sources of information for the impact speed curves. There was no way of checking these relationships against similar or prior research. The context of the paper is the establishment of the Vision Zero-based road hierarchy in Sweden, and this indirectly suggests that the curves were in use prior to 2005. Tingvall and Haworth (1999) also note the 10% fatality risk threshold speeds, referencing only high-level policy documents and keynote presentations as sources.

The third issue is that the curves in Figure 1 lack clarity. Does the term 'collision' imply a crash involving two or more vehicles, or the impact an individual vehicle has been subjected to? For instance, an adjacent direction crash involves a head-on impact by the bullet vehicle and a side impact into a target vehicle. Further, handling of different crash types is unclear: would an opposing-turning crash be a head-on or side impact? Does the term 'collision speed' refer to the impact speed of one vehicle, or the closing speed of two vehicles (a vector sum of two speeds)? This lack of clarity has led to assumptions in many Safe System policy and implementation discussions (e.g. that 50 km/h is the 'survivable' impact speed in intersection design).

Finally, a common interpretation of Wramborg's curves resulted in 'Safe System speeds' acknowledging a 'minimised' 10% fatality risk. In fact, an average fatality risk in a casualty crash is in the range 1%-7% in 80 km/h speed zones, depending on crash type (Victorian crash data 2008-13, based on uncongested periods between 7 pm and 5 am). Since casualty crashes are a fraction of all impacts, these fatal percentages would be even lower if all impacts were considered. Any Safe System-related design advice needs to result in a stepwise improvement on the current safety performance. Hence, application of Warmborg's curves and this commonly accepted fatality threshold may not be inappropriate for assessment of Safe System alignment of safety solutions.

It may be that Wramborg's impact speed–fatality probability relationships in Figure 1 represent the best evidence available to the road safety community at the beginning of the Safe System discussion in Australia and New Zealand. Given that more than a decade has passed since, and much new research has been published, the relationship between speed and injury severity may be due for review and discussion. This would be prudent given the 2021 horizon for the development of the new National Road Safety Strategy.

Delta-v and Severe Injury Probability

Review of crash reconstruction research suggests that estimated or measured impact speed of a vehicle is generally a poor predictor of crash severity, with the exception of pedestrian and cyclist crashes. It has been well established since the 1970s, that a vehicle's delta-v[1] is closely related to injury severity in two-vehicle crashes, e.g. side impact, head-on or rear-end. The only known drawback is accuracy of estimating delta-v in relation to rollover, roadside hazard and safety barrier

[1] Change in velocity magnitude of a vehicle during the crash.

crashes (Joksch 1993, Shelby 2011, Rosen, Stigson and Sander 2011, Schmitt et al 2014, Struble 2013).

There has been a significant amount of quality empirical research on the effect of delta-v on severity of two-vehicle crashes based on crash reconstruction databases held in the US (NASS/CDS, CIREN) and UK (CCIS, OTS). One of the seminal studies was by Joksch (1993), cited by Evans (1994), who developed a 'rule of thumb' power function for probability of a driver fatality given a vehicle's delta-v. This work was followed by Evans (1994) who used 22 272 crashes from the NASS database to create similar relationships for probability of driver fatality and injury. These relationships were based on crashes occurring between the early 1980s and early 1990s, and did not differentiate between crash types, e.g. head-on, side impact or rear-end. Applicability of these relationships to the three crash types was tested in this project and did not return results which correlated well with other research.

It is also worth noting other relevant studies investigating injury severity and delta-v, such as that by Richards and Cuerden (2009) in the UK. These used smaller crash samples which suffered from lack of statistical power or direct relevance to this project.

Most relevant research on vehicle-to-vehicle collisions was carried out by a group of researchers associated with the National Highway Traffic Safety Administration (NHTSA) in the USA. Augenstein et al. (2003a, 2003b) and Bahouth et al. (2012, 2014) provided much more refined sets of delta-v vs. severe injury probability relationships for occupants of vehicles involved in frontal, nearside (i.e. driver side), far side (i.e. passenger side) and rear-end impacts. These studies used large samples of crashes drawn from ever-expanding NASS/CDS and CIREN databases in the USA (in excess of 100 000).

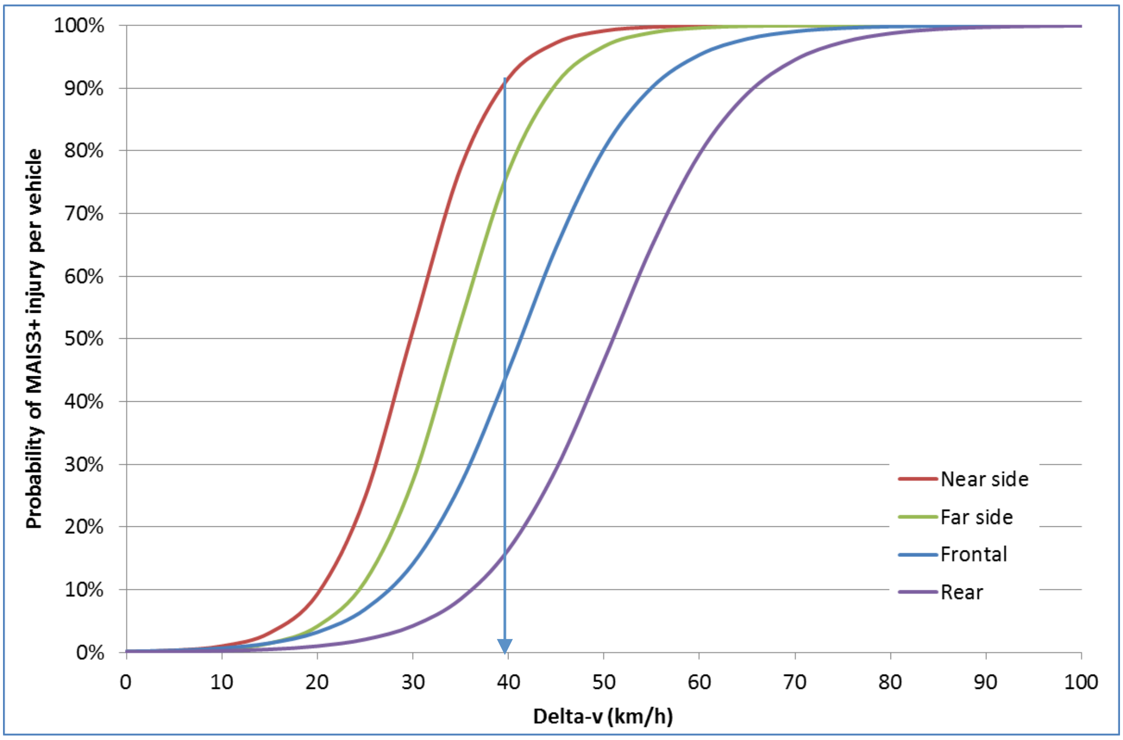
The objective of these researchers was to develop and refine reliable triggers for automated crash notification systems in vehicles. The baseline collision severity used in these studies was a non-injury tow-away crash. The authors applied strict limitations on the crash cases included in analysis to suit their objectives, e.g. availability of delta-v in the NASS records, focus on front seat passengers only, and the age of vehicle. The crash data in NASS/CDS was already weighted to match severity and type of crashes occurring across the USA. Also, all of these studies used a vehicle as a basic study unit, rather than a crash event (two or more vehicles).

Like the earlier studies, the Bahouth et al. (2014) study used logistic regression to develop relationships between probability of a MAIS3+ injury for a front seat occupant of a crashed vehicle in given crash configurations. MAIS3+ is widely considered the serious injury threshold and includes fatality. In this study, the regression models were based on new vehicles (post 2002) and controlled for a range of factors such as: delta-v, seatbelt wearing, rollover, secondary impacts, and age of the front seat occupants. The logistic regression models were developed using a randomly selected 80% of the applicable 2002-2012 NASS/CDS database and validated using the remaining 20% of data.

Figure 2 shows the resulting relationships between probability that a front seat occupant of a crashed vehicle will sustain an MAIS3+ injury and the vehicle's delta-v for a range of vehicle impact types. These curves assume seatbelt use, no rollover or secondary impacts, and occupant age between 16 and 55. Airbag deployment was not noted, but it can be assumed the vehicles were equipped with such, given the sample consisted of post 2002 vehicles only. Since the authors make no statement on the vehicle types, it is assumed the data set included both passenger and heavy vehicles.

Bahouth et al. note the principal directions of force (PDOF) on a vehicle which were used to categorise each impact into frontal, near side, far side, and rear types. The probability curves in Figure 2 reflect the logical expectations for these cases. For a given delta-v value, the near side impact was the most severe for the occupants. In this scenario, the impact occurs on the side of the driver and the amount of protection offered by the vehicle body is very low. The far side is next, showing the benefit of the crush zone to the left of the driver (assumed empty). Next is the frontal impact, with the crush zone benefit of the engine compartment but also with likelihood of the steering wheel injuring the driver. The least severe impact type is into the rear of the vehicle, with the large and typically empty crush space behind the driver.

Figure 2. Probability of a severe injury of front seat occupants vs. delta-v of a vehicle during a crash



Source: based on Bahouth et al. (2014).

Impact Speeds, Angles and Severe Injury Probability

It is difficult to directly apply the delta-v concept to Safe System road infrastructure discussion. This difficulty stems from the variable being a crash characteristic which lacks a direct relationship to road design inputs. Impact speed has been much more easily understood and related to design speed, or speed limit – variables under control of road agencies. Thus, it was important for this project to develop and demonstrate the generalised relationship between impact speeds, impact angles and severe injury probability. This would enable road agencies to modify this probability through improved design of infrastructure elements.

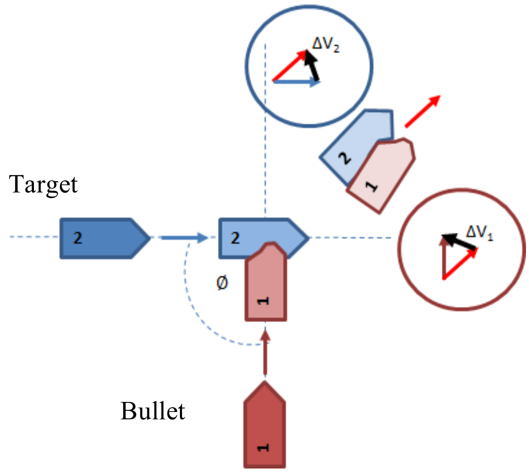
The relationships between delta-v and severe injury probability for different crash types in Figure 2 can be transformed to show the effect of impact speeds if we consider impact angles and several simple assumptions. This way the evidence from the research described in the previous section can benefit further Safe System infrastructure discussion in Australia and New Zealand .

As a first step, a useful derivation of delta-v was provided by Tolouey et al. (2011). Using Newtonian mechanics of momentum conservation, the authors showed that delta-v has the relationship with vehicle masses, impact speeds and the angle between their paths as shown by Equation 1.

$$\Delta V = \frac{m_1}{m_1+m_2}\sqrt{V_1^2 + V_2^2 - 2V_1V_2\cos\emptyset} \quad (1)$$

where ΔV is vehicle change in speed due to the crash, m1 and m2 are respective masses of 'bullet' and 'target' vehicles, V1 and V2 are their impact speeds, and Ø is the angle between the axis of travel of both vehicles, as shown in Figure 3.

Figure 3. Layout of colliding vehicles in Equation 1.



Newtonian calculation based on Tolouei et al. (2011) in Equation 1 is a very simplistic approximation, as delta-v of an individual crash is a function of many additional factors such as:

- relative masses of the vehicles involved
- part of the target vehicle hit
- vehicle construction and stiffness
- brake application timing and skidding
- vehicle yawing (rotation)
- post-impact rebound, if any.

One of the first assumptions in creating the impact speed–severe injury relationship was to normalise the role of relative vehicle masses in Equation 1. This is not necessarily something which can be easily controlled by road agencies at intersections. The mass ratio affecting delta-v's and severity of injuries for individual vehicles is likely to have a normal distribution, i.e. it will be favourable for some vehicles (large) and worse for others (small). It has been assumed from this point onwards that the masses of the two vehicles are identical. The term m1 / (m1 +m2) in Equation 1 thus becomes ½ and allows sole focus on the role of impact speeds and angles. This assumption would need to be reconsidered when investigating road design for traffic flows with a large percentage of heavy vehicles.

Another assumption in Figure 3 is that the collision is inelastic, i.e. there is no rebound of vehicles. In such cases, delta-v has the same magnitude for both vehicles of equal mass, as they stick together after collision. This assumption leads to a slightly overestimated value of delta-v in side collisions, and hence of the risk. Thus, the critical side impact speeds discussed further on may also be conservative, i.e. slightly lower values than if elasticity was accounted for.

The next step was to use Equation 1 to calculate a delta-v given a known impact speed of a bullet vehicle, assumed speed of a target vehicle, and an approximate impact angle representing a given crash type. Since, the angle is a variable in delta-v (Equation 1), it can be varied to carry out sensitivity analysis.

As noted earlier, Bahouth et al. (2014) provided their results based on individual vehicles in specific impact types (frontal, near-side, etc.), rather than on crash events (two vehicles, two impact types). This limitation was carried over to this project. Thus, using the assumed impact speeds, angles, and delta-v relationships from Figure 2, it was possible to calculate Pr(MAIS3+) for each targeted crash type. This is plotted in Figure 4 together with various assumptions indicating which impact type produced the highest severity[2].

For vehicle-pedestrian crashes, the physics of collision are different. The delta-v principle does not provide a good estimation of injury (Evans 1994). Davis (2001) provided an updated empirical relationship for pedestrian severe injury at different impact speeds. This relationship was chosen from a number of others reviewed by Rosen, Stigson and Sander (2011) on the basis of its relevance (severe injury) and solid methodology.

All five leading severe crash types are shown in Figure 4, with the approximate critical impact speeds in Table 1, and additional assumptions stated in Table 2. For a given bullet vehicle impact speed the pedestrian crash is the most severe, as expected due to biomechanical vulnerability of the target. This is followed by head-on crash, where the very high delta-v outweighs the benefit of the vehicle’s crumple zone. On par is the adjacent direction crash into the near side, where the lower delta-v is offset by greater vulnerability of the driver due his/her position. Next is the opposing-turning crash which assumes the impact on the far side and shows benefits of the passenger space as a crumple zone (see Discussion). The least severe is the rear-end crash type, given the low typical value of delta-v and a large crumple zone. The most critical impact in this case was on the bullet vehicle. These severities follow the order of the average casualty crash severity findings from Jurewicz et al. (2013). The suggested critical impact speeds for each crash type in Table 1 are based on an assumption that a 10% severe injury risk would be a substantial improvement in current safety performance.

Further analysis was carried out for roundabout collisions, where adjacent direction and opposing-turning crash types are essentially the same type of impact (far side). For a typical roundabout with a 70 degree entry and impact angle, and a 40 km/h circulating speed, the critical entry speed would be 30 km/h (or 40 km/h if the circulating speed was 30 km/h). As the entry angle is reduced at some larger sites, the critical entry speed increases. For a roundabout with a 30 degree entry and impact angle, and a 40 km/h circulating speed, the critical entry speed was calculated to be 60 km/h (lower speeds would reduce probability of severe injury below 10%). This demonstrates how geometric design can fundamentally improve safety performance.

These values are indicative only, due to many assumptions and model limitations. They have been rounded to the nearest 5 km/h. The pedestrian-vehicle critical impact speed could be extended to other vulnerable road users (cyclists and motorcyclists) until more specific evidence can be identified.

Table 1. Approximate critical impact speeds for common crash types

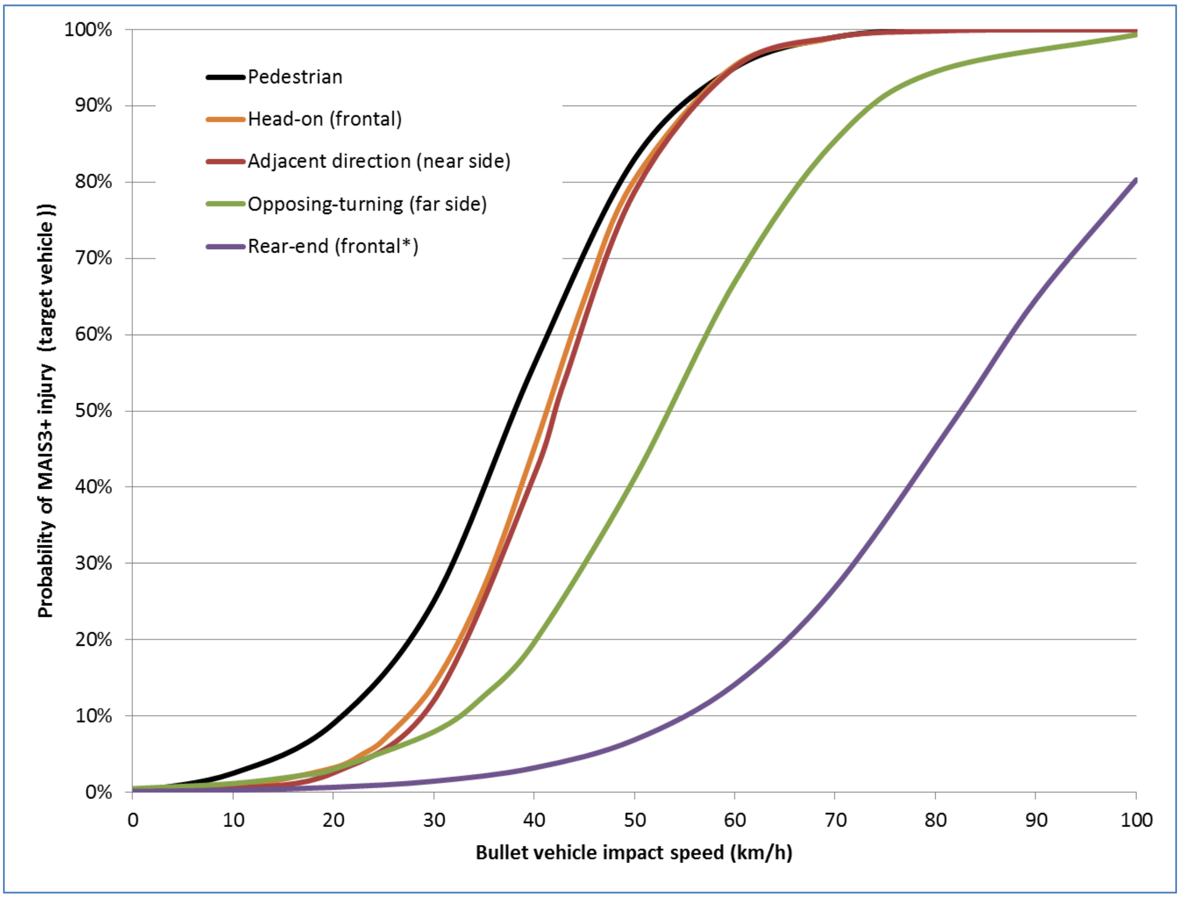
Crash type	Critical impact speed (km/h)
Pedestrian-vehicle	20
Head-on	30

[2] E.g. adjacent direction can occur on far or near side, but it is the latter which is more severe, and was thus used in the relationship.

Adjacent direction	30
Opposing-turning	30*
Rear-end	55

* Depending on the impact angle and the turning vehicle speed, this value may vary.

Figure 4. Proposed model of severe injury probability vs. bullet vehicle impact speeds in different crash types



Source: based on Bahouth et al. (2014), Davis (2001).

Table 2. Assumptions used in Figure 4, and sensitivity of P(MAIS3+) to angle of impact

Crash type	Impact angle (Refer to Figure 3)	Target vehicle speed	Scenario adopted	Pr(MAIS3+) sensitivity to impact angle change ±10°
Pedestrian	NA	NA	Any	Unknown
Head-on	180°	Same as bullet	Frontal	Negligible
Adjacent direction	90°	Same as bullet	Near side	High, ~30% change
Opposing-turning	225°	20 km/h	Far side	Moderate, 15-20% change
Rear-end	0°	0 km/h	Frontal	Nil if the target vehicle is stationary

* General assumptions: baseline severity is a non-injury tow-away event, vehicle occupants were seat-belted, no secondary or rollover collisions, applies to post-2002 vehicle models, front seat occupants only aged 16-55 (Bahouth et al. 2014); inelastic collision (no rebound), equal vehicle mass.

Estimation of critical impact speed for run-off-road crashes into narrow roadside hazards or safety barriers is more complex. Delta-v is not a good predictor of severity which is also affected by the area of impact, the size, mass and rigidity of hit vehicle (Joksch 1993). Hence, no simple impact speed–severity relationship could be found or developed at this time. As an indication, ANCAP uses an impact speed of 29 km/h in its rigid pole impact test which should result in low risk of severe injuries for a five-star vehicle (Australasian New Car Assessment Program 2015). This may act as temporary guidance until a more definitive relationship can be identified or developed for different roadside object types.

Discussion

The curves in Figure 4 shed a new light on the relationship between crash severity and impact speed. Given the clear research references and relevance to both fatal and serious injuries, these new relationships may be more appropriate for use in road design than the Wramborg (2005) curves. Still, they require further research and refinement as outlined below.

The impact speed relationship for opposing-turning crash type is the most complex of those in Figure 4. It is subject to several assumptions which influence the Safe System critical speed value. If a more conservative but less likely scenario is assumed where a passenger is present[3], the critical impact speed is approximately 25 km/h. These considerations were being included in the detailed analysis of designs in the concurrent Austroads project focussing on Safe System intersections.

A major shift in understanding of the impact speed–severity relationship relates to head-on crash type. While Wramborg (2005) suggests this is the most forgiving crash type for fatality, the new evidence indicates the opposite for severe injury. It is possible, that Wramborg's curve was based on an earlier version of a delta-v relationship. Or perhaps, there is a large disparity between serious and fatal injury impact speed thresholds. It is the large drop in vehicle speed during a head-on crash, a complete stop is assumed, which elevates this crash type's serious injury risk. Not coincidentally, head-on's are the second most severe intersection crash types in Victorian data, after pedestrian crashes (Austroads 2013).

The review of other MAIS3+ probability–delta-v relationships from the literature produced varied results, even when similar methods and data sources were used. This raises questions about the absolute accuracy of these relationships. For instance Bahouth et al. (2012) suggest a less harsh set of relationships than Bahouth et al. (2014) or Augenstein et al. (2003a, 2003b). Attempts to contact the authors to discuss these differences were not successful. It is clear that NASS/CDA data selection procedures, crash periods used, and other assumptions would influence the findings. Also, the studies had a specific objective in mind, which was different from this study's objective. It would be beneficial to have less exclusive relationships, e.g. for all vehicle occupants not just those in the front, and to include all ages of occupants; and developments in vehicle safety over time.

Figure 4 should be used as an indication only. Each curve is conceptually broad and the lines shown are the best estimates only. Due to many assumptions in the preparation of the relationships, the threshold speeds in Table 1 should not be taken as precise values. Each has a broad variance about it, representing the range of circumstances that happen in real life. The small size of the high delta-v collision sample in Bahouth et al. (2014) means the top end of these relationships is subject to a particularly wide standard error and should be not be considered as reliable at high speeds.

The limitation of the age of vehicle occupants to the 15-55 range means the Figure 4 relationships would need to be modified to model outcomes for older or younger road users.

At present, the interaction between vehicles of substantially different mass is to be expected in the system, and should be explored. Future investigations could determine the distribution of vehicle weight ratios in potential conflicts. A more appropriate ratio could be adopted in Equation 1 to derive a more representative version of Figure 4 relationships.

[3] Previous investigations in Jurewicz et al. (2014) showed occupancy rates are low in urban areas ~1.3 persons per vehicle, 1.5 on rural highways and 1.7 on interstate freeways in Victoria.

Davis (2001) used pedestrian crash data from the 1960s and 70s to inform the relationship in Figure 4. Thus this relationship would be ideal for revision using a more recent data.

For these reasons, it would be highly desirable to carry out further research in this area. The first objective would be to redevelop the statistical models for Pr(MAIS3+) vs. delta-v for Australasian policy context, i.e. for different crash types (e.g. adjacent direction), rather than for different impact types (e.g. near-side). Further, more inclusive model assumptions could be tested, e.g. regarding age and vehicle position of occupants, and vehicle age. Local verification of the models could be attempted using Australian and/or New Zealand crash reconstruction data, e.g. by combining CASR and ANSIS in-depth crash data bases if possible. Such relationships would need to be subjected to thorough peer scrutiny and discussion before they could be recommended for consideration in future road safety policies in Australia and New Zealand.

Appropriateness of a 10% MAIS3+ probability threshold as a critical benchmark should be confirmed. This could be done using data from a jurisdiction with current tow-away and casualty crash data. In the interim, rather than adopting an above/below 10% dichotomy, it would be preferable to evaluate and rank alternative design solutions according to their relative alignment with the zero probability of severe injury objective of the Safe System.

It is also clear that Safe System performance of road infrastructure cannot be wholly achieved by controlling impact speeds and angles (i.e. geometry and layout), especially where high speeds are desired to meet the mobility function. This means that more weight should be placed on minimising probability of road user conflicts. Road user separation, minimisation of number of conflict points, and greater management of road user movements can all be used to provide solutions supporting the Safe System vision.

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