Accident Analysis and Prevention 74 (2015) 314–323

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

An exploration of alternative intersection designs in the context of Safe System

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ARTICLE INFO

Article history:
Received 9 January 2014
Received in revised form 22 July 2014
Accepted 28 July 2014
Available online 28 August 2014

Keywords:
Safe System
Intersection design principles
Intersection crashes
Design compatibility ranking

ABSTRACT

Fatal and serious injury crashes persist at intersections despite current efforts to address this. Little research specifically investigates the role played by existing intersection design in perpetuating serious intersection crash outcomes despite an increasing move to incorporate Safe System design on to roads. This paper identifies design principles deemed important to align intersection design with Safe System approaches, including exploring the impact of speed and angle on overall kinetic energy of a crash. Existing as well as new intersection designs are presented that are believed to incorporate the identified principles. An assessment is made of the alignment of the new and existing designs with the identified principles.

1. Introduction

Intersections are of great importance within the road network due to their role in facilitating movement of different roadusers in conflicting directions, and change of travel direction. However, both these roles can create a naturally high potential for crashes, intersections found to be three to four times less safe than midblocks (AustRoads, 2010). Crashes at intersections are also a persistent problem, with crash percentages at intersections remaining relatively constant over the years (Hoareau et al., 2009), producing injuries of high severity. For example, in Australia, annually, a third of all serious casualties occur at intersections (around 11,000) (Australian Transport Council, 2010) similar to percentages of intersection crashes in China (Yong-Gang et al., 2011). In The Netherlands, a third of all fatalities occurred at intersections (European Road Safety Observatory, 2010), and in Canada, annually, around 800 fatalities and 8000 serious injuries occurred at intersections between 2002 and 2004, comprising around a third of all fatalities, and around 45% of serious casualties (Transport Canada, 2008). The traditional approaches to addressing such crashes at intersections, including the use of sophisticated traffic signal technology, red light and speed cameras, and drug and alcohol enforcement programmes have had its merits (Australian Department of Health and Ageing, 2003; Cameron et al., 2003). A residual number of intersection crashes, however, remain unaffected by this approach. In Victoria, Australia, for example, around 2300 serious casualty crashes currently occur at intersections in any given year (VicRoads, 2014).

Current intersection design is such that intersection crashes can occur in conditions of impact angle and impact speed several times greater than those considered tolerable for humans. That is, in the event of an intersection crash, design conditions are such that impact forces and kinetic energy levels can be generated beyond what a typical vehicle structure can be expected to resist, and far greater than the biomechanical tolerance of a human body (Tingvall and Haworth, 1999). Firstly, intersection crashes are likely to occur at or near initial travel speeds. Given typical driver perception reaction times (PRT) and considering the width of a typical intersection, a driver alert to an impending hazard on entry to an intersection is likely to drive through the entire intersection prior to commencement of brake activation (Kloeden et al., 2002; Scully and Corben, 2007). This suggests that crash occurrence and injury outcomes at intersections are heavily dependent on the design speed and posted speed limits of the intersection. For side-impact collisions, impact speeds greater than 50 km/h increase the likelihood of injurious outcomes (Bostrom et al., 2008; Fildes et al., 1994; Tingvall and Haworth, 1999) and yet, some intersections, for example in Victoria, Australia, have posted speed limits through the intersection of 80 km/h (VicRoads, 2012). Secondly, vehicles are likely to collide at angles predetermined by the intersecting angles of the roads on which they are travelling. Currently, most roads intersect at 90°,

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http://dx.doi.org/10.1016/j.aap.2014.07.030
0001-4575/

considered to be the most severe of angles at which to collide, given there is no potential for dissipation of crash energy through lateral components.

This suggests that there are in-built features within current intersection design that could possibly hinder the creation of intersections devoid of serious or fatal injury crash potential, conflicting with the goals of existing road safety strategies such as Vision Zero, Sustainable Safety and Safe System. Founded on the basis of Swedish Vision Zero (Tingvall and Haworth, 1999) and the Dutch Sustainable Safety (SWOV – Institute for Road Safety Research, 2006) philosophies, the Australian and New Zealand "Safe System" approach to road safety encompasses a systems approach to safety, recognising the need for collaboration and shared responsibility between users, designers and operators to ensure low-risk crash outcomes (Australasian College of Road Safety, 2010). The Safe System is underpinned by several key principles (CMARC, 2011; OECD, 2008):

- Principle 1 Recognition of human frailty
- Principle 2 Acceptance of human error
- Principle 3 Creation of a forgiving environment and appropriate crash energy management
- Principle 4 Need for a systems approach to safety (safety human, vehicle, infrastructure and speed environment components) and an expressed shared responsibility of road user, road designer and vehicle manufacturer

Many current intersection designs do not meet all the above principles yet few studies appear to challenge the fundamentals of intersection design with respect to intersection safety in light of the Safe System approach (Candappa and Corben, 2011). Or if the designs do meet the principles, catering for conflicting traffic movement requirements or implementing design within existing intersection geometry present challenges. The traditional roundabout, for example, is a current design that generally aligns with Safe System approaches but is underutilised at major road intersections in Victoria, Australia, often due to considerations of traffic capacity and traffic manipulation. A national roundtable discussion in Australia on some of the challenges in designing road infrastructure to be aligned to the Safe Systems approach identified several key considerations, with cost and timeframes being two of the overriding impediments (ARRB, 2009). The discussion highlighted a need for staff within road authorities to be better aware of Safe System principles and how a systems approach can be applied to infrastructure designs, as not all road safety practitioners have an in-depth understanding of this concept.

This paper attempts to meet this need in part, using the key Safe System principles and adapting these with respect to safe intersection design principles to create a more clear structure in which road authorities can consider infrastructure design in the context of Safe System. A number of intersection designs that incorporate features that either minimise travel speed or impact angle are also presented in the paper. Vital as they are to the smooth operation of a road network, aspects such as impact of the alternate designs on traffic capacity, and details relating to other vehicles such as public transport or cyclists, have not been included in this stage of the study. Scope of the project was also restricted to the standard cross-intersection to limit the options and design features needing consideration. Subsequent stages of the study will allow these factors to be investigated further, and detailed designs developed and trialled, potentially increasing the collection of intersection designs better aligned with Safe System objectives. Primary objectives of this paper are to highlight the disjoint between some existing intersection design features and the goals of Safe System, as well as to stimulate further thinking of design options that modify typical intersection angles and speeds through the intersection to create Safe System compatible intersections.

2. Methodology

Government funding was provided to investigate the persistent problem of crashes at intersections in Victoria, Australia, with the objective of generating intersection designs that better align with Safe System philosophy. A methodological framework was adopted that originated in the industrial design field, starting from the definition of the problem, moving to problem analysis, then establishment of design principles, through to the creation of the design itself. It was recognised that the design process should be iterative, such that at each step the need for feedback be evaluated and, if necessary, earlier stages in the design process be revisited.

2.1. *Crash analysis*

As background to the crash situation in Victoria, a detailed analysis of the crashes at intersections in Victoria was completed. Analysis included police reported data for a six-year period and the use of the statistical analytical programme, SPSS. The results identified an overall indication of the trends in serious casualties resulting from intersection crashes. Serious casualties are defined as the number of seriously injured roadusers who either died within 30 days as a result of a road crash or were transported to hospital as a result of the crash (Scully et al., 2008).

2.2. *Targetted literature review*

A targetted review of literature on intersection design, current practices and existing safety issues was completed. The main objectives of the review were to identify any existing infrastructural countermeasures that were considered both innovative and likely to produce significant reductions in the incidence of severe intersection crashes, as well as to identify any current research in related areas. While vehicle technology and positively modifying road user behaviour both have the potential to contribute to safer intersections, these were not a primary focus of the literature review.

2.3. *Development and definition of safe intersection design principles*

In the case of a Safe System intersection design, the fundamental constraints within which the road system can operate successfully can be defined through the laws of physics. Physics dictates the levels of kinetic energy that are generated through the intersection's defined speed limits; the impact forces a typical vehicle can resist through its body structure; how quickly a driver can brake to avoid a collision; and most importantly, the impact force that is transferred to the human body, which is limited in the force it can withstand before sustaining life-threatening injuries.

Ideally then, intersection designs aligned with the Safe System will be based on the objective of limiting the overall kinetic energy of a crash to within accepted biomechanically tolerable thresholds. Using the Kinetic Energy Management Model (KEMM) developed by Corben et al. (2004) to analyse conflict potential between a pedestrian and a vehicle, the authors modified the KEMM to analyse conflict at intersections, referred to as KEMM-X. The KEMM-X was used as a basis to define practical design principles that can be used to achieve intersections with a high degree of safety. The model focusses specifically on the safe management of kinetic energy in the road-transport system in terms of five layers: exposure, crash risk per exposure, kinetic energy per exposure, transfer of kinetic energy to human, and biomechanical tolerance of humans. The risk factors in these layers are analysed in relation to the system components: human, roads and roadsides, the vehicle and speed (see Corben et al. (2004) for further details). As an example of its use, the model was used as a template to discuss and identify the factors relating to road and roadside under the layer of "crash risk per exposure". Within this framework, identified roadside hazards at intersections included traffic signal posts, bus stops, and rubbish bins. Relevant literature that defined "thresholds of impact speeds" also informed the definition of the principles. Workshops were held with subject matter experts and practitioners from the Victorian road authority, VicRoads, and the Victorian Road Insurance agency, TAC, to gain feedback on the work to date. Based on these discussion as well as findings from the literature review, the authors identified the boundaries or constraints within which an intersection can operate "as expected", and explored these within a Safe System context to define several design principles deemed necessary for safer intersections. These are referred to in the rest of the paper as Safe Intersection Design Principles (SIDPs).

2.4. Incorporate principles into practical intersection designs

A workshop was conducted with a number of key experts in road safety as well as staff from the Arts and Creative Design Department of Monash University to brainstorm new designs that would incorporate the identified principles (Corben et al., 2010a). The participant selection ensured road engineering expertise through the group of road experts, and enabled lateral thinking through the creative design staff. Consistent with recent thinking on system approaches to design (Read et al., 2013), the workshop was undertaken away from usual work environments to encourage creativity and innovation, in group and individual sessions. Initial brainstorming was completed without guidelines to maximise freethinking, subsequent iterative steps included guidelines on basic requirements for a workable intersection design. The workshop was framed by the question, 'what would intersections look like if they were designed purely from a road safety viewpoint such that roadusers are unlikely to be killed or seriously injured travelling through it?". The process yielded a number of possible designs of widely varying practicality. Of these, the designs presented in the results sections are the ones considered more practical and more readily incorporated onto our road systems (Corben et al., 2010b).

2.5. Compatibility assessment

In an attempt to assess the new designs' compatibility with the identified SIDPs, a broad ranking system was developed to rank compatibility of each design with the principles. In this preliminary attempt at assessing relative compatibility, each intersection design was assessed against the identified principles in terms of high, medium or low compatibility. The impact of the identified principles (five in total) on achieving Safe System ideals was considered based on the available literature and road safety expertise. To provide a basis for categorisation of the design in to high, medium or low compatibility, a point system was developed. Principles identified as contributing to the level of injury outcome of a crash were considered either 'key' or 'important' principles in the goal of achieving Safe System ideals. Others that related more to crash occurrence were considered 'supportive' principles. The principle considered 'key' to achieving Safe System ideals at intersections was given an arbitrary score of 10 and other principles scaled relative to this or as a binary function.

Designs were then assessed against this point system. The total for each design was summed and a percentage calculated of the total available points. The design was then categorised as 'high', 'medium' or 'low' compliance in order to determine how the principles and the identified designs generally aligned with each other.

3. Results

For brevity, the results section presents only the key principles and the designs. A detailed methodology has been provided above to indicate the basis for establishment of the designs and principles.

3.1. Safer intersection design principles (SIDPs)

3.1.1. Principle 1 – key principle – limit travel speeds through intersections to 50 km/h

There is general acceptance that 90° collisions between two passenger vehicles involving impact speeds greater than 50 km/h are likely to exceed the biomechanical tolerance threshold of humans given current vehicle structures (Bostrom et al., 2008; Fildes et al., 1994; Tingvall and Haworth, 1999). Considering the longer PRT of an older driver of 2.5 s (Staplin et al., 2001), vehicles can travel around 35 m prior to braking being initiated (Scully and Corben, 2007). Many intersections are far narrower than this suggesting that impact speeds at intersections can frequently be equivalent to travel speeds. Based on this research, to aim for a Safe System intersection design, *restraining impact speed to less than 50 km/h* is considered a key Safe Intersection Design Principle (SIDP).

3.1.2. Principle 2 – important principle – avoid 90° impact angles

Fig. 1 presents the reduction in kinetic energy in the lateral direction that can be achieved through the manipulation of impact angle. For example, at 70 km/h, colliding at a 90° angle generates kinetic energy of around double the maximum tolerable lateral kinetic energy of 96.5 kJ. Halving this impact angle, similar to impact angles at roundabouts, reduces the lateral kinetic energy to the biomechanical threshold. Table 1 presents the combinations of speed and angle that are compatible with Safe System. It can be seen that with travel speeds above 50 km/h, 90° impact angles are not compatible with Safe System ideals. Impact speeds of up to 70 km/h were considered tolerable if 90° impact angles could be modified to more favourable angles (Corben et al., 2010). To aim for a Safe System intersection design then, optimising impact angles where possible is considered an "important" SIDP.

3.1.3. Principle 3 – important principle – physically separate vulnerable roadusers or provide travel speeds <30 km/h

Vulnerable roadusers, defined here as pedestrians and two-wheeler users (Australian Government Standing Committee on Planning Environment and Territory and Municipal Services, 2014; SWOV – Institute for Road Safety Research, 2012), are particularly affected by the potential levels of kinetic energy at intersections. The absence of any vehicle protection leaves vulnerable roadusers open to the full force of a crash. In fact, the safest means of ensuring Safe System compatibility with respect to vulnerable roadusers is to *physically* separate them from other roadusers. Temporal separation of vulnerable roadusers from vehicles is less effective in meeting Safe System ideals as this still relies on roaduser compliance and avoidance of error. For this reason, temporal separation has not been defined within Principle 4 as it still leaves open the possibility of serious injury. However, this form of separation can still assist in creating a lowered risk of crash and injury outcome, and therefore it has been credited with increasing safety at signalised intersections. To aim for a Safe System intersection design, separating vulnerable roadusers from other traffic is considered an "important" SIDP. Where physical separation is not possible, inducing travel speeds to below 30 km/h is recommended (Tingvall and Haworth, 1999). In this paper, facilities for vulnerable roadusers refer only to pedestrian facilities.

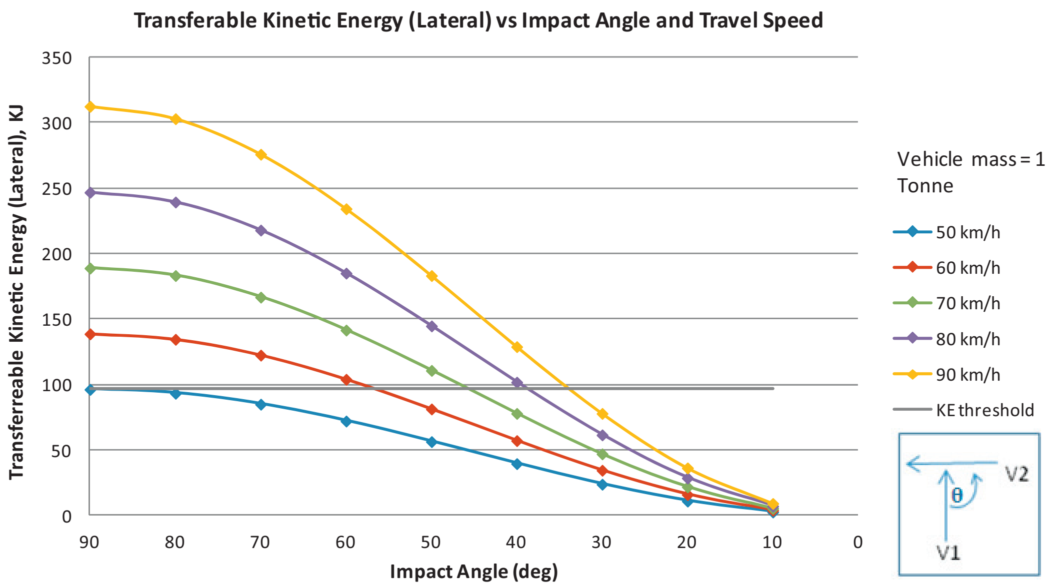

Fig. 1. Influence of impact angle on transferrable kinetic energy.

3.1.4. Principle 4 – supporting principle – limit points of conflict

It can be argued that the risk of severe injury is reduced firstly by preventing the collision altogether. In particular, limiting the points of conflict at an intersection limits the possibility of a crash and so can increase overall safety at an intersection. Based on available research, a typical cross-intersection presents to the driver 32 conflict points as opposed to a typical roundabout which presents four to eight conflict points, depending on definitions (AustRoads, 2013; Hauer, 1990). Specifically, it must be noted that reducing the permitted movement types within the same intersection design automatically reduces the number of conflict points. To aim for a Safe System intersection design, reducing the number of conflict points is considered a supporting SIDP.

3.1.5. Principle 5 – supporting principle – promote active mutual responsibility at intersections

As defined earlier, Principle 4 of the Safe System approach relies on the various components of the system working harmoniously together. Designs that tangibly promote mutual responsibility are suggested to improve safety, as opposed to designs that give sole right-of-way, for example, to one group of roadusers, which can encourage a more aggressive passage through the intersections. To aim for a Safe System intersection design then, promoting active mutual responsibility at an intersection is likely to affect crash occurrence and is considered a supporting SIDP.

3.1.6. Other possible supporting principles

Collisions can also be avoided by minimising exposure to the factors contributing to collision risk, namely, by limiting driver exposure to intersections; minimising driver exposure to other vehicles at the intersection, and minimising various other means in which conflict can occur at the intersection. Therefore, other design principles for Safe System intersection design could include *minimising intersections within a given route, as well as minimising vehicle volumes through the intersection* (Elvik et al., 2008). Exploring these principles is beyond the scope of this paper. In addition to the above defined principles, the role of human behaviour in the success of any new treatment is well recognised. For new designs to operate as intended, human understanding and adequate public education of the design are considered important factors in any process involving the development and implementation of new designs.

3.2. Designs incorporating identified principles

3.2.1. The Cut-Through

The Cut-Through design (Fig. 2) presents a means of incorporating the safety benefits of roundabouts at signalised intersections, thereby combining the advantages of both means of intersection control. The design comprises central islands introduced within a signalised intersection (Corben et al., 2010). Named the “Cut-Through”, the design permits drivers turning right to “cut through” the central island, while through-vehicles travel around the central island. The island is intended to minimise the angle of collision through appropriately designed deflection. Drivers are slowed down on approach to the intersection by the need to negotiate the central island. Where right-turns at the intersection are fully controlled by a turning-arrow, the Cut-Through option ensures the right-turning vehicles from either direction do not ‘interlock’ with each other. Optional additions to the design include raised

Table 1
Speed and angle combinations that produce Safe System compatible levels of KE (KJ) (green highlight).

Speed (km/h)	Impact Angle (degrees)							
	90	80	70	60	50	40	30	20
100	385.8	374.2	340.7	289.4	226.4	159.4	96.5	45.1
90	312.5	303.1	275.9	234.4	183.4	129.1	78.1	36.6
80	246.9	239.5	218.0	185.2	144.9	102.0	61.7	28.9
70	189.0	183.3	166.9	141.8	110.9	78.1	47.3	22.1
60	138.9	134.7	122.6	104.2	81.5	57.4	34.7	16.2
50	96.5	93.5	85.2	72.3	56.6	39.9	24.1	11.3

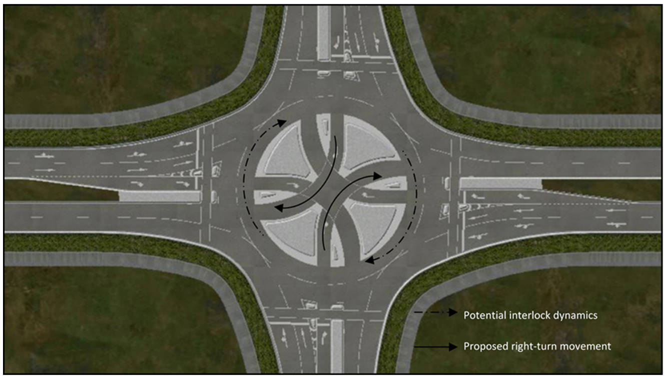

Fig. 2. Computerised image of the Cut-Through design.
Source: © MUARC 2012.

Fig. 4. Example of an Elevated StopLine in The Netherlands.
Source: MUARC 2010.

lane-separators on approach to the intersection, and straightening of the approaches as with the Turbo roundabout (described in the following section) to limit lane change and induce slower speeds on approach to the intersection. The Cut-Through would not be signed as a roundabout, but is intended to operate as a signalised intersection, with in-built favourable angles.

This design is envisaged to be suitable for the larger arterial roads with existing traffic signals, where the risks of side-impact crashes are high. It is intended that the central island be included within the geometry of the existing intersection rather than requiring widening. Some challenges to its implementation include ensuring the design produces the intended reductions in speed and impact angles through appropriate deflection while not creating manoeuvrability concerns, particularly for heavy vehicles; installation costs; and presenting clear delineation for the driver so the design is not used as a roundabout. A design similar to the Cut-Through and named a "Squircle", contains essentially the same anticipated traffic movements through the intersection and is considered suitable for use at local road intersections (Corben et al., 2010).

3.2.2. The Turbo roundabout

Another variation of a roundabout is the Turbo roundabout (Fig. 3). Multi-lane roundabouts do not exhibit all the safety benefits of single-lane roundabouts (Walsh, 2005), and may not always align with Safe System goals. The additional lanes within these roundabouts allow vehicles to cut across the lanes, permitting severe angle interactions and high travel speeds, resulting in crashes of higher severity. Turbo roundabouts address this deficiency by introducing raised lane-separators between the lanes to restrict movement across the lanes within the roundabout. Originating in The Netherlands, the Turbo roundabout design involves spiral vehicle paths through the intersection, raised lane-separators, and perpendicular, rather than sweeping, approaches to the roundabout (Corben et al., 2010; Fortuijn, 2009). On approach to the Turbo , directional delineation and signage are used to assist drivers select the required lane for their intended destination. This design can be considered particularly at two-lane roundabouts to improve safety levels at the existing roundabout. The design has been used in The Netherlands on large arterial roads and highways. Some challenges to implementing this design could be mitigating the initial driver unfamiliarity with the design, and ensuring adequate and appropriate signage is provided for easy negotiation through the intersection.

Given that speed is a key criterion in most designs, the following three designs focus on means of inducing reduced travel speeds through the intersection.

3.2.3. Elevated StopLines

Elevated StopLines (Fig. 4) are mild elevations in the vicinity of the stopline that induce speed reduction through the intersection. Used in The Netherlands (Corben et al., 2010), various speed profiles have been used to suit the requirements of the specific road type and can be designed to limit travel speeds to 50 km/h through the intersection. Fig. 5 presents a similar version of this applied on a local road in Victoria, Australia, with pedestrian facilities included. Elevated StopLines can be considered at most divided, signalised intersections, the profile of the raised hump dependent on the existing posted speed limit and the desired speed reduction. The measure can be considered for use on roads with a propensity for speeding through the amber light. Implementation challenges include public acceptance and the provision of sufficient warning

Fig. 3. Image of a Turbo roundabout.
Source: Aerodata International Surveys, 2014 Google Maps.

Fig. 5. Example of a similar treatment with a pedestrian crossing in Victoria, Australia.
Source: Janet Bolitho, 2010.

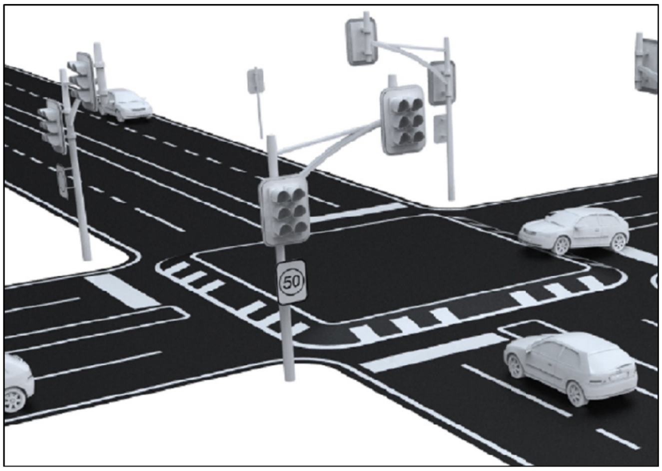

Fig. 6. Computer image of a conceptual design of a raised intersection.
Source: © MUARC 2011.

to the driver. Noise pollution, regarded as a typical issue with speed humps (Wewalwala and Sonnadara, 2011), was found to not be of concern by a UK study, which found that noise levels produced by light vehicles across speed humps were in fact lower than for vehicles driving on a flat section of road, given their respective mean speeds (Daniel, 2012).

3.2.4. Raised intersections

Similar to Elevated StopLines, raised intersections (Fig. 6) are intended to induce speed reductions at the intersection (Corben et al., 2010). The difference, however, is that Elevated StopLines involve only the section of road in the vicinity of the stopline to be raised whereas raised intersections involve the entire intersection being raised. Raised intersections have been found to induce speed reductions on approach to the intersection and can create a traffic-calming effect (Huang and Cynecki, 2007; Van Schagen, 2003). The design is suitable for roads with low volumes and a low emphasis on traffic movement. This measure is not considered suitable for roads with trams, as in Victoria, Australia. It is recommended that the intersection be raised to include the pedestrian crossings as well, to provide the benefits of the reduced speed to any pedestrians who are crossing. Challenges to implementation can include the expense of raising the whole intersection and public acceptance of the measure. As with Elevated StopLines, noise pollution may be a potential concern (Wewalwala and Sonnadara, 2011), though a recent UK study indicates otherwise (Daniel, 2012).

3.2.5. Green Light Speeds

The above measures are intended to induce reduced travel speeds through intersections using infrastructural measures. A more direct and simpler means of doing this is through the concept of introducing default intersection speed limits at signalised intersections, or what could be termed “Green Light Speeds”, Fig. 7. In Victoria, Australia, various reduced speed limits are introduced within the road system to address locations of particular concern, including school speed limits, shopping strip speed limits, local road speed limits (VicRoads, 2012). The introduction of such speed limits recognises that there is heightened risk of collision at that location–through increased pedestrian activity in the vicinity of schools, shops or on local roads. Intersections have the highest number of conflict points within the road network. Through the introduction of Green Light Speeds, the heightened risk of collision at intersections can be recognised and mitigated, economically and simply. Green Light Speeds are defined as a regulatory speed limit which would apply to vehicles travelling through a signalised

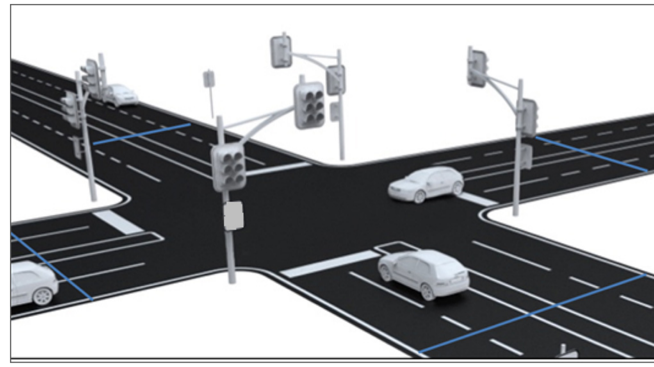

Fig. 7. Computerised concept image of “Green Light Speeds”.
Source: © MUARC 2011.

intersection during the green light phase, regardless of the route’s speed limit. The location after which the speed limits apply would be ideally where the vehicle can be brought to a complete stop prior to entering the intersection. This would be typically, around 40 m for 60 km/h and around 63 m for 80 km/h speed limits (Scully and Corben, 2007). However, for consistency, a distance 50 m prior to the stopline is considered a suitable location at which to introduce the Green Light Speeds, creating an intersection “zone”. Linemarking may be the clearest means of demarcating this intersection zone (Corben et al., 2010). To reinforce this speed limit, posted speed limit signs can be introduced within the intersection zone and a media campaign could be utilised to promote Green Light Speeds, underpinned by an extensive speed enforcement programme. An alternative, highly cost-effective means of achieving lower travel speeds at traffic signals at relatively low cost is to define within the road traffic regulations that a green traffic signal may only be passed at speeds no faster than 50 km/h. The potential benefit of such a measure is the creation of more Safe System compatible speeds without high implementation costs. If implemented, for consistency it is recommended that all signalised intersections be subject to Green Light Speeds rather than on a selective basis. Challenges to implementation would be to gain community and political support, particularly given recent furore on the variation in posted speed limits within the network. Introduction of the measure such that it minimises driver confusion, as well as enabling greater compliance to the speed limits are other challenges. Nonetheless, if adopted, the cost-effectiveness of the measure is likely to outweigh the difficulties faced in its implementation. While not common in Victoria, a similar initiative to this is the US example of All-Way or Four-Way Stop intersections (FHWA, 2007; Preusser et al., 1998). This design requires all vehicles to come to a stop prior to entering the intersection. Again, this promotes tolerable impact speeds and encourages mutual responsibility for the safe negotiation of the intersection.

3.3. Alignment of current and new intersection designs to defined principles

3.3.1. The Cut-Through

The Cut-Through design was found to be aligned to a high degree with the identified design principles (>68% alignment). It is designed to induce lower travel speed as the driver proceeds through the intersection (Principle 1), minimise large-angled crashes through the intersection (Principle 2) and reduce the number of conflict points from the standard cross-intersection (Principle 4). The pedestrian refuge incorporated in to the design physically separates the vulnerable road user during the crossing movement (Principle 3). Given the signal operation of the Cut-Through, it is argued that Principle 5 is not met in the Cut-Through design as signalisation can encourage a heightened sense of right-of-way.

3.3.2. The Turbo roundabout

As with the Cut-Through, the Turbo roundabout was found to be aligned to a high degree with the identified design principles (>68% alignment). The Turbo roundabout can be seen to recreate the safety benefits of a single roundabout within a multi-lane roundabout. The central island and lane-separators reduce potential for collisions involving high-speed (Principle 1) and physically reduce potential for drivers to cut across the lanes, further minimising likelihood of high-angled crashes (Principle 2). Vulnerable roadusers are separated through pedestrian refuges (Principle 3) and conflict points are reduced (Principle 4) (Fortuijn, 2009). Turbo roundabouts are often signalised and therefore Principle 5 is considered to be not met within the design as signalisation can encourage a heightened sense of right-of-way.

3.3.3. Elevated StopLines

Elevated StopLines were considered to be aligned to a medium degree with the identified design principles (between 34 and 67%), meeting the key safety principle of appropriate speed levels. Vertical deflections such as raised humps encourage lower travel speeds (Principle 1) and are generally more effective than other traffic calming measures (Harvey, 1991). Principles 2–5 are not necessarily met by the design.

3.3.4. Raised intersections

As with the Elevated StopLines, raised intersections were considered to be aligned to a medium degree with the identified design principles (between 34 and67%). Again, the key principle of appropriate speed is achieved in the design (Principle 1). Principles 2–5 are not necessarily met by the design.

3.3.5. Green Light Speeds

Green Light Speeds were considered to be aligned to a medium degree with the identified design principles (between 34 and 67%), as it meets the key safety principle (Principle 1). Technically, this design can be considered Safe System incompatible as it relies on the compliance of the driver to produce its safety benefits. However, two arguments are presented here in defence of its inclusion as a Safe System measure: one, given the impact of speed on crash outcomes, the creation of a low speed environment is a key component to Safe System intersection design and it is proposed that measures such as this, that integrate a Safe System compatible speed environment within the design can address a large percentage of potential crashes at a fraction of the cost of some of the infrastructural measures, despite its reliance on roaduser compliance. Therefore, the inclusion of the measure in a collection of designs aimed at creating such safe environments was seen as important, if only to generate further discussion and development of the idea. Secondly, a distinction is made between, designs that include a principle in the design that is Safe System compatible but its reliance on driver compliance to the design reduces its overall alignment ranking with Safe System; and a design where the design itself is deficient in relation to adhering with the identified design principles. In this case, the design itself is aligned with the identified design principles of creating safe impact speeds. Regardless, the assessment recognises that on occasions when speed limit is not adhered (incidence as low as 10% in some areas of Australia (Government of Western Australia, 2012), high severity crashes are still possible and the scoring was adjusted accordingly. The other SIDPs are not considered to be met in this design.

3.3.6. Sign controls and traffic signals

Within the existing designs, signalised intersections and sign-controlled intersections can permit high-speed crashes as a result of high in-built design speeds. Both measures have been assessed as being aligned to a low degree with the SIDPs (<33%) as high-severity crashes can occur at these intersections. Both signal and sign-controlled intersections were considered incompatible with Principle 1. In some instances, the posted speed limit (and therefore travel speed), through a signalised intersection can be up to 80 km/h in Victoria, Australia (VicRoads, 2012). A vehicle travelling through such an intersection can collide with another vehicle at speeds of up to 80 km/h, leading to kinetic energy levels over two and a half times the tolerable levels (Fig. 1). Likewise, little alignment was evident with respect to Principle 2, crashes at both signalised intersections and sign-controlled intersections likely to occur at the most hazardous of angles – 90°, with no mitigation of impact angles built into the design. The number of conflict points (Principle 4) remains unchanged at these intersections. It is acknowledged that traffic signals do provide guidance in negotiating the intersection in safety through its signal phasing, and in this way, mitigate crash risk and is thus recognised in the rankings. Between 10 and 40% of crashes involve red-light running (Green, 2000; Schattler and Datta, 2004). This relatively low compliance to signals suggests erroneous action can still lead to severe injury, and so it is yet considered less compatible with Safe System. Assessed against Principle 3, both signalised and sign-controlled intersections are likely to leave pedestrians vulnerable to high-speed collisions, the speed limit at the intersection being the defining factor in the impact speed. However, it can be argued that on divided roads, the median at a signalised intersection provides some physical separation and crossing assistance for the pedestrian. This has been included as a safety feature within the compatibility rankings. Designs that encourage all roadusers to display mutual caution, and act in collaboration with other roadusers to ensure the safe travel of all concerned is considered to be aligned with Principle 5. While somewhat difficult to implement, one practical option for achieving this is to avoid design features that give one stream of traffic unquestionable right-of-way. This is not the case when driving through a signalised intersection, for example, where the driver facing a green light often travels through the intersection with a sense of proprietorship, expecting to have right-of-way, often intolerant of any roaduser that inhibits smooth passage through the intersection. It is believed some degree of mutual responsibility occurs at sign-controlled intersections where drivers facing the sign control have to display caution in selecting appropriate gaps (Principle 5) and this is reflected in the compatibility rankings.

3.3.7. Roundabouts

The roundabout is one current intersection control that appears to limit the potential for serious collisions, kinetic energy levels half those at signal and sign-controlled intersections (Fig. 8). In essence, the roundabout comprises many of the design principles identified earlier. A well-designed roundabout induces lower travel speed as the driver proceeds through the intersection (Principle 1). 90° collisions are minimised through the creation of non-perpendicular movements through the intersection (Principle 2), with impact angles reducing by a third, and impact speeds essentially halved through the roundabout design (AustRoads, 2011). The central island dramatically reduces the number of conflict points at the intersection, from the typical 32 conflict points at a cross-intersection to between four and eight conflict points, depending on definitions (Principle 4) (AustRoads, 2013). The standard pedestrian refuge physically separates the vulnerable road user during the crossing movement (Principle 3). Looked at from one angle, it can be argued that Principle 5 is not fully met in a roundabout design. Vehicles within the roundabout by law have right-of-way in Australia (VicRoads, 2009), and similar to drivers at signalised intersections, drivers with right-of-way at a roundabout can expect and demand it. From this viewpoint, an opportunity presents itself to further encourage mutual respect at a roundabout by both drivers

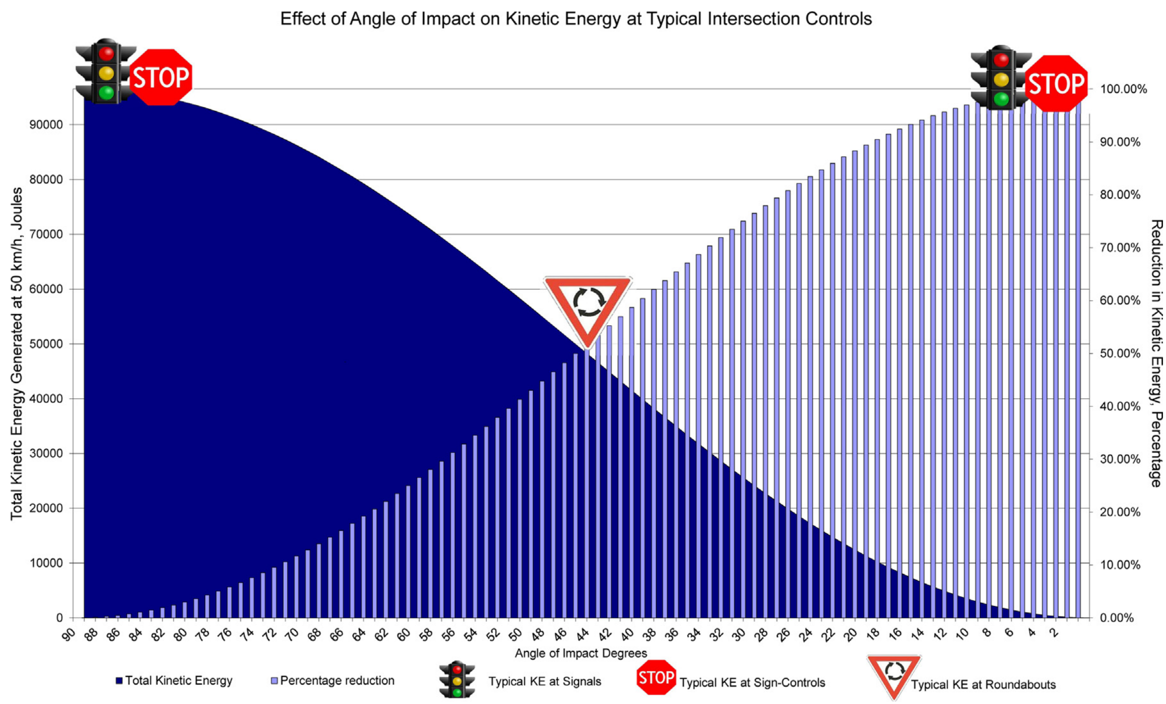

Fig. 8. Typical kinetic energy at intersection controls.

Table 2
Compatibility assessment criteria for each principle.

Principle 1	Does the design encourage slower speeds through the intersection
Principle 2	Does the design mitigate impact angle to some degree
Principle 3	Is there facility to separate vulnerable road users from traffic
Principle 4	Are conflict points reduced from the typical cross intersection
Principle 5	Is mutual responsibility encouraged through the design

and vulnerable roadusers. Alternatively, it can be viewed that, as in the situation of vehicles merging in to a stream of traffic, drivers both within the roundabout and entering the roundabout modify their travel speed to facilitate a safe negotiation of the roundabout, thereby displaying mutual responsibility while travelling through the intersection. The reduced speed environment at roundabouts is additionally conducive to encouraging mutual evasive action to be taken regardless of driver blame. Regardless, to be conservative, Principle 5 was considered to be not met in a roundabout.

Table 2 identifies the criteria used to be assess the designs against the SIDPs and Table 3 summarises the relative rankings for each design.

The assessment findings are only indicative of design compatibility and are not presented here as findings of statistical significance. At this stage, the rankings are calculated broadly to gauge the relative compatibility of each design to Safe System ideals and to indicate whether one design tends to comply to a higher or lower degree with the design principles than another. It is noted too that the rankings for the designs are not intended to be absolute; a design with twice the score of another does not imply that it is twice as safe or twice as compatible. Detailed development of such an assessment scheme would be required to produce firmer outcomes.

Table 3
Presents the relative alignment of new and current designs with the above-defined SIDPs.

	P1 Low speed collisions ($Y=10$)	P2 Favourable angles ($Y=5$)	P3 Separation (physical) of vulnerable road users ($Y=1$)	P4 Limit conflict points ($Y=1$)	P5 Active mutual responsibility ($Y=1$)	Total	Safe system compatibility (%)	Ranking
Traffic signals	N	N	Y	N	N	2[a]	11	L
Sign controlled	N	N	N	N	Y	1	6	L
Roundabouts	Y	Y	Y	Y	N	17	94	H
Cut-Through	Y	Y	Y	Y	N	17	94	H
Turbo	Y	Y	Y	Y	N	17	94	H
Elevated StopLines	Y	N	N	N	N	10	56	M
Raised intersections	Y	N	N	N	N	10	56	M
Green Light Speeds	Y[b]	N	N	N	N	9	50	M

L	M	H
0–33%	34–67%	68–100%

[a] +1 in recognition of gap choice assistance provided by signals.
[b] Reduced benefit (9) as relies on driver compliance.

4. Conclusions and future research

Findings of this study, aimed at improving intersection safety in Victoria, Australia, suggest that few current intersection designs align well with the Safe Intersection Design Principles identified in the study. While there remains potential for crashes that produce levels of kinetic energy incompatible with human tolerances, there remains potential for fatal and serious injury crash outcomes, and a truly 'safe system' on the road network will remain unattainable. It is believed that persisting with the designs in their current form limits the possibilities of achieving the Safe System ambition of eliminating the risk of fatal and serious injury intersection crashes in the long term.

The designs proposed in this paper present road authorities with an opportunity to consider alternative designs that show potential for creating energy exchange within biomechanically tolerable levels. The designs are founded on Safe System principles governed by the realities of human interaction, crash dynamics and the principles of physics. The designs presented here were limited to the more conservative options, the designs being not dissimilar to existing designs, potentially minimising driver resistance to the designs. It is acknowledged that there are numerous other ways of incorporating the safety principles in to designs and the reader is challenged to explore these options further.

A preliminary attempt was made to quantify how well these designs do in fact align with Safe System principles and how they compare with existing designs. The assessment provides broad conclusions on design factors that influence crash injury such as potential impact speeds and angles, and presents a platform for a more detailed assessment system to be created. Some of the limitations of this assessment scheme include the subjective nature of the assessment and the somewhat arbitrary nature of the scoring system; true assessment of designs also depends on the final on-site construction while this assessment was completed on assumed design standards. As a form of validation of the rankings however, the overall ranking of the existing designs does coincide with typical road safety benefits identified in countermeasure evaluations, the introduction of a roundabout producing the highest safety benefits, followed by signals and then sign-control measures (FHWA, 2010; Scully et al., 2006). Future research could identify sub-criteria for assessment within the principles and would involve kinetic energy calculations based on a projected range of impact speed and angles to provide more objective and quantifiable assessments. The system could be applied to other designs as well as a means of assessing Safe System alignment.

While in theory, a Safe Systems approach to road safety is ideal, it is acknowledged that implementation of designs or adaptation of current infrastructure design to align with this approach is not necessarily straightforward (ARRB, 2009; Hall, 2011). Potential to modify many established urban settings is limited given geographical constraints. Making fundamental changes to these established sites requires extensive and often impractical redesigning of the site, with heavy financial costs. To garner public support for somewhat radical changes to the road network can also be a challenge without well-presented evidence and political leadership.

However, collection of data on the performance of many of these designs is in progress. Several of the designs are currently in use internationally, allowing adequate data on design performance to be progressively collected. Others, such as the Cut-Through and the Green Light Speeds, are being evaluated using the driver simulator of MUARC (Monash University Accident Research Centre) to assess driver understanding of the design and expected driver behaviour. The simulation will also investigate the success of retaining signal pedestal locations in their current location to permit minimum modification to the site, reducing costs, as well as minimising roadside hazards. An on-site trial of the Elevated StopLines is underway in Victoria, which will provide invaluable data on potential implementation issues and driver behaviour. Once performance of the measures is determined through these various means, the empirical data can be used to more readily address issues of public concern and draw support for more detailed investigations of the measures and further trial. The evaluation of the designs is also an integral factor in maintaining a systems approach to improving intersection safety. Establishing the human and vehicle thresholds beyond which crashes at intersections are considered hazardous to health; creating a road environment, through intersection design, that supports these thresholds; and finally, evaluating driver response to these designs, allow the various components of the system and their interplay to be recognised and strategically modified to achieve the end goal of a Safe System.

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