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Designing Safer Roads to Accommodate Driver Error

C-MARC

**CURTIN - MONASH
ACCIDENT RESEARCH CENTRE**

School of Public Health

Curtin University

Hayman Road

Bentley WA 6102

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CURTIN - MONASH ACCIDENT RESEARCH CENTRE

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Designing Safer Roads to Accommodate Driver Error

Author(s) Anna Devlin, Nimmi Candappa, Bruce Corben & David Logan

Performing Organisation

Curtin - Monash Accident Research Centre (C-MARC)
School of Public Health
Curtin University
Hayman Road
BENTLEY WA 6102

Tel: (08) 9266 9591

Fax: (08) 9266 2958

www.c-marc.curtin.edu.au

Abstract

The main aims of this study were to assess the respective roles of driver errors in serious casualty road crashes at intersections, and to identify road design features which minimise errors and their consequences. A literature search was conducted to identify the range of errors underlying key casualty intersection crashes. This literature search was supplemented by data obtained from a crash investigation database pertaining to serious casualty crashes in Western Australia. A second literature search was conducted to identify road design features which aim to reduce driver error/or the consequence of these errors at intersections. The list of design features were classified according to Safe System principles and matched against the range of inadvertent and deliberate errors resulting in taxonomy for signal controlled, sign controlled and uncontrolled intersections.

Sponsoring Organisation

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Keywords

Human error, intersection, road safety, transport safety

Disclaimer

This report is disseminated in the interest of information exchange. The views expressed here are those of the authors and not necessarily those of Curtin University or Monash University.

Preface

Project Manager / Team Leader:

Bruce Corben

Research Team:

- David Logan
- Nimmi Candappa
- Anna Devlin
- Jeff Archer

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Contribution Statement

Bruce Corben (MUARC) and David Logan (MUARC) designed the study. Anna Devlin (MUARC) and Nimmi Candappa (MUARC) contributed to data analysis and data interpretation. Jeffery Archer provided intellectual input into the literature review. The acquisition of the data was provided by Syeda Sultana (Main Roads Western Australia). Anna Devlin drafted the paper. Critical revisions of the paper, including intellectual input was provided by Bruce Corben, David Logan, Terri-Anne Pettet (WA Local Government Association), Graham Lantzke (WA Local Government Association), Gary Manning (Main Roads Western Australia), Jon Gibson (Office of Road Safety) and Matthew MacPherson (WA Local Government Association).

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EXECUTIVE SUMMARY

The aim of this report was to assess the respective roles of inadvertent errors and unsafe driver behaviour at intersections and to identify road design features which aim to minimise the occurrence of inappropriate speeds and other errors and their consequences. This study was conducted as part of the Curtin-Monash University Accident Research Centre Baseline Research program and consisted of two literature searches that were supplemented by a detailed examination of intersection crash data of serious injury and fatal casualties from Western Australia (WA). First, a review of the published literature was conducted on driver behaviour and source of errors at intersections. It was anticipated that the findings from the literature search would be matched against the types of intersection crashes that occurred in WA from 2004 to 2009 as indicated by the crash investigation data.

The analysis of serious casualty crashes (fatalities and hospitalisations) at intersections in WA revealed the majority of intersection crashes occurred in metropolitan areas. A similar proportion of serious casualty crashes occurred at sign control intersections (35%) and signal control intersections (35%), with fewer casualties occurring at uncontrolled intersections (30%). Overall, the most common crash type was right-angle crashes accounting for 38% of all serious casualty crashes. Right-angle crashes typically occurred at sign control intersections. The second most frequent crash type was right-through crashes (cross traffic collisions) which occur when a vehicle completes a right hand turn in front of an oncoming vehicle. These crashes predominantly occurred at signal-controlled intersections rather than sign-controlled or uncontrolled intersections. In contrast to right-angle crashes and right-through crashes, the majority of crashes at roundabouts were hit object crashes.

A review of the literature found a variety of sources of error specific to each crash type. For example, right-angle crashes at signal-controlled intersections often occur because drivers fail to stop at a red light and engage in red-light running behaviour (Wang & Adeltaty, 2007). Conversely, right-angle crashes at sign controlled intersections have been attributed to poor visual scanning behaviour (Bao & Boyle, 2009), and failure to yield right of way (particularly for older drivers) (Preusser, Williams, Ferguson, Ulmer & Weinstein, 1998). Although roundabouts are known to reduce the number of rear-end crashes, the review identified the following sources of driver error: knowledge of priority rules (Räsänen & Summala, 2000), driver entry speed to the roundabout (Arndt & Troutbeck, 1998) and driver attention and visual search difficulties (Summala, Pasanen, Räsänen, & Sievanen, 1996). There were a limited number of studies specifically related to crashes at intersections in Australia (Baldock, 2005; Cameron, in press; Corben, Ambrose, & Foong, 1990). General road user characteristics that are pertinent to all intersection control types include speed, driver intoxication, driver fatigue and driver experience.

The second stage of the study included a literature review of available countermeasures to focus on road design features to reduce driver error and the consequence of these errors at intersections. A list of potential countermeasures identified from the literature is discussed in relation to each intersection control type. Finally, a fault tree analysis of the Australian National Crash In-depth Study crash investigation database is provided to outline the causal factors of an intersection crash.

1. INTRODUCTION

1.1. BACKGROUND

While the Safe System approach to road safety aims to produce alert and compliant drivers, at least some road users will remain less alert and compliant, thereby threatening other road users. Even the most skilled and compliant road users may make errors while driving. A main challenge for the Safe System approach is to minimise the occurrence or impact of these errors – be the errors inadvertent (error accidents) or arising from deliberately unsafe behaviours (violations). Behaviour change programs have been successful in the past but their effects are slowing and it is time to seek new ways of designing and operating roads to accommodate inevitable human error.

1.2. SYSTEMS BASED APPROACH

Intersections are an important part of the roadway system and can be particularly hazardous because they present a driver with many points for possible conflict with other road users, often at high speeds and with minimal time to respond, and a lack of adequate in-vehicle crashworthiness opportunities. While the aims of intersection design are generally to improve traffic flow, reduce the number of conflict points and reduce the likelihood of crashes, poor design of intersections can mean an increase in the risk of collisions and/or the risk of severe injuries for all road users, particularly for older road users. The main types of collisions that occur at intersections are: angle collisions, rear end collisions, sideswipe collisions, cross traffic collisions, and crashes involving pedestrians and cyclists. Crashes resulting from the loss of vehicle control are also common. Intersection crashes can occur for a number of reasons, including poor road design, environmental conditions, inadequate vehicle maintenance, and the behaviour of the driver and other road users.

Research suggests at least 70% of all traffic crashes are attributable to the role of the human in the transport system, and accidents may be preceded by up to 75 000 errors (Hakkinen & Luoma, 1991). Human error occurs in complex systems such as intersections and can involve multiple causes related to the individual, situation, task and environment. Human error can be classified as either a violation or an error accident (Daigneault, 2002). A violation occurs when the driver deliberately violates a regulation or socially accepted code of behaviour. An example of a violation is speeding. Alternatively, an error accident can occur when a desired or planned action does not achieve the desired outcome.

When considering human error it is important to adopt a holistic approach that includes the role of the driver, other road users, vehicle travel speeds, the vehicle and the road environment. This approach fits in to the Safe System approach which requires that all aspects of the transport system (i.e., roads, vehicle speeds, vehicles and the users of the system) work together for the safest possible outcomes. For its success, the Safe System relies on system users to comply with key road rules, and the designers and operators of the road transport system to manage successfully kinetic energy within the system. A key task of the Safe System therefore is to manage vehicles, road infrastructure, speeds and road users, and the interactions between these components. This will then ensure that when crashes do occur, crash energies will remain at levels that minimise the probability of death and serious injury. In other words, designers and operators desire to provide ‘5-star’ roads, and manufacturers desire to provide ‘5-star’ vehicles, all used by ‘5-star’ people that comply with road safety rules. A kinetic energy management model can be used to

conceptualise and quantify the safety levels of different intersection types (Corben et al. in press). The human body is situated in the centre of the conceptual model and is surrounded by protective layers to counter the threat of kinetic energy in the traffic system. The model can be used to describe and quantify different safety levels of intersection designs.

The focus of the following literature review is to identify the range of human errors leading to injuries or death at intersections.

1.3. AIM OF THIS RESEARCH

The aim of the research is to:

- Assess the respective roles of inadvertent errors and unsafe driver behaviour, specifically including speed and speeding in road crashes; and
- Identify road design features which aim to minimise the occurrence of inappropriate speeds and other errors and their consequences.

1.4. METHODOLOGY

A literature search was performed to identify the range of errors that underlie serious injury crashes at intersections. As far as the literature permits, these errors were classified as either i) error accidents or ii) violations arising from deliberate unsafe behaviour. The focus of the review was on driver errors that result in vehicle crashes, rather than vulnerable road users such as motorcyclists, cyclists or pedestrians. The potential role of traffic congestion as a source of error was examined. A detailed examination of an in-depth crash analysis database of serious casualty (killed and hospitalised) crashes supplemented the initial literature search. The findings were interpreted to ensure problems particular to WA were addressed.

In addition, a second literature search focused on road design features and their capacity to reduce driver error and the consequences of those errors. Design features that aim to produce compliance with set speed limits and safe travel speeds were researched. The list of design features as been matched against the list of error accidents (inadvertent errors) and violations (deliberate errors).

With the available budget, we were able to develop a taxonomy of behaviour that commonly leads to driver errors. This driver error was displayed in the taxonomy as a function of intersection control type, and crash configuration. To extend the potential benefits of the work carried out to date, consideration could be given to presenting the matched list of driver error and road design features at a one day workshop attended by road engineers, designers and planners from State and Local Governments, professional associations and research organisations, with a view to developing and prioritising a suite of road design improvements and countermeasures. Recommendations from the project for design improvements could use, as a reference, the current Austroads standards and guidelines. Where practicable, improvements could be presented having regard to their potential to produce system wide safety benefits from treating systematic problems.

2. CRASHES AT INTERSECTIONS

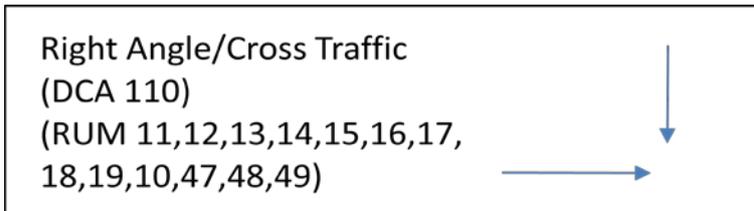
2.1. DEFINITIONS OF CRASH TYPES

Crashes at intersections can be classified according to the VicRoads “Definition for Classifying Accidents (DCA)”. The DCA code describes the type of crash that occurred. A description of the major crash types that typically occur at intersections, and the associated DCA codes, are provided below. Listed are the corresponding Road User Movement codes used in WA.

2.1.1 Vehicles from opposing directions (Right through/indirect right angle crashes)



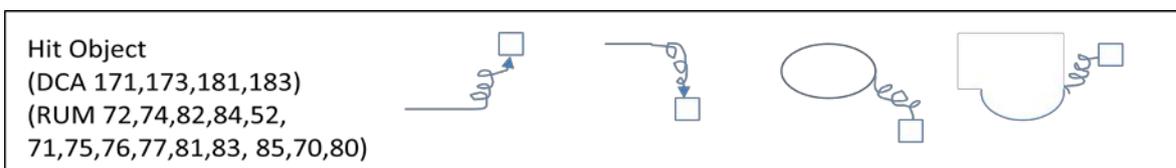
2.1.2 Vehicles from adjacent directions (Cross traffic/right angle crashes)



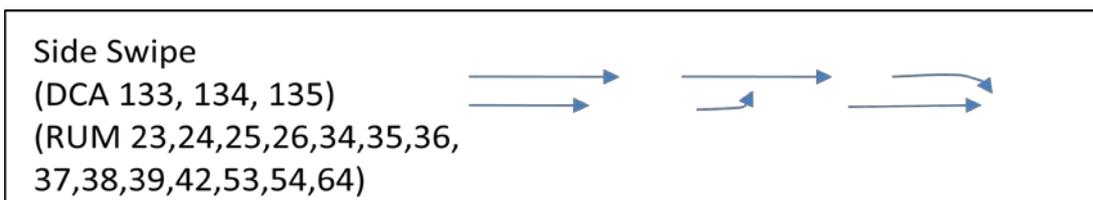
2.1.3 Rear end crashes



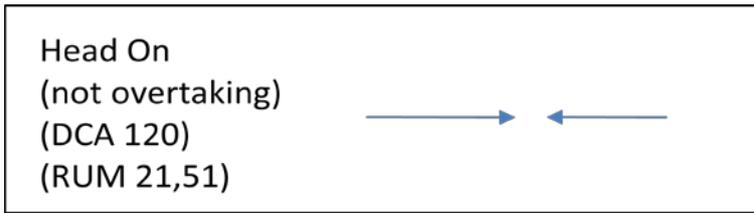
2.1.4 Hit object crashes



2.1.5 Side swipe crashes



2.1.6 Head on crash



2.2. WESTERN AUSTRALIA CRASH ANALYSIS

2.2.1 Crash Type

As identified in the introduction, five major crash types typically occur at intersections. The main crash types are: right-angle, rear-end, side-swipe, right-angle (cross traffic) and hit object collisions. Intersection crash data for WA from 2005 to 2009 in the Main Roads WA road crash database was analysed. The data was analysed in terms of crash type, intersection type, speed limit and region (rural versus metropolitan location).

The data provided refers to serious casualty crashes which comprised those crashes that included fatalities and hospitalisations. One of the limitations of the data is accuracy in relation to speed limit and traffic control. Accuracy of the data is reliant on the precision of attending police or of a person who self-reports the crash.

For serious casualty crashes that resulted in hospitalization, approximately 16% are not attended by police and therefore the figures reported may be an underestimation.

In regards to the classification of posted speed limit, the speed limit of the road on which the crash occurred (and the intersection leg on which the crash occurred) would be assigned to the crash. If the crash occurred at the node of the intersection, the crash would most likely be allocated to a leg of the key road and the speed limit assigned to the crash would most likely be the speed limit of that road.

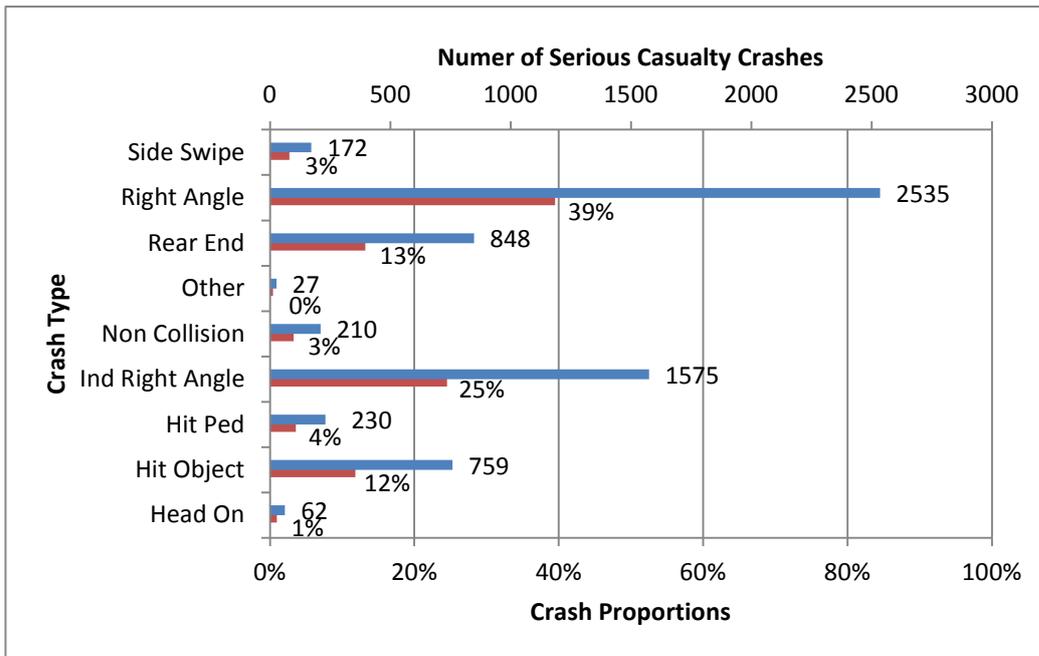


Figure 1: Number and Proportion of Serious Casualty Crashes by Crash Type at WA Intersections between 2005 to 2009

The most common crash type at intersections in WA from 2005 to 2009 resulting in serious casualty crashes was the right-angle crash, which comprised 39% of all crashes (Figure 1). Right-angle crashes involve two vehicles approaching from adjacent directions, for example, a vehicle travelling from the north collides with a vehicle travelling from the east (see 2.1.2). The right-angle crash was the predominant crash at sign-controlled intersections. A slightly greater proportion of right-angle crashes occurred at intersections controlled by stop signs compared to intersections controlled by give-way signs (Figure 2).

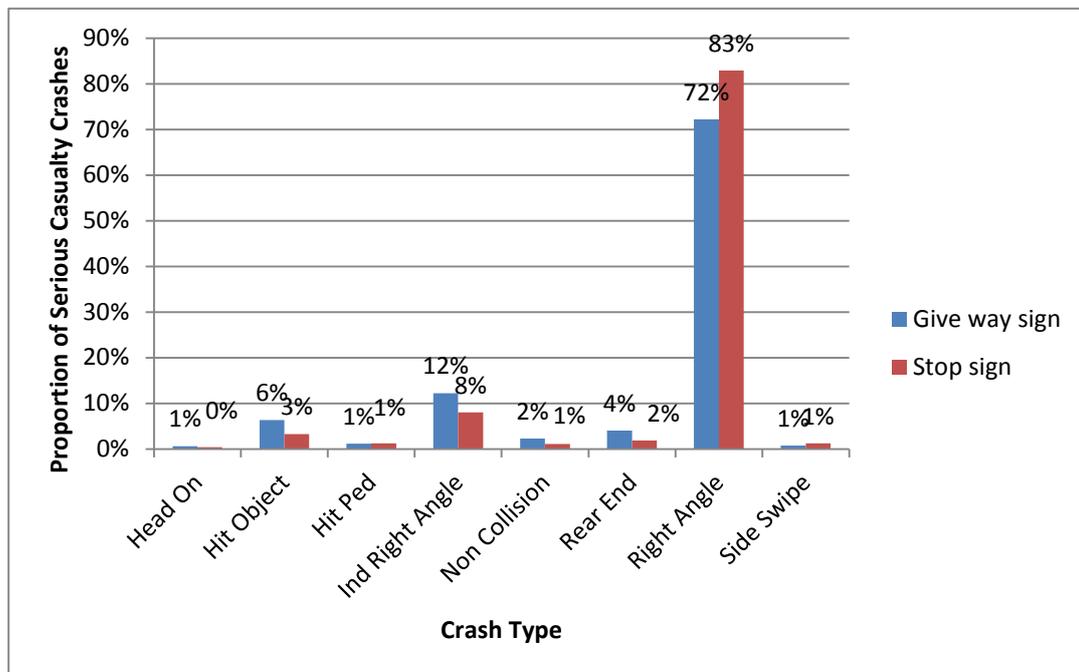


Figure 2: Crash Types at Intersections Controlled by a Stop or Giveaway Sign

2.2.2 Intersection Control

The number of fatal and serious injury crashes combined occurring at three different intersection control types, namely, sign-controlled, traffic signal-controlled and roundabouts are presented in Figure 3. Uncontrolled intersections are also presented.

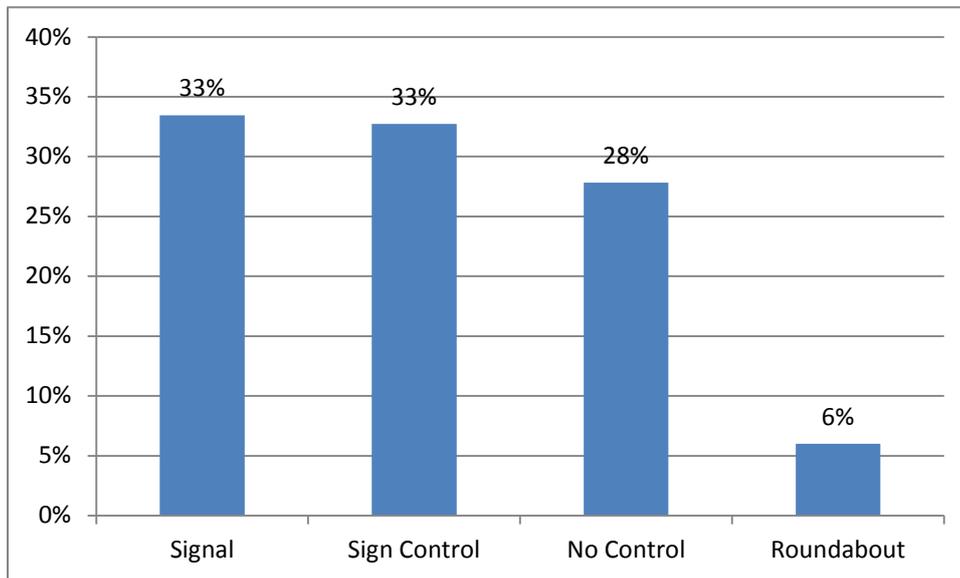


Figure 3: Proportion of Serious Casualty Crashes by Intersection Control Type

Overall, similar proportions of crashes occurred at sign-controlled (33%) and traffic signal-controlled (33%) intersections. Only 6% of the total proportion of serious casualty crashes occurred at roundabouts. It is important to note that in WA all give-way intersections are sign-marked. There are no uncontrolled four-way intersections.

Although sign-controlled and traffic signal-controlled intersections recorded similar proportions of crashes overall, the types of crashes at the intersections differed. For example, at sign-controlled intersections, approximately 70% of all crashes were right-angle crashes. Conversely, at traffic signal-controlled intersections only 28% of crashes were right-angle crashes. The predominant crash types at signal-controlled intersections were indirect right-angle or right-turn-against crashes which occurs when a vehicle makes a right-turn in front of an oncoming vehicle.

A breakdown of crash type by intersection control type is shown in Figure 4.

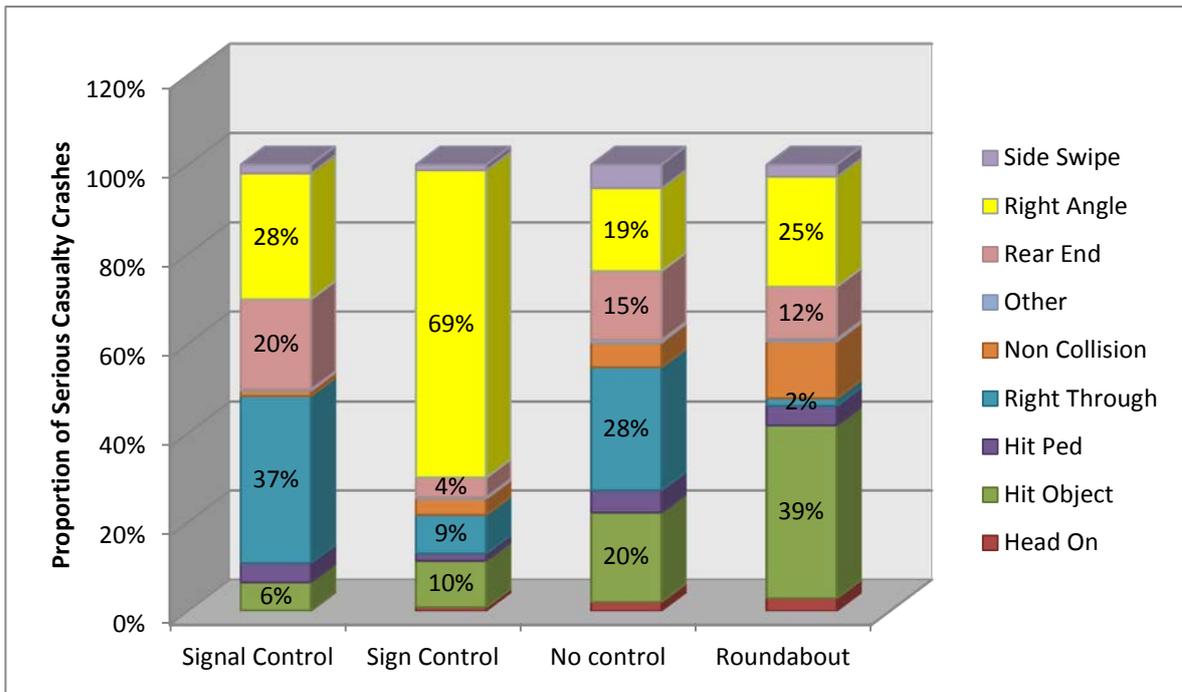


Figure 4: Proportion of Serious Casualty Crashes by Crash Type and Intersection Control Type

Intersection Control by Speed Zone

Figure 5 shows, irrespective of intersection control type, the majority of serious casualty crashes occurred in 60km/h speed zones. Traffic signal-controlled intersection crashes typically occurred at 60km/h and 70km/h speed zones. The crashes at higher posted speed limits of 90km/h and 100km/h typically occurred at sign-controlled and uncontrolled intersections.

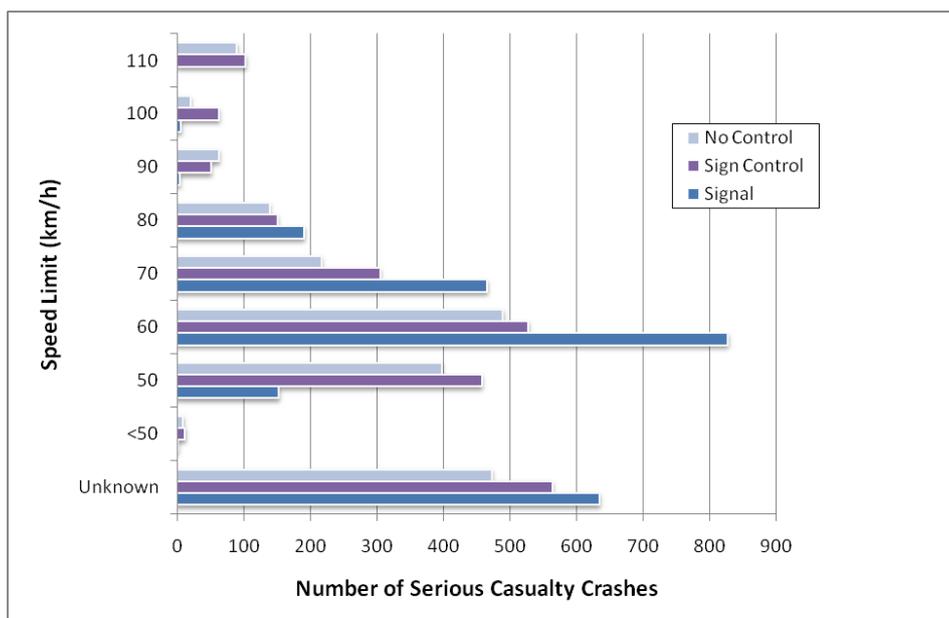


Figure 5: Number of Serious Casualty Crashes by Speed Zone and Intersection Control Type

Urbanisation: Rural versus Metropolitan Areas

A much larger proportion of intersection crashes occur in the metropolitan areas of WA compared to rural areas, as shown in Figure 6. This is most likely due to the higher traffic volumes and the greater number of intersections in metropolitan regions. This finding is in agreement with that of Fitzpatrick and colleagues (2003) who found the highest percentage of intersection crashes occurred in urban areas of Texas rather than rural areas.

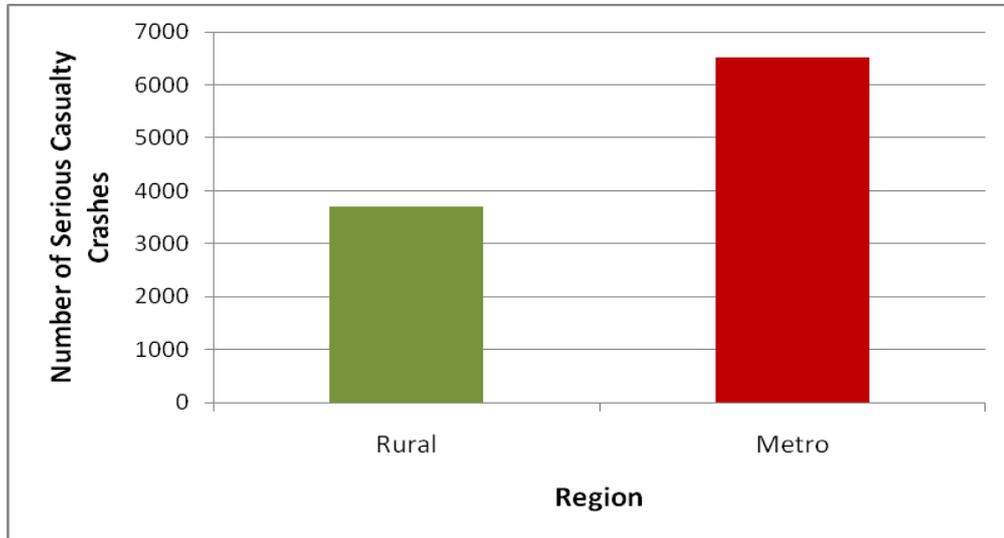


Figure 6: Number of Serious Casualty Crashes by Region

The majority of urban crashes occurred at traffic signal-controlled intersections, while the majority of rural crashes occurred at sign-controlled intersections (Figure 7). This is to be expected due to the greater number of traffic signal-control intersections in urban areas.



Figure 7: Number of Serious Casualty Crashes According to Intersection Control Type and Region

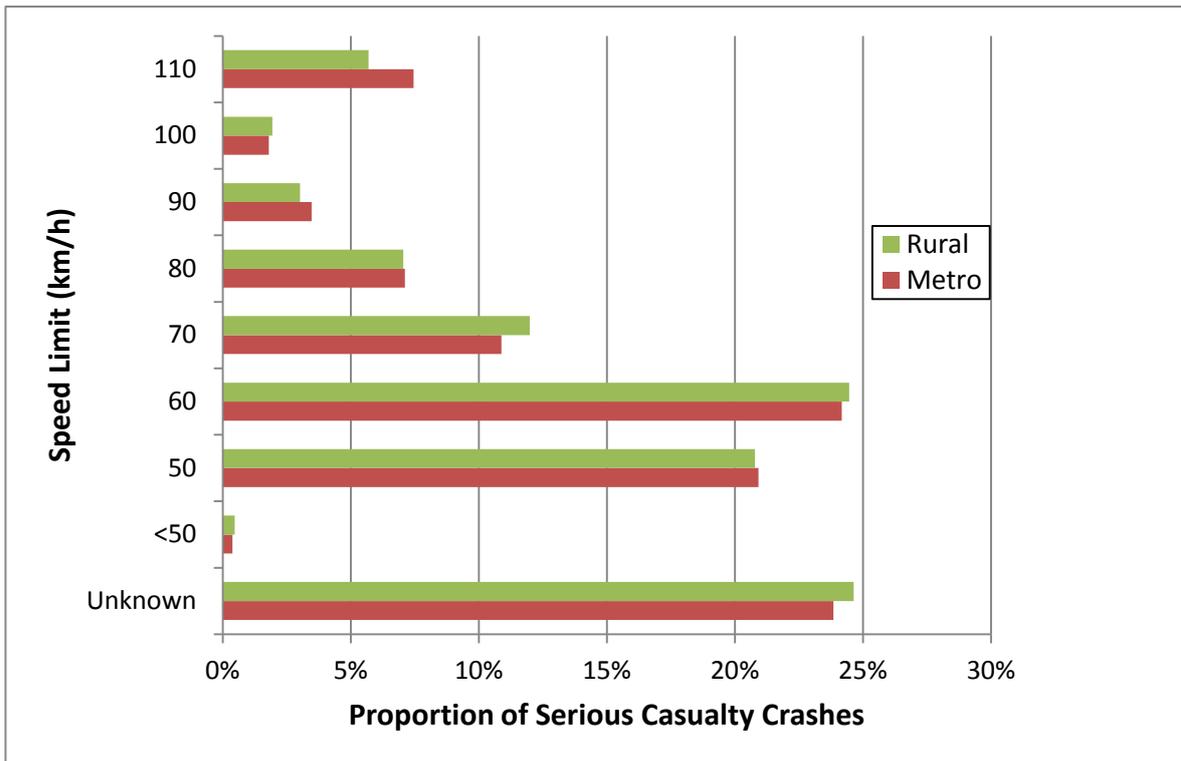


Figure 8: Proportion of Serious Casualty Crashes According to Posted Speed Limit by Region

Of the posted speed limits, the 60km/h zone was predominant (Figure 8). Approximately 24% of all serious casualty crashes in rural areas occurred in 60km/h speed zones. Similarly, approximately 24% of all serious casualty crashes in metropolitan areas occurred in 60km/h speed zones.

Crashes at Roundabouts

All serious casualty crashes at roundabouts occurred at give-way signs. There were no roundabout crashes recorded at stop signs, possibly a reflection of the small number of stop signs at roundabouts. Hit object crashes were the most predominant crash type at roundabouts comprising 39% of all crashes (Figure 9). The greatest proportion of crashes that occurred at sign-controlled intersections was right-angle crashes.

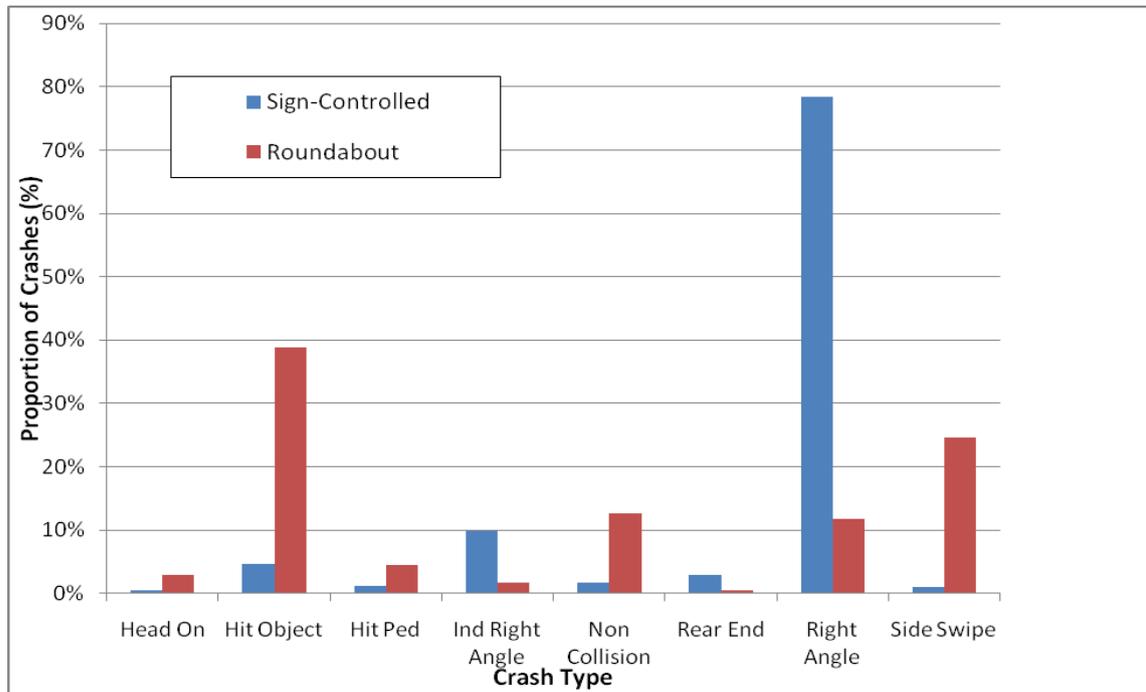


Figure 9: Serious Casualty Crash Types at Roundabouts versus Sign-Controlled Intersections (Stop and Giveaway Signs)

2.2.5 Summary of analysis

According to Main Roads WA road crash database, during the four year period (2005 to 2009) there was a total of 6418 serious casualty crashes at intersections in rural and metropolitan areas of WA. The majority of these (38%) consisted of right-angle crashes, particularly at sign-controlled intersections. Red-light running behaviour and failure to stop at stop signs are probable explanations for the number of right-angle crashes. Another common crash type was indirect right-angle crashes (cross-traffic collisions) comprising 23% of all serious casualty crashes. These crashes predominantly occurred at signal-control intersections and uncontrolled intersections, while very few occurred at sign-controlled intersections.

The most predominant crash type at roundabouts controlled by give-way signs was hit object crashes, followed by right-angle crashes. This is possibly due to the high number of loss of control crashes resulting from single vehicle run off road crashes fuelled by driving at high speeds (Mandavilli, 2009).

Not surprisingly, according to the analysis a considerable proportion (83%) of intersection crashes occurred in metropolitan areas compared to rural areas. For all intersection types the majority of crashes occurred in 60km/h speed zones. This finding is consistent with the evidence that vehicles that approach intersections at higher speeds are more likely to be involved in a crash as they are more likely to enter the intersection in the amber light phase (Datta et al., 2003).

2.3. WHAT ERRORS ARE SPECIFIC TO EACH CRASH TYPE?

In the following section, a literature review provides information regarding the contributing errors to each crash type identified in the WA crash analysis. In addition,

identified are a selection of countermeasures and road design features specific to each intersection control type.

2.3.1 Rear-end intersection crashes and contributing factors

Rear-end crashes are one of the most common types of crashes to occur at urban signal-controlled intersections (Fitzpatrick, Brewer, & Parham, 2003; Wang & Abdel-Aty, 2006). The analysis of crashes in WA from 2005 to 2009 also revealed that serious casualty rear-end crashes were most likely to occur at signal-controlled intersections compared to intersections with other control types. Driver error and road infrastructure have been identified as contributing factors to rear-end crashes. In addition, time to collision or following distance has been identified as a contributing factor (Baldock, 2005).

In a recent study, Muhrer and Vollrath (2010) assessed the contribution of driver error to rear-end crashes using a driving simulator. The researchers were particularly interested in how the drivers following distance changed according to the expectation of the driver's behaviour in the lead vehicle. In one scenario, the lead car braked upon approach to an intersection while in another scenario the lead car braked on a straight road. The time to collision was greater for the intersection scenario where participants were more likely to anticipate the lead car braking. Driver expectation of the lead vehicle is a contributing factor to following distance. Another contributing factor is habitual behaviour. Drivers who follow too closely without any serious consequences may continue to do so.

The lead vehicle's brake lights provide an indication of the expected driver's behaviour. There is evidence to suggest that during daytime brake lights of the lead vehicle lead to poor reaction times if the brake light is in the driver's peripheral vision (Summala, Lamble, & Laakso, 1998). This situation is likely to occur when the driver is focussing on the speedometer or on a vehicle ahead of the lead vehicle. Baldock and colleagues (2005) investigated a number of rear-end crashes in South Australia over a five year period (1998 – 2002) using police reports, evidence collected at the crash scene and interviews with drivers and witnesses. The researchers found the most important contributing factor to rear-end crashes was poor driver attention. Poor or inadequate allocation of attention can include "inattention" which is a lack of awareness of critical information (or lack of focus on critical information), "distraction" related to internal or external stimuli, or the inability to divide attention between two driving-related tasks (Baldock, et al., 2005). Inadequate allocation of attention can also occur from a lack of alertness or awareness often associated with decreased arousal accompanied with fatigue. Inattention and distraction can be further classified into inadvertent errors or error accidents. Table 1 lists the factors contributing to driver distraction and inattention.

Table 1: Forms of human error relating to inattention and distraction

Distraction	Inattention
<p><u>Internal</u></p> <ul style="list-style-type: none"> • Inappropriate use of technology within the vehicle (i.e. mobile phone, GPS, street directory) • Another person or event in the vehicle <p><u>External</u></p> <ul style="list-style-type: none"> • Distracted by an event outside vehicle • Distracted by signage, roadwork, another vehicle 	<ul style="list-style-type: none"> • Emotional/psychological distress • Inadequate planning/reasoning • Bored or cognitively distracted • False observation i.e. an instruction or sign is misunderstood • Memory failure • Failure to check rear view mirror and/or side mirrors • Driver impairment such as intoxication, medication side-effects • Driver fatigue • Driver impatience

Another contributing factor to distraction and inattention is driver intoxication which has also been associated with a high proportion of rear-end crashes (Corben & Young, 1983). An analysis of 95 roundabouts in New Zealand by Harper and Dunn (2003) revealed that the most common crash type was entering versus circulating (right-angle) crashes, of which a large proportion result in rear-end crashes. The majority of rear-end crashes occurred when entering the roundabout compared to circulating or exiting (Harper & Dunn, 2003).

Vehicle operation errors are another contributing factor to rear-end crashes. For example, the vehicle may not respond as the driver intended due to poor weather conditions or a failure of brakes (Braitman et al., 2007).

2.3.2 Right-angle (cross traffic) crashes and contributing factors

Intersecting path/right-angle/cross-traffic crashes occur when two vehicles travelling from adjacent directions cross paths and collide. The majority of serious casualty crashes at intersections in WA between 2005 and 2009 involved right-angle crashes. This crash type occurred more frequently at intersections controlled by signs.

A recent in-depth analysis of intersection crashes in Washington DC from January 2005 to December 2009 was conducted by Choi (2010) on behalf of the National Highway Administration. Data from the National Motor Vehicle Crash Causation Survey was analysed and included information on crash causation, driver age, driver gender and intersection control type. In approximately 96% of intersection crashes the cause was attributed to driver error. In 55% of cases driver error was a result of a recognition error (i.e. driver inattention, inadequate surveillance, and distraction). In 30% of cases driver error was due to driving too fast, aggressive driving, incorrect expectations of driver behaviour, and misjudging gaps in traffic. Further analysis of crashes by age group revealed younger drivers (less than 24 years) were more likely to be involved in crashes due to turning with an obstructed view, while older adults were more likely to be involved in right turn crashes as a result of misjudging gaps in traffic and inadequate surveillance (Choi, 2010). Inadequate surveillance has been defined as a situation where a driver is required to look to safely complete a manoeuvre and either fails to look or looks but does not see (Dingus et al., 2006).

Right-angle crashes often occur at signal-controlled intersections because one driver fails to stop at a red-light (Wang & Abdel-Aty, 2007). Further detail on the contributing factors to red light running behaviour is provided in section 2.4.1 (road user characteristics). These crashes typically involve severe injuries often result from high speeds and impact to the side of the vehicle. It is estimated that the greater the traffic flow on the approach to an intersection the more likely the crash is to occur (Wang & Abdel-Aty, 2007).

2.3.3 Right through (turning) intersection crashes and contributing factors

Turning right across approaching traffic at a signal-controlled intersection can be one of the most difficult traffic manoeuvres. The WA analyses revealed the greatest proportion of serious casualty right through crashes occurred at signal-controlled intersections compared to other intersection control types. Numerous factors can contribute to the increased crash risk including: the drivers ability to select an appropriate gap in traffic, adequately judging distance and speed of approaching vehicles, and completing the turn in a timely manner. As mentioned in section 2.4.1 older drivers (> 65 years) are over-represented in these types of intersection crashes due to age-related decline in functional abilities and difficulties completing gap selection tasks. A study conducted by Clarke and colleagues (2010) analysed the number of older driver right turn crashes in the UK by age group and estimated a 16% rise in the proportion of crashes for 85-89 year olds compared to 60-64 year olds. The researchers suggested that the majority of right-through crashes were related to visual search problems (Clarke et al., 2010). It was also suggested that drivers aged older than 70 years were more likely to be either solely or partly to blame for the crash rather than be innocently involved compared to drivers aged 60-69 years. In concordance with this finding, an analysis of crash data by Preusser et al. (1998) revealed that 50% of older drivers aged above 74 years were involved in crashes due to failure to yield rather than run off road or straight oncoming crashes.

Speed is another significant contributor to right through intersection crashes. Drivers have less time to react and brake the faster they approach the intersection. As discussed in section 2.4.1 excessive speed and speeding contribute to the likelihood of being involved in an intersection crash.

Right-through crashes or right-turn against crashes are reported to be a common crash type that occurs at roundabouts when an entering vehicle collides with a circulating vehicle

(Turner & Roozenberg, 2006). Turner & Rozenberg (2006) estimated that by reducing the circulating speed from 60km/h to 20km/h the rate of right through crashes would decrease by a factor of 10.

2.3.4 Side swipe crashes and contributing factors

Side-swipe crashes are the least likely to occur at intersections when compared to the other four crash types (i.e. right-through, right-angle, rear-end and hit object) (Savolainen & Tarko, 2004). Possibly, for this reason, the literature concerning the contribution of driver error to side-swipe crashes at intersections is relatively sparse. However, it has been noted that side-swipe crashes can result from the driver encroaching upon another vehicle's lane due to driver fatigue, inattention or speed (NHTSA, 2003 cited in Persaud, Retting, & Lyon, 2004). The greatest proportion (54%) of serious casualty sideswipe crashes in WA from 2005 to 2009 occurred at intersections which had no control.

2.3.5 Hit object crashes and contributing factors

Single-vehicle hit object crashes are more likely to occur in situations where traffic volume is low where there is less chance the driver will hit another vehicle. Often, single-vehicle hit object crashes occur when a driver loses control of the vehicle and collides with a fixed object on or off the roadway (Ivan, Pasupathy & Ossenbruggen, 1999). In WA from 2005 to 2009 the greatest proportion of hit object serious casualty crashes occurred at roundabouts controlled by give-way signs. Multi-vehicle crashes are more likely to occur at intersections as there are a greater number of potential vehicle conflict points. In some cases the hit object crash may be secondary to another crash type. For example, a vehicle may collide with another vehicle first before colliding with a fixed object. The exact nature of this type of hit object crash is difficult to define as it is usually coded as a multivehicle crash (i.e. right-through, cross-traffic). There are so many objects at an intersection from signal poles to lighting poles, sign posts, tram stops, rubbish bins, a number of which are virtually on the edge of the lane. Therefore, any misjudgment in turning manoeuvre can mean clipping/mounting the kerb and colliding with these. Particularly at roundabouts, the larger proportion of hit objects is likely to be drivers misjudging the approach speed and not being able to negotiate the roundabout and so colliding with the chevron and other signs at the roundabout.

2.3.6 Pedestrians involved in intersection crashes

Intersections are complex traffic situations that can result in a pedestrian collision when the field of view of the driver is blocked. For example, it is estimated that a number of collisions occur when a truck driver is turning right (in the US, equivalent of a left-turn in Australia) across a pedestrian or cyclist path (Niewoehner & Berg, 2005). The large size of the truck compared to a vehicle means that the field of view that is blocked is larger. Alteration of the road surface at intersections acts to increase the awareness of the presence of an intersection as well as to slow the speed of vehicles through an intersection. It was interesting to note from the WA intersection analysis that the number of serious casualty pedestrian crashes were relatively similar for both signal-controlled and intersections with no control. In contrast, serious casualty pedestrian crashes were least likely to occur at sign-controlled intersections. This is possible due to the fact that pedestrian volumes are likely to be lower at these intersections. Contributory driver errors include difficulty determining priority rules of yielding right of way (Hatfield et al., 2007), as well as driver distraction (Sutts et al. 2001).

2.4. ERRORS AT EACH INTERSECTION CONTROL TYPE INCLUDING COUNTERMEASURES

2.4.1 Errors at signal-controlled intersections

As previously mentioned, right through crashes followed by right-angle crashes were the most frequent crash types at signalised intersections in WA from 2005 to 2009. Traffic signal-controlled intersection crashes typically involve vehicles from opposing directions, vehicles from adjacent directions as well as vehicles from the same direction, that often result in rear-end crashes, side-swipe crashes and right-angle crashes (Obeng, 2008). Observation studies and simulator studies indicate that road-user behaviour such as driver speed choice (Yan & Radwan, 2007), driver characteristics such as age, driver expectation, and driver compliance and driver behaviour in dilemma zones all contribute to crashes at signal-controlled intersections. In addition, environmental and geometric factors can contribute to occluded vision and distraction (Neyens & Boyle, 2007), and may limit driver sight distance (the distance to which the driver can see clearly) (Chin & Quddus, 2003). Each of these factors is described below.

Road-user characteristics

Speed

Clearly, the faster drivers choose to travel, the more likely they are to be involved in a crash and consequently produce severe injuries. Higher driving speeds reduce predictability and reduce a driver's ability to control the vehicle, negotiate the intersection and stop in time to respond to a signal. Higher speed also increases the distance a vehicle travels while the driver reacts to a potential collision, reducing the time available to avoid a collision.

Intersection approach speed is directly related to the driver's ability to respond appropriately to traffic signals and can encourage red-light running (Bonneson et al., 2003). Caird, Chisholm, Edwards and Creaser (2007) conducted a driving simulator study and found that older drivers were more likely than younger drivers to be positioned in the middle of the intersection when the light changed to red due to their tendency to drive at a lower velocity through an intersection combined with their tendency to come to a complete stop before making their turning manoeuvre (Caird, Chisholm, Edwards & Creaser, 2007). A recent study by Gstatler and Fastenmeier (2010) observed older driver behaviour using an instrumented vehicle and found that older drivers were more likely than experienced and inexperienced younger drivers to drive at a greater velocity through a signal-controlled intersection. Consequently, older drivers were more likely to be positioned in the path of pedestrians and oncoming traffic before commencing their turn. Although both studies were evenly matched in regards to their sample size (20 older drivers aged above the age of 65 years), the contradictory results in the Caird et al. (2007) study may be explained by the lack of familiarity of older drivers with the driving simulator. Additional naturalistic driving studies are warranted to provide more conclusive evidence.

Older drivers

Individual characteristics such as age and driver experience can place drivers at a greater risk of crash involvement at intersections. Boufous and colleagues (2008) analysed factors contributing to injury severity of crashes of older drivers (aged above 50 years) in New South Wales using data from hospitals and police records. Injury severity was predicted by

the complexity of the intersection, driver error, driver speed and use of a seat belt. A review of 2000 crashes in the UK spanning from 1994 – 2007, involving drivers aged over 60 years, found the greatest proportion of collisions for this age group occurred at intersection collisions (Clarke, Ward, Bartle & Truman, 2010). In agreement with previous studies on older driver behaviour at intersections (Braitman et al., 2007; Preusser et al., 1998), failing to give-way was cited as a significant contributor to these crashes.

Gap Selection

It is well known that older drivers are susceptible to high injury risk at intersections and are overrepresented in intersection crashes compared to younger drivers (McGwin & Brown, 1999). Numerous studies have shown that older drivers are involved in collisions where they are turning against approaching traffic that has right-of-way and fail to select appropriate or safe gaps in opposing traffic (Oxley, Fildes, Corben & Langford, 2006; Preusser et al. 1998; Stamatiadis et al., 1991). In particular, younger and middle aged drivers have been shown to select gaps in traffic ranging from 6.4 – 8.1 seconds, while older adults (>75 years) typically select longer gaps ranging from 5.8 to 10 seconds (Stamatiadis et al., 1991). Furthermore, older drivers typically approach an intersection at a slower speed before making the turn compared to younger drivers who approach at a faster speed (Keskinen, Ota & Katila, 1998). These age differences in gap acceptance characteristics by older drivers indicate they adopt a more cautious driving behaviour to regulate their driving to match their changing cognitive, sensory and physical capacities. Changes in cognitive and perceptual abilities associated with increased risk at intersections include: divided attention problems, visual search problems, restriction in the driver's functional field of vision and limited contrast sensitivity, speed perception and distance of approaching traffic and slow maneuvering of the steering wheel and vehicle (Yang & Najm, 2007).

Although self-regulatory driving behaviours are thought to be important for reducing crash risk, cautious driving behaviour at intersections can be a problem when older drivers select longer gaps in traffic resulting in traffic congestion. A build up of cars waiting behind the driver can place added stress and time pressure upon the driver and following drivers which in turn may increase the risk of a crash occurring.

Functional ability

Increasing age is associated with an increase in medication use and disability. Numerous studies have investigated the relationship between older driver functional ability and driving performance (Anstey, Wood, Lord & Walker, 2005; Hakamies-Blomqvist, Siren & Davidse, 2004). There is widespread agreement that even 'normal ageing' is associated with the onset of medical conditions, many of which have safety implications. For example, Hakamies-Blomqvist, Sirén and Davidse (2004) identified arthritis, heart diseases, arterial hypertension, diabetes and the various forms of dementia as common age-related conditions. Any of these medical conditions can impact negatively upon driving performance and place a driver at an increased crash risk.

Anticipation of other road users

The behaviour of other road users in the intersection can add to the complexity of the task. A driver may vary their own behaviour according to their expectations and anticipation of other road user behaviour. Sato and colleagues (2007) were interested in the influence of

other vehicles on a driver's ability to perform a right hand turn (i.e. Australia and UK). A naturalistic vehicle was used to assess driving behaviour at an intersection with and without a lead and following vehicle. Regardless of the presence of a lead or following vehicle, participants engaged the indicator at a similar position in the intersection to complete the turn. However, in the car following situation, drivers released the accelerator (started to decelerate) closer to the centre of the intersection compared to when the cars were absent. It is possible that the presence of additional vehicles placed increased pressure on the driver resulting in different driving behaviour. This behaviour could also occur due to habit of following a lead vehicle at a particular distance leading up to an intersection.

Driver Compliance – Red-light running

Traffic signals are ideally designed to promote safe behaviour at intersections however their safety is largely dependent upon driver compliance with the signals. Red-light running is a risky and highly dangerous behaviour that can lead to high-speed and high-severity collisions (Romano, Tippetts & Voas, 2005). Red-light running is often intentional, although it can also be unintentional. It is estimated that approximately 16-20% of crashes that occur at urban intersections in the United States are a result of red light running (Mohamedshah, Chen & Council, 2000). Evidence from observational studies suggests that red light runners are typically aged less than 30 years old, do not wear a seatbelt, drive smaller and older cars and are more likely to be under the influence of alcohol (Porter & England, 2000; Retting, Wiestein & Solomon, 2003). Bonneson and colleagues (2003) assessed the predictor variables of red light running in a field study including: stopping speed, approach speed, intersection width, signal cycle length, and number of approach lanes. Fewer red-light runners were observed when the driver approach speed was low, the traffic flow was low, the intersections were wide, and on occasions where there was an increased amber light duration (Bonneson et al., 2003). According to Brewer et al. (2002) there is a greater frequency of red-light runners at yellow light periods less than 3.5 seconds. In addition, an observation study by Porter and England (2000) recorded a greater number of drivers run red lights during peak hours when there was an increased traffic volume.

An analysis of driver violation records revealed that a large proportion of red-light runners are aged between 20 and 29 and typically travel at a speed greater than the posted speed limit compared to other age groups (Yang & Najm, 2007). It is possible that the young age group are more likely to violate red signals due to a tendency towards aggressive and risky driving in order to save time. Conversely, older drivers tend to display a different pattern of behaviour when running red lights. Older drivers typically drive at slower speeds and are therefore more likely to drive through the intersection two seconds after the red light (Yang & Najm, 2007). The delayed response may be related to the ability of older drivers to deal with the complexity of the task, which can deteriorate with age. Results from an observational study conducted by Kent et al. (1995) indicated that the majority of red-light runners occurred when turning right rather than driving straight ahead.

In a number of these circumstances, regardless of age, red-light running behaviour may be unintentional due to the driver misjudging the time needed to cross the intersection, or a lack of attention towards the signal change and duration.

Dilemma zones

The dilemma zone of an intersection refers to the region of the road that exists upstream from the intersection when the driver is faced with the decision of whether to stop or to

clear the intersection successfully (Yan, Radwan, Guo, & Richards, 2009). Driver indecision in a dilemma zone can lead to rear-end crashes or right angle crashes. The driver dilemma zone can range from 5.5 seconds to 2.5 seconds (Rakha, Amer, & El-Shawarby, 2008). Elderly drivers have a much longer dilemma zone than younger drivers (Rakha et al., 2008). Analysis of driver behaviour at a signalised intersection in Greece was conducted by Papaioannou (2007). Papaioannou examined gender, speed, stopping distance and age of 697 drivers. A greater number of male drivers disobeyed the amber signal compared to female drivers, and females typically drove at slower speeds. Overall more than 50% of the sample approached the intersection at a speed above the posted speed limit suggesting that speed plays a significant role in contribution to violation of traffic lights. It has also been suggested that heavy vehicles are more likely to engage in red-light running compared to other vehicle types (Bonneson, Brewer & Zimmerman, 2003).

Environmental characteristics

The geometric factors of the road environment can contribute to intersection crashes. Chin and Quddus (2003) identified significant geometric and traffic control factors that contributed to the crash frequency at 52 signalised intersections in Southwest Singapore. The significant contributing factors to high crash rates were: the presence of a bus stop, median widths greater than 2 metres, increase in the number of traffic signal cycle phases, the presence of an uncontrolled left-turn lane (i.e. in Singapore cars drive on the left side of the road as in Australia), intersection sight distance, the presence of a surveillance camera and the total volume of approaching traffic (Chin & Quddus, 2003). A greater number of phases per traffic signal cycle were estimated to be the most significant contributor to crashes at intersections. It is interesting to note that the presence of surveillance camera was associated with a higher crash rate. The researchers suggest that the presence of the camera may contribute to an increase in rear-end crashes as vehicles approach the intersection.

Sight distance

Executing a right-hand turn manoeuvre often requires completing a gap selection task at a signal-controlled intersection when the driver is confronted with approaching traffic. The ability to perform the gap selection task has been associated with driver age, vehicle speed, traffic volume, and turning angle just to name a few (Stamatiadis, Taylor, & McKelvey, 1991). Another important factor contributing to driver performance at right-hand turns is sight distance. The position of an opposing right-hand turn vehicle can block the driver's view of approaching traffic in an intersection with opposing right hand turn lanes (Yan & Radwan, 2007). The restriction in sight visibility can result in the driver making a hasty decision by accepting a small gap, or at the other extreme the driver could wait until there is clear visibility creating unnecessary build up of traffic and driver frustration, potentially causing the following driver to select a more impatient gap choice. Such sight restrictions typically occur at intersections with large medians, i.e. medians greater than 18 feet wide (AASHTO., 2001). Analysis of 30 intersection Black Spots in Victoria revealed a reduction in casualty crashes by up to 40% with the introduction of a right-turn signal phase (Corben, Ambrose & Foong, 1990).

Countermeasures to the errors at signal-controlled intersections

The possible countermeasures available to minimise errors at signal-controlled intersections are listed below:

Environmental Factors – Based on the results of Chin and Quddus (2003) it is recommended to relocate bus stops away from intersections and introduce no parking signs to reduce the number of parked cars, increasing the turning circle for large turning vehicles.

Sight Distance - it is recommended that intersections are designed with right-hand turn lanes that are offset from one another in each road direction. When designing intersections it is also important to take into account any obstacles such as foliage which reduce visibility and limit sight distance. As mentioned above, limiting parking at intersections can also improve sight distance.

Dilemma Zones – it is suggested that the installation of advance warning flashing lights can alert drivers of an imminent red light, providing them with additional time to make a decision. A demerit point system has also been suggested as a means reducing driver speed on approach to the intersections, and so quicker braking, (Papaioannou, 2007).

Driver Characteristics – declining faculties: effective countermeasures include ways to compensate for a decline in functional and physical abilities that occur with age. For example, reduce the need to attend to dynamic information in a time dependent manner by installing four-way Stop signs instead of two way Stop signs (Preusser et al., 1998). Other potential measures include reducing the speed limit upon approach to the intersection, providing more guidance through the intersection with the aid of technology (fully controlled right turns, gap selection guidance, and approach speed advice). In order to increase driver following distance and reduce rear-end crashes collision avoidance systems could be installed in vehicles.

Self Regulation - Self regulation refers to the adjustments that drivers make in their driving behaviour that adequately match changes in cognitive, sensory, and motor capacities (Charlton et al., 2006). For example, older drivers may choose to avoid situations they find challenging such as driving at night. An example of self regulation that might alleviate risk of crashes at signals is perhaps older drivers choosing to drive through signal-controlled intersections that are fully controlled to remove the need for gap selection.

Driver Compliance - According to a report by the Institute of Transportation Engineers (Institute of Transportation Engineers) (2003) enforcement countermeasures are most effective for reducing intentional red-light runners while engineering countermeasures are most effective at reducing unintentional red-light runners. Furthermore, extending the period of the red light has shown to reduce the number of right-angle crashes resulting from red-light running (Datta et al., 2007). Increasing the length of the amber period (to a maximum of 5.5 seconds) has also proven to be effective in reducing red-light running of heavy vehicles (Archer & Young, 2009). Fixed camera systems (speed/red-light) have been estimated to reduce casualty crashes by an estimated 25-30% (Retting, Weistein & Solomon, 2003). Recently, Cameron (in press) estimated the effect of installing speed/red-light cameras at the top 60 intersections in Western Australia which are currently fitted with red-light camera infrastructure. The estimation concluded that there would be a

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greater cost-benefit ratio for the installation of speed/red-light cameras compared to red-light cameras, particularly at seventeen intersections located in WA (Cameron, in press).

A further list of possible countermeasures to reduce red-light running is provided below:

Signal Operation	<ul style="list-style-type: none">• Increase the amber light duration that does not exceed 5.5 seconds• Improve signal co-ordination• Increase cycle length to a degree
Driver Information	<ul style="list-style-type: none">• Improve sight distance• Improve visibility of signal• Increase conspicuity of signal• Add advance warning signs
Physical improvements	<ul style="list-style-type: none">• Remove unnecessary signals• Add capacity with additional traffic lanes• Flatten sharp curves

Source: Bonneson et al. 2003

Driver Speed - Reducing the approach speed of younger drivers can be achieved by increasing the visibility of the intersection through appropriate signage that provides the driver with information of a reduced speed limit. Geometric traffic calming measures such as rumble strips on the approach to an intersection or pavement markings can also be used to reduce driver speed. Intersection speed humps are used commonly in the Netherlands as a form of speed mitigation.

Yan et al. (2009) investigated the influence of a pavement marking sign reading 'signal ahead' on driver approach behaviour at a sign-controlled intersection using a driving simulator. Intersection approach (speed/behaviour) to an amber light was assessed in two conditions, with and without the marking. The marking resulted in a greater speed reduction leading up to the intersection and therefore a potential reduction in the number of abrupt stops and resultant rear-end crashes. The researchers concluded that pavement markings could be an effective countermeasure to reduce red-light running and to help drivers to make the stop/go decision.

2.4.2 Errors at roundabouts

Roundabouts are designed to control the traffic flow at intersections and facilitate safe negotiation of the intersection without the use of Stop signs or traffic signals. They have become increasingly popular as safe traffic control devices, showing substantial reductions in severe injury crashes (Newstead & Corben, 2001; Persaud, Retting, Garder & Lord, 2001). While roundabouts have been shown to reduce the number of vehicle-vehicle collisions, particularly rear-end, right-through and left-turn crashes, the evidence regarding their efficacy as a safety measure for pedestrians and cyclists is less positive. One of the most common crash problems at roundabouts is the increase crash risk for cyclists (Harper & Dunn, 2003). The most important factors contributing to these crashes are driver attention and visual search (Summala, Pasanen, Räsänen & Sievänen, 1996), driver entry speed to the roundabout (Arndt & Troutbeck, 1998), as well as knowledge of priority rules (Räsänen & Summala, 2000). Furthermore, Arndt et al. (1998) found that the speed of traffic was a greater predictor of roundabout crashes than traffic volume.

Often drivers involved in intersection crashes at roundabouts report that they did not see the cyclist. This phenomenon, labelled looked-but-failed-to-see occurs when a driver is looking in the direction of the cyclist but fails to direct their attention towards it. According to Herslund and Jorgensen (2003) the failure to perceive cyclists may be due to a difference in visual search strategies employed by experienced drivers. Evidence suggests that compared to novice drivers experienced drivers typically focus their gaze on high priority areas where they would expect to see the most relevant information (Summala et al., 1996). Therefore drivers are more likely to be looking towards the direction of approaching cars and are less likely to focus on cyclists in their peripheral vision. Roundabouts are often developed primarily for vehicle to vehicle interaction and, as a result, the needs of cyclists and pedestrians are often overlooked (Katz & Smith, 1994).

Concerns for drivers at roundabouts include: confidence approaching the roundabout, navigating around the roundabout, direction of travel and yielding rules.

Mandavilli et al. (2009) investigated crash types and causative factors of 283 crashes that occurred at roundabouts in Maryland. Police reports were obtained to determine the characteristics of the crash and observations were conducted at eight roundabouts to understand the causative factors. The four main crash types that occurred at single lane and double lane roundabouts were: rear-end, side-swipe, run-off-road and entering-circulating (entering vehicle collides with a vehicle on the roundabout) (Mandavilli et al., 2009). The most common crash type was a single-vehicle run-off-road crash whereby the major contributor was speed. In approximately half of these crashes the vehicle hit the central island before running off the road; driver speed was likely to be a significant factor in these crashes. Furthermore, roundabout design and geometric layout of roundabouts can be a contributor to poor safety performance.

Countermeasures to the errors at roundabouts

The possible countermeasures available to minimise errors at roundabouts are listed below:

Look but failed to see - countermeasures include reducing entry speeds to roundabouts, increasing visibility of cyclists by wearing reflective clothing, and positioning cyclists closer towards the central circular of the roundabout (Räsänen & Summala, 2000).

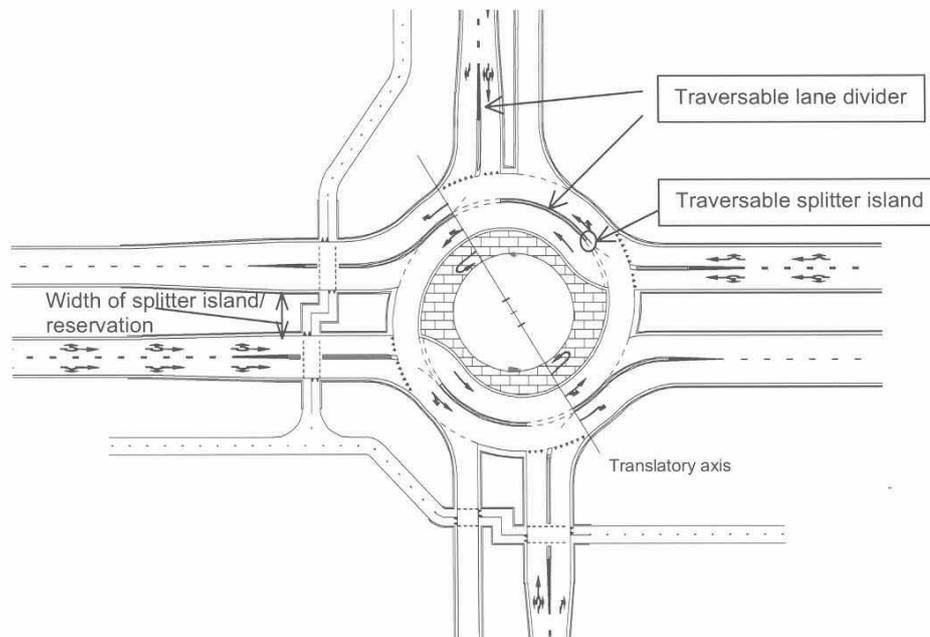
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Driver expectation - Lord and colleagues (2007) investigated the installation of countermeasures to improve roundabout design to meet the expectation of drivers, particularly that of senior drivers. Results from focus groups and structured interviews found positive feedback for the following countermeasures:

- Directional signs (one-way sign)
- Roundabout lane control signs
- Advance warning signals
- Yield treatment
- Advance warning exit treatment (placing an exit sign prior to reaching the exit)
- Turbo Roundabouts

An innovative roundabout design in use in the Netherlands is the Turbo roundabout (see Figure 10). The aim of this roundabout design is to better define and facilitate smooth movement through the roundabout. As a result lane changes are prevented upon entering the roundabout. The design consists of raised kerbing separating the lanes on approach and through the roundabout. Where right-turning volumes are significant, a right-turn lane is incorporated into the roundabout island. Explicit directional signage is also presented to drivers on approach to the roundabout to advise on the appropriate lane selection prior to entry, based on destination.

The alignment on approach to the Turbo roundabouts is also said to differ from the standard roundabouts in that while the common roundabout entry flares out, the Turbo roundabout channels the approaching vehicle virtually perpendicular to the central island, with chevron signage. This encourages the driver to slow down prior to entry, aiding safer negotiation of the roundabout.



(Campbell & Jurisich, 2007).

Source:

Figure 10: Example of a Turbo Roundabout

Single-vehicle Crashes - as a result of the study the researchers suggested the following countermeasures:

- Increase the conspicuity of the central island (i.e. reflective pavement markers or increased signage).
- Install circular central islands rather than oval or elliptical islands to promote slow speeds.
- Consider single lane roundabouts rather than double lanes when appropriate.

Entering and Circulating Crashes – Turner and Roozenberg (2006) utilised an intersection model to determine the contributing factors to roundabout crashes in New Zealand and proposed the following countermeasure:

- Reduce the circulating speed from 60 km/h to 20 km/h. This is estimated to reduce the number of entering versus circulating crashes.

In addition, Ardnt and Troutbeck (1998) analysed data concerning 100 roundabouts in Queensland, Australia, with a focus on the road geometry. As a consequence of the findings the researchers recommend:

- Using the largest possible curve upon entry to the roundabout in order to minimise vehicle entry speed (i.e., use the largest possible diameter for the central island).

2.4.3 Errors at sign-controlled intersections

The most common form of control at an intersection is a Stop or Give-Way sign, referred to commonly as sign-controlled intersections. A substantial number of these occur at intersections controlled by Stop signs (57%) compared to Give-Way signs (43%). A better understanding of the factors contributing to crashes at intersections with Stop signs is warranted in order to implement effective countermeasures. The literature is heavily weighted towards studies concerning crashes and driver behaviour at Stop signs and very few studies investigate driver behaviour at intersections controlled by Give-Way signs (Takemoto, Kosaka & Nishitani, 2008).

Visibility and visual scanning

In a naturalistic driving study Key et al. (2009) investigated the cognitive and visual contributing factors to older drivers' ability to stop at Stop signs. The sample consisted of 1,425 participants aged above 67 years whose driving behaviour was monitored over a five-day period. The number of failures to stop at a Stop sign was stratified against the total number of Stop signs encountered during the recording period. Close to 16% of the sample failed to stop at least once at a Stop sign. Poor vision and poor performance on cognitive tests were not significantly associated with failure to stop at a Stop sign. The authors attribute the lack of association between failure to stop and cognitive ability to the possibility that their sample consisted of high functioning individuals.

Bao and Boyle (2009) provided an insight in to age differences in visual scanning behaviour at Stop sign-controlled intersections using a driving simulator. Three participant groups completed the study and comprised of 20 young adults (18-25 years), 20 middle aged adults (35-55 years) and 20 older adults (65-80 years). The proportion of time

sampling the road environment and rear-view mirror was measured. The results revealed younger drivers sampled fewer high risk areas at the intersection before proceeding compared to older adults. All drivers directed a greater proportion of their gaze on the approaching traffic while making a right-hand turn (i.e. as in Australia and the UK) compared to other areas of the intersection. However older drivers focussed less on the direction they were turning in compared to middle and young drivers. The researchers concluded that middle aged drivers displayed the greatest awareness of the road environment evident by the greatest number of checks in the rear view mirror, and displayed a wider scanning pattern by focussing on more areas on intersection approach and while driving through the intersection (Bao & Boyle, 2009). While this scanning behaviour is likely to assist in greater conflict anticipation, and so potentially reduce crash likelihood, little evidence was available to support this hypothesis.

Failure to yield

A large proportion of drivers who have crashes at intersections controlled by Stop signs are older drivers (Braitman, Kirley, Ferguson & Chaudray, 2007). These crashes typically occur when older drivers are turning right across traffic and fail to yield right of way. In general, older drivers have more difficulty negotiating traffic at sign-controlled intersections compared to signalised intersections (Oxley et al., 2006; Preusser et al., 1998). This may occur for a number of reasons, with the most prominent being the apt gap selection. Older drivers aged 70-79 years typically see approaching traffic but have difficulty judging the approaching vehicles speed and position (Braitman et al., 2007). Furthermore, older drivers have a higher probability of suffering from age-related visual conditions, and have worse visual acuity than younger drivers, all of which can contribute to them failing to yield to approaching traffic.

Takemoto, Kosaka and Nishitani (2008) utilised a naturalistic driving study combined with an interview survey to investigate stopping behaviour at a Give-Way sign-controlled intersection. Drivers who entered the intersection without stopping reported that they thought they could spot any pedestrians, cyclists or other vehicles without completely stopping upon approach to the intersection. They also reported that they thought they could make a safe head check for other road users without coming to a complete stop (Takemoto, Kosaka & Nishitani, 2008). Drivers who do not stop are at an increased risk for crashes as they are more likely to continue to make head checks for other road users while driving through the intersection. This compares with drivers who stop, finish making their head check then pass through the intersection.

The researchers attribute these findings to lack of education and awareness about the restricted visibility of other road users when approaching an intersection compared to the increased visibility once stopped at the stop line. It is likely that this risky driving behaviour becomes habitual over time in the absence of any hazardous outcomes. Poor motivation to adhere towards safety regulations may also be a contributing factor to this behaviour (Gstalter & Fastenmeier, 2010).

Road geometry

Intersection road geometry can influence turn trajectories and driver behavior such as driver speed. Burchett and Maze (2006) analysed crash data at rural stop-sign controlled intersections according to road geometry. The geometric features comprised an intersection located on a horizontal curve, a vertical curve, a skew or a tangent. Intersections in a skew

were found to correlate with the greatest proportion of high severity crashes. Right-angle crashes were the predominant crash type at intersections with geometric features (Burchett & Maze, 2006). The high frequency of severity crashes at skewed intersections is possibly due to the lack of advanced warning on intersection approach. Site geometry is important to account for when designing an intersection. For example, intersections on slopes of crests of hills should be avoided (Lay, 2009).

Countermeasures to the errors at stop-sign controlled intersections

According to Retting et al. (2003) crashes involving Stop sign violations can be classified according to the following criteria: when the driver stopped before entering the intersection, when the driver did not stop before entering the intersection and entered across traffic, weather related crashes where the driver was unable to stop due to snow, rain or ice, as well as other Stop sign violation crashes. An analysis of crashes at intersections with Stop signs at four major US cities was conducted by Retting et al. (2003) who found that the majority (70%) of intersection crashes were Stop sign violation crashes. In these crashes, the majority of drivers claimed to have stopped before entering the intersection prior to accelerating but did not see the approaching traffic or their view of cross-traffic was obstructed. Typically the drivers who failed to stop were younger drivers aged less than 21 years who experienced crashes of greater severity.

The researchers suggested the following countermeasures:

- install all-way Stop signs to encourage speed reduction of all approaching vehicles
- increase visibility of Stop signs by installing Stop signs on the left and right-hand side of the road
- increase visibility of Stop signs with reflectors or luminance
- maintain visibility of Stop signs by eliminating objects obstructing vision
- add pavement marking in addition to the Stop signs

Rumble strips installed across the lane are another effective countermeasure of reducing crashes at Stop and sign-controlled intersections (Wentz, Warzala, & Harder, 2006). Rumble strips promote drivers to slow down their intersection approach speed and encourage safer stopping behaviour. According to Wentz et al. (2006) rumble strips are particularly effective for reducing speed at intersections where the cross-traffic is obscured in one or both directions by foliage or buildings. It is important to note that rumble strips were found to have no effect on snow covered roads.

Converting intersections into roundabouts, although costly, is another effective countermeasure. An estimate of the reduction in crashes was performed by Persaud and colleagues (2001) who estimated a 40% reduction in all crash types if 27 Stop-sign controlled and signal-controlled intersections were converted into roundabouts. Similarly, Candappa et al. (2007) estimated a 77% serious casualty crash reduction for converting intersections to roundabouts.

Van Houten and Retting (2001) assessed the stopping behaviour of drivers at a Stop-controlled intersection in response to prompts. The prompts consisted of a sign near a Stop sign stating 'look both ways' and an LED diode positioned underneath a Stop sign

representing a pair of eyes that looked both ways as a prompt for the driver. In conjunction with the two prompt conditions there was a baseline condition which was free of any prompts. An observation analysis was conducted to assess: scanning behaviour, stopping behaviour and percentage of right-angle conflicts as defined by a car swerving to avoid a crash or sudden braking. A greater number of drivers came to a complete stop in the conditions where a prompt was present, and the greatest compliance was found for the diode prompt. Consequently, few right-angle conflicts occurred in the diode prompt condition compared to the sign prompt and baseline condition. The researchers concluded that installation of a LED diode was a cost effective countermeasure (at \$300 US per system) to reduce crashes at Stop sign-controlled intersections. Education and awareness campaigns could also assist with educating drivers about the risk associated with failing to come to a complete stop at an intersection and the ability to perform an adequate head check for other road users.

Charlton (2003) observed drivers engaging in a short stop-go period before entering a stop-sign controlled intersection. The intersection of interest provided an unrestricted view to any oncoming traffic in either direction and therefore led Charlton to propose that drivers were making an early decision about whether to proceed across the intersection upon approach to the intersection. As a consequence, Charlton trialled a controversial intervention of reducing sight visibility upon the approach to the intersection by erecting a visual restriction treatment in the form of a hessian screens. Analysis of approach speed 3 weeks post intervention was 30% lower than before the installation of the screen. Survey data of drivers indicated that the screen was visibly acceptable and did not appear to pose any safety threat. Follow up data for a longer period of time is required before any conclusive evidence can be drawn about the efficacy of the hessian screen.

Arnold and Lantz (2007) were interested in assessing the effect on driver behaviour of installing an LED stop sign at a T intersection. The LED stop sign was powered by a solar panel and cost approximately \$4000 US to purchase and install. Driver approach speed was measured before installation, immediately after installation and 90 days after installation, and recordings were made during night and day. Drivers were found to significantly decrease their speed immediately after the installation of the sign, however the decrease in speed was small. There was an average 2% decrease in average speed during the day and a 4-7% decrease in average speed at night. The effects did not appear to be lasting as the speed reductions was not as great 90 days after installation. The authors conclude that LED stop signs are effective at reducing driver approach speed, although the reductions in speed appear to be small.

2.4.4 Errors at uncontrolled intersections

An uncontrolled intersection is an intersection that has no signals and no signs. In WA when a vehicle approaches an uncontrolled 4-way intersection the driver always needs to give way to the right and at a no control T-junction the driver at the top (continuing road) has priority over the driver at the stem (terminating road) of the intersection. A common error at such intersections is driver confusion at these priority rules, and incorrect judgement of approach speed of the oncoming vehicle before making a decision about turning right (Stokes et al. 2000).

Driver confusion can result when drivers follow informal rules in regards to giving way. Informal rules are guided by expectations that are understood by a group that guide social behaviour and are not derived from the legal system (Cialdini & Trost, 1998). For

example, rather than abiding by the give way to the right rule there is evidence to suggest that drivers also rely on informal cues such as the speed of the approaching vehicle and the road geometry (Björklund & Aberg, 2005). In some circumstances drivers report giving way to vehicles that are approaching on broader roads than the road they are on as they see the broader road as having a higher priority status (Björklund & Aberg, 2005).

Decision making at an uncontrolled intersection often involves selecting an appropriate gap between approaching traffic. Evidence suggests that judgements become more difficult the faster the speed of approaching traffic (Alexander, Barham & Black, 2002). Drivers must correctly perceive the speed and the distance of approaching vehicles and accept larger gaps for faster travelling vehicles. As previously mentioned in section 2.4.1 (gap selection), compared to younger drivers older drivers choose larger gaps and take more time to drive through the intersection. Therefore older drivers can be at risk of taking too long to complete a turn while younger drivers are at risk of near misses when accepting high risk gaps. According to Alexander and colleagues (2002) personality traits, risk perception, age and sex can all contribute to driver gap acceptance behaviour. Similar to errors at signalised intersections, environmental characteristics, sight distance and speed are all factors that can contribute to a crash at an uncontrolled intersection (refer to 2.4.1 for more detail).

Car-cyclist collisions are common at uncontrolled intersections because drivers typically look in the direction of approaching cars and fail to see cyclists.

Countermeasures to the errors at uncontrolled intersections

Gross et al. (2007) evaluated the effectiveness of installing road marking stating STOP AHEAD on the approach to uncontrolled intersections in Maryland, Arkansas and Minnesota. The authors estimated that the countermeasure would be most effective for four legged intersections compared to three legged intersections and would result in a significant reduction in the number of rear-end and right-angle collisions (Gross et al. 2007).

Increasing the skid resistance of the road surface is an effective countermeasure for reducing the number of intersection crashes in areas where there are a high frequency of wet surface crashes (Federal Highway Administration, 2009). The researchers estimated a 50% reduction in crashes occurring at intersections on wet road surfaces as a result of installing skid resistant surfaces.

A study by Summala et al. (1996) evaluated the effect of measures to increase driver awareness of the presence of cyclists at T-intersections in Helsinki, Finland (Summala et al., 1996). The measures included: warning signs painted or installed at intersections, installation of a speed hump, an elevated cycle crossing and a stop sign prior to the cycle path, and an information sheet distributed to householders in the area near intersections. They found that installation of speed-reducing countermeasures (presence of speed hump, elevated cycle crossing lane and stop sign) resulted in a marked increase in drivers looking to the right (from 8% to 31%) (i.e. the left in Australia and UK) and a decrease of drivers looking to the left only (from 43% to 25%). The researchers also noted that average driving speeds decreased. They argued that these measures changed drivers' visual search patterns more favourably for cyclists approaching the intersection from the right and concluded that this was so, in part, simply because drivers were provided with more time to focus on traffic in each direction.

2.5. GENERAL FACTORS INCLUDING DRIVER CHARACTERISTICS

Road user characteristics are contributing factors to a number of intersection crashes. Behavioural characteristics that can increase crash risk at intersections include: driver inexperience, driver age, inattention, driver fatigue, driver intoxication, failure to wear a seat belt and people who suffer from a chronic illness that can impair driving performance. Vehicle operation errors can also contribute to driver error in some circumstances.

2.5.1 Driver intoxication

It is a well established phenomenon that driving under the influence of alcohol can impair driving performance. Driving performance can become compromised with a Blood Alcohol Concentration at 0.05% (Lenné, Triggs & Redman, 1999). Driving can become compromised through increased deviation in speed, slowed reaction time and information processing, and increased lateral deviation while driving.

Research has shown that individuals who abuse alcohol have widespread, multifaceted impairments in many domains of cognitive function (see Bates, 2002, for a review), including:

- Short-term memory and learning impairments, which become more evident as the task difficulty increases. On the road this can equate to difficulty in remembering recently passed signage, and the ability to cope with complex intersections;
- Impaired perceptual-motor speed, which can affect the ability to perceive the driving situation and respond in a timely manner;
- Impairments in visual search and scanning strategies, which can affect how well vehicles from conflicting directions or other potential hazards are noted;
- Peripheral neuropathies experienced as numbness or paresthesias of the hands or feet, which can affect motor skills; and
- Deficits in executive functions such as mental flexibility, problem solving skills, difficulty in planning, organising and prioritising tasks, difficulty focussing attention, sustaining focus, shifting focus from one task to another, or filtering out distractions, difficulty monitoring and regulating self-action and impulsivity. These can limit the ease with which a driver can readily respond to the demands of a driving task, particularly one that is unexpected.

There has been little research conducted on what influence intoxication has on specific crash types at intersections. However, there is evidence to suggest that a large proportion of intoxicated drivers constitute red-light runners (Romano et al., 2005). Specifically, red-light runners are more likely to have had prior convictions of driving while under the influence of alcohol (Retting, Ulmer, & Williams, 1999). Based on Lenné findings (1999) on compromise of driver ability through intoxication however, it is likely that “increased lateral deviation” can produce more loss of control crashes, and side swipes; while others like delayed reaction time and information processing and increased speed deviation can contribute to most crash types including cross traffic and rear-enders and indirect right-angle crashes.

Countermeasures for driver intoxication

A number of countermeasures are available to address the problem of drink driving. These include: enforcement, in particular Random Breath Testing (RBT), anti-drink driving media campaigns to alert drivers to the danger, and education programs.

RBT can be associated with a reduction in drink driving crashes of at least 25% though increased penalties for drink driving may produce counterintuitive findings (Briscoe, 2004).

Alcohol interlocks can also have some effect in reducing the number of drivers on the road with excessive alcohol in their systems. A Swedish study of professional drivers found that should alcohol interlocks be installed in the entire fleet of trucks, buses and taxis in Sweden, an average half a million drink driving trips per year could be prevented (Bjerre & Kostela, 2008).

Effectiveness of public anti-drink driving campaigns are mixed, some results showing that anti-drink driving enforcement and publicity campaigns had an independent effect in reducing crashes (Tay, 2005; Tay, 1999) while others indicate little or no evidence that such campaigns change drink driving behaviour (Macpherson & Lewis, 1996, 1998; Rotfeld, 1999).

2.5.2 Driver distraction

Driver distraction is a prominent type of driver error that can increase the possibility of a crash occurring at an intersection. Distractions include mobile phones, text messaging, in-vehicle Internet facilities, sound systems and visual devices like DVD players, as well as eating, drinking, smoking and interacting with other occupants (Regan et al., 2003).

Mobile phone use while driving is a serious distracter that typically results in rear end crashes (Huang, Stutts, & Hunter, 2003; Neyens & Boyle, 2007). In a driving simulator study Hosking et al. (2006) investigated the effects of text messaging while driving in sample of young novice drivers. Twenty young adults were required to participate in a simulator drive consisting of eight critical events such as following a car. Throughout each of the critical events participants were asked to send and retrieve text messages. The researchers found that retrieving messages, and in particular sending, had a detrimental effect on the ability to maintain lane position, detect hazards, and to respond appropriately to traffic lights (Hosking et al., 2006). More specifically, participants spent approximately 40% of their time during each critical event not looking at the road while text messaging. This compared with approximately 10% of the time not looking at the road while not text messaging. Therefore text messaging while driving has serious implications for driving at intersections.

Recently, Neyens and Boyle (2007) predicted the influence that different types of distractions had on young drivers (16 – 18 years old) involved in three crash types. The crash types consisted of rear-end crashes, angle crashes with moving objects and collisions with fixed objects. The study provided an insight in to the types of distractions that were associated with intersection crashes in the sample. For example compared to collisions with fixed object crashes, angle crashes and rear-end crashes at intersections were more likely to involve cognitively distracted drivers. Similarly, drivers who were distracted by passengers were also more likely to be involved in angle crashes and rear-end crashes.

Drivers who were distracted by in-vehicle technologies were less likely to be involved in these two crash types.

According to the results from the 100-Car Naturalistic Driving Study (Dingus et al., 2006) inattention to the road in front was a contributing factor in approximately 40% of single-vehicle crashes. One half of all single-vehicle crashes in the study were located at intersections. In these crashes, distractions included: using a mobile phone, passengers in the car, drinking from a cup, talking/singing and attending to an object in the vehicle (Dingus et al., 2006). Further information regarding types of distraction is provided from a crash analysis by Stutts et al. (2001). According to their analysis, a greater proportion of older driver crashes (aged greater than 65 years) were attributed to 'looked but failed to see' (23%) compared to distraction (7%). Conversely, a greater proportion of younger driver crashes (aged less than 20 years) were attributed to distraction (23%) compared to 'looked but failed to see' (17%) (Stutts et al., 2001). It is important to note that there was no precise measure of distraction or loss of concentration as these results were obtained by asking police crash investigators to interview the drivers about the cause of the crash.

Singh (2010) conducted a survey study to assess the contribution of factors that could divert a drivers attention resulting in a crash. The researchers classified driver inattention as either resulting from an internal source of distraction (i.e. adjusting the radio), or a non-driving cognitive activity (thoughts about an activity un-related to driving). Data was collected immediately after the crash from multiple sources including drivers and any witnesses who were present at the scene. In-vehicle sources of distraction included: eating and drinking, reading a map/newspaper, conversing on the phone, smoking, adjusting the radio, conversing with a passenger, retrieving objects from the floor or seat. Second category of distraction was non-driving cognitive activity which refers to inattention due to thoughts about events un-related to driving. For example, the thoughts could be about a personal problem or family problem. Of an estimated 2,188,970 crashes approximately 16% were attributed to conversing with a passenger. This was cited as the most frequently internal distraction. Approximately 8% of the estimated 3,889,775 crashes were attributed to drivers engaged in cognitive thought unrelated to driving. Once the researchers accounted for age and gender, engaging in conversation with a passenger continued to be associated with the greatest proportion of crashes. The researchers of the study conclude that engaging with passengers in the car followed by engaging with people using the phone were the most common sources of distraction. Unfortunately the crash type was not provided in the analysis therefore it is difficult to ascertain the contribution of driver error to intersection crashes.

Countermeasures for driver distraction

Driver education and training about crash risk, vehicle control and reduction in distractions can assist in the reduction of crashes caused by distractions. Human machine interface technologies that detect driver drowsiness and maintain focus (away from distractions) could also alleviate this problem. Other courses of action include reviewing current legislation and undertaking further research (Regan, 2003). Minimising distractions external to the vehicle, such as advertising billboards, could also be a potential countermeasure to distraction.

2.5.3 Driver stress and driver fatigue

According to Matthews (2002) disturbed states of driving behaviour can be classified as either: stress and anxiety, or fatigue. Any of these altered mind states can result in

maladaptive behaviour that places the driver at an increased risk for making an error. For example, an aggressive, impatient, or angry person may react in a hostile manner towards other road users, and choose to engage in high risk behaviours such as tail gating, weaving through traffic and flashing lights (Matthews, 2002). Furthermore, someone experiencing high anxiety levels or fatigue may suffer from a reduced situational awareness, demonstrate poor information processing capabilities and display impairments in driver performance. In addition, the driver may be thinking about things other than the driving task resulting in loss of concentration. This is particularly likely to occur in monotonous driving situations. The exact contribution of loss of concentration to crashes is difficult to measure.

Countermeasures for disturbed driver states

The primary goal of interventions for drivers with disturbed states should be to minimise task complexity to allow the driver to remain focused on the task at hand and to reduce distractions that can occur from an overload of information. This is difficult to implement at intersections, which are by nature complex road environments. However, in-vehicle technologies that are simple to use could reduce driver workload by automating driver speed, and alerting the driver towards critical events in the road environment. Cummings and colleagues (2001) recommend sharing the driving, using rest stops along the highway and turning on the radio to prevent drivers from falling asleep when they are drowsy.

2.5.4 Vehicle operation errors

Vehicle handling and operation errors can contribute to intersection crashes and have been classified as action errors (Brace, Archer & Lenné, 2008). Action errors (inappropriate actions) can occur from an improper driving technique or manoeuvre, lack of training on how to operate the vehicle and/or lack of training or understanding of traffic rules. Examples of action errors include: mistiming the manoeuvre by braking too early or too late, failing to complete a steering manoeuvre, or pressing the accelerator instead of the brake. Technological systems can play a role in reducing these action errors by directing the driver towards performing the correct manoeuvre, or compensating for inappropriate driving behaviour after an error occurs.

Countermeasures for vehicle operation errors

Some countermeasure and driver assistance systems available to target these errors include Anti-Lock Braking Systems (ABS), Electronic Stability Control Systems (ESC), Speed Limit and Traffic Light Warning Systems. Electronic Stability Programs appear to produce some reductions in crashes and injuries, one study finding as much as 35 % reduction in the risk of a run off the road crash (Burton et al., 2004). Forkenbrock, 1998, 1999 (cited in Burton, 2004) found vehicle performance on a test track to be superior with ABS enabled - braking distances were shorter and the vehicle was more stable during braking. “Heads-up” displays can also be used to aid driver spatial awareness in low visibility conditions, and consequently increase reaction time.

2.6. SUMMARY OF FINDINGS

In summary, there are a range of factors that contribute to human errors when driving through an intersection, all of which can place the driver at an increased crash risk. The contributing factors to human errors can vary according to the type of intersection (signalised, roundabout, sign-controlled or uncontrolled) and consequently give rise to

different crash types (such as, angle collisions, rear-end collisions, cross-traffic collisions and side-swipe collisions).

A common behaviour at signalised intersections includes red-light running behaviour. The behaviour can either be unintentional (an error crash) or deliberate (a violation). Regardless of the intent, red-light runners place themselves at an increase risk of right-angle crashes. The following factors can also increase the drivers risk of being involved in a crash: limited sight distance leading up to the intersection, driver indecision when positioned in the dilemma zone, difficulties with gap selection, approach speed and incorrect anticipation of other road users.

Human errors at roundabouts are particularly influenced by visual scanning behaviour, driver visual attention and failure to yield to other road users. The most common crashes occurring at roundabouts in this analysis were hit object crashes. A greater proportion of vulnerable road users such as cyclists are involved in crashes at roundabouts compared to other intersection control types such as uncontrolled intersections (Harper & Dunn, 2003). Vulnerable road users are also at risk at uncontrolled intersections where drivers often fail to see or check for cyclists and pedestrians. Gap selection difficulties can also occur at uncontrolled intersections leading to right-angle or right-through crashes.

Regardless of the intersection type, driver characteristics such as driver intoxication, an altered state of mind, vehicle handling problems and distractions can all lead to human errors and increase the chance of a crash occurring at an intersection.

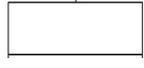
3. IN-DEPTH INTERSECTION DATA ANALYSIS

Fault Tree Analysis (FTA) (Vesely et al., 1981) is a universal method that is widely used to analyse system reliability and safety (Jiao et al., 2006). Jiao and colleagues (2006) state that by structuring a fault tree, this method can describe the logical process from basic failure events (often damage or failure of system elements) to the top outcome event (crash). All the paths of the fault tree describe the sequences and relationships between basic events and the top event. Joshua and Garber (1992) proposed FTA for a causal analysis of large vehicle crashes. In 1995, Kuzminski and colleagues developed an etiological model of ‘vehicle leaves roadway’ type accidents using fault tree modelling. The authors suggested the chief qualitative advantage of FTA is that it provides a structured approach to the study of failure and that on completion of the fault tree structure, quantitative analysis would readily provide a statistical depiction of the causal aspects of the failure and a measure of the relative contributions of these causes to overall crash occurrence (Hillard et al., 2005). Consequently, this study proposes the use of FTA to better understand the factors contributing to intersection crashes.

3.1. FAULT TREE ANALYSIS METHOD

FTA provides a method of examination of a particular event which is an undesired outcome of some process. The event is referred to as the ‘top event’, as it is located at the top of the fault tree. The paths of the fault tree describe the sequences and relationships between basic events and the top event. These paths are defined such that all possible events or actions leading to the occurrence of the top event are sufficiently described through them (Joshua et al., 1992).

There are a number of basic symbols that have been developed for use in FTA diagrams. A full list of these symbols is provided in Figure 11.

Primary event symbols		Basic event	A basic initiating fault requiring no further development.
		Undeveloped event	An event which is not further developed either because it is of insufficient consequence or because information is unavailable.
		Intermediate event	A fault event that occurs because of one or more antecedent causes acting through logic gates.
Logical gate symbols		And gate	Output fault occurs if all of the input faults occur.
		Or gate	Output fault occurs if at least one of the input faults occurs.
Transfer symbols		Transfer in	Indicates that the tree is developed further at the occurrence of the corresponding Transfer out.
		Transfer out	Indicates that this portion of the tree must be attached at the corresponding Transfer in.

Source: Vesely et al. (1981)

Figure 11: Symbols Used in Fault Tree

3.2. METHODS

Source of data

The Australian National Crash In-depth Study (ANCIS) is an Australian collaborative research program involving the automotive manufacturing industry, State and Federal Government agencies and automobile associations. In-depth data on a sample of passenger vehicle crashes is collected currently in the Australian states of Victoria and New South Wales on severe crashes where at least one occupant has been hospitalised as a result of the crash (Fildes et al., 2003). The list of Fault Tree symbols is shown in Figure 11. Information collected includes occupant injuries, vehicle damage and crash contributing factors obtained from a retrospective examination of the crash.

Designing Safer Roads to Accommodate Driver Error

The recruitment process commences in the hospital (see Figure 12), with only those seriously-injured motor vehicle crash victims who have provided informed written consent admitted to the study. In the case of admitted patients unable to give their own consent, the study provides for next-of-kin consent to be obtained. Moreover, the only fatally-injured participants will be those who die but within 30 days of the crash.

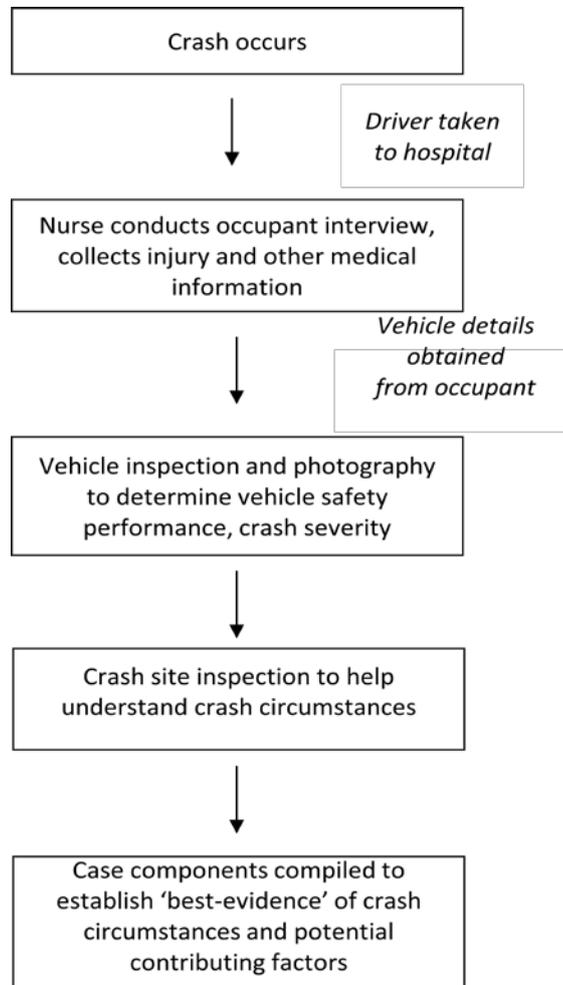


Figure 12: ANCIS Crash Investigation Process

The ANCIS database had 502 real world crashes available for analysis. Of these, 132 were valid intersection crashes. For more information on the characteristics of the ANCIS data, see Logan et al. (2006).

Development of the fault tree

A fault tree is neither a model of all possible system failures nor of all possible causes for system failure. Rather, a fault tree is tailored to its top event which corresponds to a particular system failure mode, and the fault tree thus includes only those faults that contribute to the chosen top event. Moreover, the list of faults is not exhaustive, covering only the most credible faults as assessed by the analyst (Vesely et al., 1981). In this study, the list of faults was derived from the contributing factors judged by real-world crash experts to have played a part in the occurrence of each crash. These contributing factors were assigned on the basis of the evidence available from the data collected from the driver

interview, as well as the detailed vehicle and crash site inspection forms and photography collected for each ANCIS case.

The fault tree is a top-down process constructed from ANCIS intersection crashes (Refer to Figure 13). The top event was chosen to be the crash event. The contributing factors for all the intersection crash causation were categorised into two types depending on whether the driver is compliant with road rules or not. Joshua et al. (1992) categorised the causation into driver-, vehicle-, and environment-related, and each accident was attributed to one of the major causative factors. This approach was not used in this study, since separating them at the first level implies that the three elements have independence from one another. This is clearly not the case in real-world crashes, where interaction between the driver, the vehicle and the environment is inevitable in crash causation. In Joshua et al. (1992), this was accounted for by reintroducing elements from the other branches into the branch under consideration. In this study, a different approach was taken, with the fault tree structure being based on the driver's viewpoint, interacting with the vehicle and environment. In Kuzminski et al. (1995), the fault tree was developed in great detail. As a result, it was impossible to obtain all the basic event probabilities. The model was then truncated, potentially leading to over simplification. The fault tree chosen for this research was structured around the available fields in the ANCIS database and thus allowed all the basic event probabilities to be determined.

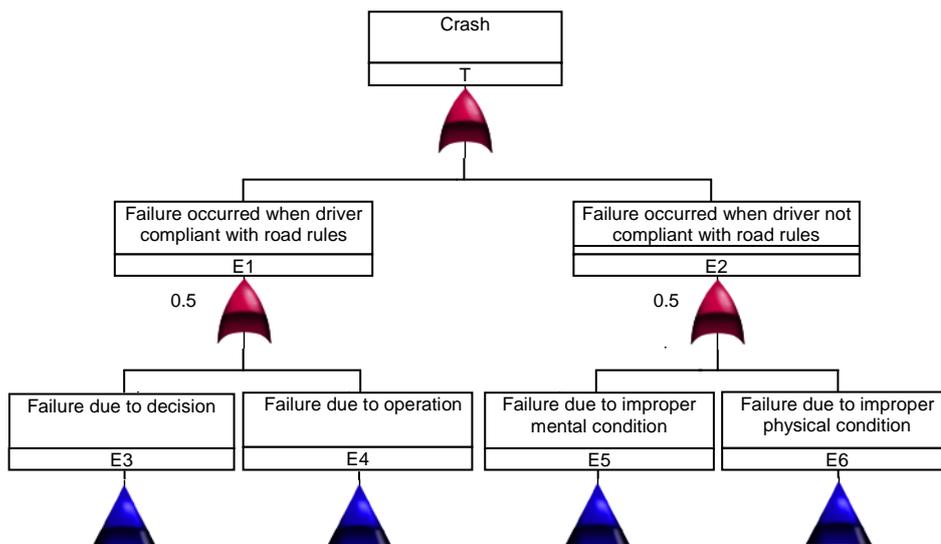


Figure 13: Top-Level Fault Tree

The left-hand branch at the first level in Figure 13 describes the situation when failure occurs despite the driver having complied with the road rules. This is caused by either a decision-making failure or an operational failure.

The concept was borrowed from the paper by Kuzminski et al. (1995), exploring four driver subsystems: perception, comprehension, decision, and action.

- a) Perception system: collection of relevant information from the environment and vehicle.

- b) Comprehension system: proper understanding of information from the perception system.
- c) Decision system: based on comprehension of the traffic situation, making a decision to maintain a specific vehicle operating condition.
- d) Action system: performance of the decision made.

Kuzminski's concept of the driver subsystem was extended to a 'driving' subsystem to acknowledge the fact that not all of the factors involved in a traffic situation are necessarily under the control of the driver. Furthermore, in this study, the perception system and comprehension system were incorporated into the decision system to simplify the analysis. This revised decision system is defined as the ability of the driver to perceive, comprehend and make a correct decision. Consistent with the definition of a 'driving' subsystem, the action system was redefined as an 'operation' system, representing the ability of the vehicle to operate normally.

The right-hand branch at Level 1 (Figure 13) shows the crash causation path when the driver was not compliant with the road rules. This is proposed to be the result of an improper mental or physical condition. Fault tree analysis involves the determination of 'cut sets', which are the unique combinations of events leading to the top event' (in this case, the crash event). A cut set becomes a minimal cut set if, when any basic event is removed from the set, the remaining events collectively are no longer a cut set.

Data extraction

There were 502 real-world cases in the database. As ANCIS is a hospital-based study, cases are initiated by the Research Nurse, and case numbers are assigned by occupant rather than by crash. Consequently, there may be more than one case for each crash. The extraction of the dataset was accomplished using SPSS software. Manual filtering was used to isolate a number of crashes that, while occurring at an intersection, were not primarily related to the presence of the intersection. This reduced the dataset to 134 crashes, two of which had insufficient information to be adequately analysed, leaving a total of 132 crashes.

3.3. ASSIGNMENT OF CONTRIBUTING FACTORS

The process involved using expert judgement to assign contributing factors for each of the available crashes.

For each of the sampled crashes, a best-evidence estimate of the factors contributing to each was made, primarily on the basis of an assessment of the driver interview, backed up by corroborating evidence provided by the damage patterns on the vehicle and the layout and known paths of the involved vehicle or vehicles at the crash site. One disadvantage of the data set was that interviews were only collected for the case vehicle drivers, with the crash circumstances and contributing factors from the other driver's viewpoint unavailable due to the ethics and privacy conditions under which the source study operated. However, information regarding the actions of the other driver (as opposed to their intentions) was able to be implied on the basis of estimated impact speeds, vehicle damage locations and the like.

It is noted that in addition to the above data, a number of cases had been assigned contributing factors at multidisciplinary expert crash investigator panels, with the information from these also contributing to the analysis.

3.4. CALCULATION OF PROBABILITIES

The probabilities were calculated for the branch events at the OR gates. No probability was estimated for events at AND gates, as both events must occur with certainty for a fault to proceed to the top event through such a gate (Joshua et al., 1992). The presence or absence of an evasive manoeuvre was based on the expert judgements, using the available evidence, including the presence or absence of visible skid marks at the crash site. For some basic events in the fault tree, there were no crashes in the sample where the particular contributing factor was judged to have had sufficient influence on the occurrence of the crash. Therefore, these basic events were assigned zero probability in this study, but may occur in a larger sample of intersection crashes.

3.5. RESULTS

From the FTA, the shortest paths to an intersection crash were identified and the associated relative probabilities determined. The statistical representation of interacting faults provides insights into how various contributing factors lead to intersection crash occurrence.

A total of 66 combinations of events were found to lead to an intersection crash. The top 15 are shown in Table 2. Among these, the most prevalent form of intersection crash occurrence was when the driver misjudges speed/gap without taking any evasive action (15%). The second most common occurrence was the driver disregarding traffic sign/signal without taking any evasive action (11%).

Table 2: Top Fifteen Events

Events	Probability
Misjudging speed/gap, No evasive action	0.15
Disregard traffic sign/signal, No evasive action	0.11
Misjudging speed/gap, Evasive action failed	0.07
Excessive speeding, No evasive action	0.06
Following too close, No evasive action	0.04
Alcohol impairment, No evasive action	0.04
Vision obscured by roadside objects, Improper lookout, No evasive action	0.04
Disregard traffic sign/signal, Evasive action failed	0.04
Vision obscured by poor weather, Improper lookout, No evasive action	0.03
Vision obscured by other vehicles, Improper lookout, No evasive action	0.03
Distraction on mind, No evasive action	0.02
Fatigue impairment, No evasive action	0.02
Illness, No evasive action	0.02
Poor layout, Inexperience, No evasive action	0.02
Excessive speeding, Evasive action failed	0.02

3.6. DISCUSSION

In this study, the contributing factors that lead to crashes at intersections were investigated. The causation mechanism was constructed in the form of a systematic fault tree using the data from an in-depth real-world crash investigation study in order to better understand the relationships between the basic events (contributing factors) and the top event (crash).

A number of interesting facts can be concluded from the FTA. First, the overall probability of the driver being judged as the sole contributing factor in the crash was 0.72, while the probability of the combination of driver and environment was 0.26. The environment alone was a contributing factor with a probability of 0.02. No vehicle or vehicle-related factors were identified in any of the crashes in this analysis. One possible reason is that the vehicle investigation form, while including some information relating to vehicle pre-crash condition, does not have a specific focus on this issue. The second possibility is simply the small size of this sample. However, the relative contributions of each of the human, vehicle and environmental factors found in this study compares well with other analyses of crash

causation. Different studies have suggested that driver-related human factors contribute to between 70% and 90% of crashes, road/environment factors contribute to around 30% and vehicle factors to less than 10% (Sanders & McCormick, 1992; Orden & Zamanillo, 2005).

The two minimal cut sets with the highest probability of occurring in this sample were, 'Misjudging speed/gap, No evasive action' and 'Disregard traffic sign/signal, No evasive action'. If the presence of evasive action is ignored, 'Misjudging speed/gap' had a total probability of 0.22 and 'Disregard traffic sign/signal' a probability of occurrence of 0.15. The intentionally non-compliant behaviour implied by disregard for traffic signs and signals suggests a greater focus is required on enforcement of intersection rules, perhaps through more widespread installation of red light and speed/red light cameras or, alternatively, more usage of inherently safe intersection designs such as roundabouts that are much less likely to result in injury outcomes in the event of a crash occurring. The high probability of 'Misjudging speed/gap' indicates that, despite the prevalence of modern intersection designs, drivers are still encountering problems with the complex task of selecting and taking safe gaps when crossing or entering traffic streams. Potential solutions to this problem could include vehicle-to-vehicle communications systems designed to warn drivers, or even intervene by braking, to help prevent impending collisions. Again, inherently safe intersection designs would be less reliant upon human performance and therefore constitute more robust long-term solutions.

The probability of the human contributing factor falling into the 'intentional' category, including such behaviours as excessive speeding, disregard for traffic signals and the like, was 0.37, compared with a probability of 0.63 for accidental behaviours. About a quarter of crashes were caused by intentional behaviour. This kind of contributing factor is difficult to eliminate, requiring more enforcement, coupled with targeted education programs.

The probability of the driver being judged as attempting evasive action prior to the crash was 0.28, potentially indicating that in nearly three-quarters of the crashes in this sample, a higher level of advanced driver car control skills would not have prevented the crash, since no evasive action was taken. Although study outcomes are often inconclusive, defensive driver training courses may help drivers to identify potential hazards earlier and therefore take earlier, less extreme evasive actions.

It is interesting to note that the total probability of some form of physical or mental impairment (including fatigue) was 0.11. Distraction, both internal and external, was judged to have been a contributing factor with a probability of 0.09. This is perhaps an underestimate compared with estimated values for police-reported serious casualty crashes in Australia of around 16% (Logan & Hoareau, 2009). Finally, inexperience was a contributing factor with a probability of 0.08, nearly always combining with other factors relating to the road environment such as poor layout, poor road surface, inappropriate speed limits, and the like. The contributing factors, 'Inadequate interaction with vehicle' and 'misjudging speed/gap' are also likely to have an inexperience component, but neither of these was developed in this study.

Doytchev and Szwillus (2009) stated that in traditional engineering failure analysis techniques, such as FTA, the analysis of the contribution of human error to accident occurrence is under-represented. This research attempts to rectify this situation. The basic events (contributing factors) of the Fault Tree are derived from the related human error taxonomy and empirical research relating to intersection crashes. The outcomes of an FTA

model can demonstrate the overall systematic nature of a crash, and provide knowledge about the possible causation paths and the frequency of various contributing factors.

There were several limitations with this study. First, the ANCIS data collection method involves the recruitment of voluntary participants who are currently admitted to hospital and they, or a relative, are able to provide informed, written consent. As a result, those patients who perceive themselves as more at fault in the crash tend to be less likely to participate. Furthermore, the ANCIS sample primarily includes only hospitalised patients, however serious injury crashes, compared with non-injury crashes, are much more costly to both the individual and society as a whole. While ANCIS does include fatality crashes, they are slightly under-represented compared with all serious injury and fatality crashes. The number of intersection crashes may not be sufficiently large to cover all kinds of intersection crashes and the range of information collected from the crash is not always adequate to allow the contributing factors to be determined with full confidence. The contributing factors to intersection crashes are often very complicated and the fault-tree model constructed in this paper was necessarily restricted to the relatively simple situation where all the basic events were assumed to be statistically independent. A more complex and comprehensive fault tree would possibly reveal more detail.

One difficulty in conducting a fault-tree analysis is that the quantification of the basic event probabilities can be a significant challenge. The ANCIS database provides the information based on cases involving a real-world crash, so quantification of the basic events against all conflicts is impossible. The top event probability should be calculated from all of the basic event probabilities, which was clearly not possible in this study. The probabilities developed in this paper are relative probabilities calculated from the minimal cut sets.

It is clear that there is significantly more work required to better understand the contributing factors leading to intersection crashes through FTA. The two major needs for a better analysis would be a larger crash sample and more data relating to contributing factors collected by crash investigators, perhaps from a more detailed questionnaire to participants or, ideally, from crashes involving participants of naturalistic driving studies, where far more detailed pre-crash information would be available from in-vehicle data recorders and video cameras.

3.7. CONCLUSIONS

A fault tree model for helping to understand intersection crash causation was established in this paper and was shown to provide extremely useful insights into the problem of intersection crashes.

The FTA conducted using real-world intersection crashes from an in-depth study showed that the most prevalent form of intersection crash was when the driver misjudged speed or gap without attempting any evasive action (Probability of 0.15). The next most likely contributing factor was a disregard for traffic signs or signals, again without any apparent attempt at evasive action, with a probability of 0.11. Across all of the crashes, intentional behaviour was a cause in 37% of crashes, while behaviour judged accidental occurred in 63%. Vehicle defects were much less significant. This analysis provides a more systematic understanding of intersection crashes. Not only does this method provide an explanation of causal mechanisms using a fault tree, it will also help in identifying the most effective countermeasures for these crashes.

4. LIST OF POTENTIAL COUNTERMEASURES AND TAXONOMY

The efficacy of each countermeasure for each intersection type (sign control, signal control and no control) is displayed in this section as a series of taxonomy. The taxonomy illustrates how at each intersection control type there are a number of countermeasures that can address driver error in relation to the main crash types. Each countermeasure is identified as useful for addressing each crash type as indicated by the following classification system:

Possible Solution	✓✓✓✓
Not a Possible Solution	✗✗✗✗
Not Applicable	⊖⊖⊖⊖

Static versions of each of the taxonomy according to intersection control type and crash type are provided below. A dynamic excel spreadsheet version demonstrating the efficacy of each countermeasure according to each crash type accompanies this report.

Designing Safer Roads to Accommodate Driver Error

4.1 Signalised controlled Intersection Crashes Taxonomy

Right Angle

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	⊖⊖⊖⊖	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Speed Cushions	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	⊖⊖⊖⊖	✓✓✓✓	⊖⊖⊖⊖
Increase Signal Timing	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖
Ban Right Hand Turn Movements	✓✓✓✓	✓✓✓✓	✓✓✓✓	✗✗✗✗	✗✗✗✗	⊖⊖⊖⊖	✗✗✗✗	✓✓✓✓	✓✓✓✓	⊖⊖⊖⊖	⊖⊖⊖⊖
Vary Speed Limits According to Time of Day	✗✗✗✗	✗✗✗✗	✗✗✗✗	✓✓✓✓	✓✓✓✓	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	✓✓✓✓	⊖⊖⊖⊖

Right Through

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	⊖⊖⊖⊖	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Speed Cushions	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	⊖⊖⊖⊖	✓✓✓✓	⊖⊖⊖⊖
Increase Signal Timing	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖
Ban Right Hand Turn Movements	✓✓✓✓	✓✓✓✓	✓✓✓✓	✗✗✗✗	✗✗✗✗	⊖⊖⊖⊖	✗✗✗✗	✓✓✓✓	✓✓✓✓	⊖⊖⊖⊖	⊖⊖⊖⊖
Vary Speed Limits According to Time of Day	✗✗✗✗	✗✗✗✗	✗✗✗✗	✓✓✓✓	✓✓✓✓	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	⊖⊖⊖⊖	✓✓✓✓	⊖⊖⊖⊖

Designing Safer Roads to Accommodate Driver Error

Side Swipe

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Speed Cushions	✓✓✓✓	✓✓✓✓	○○○○○	✓✓✓✓	✓✓✓✓	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○

Hit Object

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	××××	××××	××××	✓✓✓✓	✓✓✓✓	○○○○○	××××	××××	✓✓✓✓	✓✓✓✓	××××
Speed Cushions	××××	××××	××××	✓✓✓✓	✓✓✓✓	✓✓✓✓	××××	××××	✓✓✓✓	✓✓✓✓	○○○○○
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	○○○○○	○○○○○	○○○○○	○○○○○	✓✓✓✓	○○○○○

Designing Safer Roads to Accommodate Driver Error

Rear End

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (if applicable)
Convert to a Roundabout	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Speed Cushions	✓✓✓✓✓	✓✓✓✓✓	○○○○○	✓✓✓✓✓	✓✓✓✓✓	○○○○○	○○○○○	○○○○○	○○○○○	✓✓✓✓✓	○○○○○
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	✓✓✓✓✓	✓✓✓✓✓	×××××	✓✓✓✓✓	✓✓✓✓✓	○○○○○	○○○○○	○○○○○	○○○○○	✓✓✓✓✓	○○○○○

Hit Pedestrian

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (if applicable)
Convert to a Roundabout	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Speed Cushions	✓✓✓✓✓	✓✓✓✓✓	○○○○○	✓✓✓✓✓	✓✓✓✓✓	○○○○○	○○○○○	✓✓✓✓✓	○○○○○	✓✓✓✓✓	○○○○○
Increase Signal Timing	✓✓✓✓✓	✓✓✓✓✓	○○○○○	○○○○○	○○○○○	○○○○○	✓✓✓✓✓	✓✓✓✓✓	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	×××××	×××××	✓✓✓✓✓	×××××	×××××	○○○○○	○○○○○	✓✓✓✓✓	✓✓✓✓✓	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	✓✓✓✓✓	✓✓✓✓✓	×××××	✓✓✓✓✓	✓✓✓✓✓	○○○○○	○○○○○	○○○○○	○○○○○	✓✓✓✓✓	○○○○○

Designing Safer Roads to Accommodate Driver Error

4.2 Sign-Controlled Intersection Crashes Taxonomy

Right Angle

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	○○○○	✓✓✓✓	✓✓✓✓
Speed Cushions	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	○○○○	✓✓✓✓	○○○○
Increase Signal Timing	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Ban Right Hand Turn Movements	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Vary Speed Limits According to Time of Day	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○

Right Through

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	○○○○	✓✓✓✓	✓✓✓✓
Speed Cushions	✓✓✓✓	✓✓✓✓	✗✗✗✗	✓✓✓✓	✓✓✓✓	✓✓✓✓	✗✗✗✗	✗✗✗✗	○○○○	✓✓✓✓	○○○○
Increase Signal Timing	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Ban Right Hand Turn Movements	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Vary Speed Limits According to Time of Day	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○

Designing Safer Roads to Accommodate Driver Error

Side Swipe

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Speed Cushions	✓✓✓✓	✓✓✓✓	○○○○○	✓✓✓✓	✓✓✓✓	✓✓✓✓	○○○○○	○○○○○	○○○○○	○○○○○	✓✓✓✓
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○

Hit Object

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	××××	××××	××××	××××	××××	××××	××××	××××	○○○○○	✓✓✓✓	××××
Speed Cushions	××××	××××	××××	××××	✓✓✓✓	××××	××××	××××	○○○○○	✓✓✓✓	○○○○○
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○

Designing Safer Roads to Accommodate Driver Error

Rear End

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Speed Cushions	✓✓✓✓✓	✓✓✓✓✓	○○○○○	✓✓✓✓✓	✓✓✓✓✓	○○○○○	○○○○○	○○○○○	○○○○○	✓✓✓✓✓	✓✓✓✓✓
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○

Hit Pedestrian

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Speed Cushions	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓	○○○○○	✓✓✓✓✓	✓✓✓✓✓	○○○○○	✓✓✓✓✓	✓✓✓✓✓
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○

Designing Safer Roads to Accommodate Driver Error

4.3 Uncontrolled Intersection Crashes Taxonomy

Right Angle

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	○○○○	✓✓✓✓	✓✓✓✓
Speed Cushions	○○○○	○○○○	○○○○	○○○○	✓✓✓✓	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Increase Signal Timing	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Ban Right Hand Turn Movements	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Vary Speed Limits According to Time of Day	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○

Right Through

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	○○○○	✓✓✓✓	✓✓✓✓
Speed Cushions	○○○○	○○○○	○○○○	○○○○	✓✓✓✓	○○○○	○○○○	○○○○	○○○○	✓✓✓✓	○○○○
Increase Signal Timing	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Ban Right Hand Turn Movements	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○
Vary Speed Limits According to Time of Day	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○	○○○○

Designing Safer Roads to Accommodate Driver Error

Side Swipe

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Speed Cushions	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○

Hit Object

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	×××××	×××××	×××××	×××××	×××××	×××××	×××××	×××××	○○○○○	✓✓✓✓	×××××
Speed Cushions	×××××	×××××	×××××	×××××	✓✓✓✓	×××××	×××××	×××××	○○○○○	✓✓✓✓	○○○○○
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○

Designing Safer Roads to Accommodate Driver Error

Rear End

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Speed Cushions	○○○○○	○○○○○	○○○○○	○○○○○	✓✓✓✓	○○○○○	○○○○○	○○○○○	○○○○○	✓✓✓✓	○○○○○
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○

Hit Pedestrian

	Error Type										
	Attention	Distraction	Failing to perform head check	Aggressive and Risky Driving	Excessive Speed	Failure to Yield (if Applicable)	Occluded Vision	Poor Visual Scanning	Poor Gap Selection	Failure to Recognise Approach to Intersection	Failure to Stop at Stop Sign (If applicable)
Convert to a Roundabout	✓✓✓✓	✓✓✓✓	××××	✓✓✓✓	✓✓✓✓	✓✓✓✓	××××	××××	○○○○○	××××	○○○○○
Speed Cushions	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	○○○○○	✓✓✓✓	✓✓✓✓	○○○○○	✓✓✓✓	✓✓✓✓
Increase Signal Timing	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Ban Right Hand Turn Movements	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○	○○○○○
Vary Speed Limits According to Time of Day	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	××××	××××	○○○○○	✓✓✓✓	○○○○○

5. CONCLUSIONS AND SUMMARY

The aim of this report was to review the published literature to identify the range of driver errors leading to serious injuries and fatalities at intersections, and to identify road design features which aim to minimise the occurrence of inappropriate speeds, other errors and their consequences.

The literature review revealed a variety of sources of error specific to each crash type. For example, right-angle crashes at signal-controlled intersections often occur because drivers fail to stop at a red light and engage in red light running behaviour (Wang & Adel-Aty, 2007). Conversely, right-angle crashes at sign-controlled intersections have been attributed to poor visual scanning behaviour (Bao & Boyle, 2009), and failure to yield right of way (particularly for older drivers) (Preusser et al., 1998). Although roundabouts are known to reduce the number of rear end crashes, the review identified the following sources of driver error: knowledge of priority rules (Räsänen & Summala, 2000), driver entry speed to the roundabout (Arndt & Troutbeck, 1998) and driver attention and visual search difficulties (Summala, Pasanen, Räsänen, & Sievanen, 1996). There were a limited number of studies specifically related to crashes at intersections in Australia (Baldock, 2005; Cameron, in press; Corben, Ambrose, & Foong, 1990).

General road user characteristics pertinent to all intersection control types include speed, driver intoxication, fatigue and experience. The limitations of researching driver error are that it is always difficult to ascertain to what extent driver error contributed to the crash using prospective reports and crash data. Therefore, the use of driving simulators, video observations and naturalistic driving studies provide a richer source of information into the contribution and type of driver error that occurred at the time of the crash. The limitations of this project is the lack of data on driver characteristics such as age, driver experience, and blood alcohol levels which would further enhance the ability to attribute causal relationships to driver error. Furthermore, the focus of this project was on intersection casualties resulting in serious injuries and therefore, driver error may also be contributing to intersection crashes resulting in minor injuries.

The findings from the literature search were matched against the type of intersection crashes that occurred in WA from 2004 to 2009 as indicated by the crash investigation data. According to the data, a similar proportion of serious casualty crashes occurred at sign-controlled intersections (35%) and signal-controlled intersections (35%), with fewer casualties occurring at uncontrolled intersections (30%). Overall, the most common crash type was right-angle crashes accounting for 39% of all serious casualty crashes. Right-angle crashes typically occurred at sign-controlled intersections. The second most frequent crash type was right-through crashes (cross traffic collisions). These crashes predominantly occurred at signal-controlled intersections rather than sign-controlled or uncontrolled intersections. In contrast to the right-angle crashes and right-through crashes, the majority of crashes at roundabouts were hit object crashes. Irrespective of intersection control type, or region the majority of serious injury casualties occurred in posted speed zones of 60km/h and therefore these zones should be a priority area. It is therefore recommended to focus on countermeasures for preventing right-angle crashes occurring at sign-controlled intersections.

According to the literature review, difficulty selecting gaps in traffic is a significant contributory factor to driver error resulting in right-angle crashes at sign-controlled intersections, particularly for older drivers (Bao & Boyle, 2009; Braitman et al. 2007;

Oxley et al. 2006). Visual scanning behaviour, and focusing more on the on-coming traffic and less on the direction of the turn can be problematic (Bao & Boyle, 2009). Difficulty judging and perceiving the speed and distance of oncoming vehicles is another challenge for older drivers (Choi, 2010).

Recommendations for countermeasures arising from the literature review are outlined in the taxonomy and include:

- Converting the sign-controlled intersection into a roundabout
- Installing speed cushions to reduce driver speed
- Varying speed limits according to the time of day
- Where possible, banning any right turn movements

The taxonomy is designed around firstly choosing an intersection control type, then based on a certain crash type, displays the effect of a range of possible countermeasures on each driver error type. In the future the taxonomy would benefit from estimates of serious casualty reductions for each of the countermeasures. However this was outside the scope of this project.

In summary, this project has identified the main intersection control types that result in serious casualty crashes in WA. In addition, a greater understanding of the nature of the crash type, the intersection control type and posted speed limit has been obtained. The literature review revealed a number of contributing factors to driver error (both unintentional errors and violations) although in the majority of studies it was difficult for the researchers to attribute the cause of the crash directly to a specific type of driver error. Future research using naturalistic driving methods will assist with establishing this link between driver error and crashes at intersections.

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