Technologies for sensing bicycles and their application at metropolitan intersections

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Abstract
This report examined methods of improving safety for cyclists at intersections, with particular emphasis on sensing technologies. Bicycle sensing can either be active (push button) or passive (e.g., inductive loop sensors, video, radar or LiDAR). The timing and co-ordination of traffic signals, and the geometric design and pavement markings of roads can also be used to promote cyclist safety. The characteristics of cyclist crashes at intersections were examined for the period 2008 to 2017 and high risk intersections were identified and ranked, using the KSI metric. Notably, only two of the highest risk intersections were signalised, so sensing technology at intersections, which can impact on timing of signals, would only be appropriate at these intersections. Signalising the remaining intersections, and installing sensing technology such as appropriately designed and positioned inductive coil sensors, should be considered for the remaining intersections.

Keywords
Crash, Road Safety, Bicycle safety, Safe System approach, Intersections

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EXECUTIVE SUMMARY

Introduction

Cycling is being encouraged in Western Australia, both as a means of transport ('active transportation') and a recreational activity. In addition to the health benefits of cycling, it is an economical mode of transport, both for the individual and in terms of public infrastructure, and uses less space than motor vehicles (Pucher and Buehler, 2008). The anticipated increases in the number of cyclists and the cumulative distance travelled by them, plus the challenges of sensing bicycles as autonomous vehicles develop, may lead to increases in crashes and injuries involving cyclists unless changes to speed and infrastructure are made to reduce conflicts with other road users (Wegman et al., 2012).

Method

The aims of the study are to

a) review literature on technologies relating to the safety of bicycles when approaching intersections and,
b) to make recommendations with respect to the technologies' applicability and ability to reduce cyclist crashes at intersections in Perth metropolitan area.

The objectives of this part of the study were to:

1. Identify literature relating to bicycle sensing technology available on the market or being trialled within and outside of Australia;
2. Undertake a review of this literature
3. Review and analyse crash data relating to cyclists (compared to pedestrians, motor vehicle drivers and motorcyclists) over the last 10 years at intersections in metropolitan Perth.
4. Identify the intersections where cyclists are at most risk;
5. Make recommendations with respect to:
    - the application of the technology at these intersections (how difficult/easy would it be to implement, who are the stakeholders); and
    - the anticipated effectiveness of these treatments on crashes involving cyclists.

Review of literature

Multiple sources were used to undertake a review of literature up to the beginning of 2019. These included the websites of government, and road safety information organisations.

In addition, grey literature (primarily technical reports and conference papers) and published, peer-reviewed journal articles were sourced.

Crash analysis data requirements

Crash Data: Ten years of crash data (2008 to 2017) was extracted from the Integrated Road Information System (IRIS), for the Perth metropolitan area. Unit record information was required for each person involved in each crash. Crashes were flagged as involving cyclists, pedestrians, motorcyclists and motor vehicle drivers and occurring at intersections.

Analysis

Crash data were summarised according to road user type by demographic details (age and sex) of the road user, time and year of the crash and conditions at the crash.

High-risk intersections for cyclist crashes were identified using the KSI (killed or serious injury[1]) metric. The most recent five years of data (2013 to 2017) were used in this analysis. The metric represents the total number of KSI crashes plus the factored-up medical crashes (Main Roads, 2016). Intersections where any cyclist fatalities occurred over the total study period (2008 to 2017) were also identified.

Recommendations

The intersections with the highest cyclist KSI metric (eight intersections) were examined more closely for possible factors which might affect cyclists' safety and their risk of a crash, using Google Maps and Nearmap. Recommendations for improved safety were then made, based on these findings and the literature review.

[1] A killed or serious injury (KSI) crash is defined as a road crash that resulted in at least one person being either killed ("*killed immediately or died within 30 days of the day of the road crash as a result of the crash*") or seriously injured ("*admitted to hospital as a result of the road crash and who does not die from injuries sustained in the crash within 30 days of the crash*"). KSI crashes therefore include all fatal and hospitalisation crashes.

Literature Review

Bicycle sensing at intersections

Bicycle sensing can either be active or passive. Active detection requires the road user to activate the signal, usually a push button. Facilities need to be provided so on-road cyclists can safely access these. Supplementary signage should be provided to alert cyclists to the need to activate the signal.

Passive detection of cyclists at intersections may be through inductive loop detectors, video or other methods of detection. Inductive loop detectors are embedded in the road and connect to the traffic control system so that traffic phases adapt as vehicles arrive at an intersection. Inductive loop detectors need to be designed and positioned to maximise detection of bicycles, and ideally a bicycle detector symbol should be painted at the most sensitive place on the pavement. Video detection needs to be adapted for cyclists due to their small size compared to a motor car, but high speed compared to a pedestrian. Other methods of passive detection include using microwave radar and piezo-detectors.

Other forms of sensing technology are mounted on the bicycle or other vehicles. These tend to be part of systems, where a sensing device, using radar or LiDAR, sends messages to another unit or small computer to alert the driver or cyclist of the presence and speed of an approaching road user. More advanced systems included advanced driver assistance systems which detect vulnerable road users to alert drivers and avoid crashes, and cooperative systems (between vehicles, or vehicles and infrastructure).

The use of traffic signals to improve cyclist safety

The timing of traffic signals or coordination of several intersections can be adjusted to improve the traffic flow and safety of cyclists. Bicycle signal lanterns can also be used to reduce conflict between motor vehicles and bicycles. Demanding bicycle phases, such as auto-introduction or early starts may be used in areas with high cyclist volumes to improve safety.

Road features at or approaching intersections

Pavement markings to improve the safety of cyclists at intersections. These include bike boxes (or bicycle storage areas), hook turn storage boxes, advanced cycle lanes, merge and weave area redesign and other markings. These areas can be painted (‘Emerald Green’ in Australia) to increase their visibility.

Regulatory signage can be used to alert motorists to the presence of cyclists and to encourage them to yield to cyclists, particularly in high conflict areas. They can also be used to direct cyclists.

Other aspects of road design that can be used to improve cyclist safety are reducing the kerb radius (to slow down turning vehicles) and matching the width of a lane on the approach and through the intersections. Raised bicycle crossings and protected intersection designs may also improve safety.

Results

Descriptive statistics

A total of 3,640 people were involved in intersection crashes as cyclists in the 10 years between 2008 and 2017. This made up 0.97% of the 374,916 road users involved in crashes at intersections. Of these, 363,367 (96.92%) were in motor vehicles; 6,511 (1.74%) were on motorcycles; and 1,396 (0.37%) were pedestrians[2]. A much higher proportion of cyclists involved in crashes at intersections were male (n=2,148, 81.83%) than female (n=477, 18.17%). There were relatively high proportions of 30 to 44year old and 45 to 64 year cyclists involved in crashes at intersections (n=569, 21.68%; n=888, 33.83% respectively), compared to other road users.

A relatively high proportion of crashes involving cyclists occurred at three way intersections (n=331, 48.53%), compared to at roundabouts (n=150, 21.99%) and at four-way intersections (n=197, 28.89%).

The highest proportion of cyclist crashes at intersections were property damage only crashes (n=1,565, 47.37%). Those aged 65 years and older were involved in relatively higher proportions of fatal crashes (35.71%) and crashes leading to hospitalisation (6.14%), compared to other age groups.

The highest proportion of cyclist intersection crashes resulting in fatalities relative to less serious crashes occurred between 06h00 and 09h59 (n=5, 35.71%) and between 10h00 and 15h59 (n=6, 42.86%). In terms of absolute numbers, the highest number of fatalities for cycling intersection crashes occurred over the middle of the day (10h00 to 15h59, n=6), and highest

[2] Please note that data was missing for certain fields so the totals in the following tables may differ from those reported in this introduction.

number of hospitalisation and medical treatment crashes were between 06h00 and 09h59 (n=230 and n=453 respectively.)

High-risk intersections

Twenty-five intersections had a cyclist KSI metric of two or more (covering the period 2013 to 2017). Of these, eight had cyclist KSI metrics of above two. Of these eight highest risk intersections, only two were signalised. Five of these intersections were three way intersections, two were roundabouts and the remaining one was a four way intersection.

Fourteen cyclist fatalities occurred, one at each of 14 intersections between 2008 and 2017.

Recommendations for high risk intersections for cyclists

Recommendations are made for the eight intersections with a cyclist KSI metric of more than 2 between 2013 and 2017:

1. Welshpool Road East and Lesmurdie Road, Lesmurdie

This unsignalised three way intersection had the highest cyclist KSI metric in the Perth metropolitan area between 2013 and 2017. Measures should be taken to improve the visibility of cyclists. Signalisation of this intersection should be considered.

2. Marmion Avenue and Marina Boulevard, Clarkson

This three way intersection is unsignalised. It has the joint second highest KSI metric. The intersection requires improved footpaths on the west side of Marmion Avenue, and facilities to improve the safety of cyclists turning into Marina Boulevard: either signalisation with cyclist sensing or a grade separated path for cyclists.

3. Marmion Avenue, Anchorage Drive and Neerabup Road, Heathridge

This unsignalised high-speed roundabout has the joint second highest cyclist KSI metric in the Perth metropolitan area. Facilities such as active sensing and signalisation of crossings, and grade-separated paths for cyclists, would improve safety for cyclists (and pedestrians).

4. Ardross Street and Macrae Road, Applecross

This single lane roundabout, where two 50km/h roads intersect, is the next highest risk intersection for cyclists. Alerts to cyclists of the higher risk of this intersection (such as flashing signs activated by sensors) would assist in increasing the safety of this roundabout.

5. South Perth Esplanade and Mends Street, South Perth

This unsignalised, three way intersection is situated close to the South Perth foreshore (favoured by recreational cyclists) and the Mends Street Jetty (for the ferry). The intersection could be improved by a dedicated cycle path north of the Boulevard or by signalisation with a cyclist-specific phase, which could be activated by a passive sensor.

6. Wellington Street and George Street, Perth

This four way intersection is signalised, with inductive loops under the vehicle lanes. It is suggested that crossing facilities be provided for cyclists (and pedestrians) on the east/west side of the intersection.

7. South Street and Marine Terrace, South Fremantle

This site is a three way intersection which is not signalised. Facilities for cyclists and pedestrians have improved near this intersection in recent years, but better facilities should be provided for cyclists travelling straight along Marine Terrace, who come into conflict with turning motor vehicles.

8. Beeliar Drive and Wentworth Parade, Success

This four way intersection is signalised. It is located close to larger intersection. Both intersections are provided with a wide variety of facilities for motor vehicles and other road users. It is suggested that the two intersections' facilities be re-evaluated as a system, and changes made accordingly.

1 INTRODUCTION

Cycling is being encouraged in Western Australia, both as a means of transport ('active transportation) and a recreational activity. Cycling differs from motorised transport (including motor vehicles and motorcycles) in that it does not produce noise or air pollution. Cycling uses no motor fuel (for example, petrol or electric batteries) as the energy is produced directly by the cyclist's body, in the form of cardiovascular exercise[3] (Pucher and Buehler, 2008). As a result, cycling improves physical fitness and reduces respiratory disease at a population level (Stevenson et al., 2016). Research has found that the health benefits of cycling are largest in older people (Woodcock et al., 2014). In addition to the health benefits of cycling, it is an economical mode of transport, both for the individual and in terms of public infrastructure, and uses less space than motor vehicles (Pucher and Buehler, 2008).

The *Transport @ 3.5 million* Cycling Network Plan aims to develop routes to provide links between important locations in Perth (Department of Transport Western Australia and Main Roads Western Australia, 2016). The plan develops guidelines to develop Perth into a "*...great cycling city…*". The plan explicitly states that safety is a priority and describes the importance of routes incorporating shared paths and low speed (30km/h) roads.

Cyclists are a priority group identified in the Government of Western Australia's current road safety strategy *"Towards Zero"* (Office of Road Safety, 2009). Cyclists have been identified as a high priority group because they are vulnerable road users and are at higher risk of traffic crashes because they are unprotected by an external device that would *"absorb energy in a collision"* (pp. 1, Constant and Lagarde, 2010). The anticipated increases in the number of cyclists and the cumulative distance travelled by cyclists, plus the challenges of sensing bicycles as autonomous vehicles develop, may lead to increases in crashes and injuries involving cyclists unless changes to speed and infrastructure are made to reduce conflicts with other road users (Wegman et al., 2012). An additional challenge is the identification of bicycles (and pedestrians) by autonomous vehicles and the prioritisation of different road users by autonomous vehicles (Awad et al., 2018). Autonomous vehicles may be better able to negotiate quieter back streets, which tend to be used by cyclists to avoid motorised traffic, which could also increase risk to cyclists (Richards, 2018).

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[3] The exception to this is an electric bike. Electric bikes do, however, also allow cyclists to get cardiovascular exercise.

1.1 Aims

The aims of the study are to

a) review literature on technologies relating to the safety of bicycles when approaching intersections and,
b) to make recommendations with respect to the technologies' applicability and ability to reduce cyclist crashes at intersections in Perth metropolitan area.

The objectives of this part of the study were to:

1. Identify literature relating to bicycle sensing technology available on the market or being trialled within and outside of Australia;
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5. Make recommendations with respect to:

- the application of the technology at these intersections (how difficult/easy would it be to implement, who are the stakeholders); and
- the anticipated effectiveness of these treatments on crashes involving cyclists.

2 METHODS

2.1 Study Design

This study consisted of three parts:

1. A literature review;
2. A retrospective population-based crash data analysis of the Perth metropolitan area between 2008 and 2017, and selection of the highest risk intersections for cyclists;
3. Analysis of the highest risk intersection and provision of recommendations, based on the study findings, the literature and policy in other jurisdictions.

2.2 Review of literature

Multiple sources were used to undertake a review of literature up to early 2019. These included government documents, commercial organisations involved in developing sensing technology and intelligent road design, road safety information websites, grey literature (primarily technical reports and conference papers) and published, peer-reviewed journal articles.

Grey and peer-reviewed literature were obtained by searching Google Scholar, ResearchGate and various library databases. The search terms to be searched include the following: *"intelligent intersections", "automated intersections", "bicycle sensor", "bicycle detect*"*. Furthermore, publications of authors who had published widely in the area or had a significant publication relevant to the topic, and publications citing or cited by relevant articles were also assessed.

2.3 Crash analysis data requirements

2.3.1 Crash Data

Ten years of crash data was extracted from the Integrated Road Information System (IRIS), maintained by Main Road Western Australia. Crash data was used for the period 1 January 2008 to 31 December 2017 for the Perth metropolitan area. Unit record information was required for each person involved in each crash, including: accident number; accident type; sex, age; road user type (e.g., pedestrian, cyclist, motorcyclists, motor vehicle driver); date, time, and location details (including geocoding data) of the crash; all collected information on the nature and circumstance of the crash; and severity of the crash based on the most severe injury recorded for an involved road user. Crashes were flagged as involving cyclists, pedestrians, motorcyclists and motor vehicles: using the 'U-type' (vehicle type) variable for bicycles, motorcycles and motor vehicles, for example the U-type code for bicycles is 9, and the RUM code for pedestrian crashes (98 or 1 to 9); and occurring at intersections (using 'accident type' variable).

2.4 Statistical analysis

Crash data were summarised according to road user type by demographic details (age and sex) of the road user, time and year of the crash and conditions at the crash.

High-risk intersections for cyclist crashes were identified using the KSI (killed or serious injury[4]) metric. The KSI metric is a measure of crash density or collective risk, calculated over a five year period. The most recent five years of data (2013 to 2017) were used in this analysis. The metric represents the total number of KSI crashes plus the factored-up medical crashes (Main Roads, 2016). Intersections were ranked using the KSI metric for cyclist crashes only.

Equation 1: KSI metric

$$KSI\ metric_{(for\ cyclist\ crashes\ at\ an\ intersection)} = \sum_z \left[No.\ of\ KSI\ crashes_{(for\ cyclist\ crashes\ at\ the\ intersection)} + Severity\ Index \times No.\ of\ medical\ crashes_{(for\ cyclist\ crashes\ at\ the\ intersection)} \right]$$

where

$$Severity\ Index = \frac{Number\ of\ KSI\ crashes\ at\ intersections\ involving\ cyclists}{Number\ of\ Casualty\ crashes\ at\ intersections\ involving\ cyclists}$$

Intersections where any cyclist fatalities occurred over the whole study period (2008 to 2017) were also identified.

2.5 Recommendations

The intersections with the highest cyclist KSI metric were examined more closely for possible factors which might affect cyclists' safety and their risk of a crash. This part of the study included the eight intersections with a cyclist KSI metric of more than 2. Google Maps and Nearmap were used to examine these intersections. Data on the current safety provisions for cyclists (including any sensors) were acquired from Main Roads Western Australia. Recommendations were then made, based on these findings and the literature review.

[4] A killed or serious injury (KSI) crash is defined as a road crash that resulted in at least one person being either killed ("*killed immediately or died within 30 days of the day of the road crash as a result of the crash*") or seriously injured ("*admitted to hospital as a result of the road crash and who does not die from injuries sustained in the crash within 30 days of the crash*"). KSI crashes therefore include all fatal and hospitalisation crashes.

2.6 Ethics approval

Ethics approval was obtained from the Curtin Human Research Ethics Committee. Approval was granted on 8 August 2018. The approval number for the project is HRE2018-0513.

3 LITERATURE REVIEW

With an increase in interest in cycling, a range of solutions have been developed to improve the safety of cyclists including at intersections. These include sensing technologies, the use of traffic signal phases and timing, and geometric design of roads at and approaching intersections.

3.1 Bicycle sensing at intersections

Bicycle detection for cyclists aims to facilitate safe, comfortable and convenient intersection crossing for cyclists, while minimising delays. Bicycle detection devices may either 'call' a phase or prolong a phase to allow a cyclists travel through an intersection (Sundstrom and Nabors, 2014b).

There are two main types of calls to the traffic signal controller: locking calls and non-locking calls (Strachan and Van Den Dool, 2017). A *locking call* occurs when a vehicle or bicycle either travels over or remains on a detector for a pre-determined period of time: a demand is registered, which places a locking call for the phase. The demand is cancelled once the signal group has run in a nominated phase(s). Detection of additional vehicles may extend the phase. In contrast, a *non-locking call* is registered when a vehicle (or bicycle) is detected within the detection zone, but cancelled once the vehicle moves out of the zone. Locking calls are the preferred option for the detection of bicycles, as the smaller size of bicycles makes them more difficult to detect and it is easier for a bicycle to (inadvertently) leave the detection zone (Strachan and Van Den Dool, 2017).

3.1.1 Active detection

Active detection requires the road user to activate a signal, usually with a push button (Strachan and Van Den Dool, 2017). It is appropriate when cyclists use a footpath (Sundstrom and Nabors, 2014b), but problematic when they use the carriageway as it is difficult to access the push button designed for those using the footpath. The push button device should be located so that the cyclist is not required to dismount or be rerouted onto the footpath. Grab rails (handrails) or bicycle boxes[5] may be required to ensure that on-road cyclists can easily access the device safely (Van den Dool et al., 2014). Cyclists should be alerted to the need to activate the signal by supplementary signage (Sundstrom and Nabors, 2014b).

[5] Bicycle boxes are stop lines located at the head of traffic (that is, in front of stationary motorised vehicles). STANDARDS AUSTRALIA 2018. Manual of uniform traffic control devices part 9: bicycle facilities. Sydney, New South Wales: SAI Global Limited..

3.1.2 Passive detection

Certain intersections require road users to be passively detected in order to call a green light (Sundstrom and Nabors, 2014b). The detectors at these intersections should be designed to accommodate cyclists.

Inductive loop detectors

The most common detection technology is the (inductive) loop detector, which connects to the (traffic control) centralised computer system via the traffic signal controller to control traffic phases and optimise traffic flow[6]. Inductive loops consist of coiled wire, embedded in the road, and an electronics unit on the side of the road which creates a magnetic field around the loops. As a vehicle passes through the magnetic field, the resonant frequency of the loop increases, alerting the detector to the vehicle's presence (Hamilton et al., 2013). While it was designed for motor vehicles, it can be adapted to detect cyclists as well (Sundstrom and Nabors, 2014b).

The design of loop detectors needs to account for the amount of metal in bicycles. An inductive loop can detect any electrically conductive material (including aluminium); it does not need to be ferromagnetic (Shanteau, 2008). However, a bicycle with no metal (for example, a carbon fibre frame) cannot be detected.

The shape and position of the loop, the sensitivity setting and the position of the bicycle over the loop should be adjusted to maximise detection of bicycles (BikeWalk NC, 2018). For example, the quadrupole loop shape is more effective in detecting bicycles as the dipole loop shape may fail to detect bicycles in the centre of the loop (BikeWalk NC, 2018). Ideally there should be a bicycle detector symbol over to guide the cyclists where to stop, unless the loop is as wide as the lane (Shanteau, 2008, NZ Transport Agency, 2019). Ideally the loops should span the width of the lane (Espada, 2016).

Inductive loops can be located at the stop line (where there is a separate stop line for cyclists, or general lane) or before the stop line (allowing time for the green phase to commence) if

[6] In Western Australia, the traffic control system used is SCATS, the Sydney Coordinated Adaptive Traffic System BLAKE, P. 2013. Best practice study on the use of Intelligent Transport Systems (ITS) standards in traffic management. Sydney, Australia: Austraods., a responsive plan selective system HAMILTON, A., WATERSON, B., CHERRETT, T., ROBINSON, A. & SNELL, I. 2013. The evolution of urban traffic control: changing policy and technology. *Transportation Planning and Technology,* 36**,** 24-43..

cyclists are unlikely to turn off the road before the intersection (NZ Transport Agency, 2019). Inductive loops located at a general stop line need to be placed so that cyclists ride over them by default to ensure detection (NZ Transport Agency, 2019). Inductive loops located at a separate stop line for cyclists should be marked at the most sensitive areas with painted diamond symbols and cycle symbols on the pavement.

Inductive loops can also be used to activate a sign to show if a bicycle has been detected or to alert drivers of the presence of a cyclists in areas with poor visibility (including narrow bridges and tunnels) (NZ Transport Agency, 2019). Various types of active feedback devices have been trialled to cue cyclists that they have been detected (Okimoto, 2015, Boudart et al., 2015). The City of Portland, Oregon, trialled a traffic signal feedback device at an intersection with an inductive loop, a bicycle push button, a bicycle detector pavement marking, and a bicycle phase for northbound cyclists. A feedback device that displayed a small, blue light when a cyclist was correctly positioned over the loop detector (over the pavement marking) was mounted on the bicycle signal. This alerted the cyclist that their call for a green light had been registered. Video data was collected and analysed during daylight hours, before installation of the device, after installation of the device and after an instructional sign about the purpose of the device was installed. Following installation, more cyclists used the detection provided by the induction loop (with pavement marking) – an increase from 15% of cyclists before installation to 20% after installation and 49% after the information board was added (Boudart et al., 2017), representing a statistically significant increase (Okimoto, 2015). Further work is being done trialling the installation of a “WAIT” sign, surrounded an illuminated ring of tick marks when a cyclist is detected. The number of tick marks illuminated will indicate how long until the green light is due (Okimoto, 2015).

Piezo-detectors

Piezo-detectors are an additional option to detect bicycles (Taylor et al., 2017). These materials change electrical characteristics when deformed by pressure (that is, the bicycle creates the deformation). This can either cause a change in resistance (piezo-resistive sensor) or generate a charge (piezoelectric sensor). The former is more effective at detecting a bicycle at very low speeds (or when stationary) (Taylor et al., 2017).

Microwave radar

Radar (radio detection and ranging) operates on the radio-frequency spectrum to detect the position and movement of objects (Shladover et al., 2010, BikeWalk NC, 2018). Microwave radar not only detects the metal body of a car but also the water in a person's body, so it can be used to detect cyclists and pedestrians successfully (BikeWalk NC, 2018). Devices using this technology are mounted on a structure above the roadway, and aim to detect cyclists to modify signal timing, thereby giving cyclists more time to cross intersections (BikeWalk NC, 2018, Espada, 2016). However, microwave detection only registers a moving vehicle and has a limited range of view for detection (Austroads Inc., 2000). It does have the advantage of not requiring the bicycle to have sufficient metal, for example, to trigger an induction coil.

An example of a commercially available microwave sensor is the MS Sedco INTERSECTOR Microwave Motion and Presence Sensor. The INTERSECTOR is able to discriminate between bicyclists and motor vehicles arriving at intersections (and is able to detect if a vehicle has two, four or more wheels), and allows longer minimum green phases for cyclists to clear wide intersections. A 2010 analysis found that the INTERSECTOR produced approximately 30% false negatives and 37% false positive detections in a sample urban application (Shladover et al., 2010). However, it has subsequently been approved for use by the California Department of Transportation as of 2017 and has been piloted in Minnesota successfully. It can be retrofitted without digging up the road at an existing intersection, a big advantage over technologies such as inductive coils.

Video detection

Video-based detection of a bicycle is similar as video-based detection of a car or motorcycle; however, the smaller size of the bicycle means that the bicycle and cyclist occupy a smaller number of pixels (BikeWalk NC, 2018). Furthermore, cyclists can be more challenging to detect than pedestrians because of their higher speed and the changing appearance of bicycles on camera depending on the angle of viewing (Cho et al., 2010). Possible object detection methods include: Aggregated Channel Features (ACF - Dollár et al., 2014), Deformable Part Models (DPM - Felzenszwalb et al., 2010, Cho et al., 2010), Region-based Convolutional Neural Networks (R-CNN - Girshick et al., 2014, Foroozandeh Shahraki, 2017), Fast R-CNN (FFCN - 6) and SP-FRCN (FRCN with stereo proposal from the stixel world - Li et al., 2016). Li and colleagues (2016) showed that all solutions had high performance in the easy-to-detect subset of the cyclist dataset, with the SP-FTVN outperforming FRCN. However, for video where cyclists are at lower resolution and from various angles, performance was less consistent and further research into detection methods is required.

One video-based detection commercial option is Traficon's Video Image Processor (VIP) which interfaces with cameras that provide data on traffic (including queue length and vehicle speed) as well as information on the presence of vehicles approaching or stationery at intersections – it is distributed by ATC in Australia. It uses a highly tuned CMOS (complementary metal oxide semiconductor) sensor couple, with algorithms that detect a vehicle's presence within the sensor's field of vision.

3.2 Sensing technology on the bicycle and other motorised vehicles

Sensing technology can also be attached to the bicycle directly. This is not necessarily specific to intersections but senses other vehicles at all locations. These technologies have the advantage that cyclists are not relying on all cars having bicycle sensors (Jeon and Rajamani, 2016). However, they rely on the cyclist taking defensive action as the vehicle will not necessarily be aware of the bicycle.

3.2.1 Bicycle detection systems designed for intersections and to prevent crashes

An example of a bicycle detection system for intersections is the EMTRAC Bicycle-Detection System. This includes a mobile app which recognises when the cyclist is within a defined detection zone and notifies the traffic controller through the EMTRAC Priority Detector which have been installed at selected intersections or using the (US) NTCIP (National Transportation Communications for Intelligent Transportation System Protocol[7]). The data centre provides a transfer point for the detection data between the mobile phone and the Priority Detectors.

3.2.2 Radar

An example of this is the Garmin Varia Bike Radar System. This radar warning system has a range of 140 metres behind the bicycle and consists of two parts. The tail light attaches to the seat post, and the head unit attaches to the handle bars. The tail light brightens and flashes to

[7] NTCIP is a *"family of standards that provides both the rules for communicating (called protocols) and the vocabulary (called objects) necessary to allow electronic traffic control equipment from different manufacturers to operate with each other as a system."* NEMA, ITE & AASHTO. 2018. *NTCIP: About* [Online]. Available: https://www.ntcip.org/about/ [Accessed 19 December 2018].. In Australia, ITS (Intelligent Transport Systems) Australia is an organisation to support members (including Main Roads Western Australia as a corporate gold member) informed, represented and supported on intelligent transport systems. While NTCIP is used in some jurisdictions in Australia, Main Roads Western Australia uses the RTA suite of protocols (for field services such as variable message signs or VMS) and SCATS (Sydney Coordinated Adaptive Traffic System) to manage signal phases at traffic signals ROSS, C. 7 January 2019. *RE: RE: Query about NTCIP*. Type to WOOLLEY, M. & HOBDAY, M, BLAKE, P. 2013. Best practice study on the use of Intelligent Transport Systems (ITS) standards in traffic management. Sydney, Australia: Austraods., rather than a 'family' of integrated standards which work between computers and all ITS components, such as the traffic control system, traffic information, re-routing VMS and the public transport system .

notify the traffic that a cyclist is ahead. The head unit (or compatible cycling computer) can indicate the proximity of and the approach speed of these vehicles.

3.2.3 LiDAR

LiDAR is similar to radar but uses laser pulses (light amplification by simulated emission of radiation) instead of radar to measure the distance to a target. Wallich describes such a device that senses the distance of an approaching vehicle and displays this on a strip of coloured LEDs (2015). It does not, however, provide information about the speed of the approaching vehicles and requires the cyclists to look at the display (thus distracting them from the road). An example used PulsedLight's LiDAR-Lite, which has a range of 40 metres and an accuracy of 2.5cm to create a sensor attached to the back of a bicycle. This is wired to a series of LEDs attached to the handlebars, which indicate to the cyclist the approach of other vehicles. More recently, Blankenau and colleagues (2018) have developed a bicycle-mounted system using a LiDAR module, in combination with a camera, stepper motor and small computer to improve safety at the rear. The system was effective in measuring distance to a stationery vehicle, but less so with dynamic testing, where multiple vehicles were detected. The authors identified that the system required better computational power, and linking of the sensor and recognition software to reduce the false vehicle positives.

3.2.4 Combination systems

Jeon and Rajamani (2016) developed an instrumented bicycle to prevent side and rear crashes. To prevent side crashes, the authors designed a sonar sensor transmitter, attached to the side of the bicycle to detect and track cars turning, while cyclists were in a car's blind spot. This connects to a receiver (Hamilton et al., 2013), allowing for detection of both the distance and angular orientation of the tracked car (Jeon and Rajamani, 2016). To prevent rear end crashes, both lateral and longitudinal positions were tracked using a laser sensor (the PulsedLight LiDAR-Lite), with a longer range of 35m, on a rotating platform (Jeon and Rajamani, 2016). Rear targets are identified using a clustering methods.

An alternative low-cost collision warning system using laser, ultrasonic sensors and mass vibrators was described by Van Brummelen and colleagues (2016). The device, attached behind the seat, contains a LiDAR sensor which calculates both the distance and velocity of an approaching vehicle. The device also contains two ultrasonic sensors to sense direction. Using the collected data, a fuzzy rule-based inference system (FIS) calculates crash risk, sending a signal to the eccentric mass vibrators on the bicycles handlebars. This provides feedback through the vibration of the handlebars (haptic feedback), thus avoiding the cyclist from taking their eyes from the road (van Brummelen et al., 2016). The system also signals an LED vehicle warning light, to alert approaching vehicles to the proximity of the cyclist. A trial of the device on seven cyclists showed that they intuitively understood the haptic feedback and benefitted from minimal training on the system (van Brummelen et al., 2016).

3.2.5 RFID (Radio frequency identification)

An example of this is the Cycle Alert. This is an HGV (heavy goods vehicle, that is, a truck of 3,500kg or more) blind spot detection system. The system consists of three parts:

a) A cycle tag: mounted on the bicycle helmet or person. It transmits when moving so that vehicles' sensors can detect it, and stops when stationary for a while.
b) A side unit: a wireless unit attached to the vehicle side, with a battery life of up to 10 years.
c) A cab unit: which receives the signal strength from the cycle tag via the side unit. If the signal strength reaches a threshold, an audible alert sounds and the cab unit displays the cycle position (front, left, right or back) on a small screen.

3.3 Advanced driver assistance systems on motor vehicles which can detect bicycles

Advanced driver assistance systems (ADAS) can be useful in prevent or mitigating intersection crashes between cars and vulnerable road users, including cyclists. Habibovic and Davidsson (2011) found that reduced visibility, low awareness and poor comprehension were the most common contributing factors to crashes with vulnerable road users. They therefore suggested that an ADAS should assist drivers to observe vulnerable road users and assist their ability to predict future potential incidents. Applicable technologies include the collision warning system, or collision avoidance system (using radar or LiDAR sensors), with auto brake and cyclist and pedestrian detection. The technology requires that enough of the cyclist's body or bicycle be visible to the camera.

3.4 Cooperative systems

Cooperative systems are those where a vehicle communicates wirelessly with one of the following: i) another vehicle (V2V – vehicle-to-vehicle); ii) with road infrastructure (V2I – vehicle-to-infrastructure); and iii) from road infrastructure (I2V – infrastructure-to-vehicle) (CVIS, 2010). The systems use wireless communications, for example, the mobile phone network so that vehicles (fitted with on-board units, routers and antennae) can communicate with each other or suitable equipped road infrastructure. Applications can be designed for intersections to alert drivers of cyclists and pedestrians when turning, and to maintain local traffic control (CVIS, 2010). Cooperative systems are still being developed and deployed. One issue with their widespread use is the number of stakeholders who need to be involved, ranging from vehicle manufacturers to software develops to local and national road authorities, and private road users. Ultimately, vehicle-to-everything (V2X) technology needs to be developed, where cyclists are better detected by motor vehicles. Progress is being made, for example by Volvo using a bicycle app, Strava, sensors on the motor vehicle, a cloud-based network and a connected bicycle helmet.

3.5 The use of traffic signals to improve cyclist safety

3.5.1 Optimising signal timing and sequencing for bicycles

Traffic signals are used at intersections improve the flow of traffic, reduce congestion and meet the needs of all road users for safe intersection use (Sundstrom and Nabors, 2014c). By either adjusting timing at each intersection, or by adjusting the coordination of signals at a series of intersections, these goals can be achieved (Sundstrom and Nabors, 2014c). This includes traffic signals to direct the use of pedestrian crossings. Cyclists may use pedestrian signals (generally activated by a push button) and pedestrian crossings, or they may share the road with motorised vehicles and so use traffic signals geared towards those road users.

Additional signal timing can be introduced, particularly at high-speed locations and where crossing distances are long (Sundstrom and Nabors, 2014c). Possibilities at individual intersections include adjustments to:

a) Minimum green intervals[8]: a recommended minimum of six seconds for bicycles (Strachan and Van Den Dool, 2017);
b) Intergreen phases[9]: VicRoads state that bicycles in an exclusive bicycle phase should have three seconds of yellow time and an all red time based on intersection geometry and an assumed design speed of 20km/h (Vicroads, 2016).

Another possibility is coordinating signals to create a ‘green wave’ (consisting of a minimum of three intersections), where vehicles get a green indication and do not have to break or stop if

[8] The minimum green intervals is the first timed part of the green intervals, based on the number of vehicles queuing and if pedestrians are crossing in this phase.
[9] The intergreen phase is the period of red and yellow indication.

vehicles are travelling at a specific speed (informed by bicycle speeds). This has the additional benefit of reduced motor vehicle speeds (Strachan and Van Den Dool, 2017) and less noise pollution and energy use (from reduced breaking and acceleration).

Alternatively, the use of separate bicycle lanterns can reduce conflicts between bicycles and motor vehicles. Bicycle lanterns (also known as bicycle signals or signal heads) contain a bicycle image which may consist of two phases (red and green) or three phases (red, yellow and green) in Australia (Strachan and Van Den Dool, 2017). The lanterns should be located so they are clearly visible to arriving bicycles, with appropriate detection, and have adequate clearance so bicycles have time to clear an intersection before conflicting movements receive a green signal. When bicycles and pedestrians share the same crossing location, the crossings can be separated (but remain adjacent), which allows bicycles a longer green period (and shorter flashing red period), as their faster speed (than pedestrians) can be taken into account (Van den Dool et al., 2014).

Other options could include the use of 'priority movement repetition' (multiple phases for cyclists within the traffic signal cycle) and for bicycle signal phases to operate twice during a signal cycle (known as double cycling - Van den Dool et al., 2014).

3.5.2 Demanding bicycle phases

This section is largely based on the Australian Bicycle Council report *Traffic Signal Features for Bicycles* (Strachan and Van Den Dool, 2017).

A permanent demand request ensures that a traffic signal phase will operate even if the detector is not activated (a *permanent demand phase*). This is always applied for the main traffic phase but may be applied to create a permanent demand for bicycle phases, in certain situations. These include peak hours, along high cycle volume routes, where several bicycles use the phase each time (Strachan and Van Den Dool, 2017).

Auto-introduction is used for pedestrians at the start of a signal phase if pedestrian volume is high and traffic phases are long. Strachen and Van den Dool suggest that this could be used at high bicycle volume segregated areas (Strachan and Van Den Dool, 2017).

'Stretch Walks' can be nominated: unused time from proceeding phases are used in a pedestrian walk phase. Similarly *'Stretch Bicycle'* phases could be considered (Strachan and Van Den Dool, 2017).

Early starts, also known as a 'leading bicycle interval' (LBI), give cyclists a head start by allowing a few seconds of green time before motor vehicle get a green light, allowing cyclists to change lanes or turn without conflict (Strachan and Van Den Dool, 2017, Sundstrom and Nabors, 2014a).

Advanced detection, used in some European countries, uses inductive loop detectors in advance of an intersection, rather than at the stop line, to created demand for a bicycle phase (Strachan and Van Den Dool, 2017). This reduces the delay for bicycles arriving at intersections.

Co-Introduction is where demand from either a pedestrian or cyclist can generate demand for either (Strachan and Van Den Dool, 2017). It is appropriate with pedestrians' and cyclists' travel paths and their traffic signals are adjacent to each other, and where cyclists are not travelling at high speeds (Sundstrom and Nabors, 2014a).

3.6 Road features at or approaching intersections

3.6.1 Pavement markings

Many treatments include the painting of pavements in combination with other features. Lanes, sections of lanes or crossover areas may be painted, usually blue or green. The Australian Standards stipulate that the colour of pavement be 'Emerald Green' (G13 - Standards Australia, 2018). The use of colour is optional and should be limited to areas of potential conflict such as bike boxes and entry to roundabouts (Standards Australia, 2018). While some international studies have not shown any beneficial effect from coloured markings, others have found that driver behaviour improves (for example, Hunter et al., 2000, Warner et al., 2017) while other have found safety benefits of coloured cycle facilities (Turner et al., 2011).

Bike Boxes (advanced stop lines, ASL)

Bicycle storage areas (also known as bike boxes or advanced stop lines) are stop lines located at the head of traffic (in front of motorised vehicles), that is, in advance of motorised vehicle stop lines (Standards Australia, 2018, Mead et al., 2014). This gives priority to cyclists over motor vehicles at intersections, and reduces the conflict between cyclists and motor vehicles

(Mead et al., 2014). They may work in conjunction with a bicycle lane on the left side of the main vehicle lane. Bike boxes are often painted (Turner et al., 2011). The Australian Standard specifies 'Emerald Green' as the appropriate colour and that the bicycle symbol should be marked in the bike box (Standards Australia, 2018). Dill et al. found that bike boxes affected behaviours that could improve safety (Dill et al., 2012). A study in Adelaide and Christchurch found that coloured bike boxes were more effective in reducing crashes than unpainted bike boxes (Turner et al., 2011).

Hook turn storage box

This is a form of safe storage area facilitating a 'hook turn'[10], an alternative way for cyclists to turn right at signalised intersections which is suitable if a cyclist has to cross multiple lanes to turn (Standards Australia, 2018). It includes a small bicycle symbol and a 'hook' pavement arrow to show cyclists where to stop and wait for the turn.

Advanced cycle lanes

Advanced cycle lanes, or bicycle stop lines are bicycle lanes which extend beyond the vehicular stop line by a minimum of 2m. This gives the cyclists a head start at the beginning of the green signal phase if the line is clear of cross traffic or a marked pedestrian crossing (Standards Australia, 2018).

Merge and weave area redesign

Merge and weave areas can be developed where there is a bicycle lane with a merging segment, because motorist have to cross the bicycle lane to enter the left turning lane (in Australia) (Mead et al., 2014). The merging segment may be unpainted, or painted green or blue, and be with or without signage. Research has shown that this is associated with significantly lower yielding to cyclists by motorists, but reduced motor vehicle/bicycle conflicts (Mead et al., 2014).

Other intersection pavement markings

Other options include: dotted bike lane extensions; elephants' feet markings (parallel to crossing markings to indicate that cyclists do not need to dismount to cross roads); bicycle symbols (for example, to indicate the beginning and end of bike lanes, with the words "LANE" or "LANE END"); the no-bicycles pavement symbol; and sharrows (shared road markings).

[10] Hook turns: A cyclist turning right at an intersection should move into the leftmost lane. On the green light, the cyclist moves forward, staying on the far left until reaching the far side of the intersection. When the traffic signal of the road into which the cyclist is turning changes to green, the cyclist turns right into the road.

3.6.2 Regulatory signage

These include signs instructing motorists to yield to cyclists and may include pictograms. The Australian Standards (Standards Australia, 2018) state the sign number, size, design, wording and correct usage of all signs relating to cyclists. The preferred practices of Main Roads Western Australia regarding bicycle directional signs [for cyclists on principal shared paths (PSPs)] are set out in Part C: Technical Guideline - Bicycle Directional Signs (Main Roads Western Australia, 2016). Further signage relating to the use of bicycle lanes is provided in the Main Roads Exclusive Lane Series: MR-RE (Category 1.1.7) (Main Roads Western Australia, 2018) and the Cycling Series: MR-GC (Main Roads Western Australia, 2019a), including instructions for motorists and cyclists to *"share the road"*.

A simulator study in Oregon, USA, of 28 drivers found that bicycle yielding signs improved the visual attention of drivers (Warner et al., 2017). A study in Portland, Oregon, used blue pavement marking and signage (consisting of the wording "YIELD TO BIKES" with a yield sign, an arrow and bicycle on a road, p. 110) in conflict areas near intersections (Hunter et al., 2000). This consisted of 10 bicycle-motor vehicle weaving areas near intersections. Video footage of the cyclists before and after the treatment (20 hours for each location) was analysed. The footage included 846 cyclists in the before period, and 1,021 cyclists in the after period. The observations found that more cyclists followed the recommended marked path and more motorists yielded to cyclists in the after period. However, significantly fewer cyclists turned their head to the rear to scan for approaching motor vehicles after the pavement was painted blue. In addition, significantly fewer cyclists used hand signals to indicate their movement through the conflict area. The rate of conflicts per 100 entering bicyclists decreased from 0.95 in the before period to 0.59 in the after period.

A before and after study in Denmark examined the effects of blue painted cycle crossings at intersections (Jensen, 2008). The study, which controlled for long-term crash trends, found that a single blue painted crossing reduced the number of all intersection crashes by 10%, while two and four blue painted crossings increased the number of intersection crashes by 23% and 60% respectively. These effects were larger for injury crashes. The researchers noted that intersections with one blue crossing tended to have fewer arms (and lower traffic volumes) than intersections with two or four blue bike crossings. The researchers suggest that a single blue cycle crossing provides a 'warning message' to drivers, making them more aware of cyclists. This warning message was less effective when there are more blue crossings, with motorists focusing less on traffic signals as there are more rear-end crashes and crashes resulting from running red lights.

3.6.3 Reduced kerb radius

Reducing the size of the kerb radius may slow down turning vehicles, allowing more time for motorists to see cyclists and avoid a collision, and reducing the severity of a crash if it does occur (Warner et al., 2017). Warner and colleagues (2017) in a driving simulator study, found a 4% reduction in mean vehicle velocity during high to moderate risk incidents (defined as a time-to-collision of 1.5 seconds or less).

3.6.4 Width of lane

Turner and colleagues, in a before and after study of 102 signalised intersections in Christchurch and Adelaide, found that the width of the kerbside approach lane or total width of the cycle lane and adjacent traffic lane had a larger impact on safety than where the cycle lane was marked in the space (2011). If a bicycle lane is used at intersections, its width should match the bicycle lane width on the approach to the intersection (Aumann and Whitehead, 2017).

3.6.5 Raised bicycle crossings

Gårder and colleagues (1998) did a before and after study of 44 intersections examining the effect of raised bicycle crossings (4 to 12 cm above road level) compared to other intersection types, adjusting for traffic volume. The study showed that while there was an increase of 8% in crash frequency, the bicycle volume through the intersections increased by 50%. The authors concluded that this might equate to a safety improvement following the intervention.

3.6.6 Protected ('Dutch-style') intersection design

Protected intersections include a range of geometric and traffic engineering treatments to improve the visibility and safety of cyclists (Warner et al., 2017). Warner and colleagues found that while protected intersections with islands positively affected driver behaviour, the addition of green painted pavement markings had no additional effect on driver behaviour (2017).

3.6.7 Roundabouts

The requirements to improve safety at roundabouts differ to those of other intersection types. Some research has shown poorer safety records for cyclists at multi-lane roundabouts compared to signalised intersections, while studies specifically examining the installation of single-lane roundabouts did not find an increase in cyclist crashes (Brude, 2000). In these cases, safety can be improved by including a separated bicycle lane – that is, a lane separated by a kerb or other physical barrier (Schoon and van Minnen, 1994, Reynolds et al., 2009) or a grade-separated path (Daniels et al., 2009).

4 RESULTS

4.1 Overview

A total of 3,640 people were involved in intersection crashes as cyclists in the 10 years between 2008 and 2017. This made up 0.97% of the 374,916 road users involved in crashes at intersections. A total of 363,367 (96.92%) were in motor vehicles; 6,511 (1.74%) were on motorcycles; and 1,396 (0.37%) were pedestrians[11].

4.2 Descriptive statistics

A much higher proportion of cyclists involved in crashes at intersections were male (2,148, 81.83%) than female (n=477, 18.17% - Table 1). In contrast, the proportions of female motorcyclists were considerably lower (656, 10.79%), while the proportion of female pedestrians were more similar (533, 44.23%) to the proportion of male pedestrians.

There were relatively high proportions of 30 to 44year old and 45 to 64 year cyclists involved in crashes at intersections (n=569, 21.68%; n=888, 33.83% respectively), compared to other road users. This is in contrast with pedestrians, where a relatively large proportion are children (n=183, 19.06% of all pedestrians involved in intersection crashes) and older adults (65 years and older; n=112, 11.67%). Relatively high proportions of motorcyclists involved in crashes fell into the 30 to 44 year, and 45 to 64 year old age groups (n=1,625, 30.84%; n=1,510, 28.66% respectively).

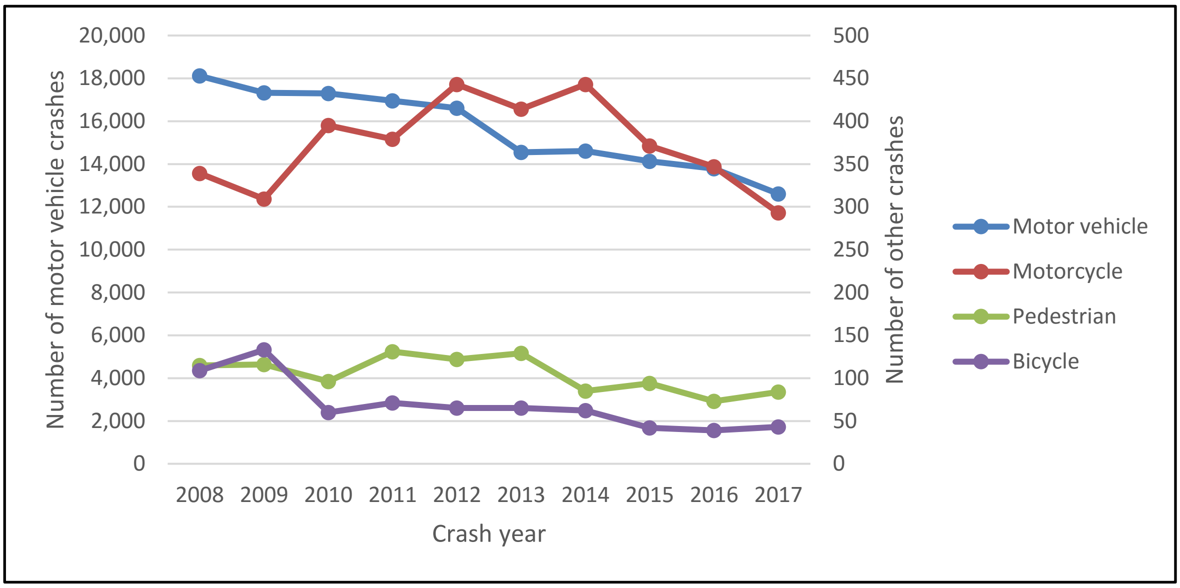
Table 1: Intersection crashes by road user, gender and age, in Perth metropolitan area from 2008 to 2017 (at person level)

Road user type	**Motor vehicle**		**Motorcycle**		**Pedestrian**		**Bicycle**	
Gender	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Female	150,332	45.37	656	10.79	533	44.23	477	18.17
Male	180,982	54.63	5,424	89.21	672	55.77	2,148	81.83
Total	331,314	100	6,080	100	1205	100	2,625	100
Age category								
Child	23,603	8.80	389	7.38	183	19.06	248	9.45
18 to 29 years	87,208	32.50	1,622	30.78	272	28.33	569	21.68
30 to 44 years	72,725	27.10	1,625	30.84	190	19.79	888	33.83
45 to 64 years	64,870	24.18	1,510	28.66	203	21.15	790	30.10
65 years and older	19,905	7.42	123	2.33	112	11.67	130	4.95
Total	268,311	100	5,269	100	960	100	2,625	100

[11] Please note that data was missing for certain fields so the totals in the following tables may differ from those reported in this introduction.

The number of crashes at intersections has varied by road user over the 10 years between 2008 and 2017 (Figure 1). Cyclist intersection crashes peaked in 2009 (133 crashes) before gradually dropping. Intersection crashes involving motor vehicles and motorcycles have declined in the last two years to levels below 2008 and 2009. Pedestrian intersection crashes have remained fairly steady at relatively low levels compared to those of other road users, but were at their highest levels in 2013 (129 crashes).

Figure 1: Intersection crashes by road user and year, in Perth metropolitan areas from 2008 to 2017 (at crash level)



A relatively high proportion of crashes involving cyclists occurred at three way intersections (n=331, 48.53%), compared to 21.99% (n=150) at roundabouts and 28.89% (n=197) at four-way intersections (Table 2). Among motor vehicle only crashes, a higher proportion occurred at four way intersections (n=72,793, 47.04). Among motor cycle crashes and crashes involving pedestrians, higher proportions occurred at three way intersections (n=1,732, 46.95%; n=491, 48.00% of the respective road user crashes). Most intersection crashes involving bicycles occurred on straight sections of road (n=481, 85.28%). Most crashes involving motor vehicles occurred on straight sections (n=114,641, 79.03%) while relatively more crashes involving motorcycles occurred on a curve (n=954, 27.69% of all road user crashes). Relatively more intersection crashes involving cyclists, pedestrians and motorcyclists occurred on the crest of a hill compared to motor vehicles (cyclists: crest of hill: n=12, 2.71% and slope: n=129, 23.98% compared to motor vehicles: crest of hill: n=2,510, 1.76% and slope: n=22,169, 15.56%). Similar proportions of crashes involving cyclists and motor vehicles only occurred at dawn and dusk (cyclists: n=46, 6.86% and motor vehicles only: n=8,998, 5.94%), while relatively few occurred during the night-time hours. A relatively high proportion of cyclist and pedestrian crashes occurred in speed zones up to 40km/h (n=12, 4.29% and n=30, 5.61% respectively) and these proportion dropped relative to the proportion of motor vehicle only crashes as the speed limit increased.

Table 2: Intersection crashes by road user and road characteristics, in Perth metropolitan area from 2008 to 2017 (at crash level)

Road user	**Motor vehicle**		**Motorcycle**		**Pedestrian**		**Bicycle**	
Road feature	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Four-way intersection	72,793	47.04	1,177	31.84	433	42.33	197	28.89
Three way intersection	63,907	41.30	1,732	46.85	491	48.00	331	48.53
Intersection >3 legs	234	0.15	4	0.11	1	0.10	0	0.00
Roundabout	16,038	10.36	754	20.39	82	8.02	150	21.99
Median opening	1,426	0.92	22	0.60	1	0.10	2	0.29
Other	346	0.22	8	0.22	15	1.47	2	0.29
Road alignment								
Curve	30,428	20.97	954	27.69	136	14.53	83	14.72
Straight	114,641	79.03	2,491	72.31	800	85.47	481	85.28
Road grade								
Level	117,809	82.68	2,666	78.69	700	82.55	397	73.79
Crest of hill	2,510	1.76	77	2.27	23	2.71	12	2.23
Slope	22,169	15.56	645	19.04	125	14.74	129	23.98
Light conditions								
Daylight	118,355	78.19	2,625	73.14	702	70.13	530	78.99
Dawn or dusk	8,998	5.94	227	6.32	40	4.00	46	6.86
Dark street, lights on	23,660	15.63	729	20.31	244	24.38	93	13.86
Dark streets, other	346	0.23	8	0.22	15	1.50	2	0.30
Speed limit								
Up to 40km/h	912	1.82	20	1.09	30	5.61	12	4.29
>40km/h to 60km/h	48,233	96.13	1,289	70.32	426	79.63	266	95.00
>60km/h to 90km/h	240	0.48	495	27.00	79	14.77	1	0.36
>90km/h	790	1.57	29	1.58	0	0.00	1	0.36

Overall, males involved in cyclist intersection crashes make up 81.83% (2,148) of the 2,625 persons involved in these crashes with gender recorded (Table 3). Most of those involved in these crashes were between 30 and 64 years (n=1,678, 63.92%). However, there were lower proportions of females between 30 and 44 years (n=151, 31.65% compared to males: n=737, 34.31%) and between 45 and 64 years (n=126, 26.41% compared to males: n=664, 30.91%). Although the number of child female cyclists involved in intersection crashes was much lower than males (49 compared to 199 respectively), child female cyclists made up a higher proportion of all female cyclists in intersection crashes than child male cyclists (10.27% and 7.58% respectively). The gender differences were reversed at cyclist intersection crashes among those aged 65 years or more (males: n=116, 5.40%; females: n=14, 2.94%).

Table 3: Intersection crashes involving cyclists by gender and age, in Perth metropolitan area from 2008 to 2017 (at person level)

Age category	**Child**		**18 to 29 years**		**30 to 44 years**		**45 to 64 years**		**65 years+**		**Total**	
Gender	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Female	49	19.76	137	24.08	151	17.00	126	15.95	14	10.77	477	18.17
Male	199	80.24	432	75.92	737	83.00	664	84.05	116	89.23	2,148	81.83
Total	248	100	569	100	888	100	790	100	130	100	2,625	100

The highest proportion of cyclist crashes at intersections were property damage only crashes (n=1,565, 47.37% - Table 4). A higher proportion of this intersection crash type involved males (83.83%) than females (16.17%). In contrast, female cyclists made up relatively higher proportions of intersection crashes resulting in hospitalisation (n=125, 20.29% of all female cyclist crashes compared to males: n=491, 79.71% of all male cyclist crashes) and medical treatment (n=218, 19.66% compared to males: n=891, 80.34%). Children were involved in relatively higher proportions of those intersection cyclist crashes leading to hospitalisations (child hospitalisations: 11.05%, compared to the overall proportion of children in cyclist crashes: 9.67%). Those aged 65 years and older were involved in relatively higher proportions of fatal crashes (35.71%) and crashes leading to hospitalisation (6.14%), compared to other age groups.

Table 4: Intersection crashes involving cyclists by crash severity, gender and age, in Perth metropolitan area from 2008 to 2017 (at person level)

Crash severity	Fatal		Hospital		Medical treatment		Property damage		Total	
	n	%	n		n	%	n	%	n	%
Gender										
Female	1	7.14	125	20.29	218	19.66	253	16.17	597	18.07
Male	13	92.86	491	79.71	891	80.34	1312	83.83	2,707	81.93
Total	14	100	616	100	1,109	100	1565	100	3,304	100
Age category										
Child	1	7.14	63	11.05	98	9.81	94	8.84	256	9.67
18 to 29 years	3	21.43	118	20.70	204	20.42	250	23.52	575	21.73
30 to 44 years	4	28.57	175	30.70	346	34.63	368	34.62	893	33.75
45 to 64 years	1	7.14	179	31.40	299	29.93	313	29.44	792	29.93
65 years and older	5	35.71	35	6.14	52	5.21	38	3.57	130	4.91
Total	14	100	570	100	999	100	1,063	100	2,646	100

The highest number of intersection crashes involving cyclists occurred between Tuesday and Thursday (Tuesday: 644, Wednesday: 642, Thursday: 614 – Table 5). The highest number of fatal intersection crashes involving cyclists occurred on Tuesdays, Fridays and Saturdays (n=3 on each day). The highest proportion of intersection crashes involving a hospitalisation occurred on a Wednesday (n=107, 17.86%), while the highest proportion of medical treatment crashes were on a Tuesday (n=200, 17.87%).

The highest number of intersection crashes involving cyclists occurred in February and March (n=345 and n=363 respectively). The highest proportion of these crashes involving hospitalisations occurred in March (n=64, 10.68%) and April (n=63, 10.52%). The highest proportion of these crashes requiring medical treatment were in March (n=123, 10.99%).

The highest proportion of cyclist intersection crashes resulting in fatalities and hospitalisations relative to less serious crashes occurred between midnight and 05:59 (n=1, 7.14%) and between 10:00 and 15:59 (n=6, 42.86%). In terms of absolute numbers, the highest number of fatalities for cycling intersection crashes occurred over the middle of the day (10:00 to 15:59, n=6), and highest number of hospitalisation and medical treatment crashes were between 06:00 and 09:59 (n=230 and n=453 respectively.)

Table 5: Intersection crashes involving cyclists by crash severity and time of crash, in Perth metropolitan area from 2008 to 2017 (at crash level)

Crash severity	**Fatal**		**Hospital**		**Medical treatment**		**Property damage**		**Total**	
Day of week	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**	**n**	**%**
Sunday	2	14.29	60	10.02	81	7.24	121	6.61	264	7.41
Monday	1	7.14	89	14.86	154	13.76	258	14.10	502	14.09
Tuesday	3	21.43	102	17.03	200	17.87	339	18.52	644	18.08
Wednesday	0	0.00	107	17.86	197	17.61	338	18.47	642	18.02
Thursday	2	14.29	94	15.69	186	16.62	332	18.14	614	17.24
Friday	3	21.43	84	14.02	179	16.00	246	13.44	512	14.37
Saturday	3	21.43	63	10.52	122	10.90	196	10.71	384	10.78
Month of crash										
January	0	0.00	33	5.51	83	7.42	128	6.99	244	6.85
February	2	14.29	57	9.52	111	9.92	175	9.56	345	9.69
March	3	21.43	64	10.68	123	10.99	173	9.45	363	10.19
April	1	7.14	63	10.52	87	7.77	148	8.09	299	8.39
May	2	14.29	55	9.18	102	9.12	186	10.16	345	9.69
June	1	7.14	58	9.68	98	8.76	147	8.03	304	8.53
July	1	7.14	44	7.35	80	7.15	108	5.90	233	6.54
August	1	7.14	42	7.01	76	6.79	130	7.10	249	6.99
September	0	0.00	38	6.34	89	7.95	161	8.80	288	8.09
October	1	7.14	48	8.01	87	7.77	177	9.67	313	8.79
November	1	7.14	51	8.51	91	8.13	150	8.20	293	8.23
December	1	7.14	46	7.68	92	8.22	147	8.03	286	8.03
Hour of crash										
Midnight to 5h59	1	7.14	24	4.10	30	2.71	49	2.69	104	2.95
6h00 to 9h59	5	35.71	230	39.25	453	40.96	646	35.49	1334	37.83
10h00 to 15h59	6	42.86	127	21.67	243	21.97	473	25.99	849	24.08
16h00 to 19h59	1	7.14	182	31.06	329	29.75	599	32.91	1111	31.51
20h00 to 23h59	1	7.14	23	3.92	51	4.61	53	2.91	128	3.63

4.3 High-risk intersections

High risk intersections were identified in two ways: intersections with the highest cyclist KSI between 2013 and 2017, and intersections with a cyclist fatality between 2007 and 2013.

4.3.1 Cyclist KSI metric

The cyclist crash risk of Perth metropolitan intersections was ranked by the cyclist KSI metric (calculating using the years 2013 to 2017). This included eight intersections with a cyclist KSI of above two, and 25 intersections with a KSI of 2 and above (Table 6). The intersection with the highest cyclist KSI was at Welshpool Road East and Lesmurdie road, Lesmurdie (cyclist KSI=4.88).

Only two of the top eight intersections were signalised, while six of the remaining 16 high risk intersections were signalised; a total of eight of the 24 intersections with a cyclist KSI of two and above were signalised. Of the top eight high risk intersections, five were three way intersections, two were roundabouts and the remaining one was a four way intersection. Of the 16 intersections with a cyclist KSI of two, six were four way intersections, six were three way intersections, three were roundabouts and one was an interchange.

Maps 1 and 2 indicate to location of the intersections with cyclist KSIs of 2 or more.

Table 6: Intersections with cyclist crashes ranked by cyclist KSI metric, in Perth metropolitan area from 2013 to 2017

Rank	Int No[1]	Fatal[2]	Hosp[3]	Med[4]	KSI metric	Intersection name	Suburb	Intersection type	Sig[5]
1	45290	0	3	5	4.88	Welshpool Rd East & Lesmurdie Rd	Lesmurdie	3+ way intersection	No
2	60447	0	3	1	3.75	Marmion Av & Marina Bvd	Clarkson	3+ way intersection	No
2	60456	0	3	1	3.75	Marmion Av & Anchorage Dr & Neerabup Rd	Heathridge	Roundabout	No
4	47253	0	2	3	3.2	Ardross St & Macrae Rd	Applecross	Roundabout	No
4	54469	0	2	3	3.2	South Perth Esp & Mends St	South Perth	3 way intersection	No
6	46983	0	3	0	3	Stock Rd & Cawston Rd	Attadale	3 way intersection	No
6	50569	0	2	2	3	Wellington St 124 0116 - H016 & Wellington St & George St	Perth	4+ way intersection	Yes
8	43139	0	2	1	2.67	South St & Marine Tce	South Fremantle	3+ way intersection	No
8	70729	0	2	1	2.67	Beeliar Dr & Wentworth Prd	Success	3+ way intersection	Yes
9	47170	0	2	0	2	Preston Point Rd & Durdham Cr	Bicton	3+ way intersection	No
9	55863	0	2	0	2	Duke St & Sackville Tce	Scarborough	Roundabout	No
9	39628	0	2	0	2	Welshpool Rd East & Roe Hwy Nth Bound Off & On	Welshpool	Interchange	Yes
9	4336	0	2	0	2	Wanneroo Rd & Newcastle St & Charles St On - Mitchell Fwy Sth Bound & Mitchell Fwy Nth Bound	West Perth	4+ way intersection	Yes
9	54437	0	2	0	2	Mill Point Rd & Queen St	South Perth	3 way intersection	No
9	46642	0	2	0	2	Clarinda Av & Hennessy Av	Orelia	3 way intersection	No
9	51213	0	2	0	2	Jersey St & Salvado Rd West	Wembley	4 way intersection	Yes
9	55009	0	2	0	2	Beach Rd & Davallia Rd & Okely Rd (North)	Carine	4+ way intersection	Yes
9	43729	0	2	0	2	Nicholson Rd & Yale Rd & Garden St	Thornlie	Roundabout	No
9	47720	0	2	0	2	The Strand & Nisbet Rd	Applecross	3 way intersection	No
9	55559	0	2	0	2	Karrinyup - Morley Hwy & Grand Prom	Dianella	4+ way intersection	Yes
9	50862	0	2	0	2	Bourke St & Loftus St	North Perth	4 way intersection	Yes
9	68322	0	2	0	2	Canning Hwy & Andrew Rd	East Fremantle	4+ way intersection	No
9	48922	0	2	0	2	Wellington St & Palmerston St	Mosman Park	Roundabout	No
9	47306	0	2	0	2	Burke Dr & Carroll Dr	Attadale	3 way intersection	No

[1]`Int No: Intersection number [2]Fatal: Fatal crashes [3]Hosp: Crashes with injury resulting in hospitalisation
[4]Med: Crashes with injury requiring medical treatment but not hospitalisation [5]Sig: Signalised intersection

Map 1: Map of Perth metropolitan area indicating intersections with a cyclist KSI metric of 2 or more (red circle[12]) between 2013 and 2017.

[12] Larger red circles indicate intersections with higher cyclist KSI metrics

Map 2: Map of inner Perth metropolitan area indicating intersections with a cyclist KSI metric of 2 or more (red circle[12]) between 2013 and 2017

4.3.2 Intersections with bicycle fatalities

Intersection where any cyclist fatality had occurred between 2008 and 2017 were also identified (14 fatalities at 14 different intersections -Table 7). Notably one intersection with a fatal cycle crash (Eric Street and Broome Street, Cottesloe) also had one hospitalisation cycle crash and three medical treatment crashes over the study period. A further three intersections had also had either one hospitalisation cycle crash (North Beach Road and Mews Entrance, Gwelup), or one medical treatment cyclist crash (Dorothy Street and Hicks Street, Gosnells, and Princess Road and Broadway, Nedlands). (Note that because these intersections included crashes which occurred between 2008 and 2017, none of these crashes were included in Table 6 as having the highest cyclist KSI metrics, which by definition only used the latter five years of data, 2013 to 2017).

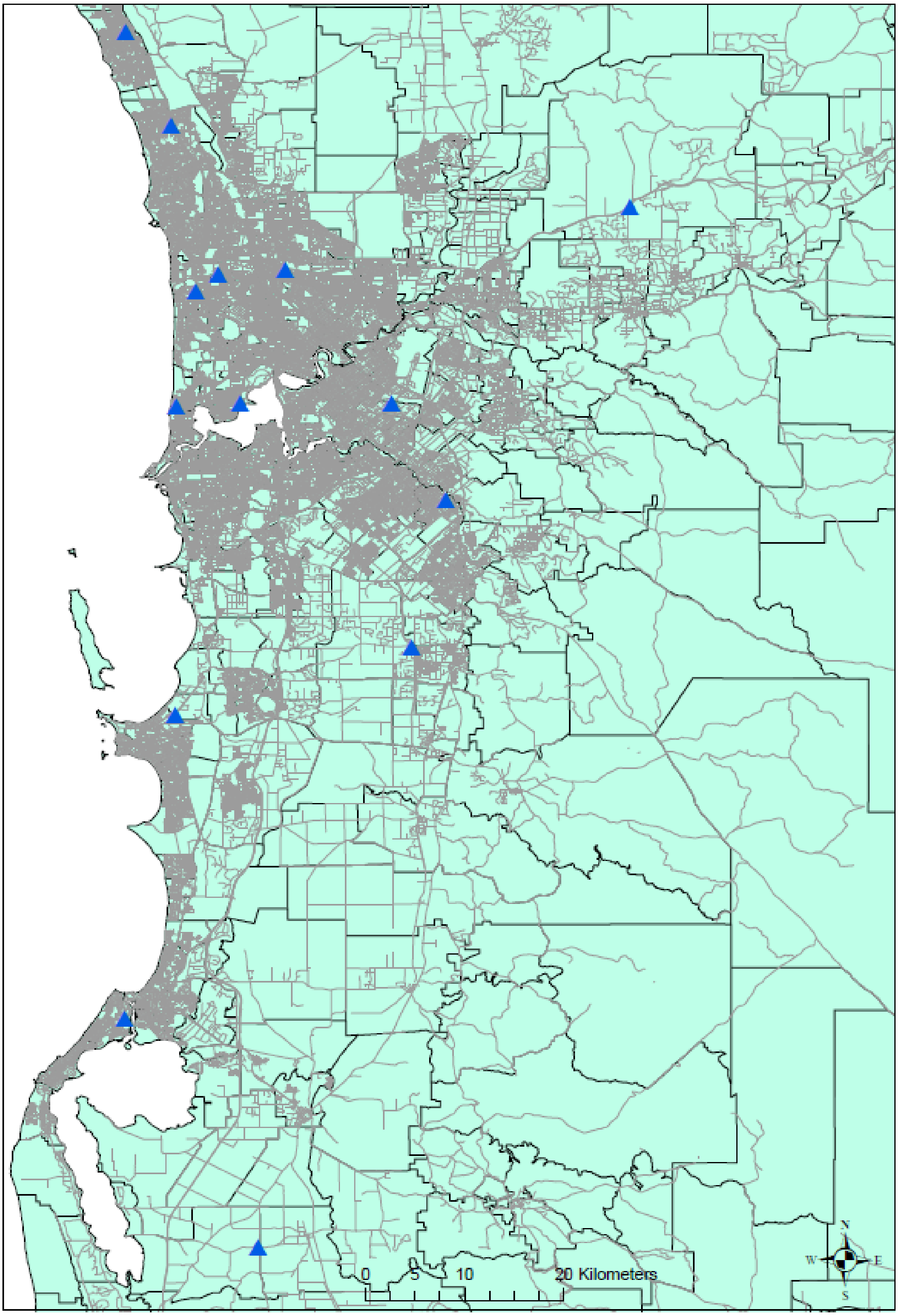
All intersections with a cyclist fatality are displayed in Map 3, with a blue triangle indicating any intersection with cyclist fatality between 2008 and 2017.

Table 7: Intersections with cyclist fatalities, in Perth metropolitan area from 2013 to 2017

Intersection Number	Intersection name	Suburb	Intersection type[1]	Signalised	Speed limit	Crash Year
82300	Reid Hwy West Bnd Off And On Ramps & Mirrabooka Av	Mirrabooka	Interchange	Yes	80	2008
50141	Princess Rd & Broadway[2]	Nedlands	Roundabout	No	50	2009
172320	North Beach Rd & Mews Ent[2]	Gwelup	3+ way intersection	No	60	2010
57496	Westview St (North) & Crabbe Pl	Karrinyup	3 way intersection	No	50	2012
42737	Eric St & Broome St[3]	Cottesloe	Roundabout	No	50	2013
39613	Kewdale Rd & Dowd St West	Welshpool	4+ way intersection	Yes	70	2014
138650	Tonkin Hwy & Thomas Rd	Oakford	3+ way intersection	Yes	80	2014
76013	Moore Dr & Christchurch Tce	Currambine	3+ way intersection	No	80	2014
4143	Patterson Rd & Ennis Av	East Rockingham	3+ way intersection	Yes	80	2014
11621	Toodyay Rd & Reen Rd	Gidgegannup	3 way intersection	No	100	2015
34975	Mclarty Rd & Old Coast Rd & Leeward Ent	Halls Head	Roundabout	No	60	2016
43847	Dorothy St & Hicks St[2]	Gosnells	Roundabout	No	60	2016
155433	Connolly Dr & Swavesey Av	Butler	3+ way intersection	No	50	2016
33590	Fishermans Rd & Mayfield Rd	Coolup	3 way intersection	No	110	2017

[1]3+ and 4+ intersections indicate more complex intersections of their respective type [2]Intersection also had either a hospitalisation or medical treatment crash [3]Intersection also one hospitalisation crash and three medical treatment crashes

Map 3: Map of Perth metropolitan area indicating intersections with any cyclist fatalities (blue triangle) between 2008 and 2017



5 RECOMMENDATIONS FOR INDIVIDUAL HIGH-RISK INTERSECTIONS

The following section examines each of the eight intersections with cyclist KSI metrics of more than two and makes recommendations for methods to improve their safety, based on the literature review[13].

5.1 Welshpool Road East and Lesmurdie Road, Lesmurdie

This intersection (Figure 2) has the highest cyclist KSI metric (2013 to 2017) of all intersections in Perth, with three crashes involving hospitalisations and five crashes resulting in medical treatment. It is not signalised and is classified as a three way intersection. However, it is relatively complex, with Welshpool Road (speed limit 70km/h) having turning lanes in both directions, and the two carriageways being separated by concrete medians. Lesmurdie Road has a speed limit of 60km/h. Welshpool Road East has an average traffic volume of 12,424 per day (Monday to Sunday, 2015/16) near the intersection (Main Roads Western Australia, 2019b).

There are no footpaths or other facilities for pedestrians or cyclists who choose to stay off the carriageways. There is a cycle lane on the approach to the intersection which is unpainted and has a separate crossing across Lesmurdie Road. The cycling lane originates partway along the approaching turning lane, creating problems for cyclists who prefer to cycle on the far left of the carriageway because of the high speeds of motor vehicles on Welshpool Road East. Cyclists are then required to cross left-turning traffic in order to enter the emerging cycle lane. A further issue is the left turn out of Lesmurdie Road into Welshpool Road East. Motorists may turn out of this 60km/h road into the higher speed Welshpool Road East quickly, which may lead to them focusing on vehicles coming from the westerly direction, and not 'seeing' cyclists ('look but did not see').

This intersection is used by cyclists on training rides in the Perth Hills, with seven of the eight hospitalisation and medical crashes occurring on a Saturday or Sunday morning between 6:30am and 8:30am. (Notably the other medical crash also occurred early in the morning, but on a Wednesday. The property damage only crashes at this intersection mainly occurred on a Saturday and all occurred between 6am and 8:30am). Cyclists on training rides tend to be more experienced with good observational skills and knowledge of motor traffic.

[13] All images in the following section were sourced from either NearMap or Google Maps.

Suggestions for this road include painting the cycle lanes emerald green to improve visibility and reduce any confusion about the function of this lane to motorists. The cycle lane could be extended to the start of the turning lane on the east travelling carriageway of Welshpool Road East, but since cyclists prefer to stay in the leftmost lane, this may not be helpful. Additional measures should be taken to improve the visibility of cyclists, particularly when vehicles are turning left out of Lesmurdie road, where the trees may partially obscure any cyclists on Welshpool Road East immediately east of the intersection.

Given the high number of cyclist crashes at this intersection, signalisation may be considered. (Passive) sensing of cyclists who are continuing straight through the intersection should be considered so that motorists turning off Welshpool Road East can be alerted to their presence.

Figure 2: Welshpool Road and Lesmurdie Road, Lesmurdie

5.2 Marmion Avenue and Marina Boulevard, Clarkson

This intersection (Figure 3) has the second highest cyclist KSI (2013 to 2017) of all intersections in Perth, with three crashes involving hospitalisations and one crash resulting in medical treatment. All the crashes (including two property damage only crashes) occurred between 6am and 7am, or between 5:30pm and 8pm at night. It is not signalised and is classified as a three way intersection. However, north- and southbound carriageways of Marmion Avenue (speed limit 80km/h) are separated by a grass median strip, creating a more complex intersection. In addition, each of these carriageways consists of at least two lanes [plus turning lanes into Marina Boulevard (speed limit 60km/h) from both directions.] Marmion Avenue has an average of 27, 859 vehicles per day (Monday to Sunday, 2018/9) (Main Roads Western Australia, 2019b).

There are limited footpaths on Marmion Road, making it difficult for cyclists to travel safely outside the northbound carriageway. Good quality shared or cyclist footpaths should be provided on the west side of Marmion Avenue, especially as it approaches from the south.
Unlike the previous intersection, the bicycle lane between the turning lane for Marmion Avenue northbound and the other two lanes commences together with the turning lane. This would mean that cyclists travelling on the far left of the carriageway (as preferred by many cyclists[14]) would have to cross turning traffic if continuing straight along Marmion Avenue. One option to improve safety is to provide a flashing light (triggered by an active sensor when as a cyclist approaches) to warn motorists that the cyclist will be crossing the turning lane, just prior to it turning into Marina Boulevard.

Further, there are no ‘on-road’ cyclist facilities on the Marmion Avenue southbound. As a result, cyclists turning into Marina Boulevard, travelling on the left side of the carriageway, have to cross several lanes of traffic to turn. To improve the safety of cyclist turning here, a grade separated path or signalisation (with cyclist sensing) is required.

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[14] In some states in the US, cyclists are legally required to use the far right of the lane (equivalent to the far left in Australia) unless it is unsafe to do so. The New Zealand Road rules state that cyclists should keep "'as near as practicable' to the left side of the roadway'. These rules may have affected cycling culture in Australia. Further, given the much slower speeds of cyclists (and their physical vulnerability), it makes sense to cyclists to stay on the far left (in Australia) of the lane. The practice of ‘taking the lane’ or ‘claiming the lane’ (riding in the centre of a lane) is less popular.

Figure 3: Marmion Avenue and Marina Boulevard, Clarkson

5.3 Marmion Avenue, Anchorage Drive and Neerabup Road, Heathridge

This intersection (Figure 4) has the joint 2nd highest cyclist KSI (2013 to 2017) of all intersections in Perth, with three crashes involving hospitalisations and one crash resulting in medical treatment. All these crashes, and the single property damage only crash, occurred during day-time hours. The intersection is a double-lane roundabout (Figure 4), with the approach roads having speed limits of 60km/h (Anchorage Road), 70km/h (Neerabup Road) and 80km/h (Marmion Avenue), so it would be considered a high-speed roundabout. At the entry to the roundabout, Anchorage Road has an average of 15,001 motor vehicles per day (Monday to Sunday, 2017/18) (Main Roads Western Australia, 2019b).

The approach and departure roads of Anchorage Road contain bicycle lanes that terminate shortly before the roundabout carriageway. The roundabout has separate (off-road) shared unpainted concrete pathways (for pedestrians and cyclists). One of these commences on the approach to the roundabout, so that on-road cyclists have the option of exiting the road prior the roundabout. Each leg has a crossing for pedestrians, but no facilities such as a push button-activated signalisation or zebra crossing, despite the high speeds of the approach roads. The entry and exit lanes of each leg are separated by a raised median, which creates a refuge island for pedestrians and cyclist not using the carriageway. Given the double-lanes in the roundabouts and high speeds on the approach, grade separation of the cyclist route would be the ideal method to improve the safety of this intersection for cyclists[15]. Signalisation of the crossings for pedestrians and cyclists not using the carriageway, with active sensing (a push button) would improve safety.

[15] Grade separation (underpasses or overpasses) is safer than an on-road cycle lane, with lower delay and inconvenience to cyclists than traditional off-road paths. DANIELS, S., BRIJS, T., NUYTS, E. & WETS, G. 2009. Injury crashes with bicyclists at roundabouts: influence of some location characteristics and the design of cycle facilities. *J Safety Res,* 40**,** 141-8, CAMPBELL, D., JURISICH, I. & DUNN, R. 2012. Improved multi-lane roundabout designs for urban areas. Auckland: NZ Transport Agency.

Figure 4: Marmion Avenue, Anchorage Drive and Neerabup Road, Heathridge

5.4 Ardross Street and Macrae Road, Applecross

This intersection, a single-lane roundabout without signalisation, was the location of two crashes resulting in hospitalisation and three crashes resulting in medical treatment. Both Ardross Street and Macrae Road have speed limits of 50km/hour. There is no traffic volumes available close to this intersection. The diameter of the central island is approximately six metres, which is smaller than is optimal (Aumann, 2015). Although there are refuge islands within the entry/exits of each leg, there are no formal crossing points for pedestrians and cyclist not travelling within the carriageway. However, footpaths are absent or partially absent on two of the approaches to the roundabout (see Figure 5).

The north and south sides of Ardross road have a black bicycle symbol within a yellow diamond on the pavement approaching the intersection (a warning sign indicating that Ardross Road will be crossing a road encouraging the presence of bicycles). Bicycle symbols are present in both directions on the pavement of Macrae Road (north-east side of the roundabout). Macrae Road is parallel to Canning Highway. The bicycle symbols on the pavement of Macrae Road function to encourage cyclists to use this route, rather than the much busier Canning Highway. As a result, the volume of cyclists is probably unexpectedly high in this suburban street. The recorded crashes all occurred between 7am and 8:30am, and 5pm and 7pm, throughout the week, possibility indicating that these cyclists are commuters.

The signage for motorists is good. Flashing signage alerting cyclists that this is a higher risk intersection may be effective in increasing their focus on their safety. These signs could be activated by passive sensing of approaching cyclists.

Figure 5: Ardross Street and MacRae Road, Applecross

5.5 South Perth Esplanade and Mends Street, South Perth

This intersection had with two crashes involving hospitalisations and three crashes resulting in medical treatment between 2013 and 2017. These crashes, and the five additional property only crashes, occurred throughout the week, between 8am and 7pm. It is classified as an unsignalised three way intersection, with both approach roads having a speed limit of 50km/h (see Figure 6). The South Perth Esplanade has speed humps starting approximately 25m to 30m from the entry point to each side of the intersection. On the opposite site to the terminating Mends street is a narrow section of the South Perth Foreshore, with two car parks close by, entrance to shared paths adjacent to the Swan River (so recreational cyclists may enter via this intersection) and the Mends Street Jetty, the embarkation point for the ferry to Elizabeth Quay.

Although there are no motor vehicle traffic volumes available near the intersection, there were 1,127 cyclists[16] travelling on the cycle paths on the nearby non-motorised section of the South Perth Esplanade (Main Roads Western Australia, 2019b). The intersection could be signalised using a separate phase for cyclists at high cyclist volume times. These could be detected by passive sensing. Further, a dedicated cycle path on the north side of South Perth Esplanade would improve the safety of this area used by many residents of Perth for recreational cycling.

[16] Bicycle counts for the South Perth Esplanade (Sir James Mitchell Park) were obtained from the Main Roads Western Australia Trafficmap online tool.

Figure 6: South Perth Esplanade and Mends Street, South Perth

5.6 Wellington Street and George Street, Perth

This intersection, located in the Perth CBD, was the site for two crashes involving hospitalisation and two crashes involving medical treatment (Figure 8). These crashes, and the three property only crashes, all occur between Monday to Thursday between 7am and 8am, and 4pm and 5:30pm, suggesting commuter cyclists were involved. This is a complex four way intersection, involving multiple lanes (including turning lanes) in each carriageway, freeway overpasses, reducing visibility of the east side of the intersection, and high volumes of traffic. Wellington Street, west of the intersection, has a steep upward slope towards the west, slowing cyclists down, which makes them vulnerable when sharing the road with motorists. In contrast, cyclists travelling east downhill on Wellington Street tend to travel at relatively high speeds, reducing their ability to respond rapidly to hazards.

This is the only intersection of the top eight high-risk cyclist intersections which is signalised. The vehicle lanes contain inductive loops. George Street has a painted shared two-lane footpath on one side of the road (including both cyclist and pedestrian symbols), and a divided median in Wellington Street which allows vulnerable road users to cross it in multiple stages. The pedestrian/cyclist crossings are signalised. Both roads have speed limits of 50km/h. The east/west side of the intersection has no facilities for pedestrian/cyclist crossings. It is recommended that the facilities on this side of the intersection are improved, through the provision of footpaths and crossing points.

Figure 7: Wellington Street and George Street, Perth

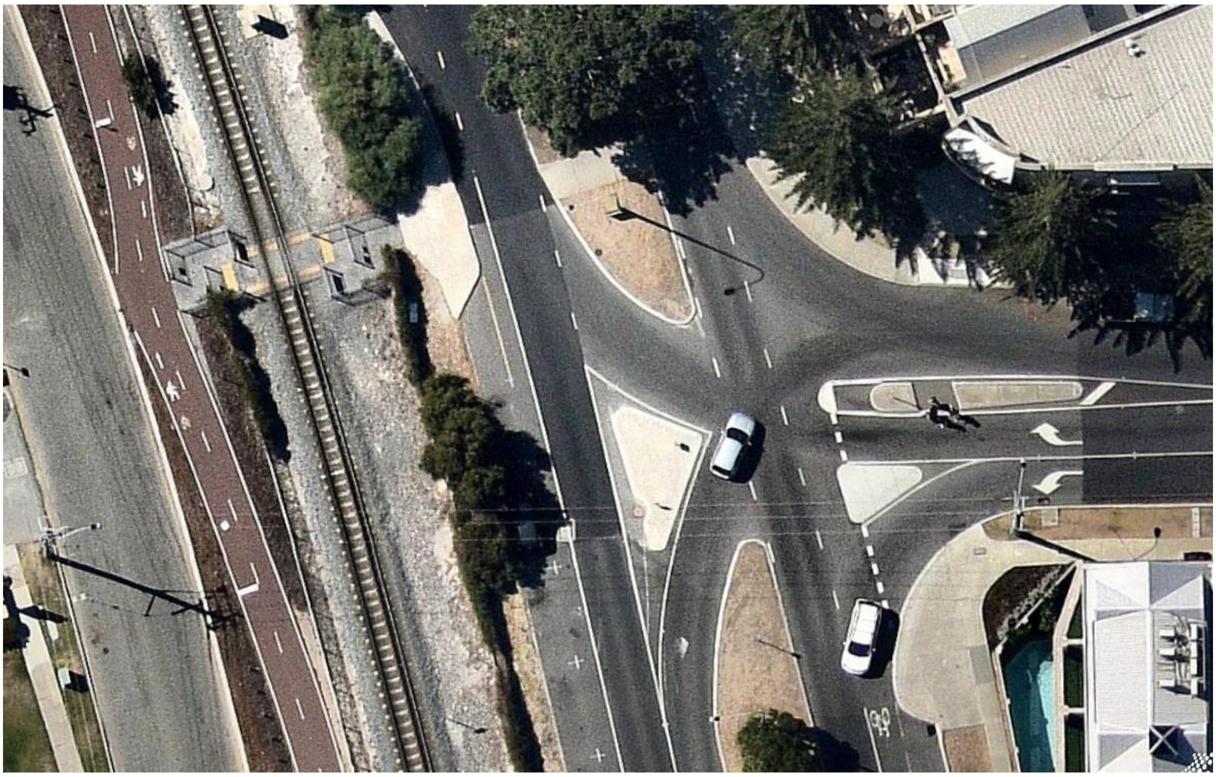
5.7 South Street and Marine Terrace, South Fremantle

This intersection was the location of two crashes involving hospitalisation and one crash involving medical treatment between 2013 and 2017 (Figure 9). This is a complex three way intersection, and Marine Terrace just south of South Street has a traffic volume of 10,118 per day (Monday to Sunday, 2018/19) (Main Roads Western Australia, 2019b). Marine Terrace (speed limit 50km/h) has a grass median strip and bicycle lanes which appear to be adjacent to street parking. Marine Terrace is also next to a train line. Mews Road is located parallel to Marine Terrace, on the other side of the train line, and can be accessed via a controlled pedestrian crossing (closed when a train is nearby.)

Between the train line and Mews Road is a two-lane red asphalt shared path (with pedestrian and bicycle symbols) which was installed with markings in approximately October 2015. All three crashes occurred before this date.

There is a marked cycle lane which continues directly across the turning lane from South Street into Marine Terrace. Painting of this crossover section and signalisation of this crossing at high cyclist traffic volumes times may also assist at improving the safety of the intersection. Volumes of cyclist traffic could be ascertained from bicycle sensing technology to inform signalisation timing.

Figure 8: South Street and Marine Terrace, South Fremantle



5.8 Beeliar Drive and Wentworth Parade, Success

This intersection was the site for two crashes involving hospitalisation and one crash involving medical treatment (Figure 10). This is a signalised complex three way intersection. Both roads have raised medians separating the two carriageways.

Green painted bicycle lanes have been installed on the approach to the intersection which terminate adjacent to the motor vehicle stop line on all three legs of the intersection. These share inductive loops with the lanes to their left. Cycle lanes on Beeliar Drive westbound and Wentworth Parade northbound are situated between turning lanes and straight travel lanes. Since cyclists tend to prefer to travel as far to the left as possible, these may not be used optimally. Pedestrian (and cyclist) crossings (zebra crossings for turning lanes and signalised crossings at the major road crossings) are provided. These connect to the shared two-lane red asphalt paths (with pedestrian and cyclist symbols). The colour was added to these shared paths in mid-2014. Only one crash has occurred since this change. No footpaths are provided on the northern side of the intersection (along the north side of Beeliar Drive).

Notably, there is another even more complex intersection immediately east (Beeliar Drive and Midegooroo Avenue). Both intersections have multiple facilities. It is recommended that the two intersections be analysed as a system, rather than individually, to assess how best to improve cyclist (and other vulnerable road user) safety.

Figure 9: Beeliar Drive and Wentworth Parade, Success

5.9 Conclusion

This report examined methods of improving safety for cyclists at intersections, with particular emphasis on sensing technologies. The characteristics of cyclist crashes at intersections were examined and high risk intersections were identified and ranked, according to the number of crashes with fatal, hospitalisation and medical treatment injuries resulting from these crashes.

Notably, only two of the highest risk intersections were signalised, so sensing technology at intersections, which can impact on timing of signals, would only be appropriate at these intersections. Signalising of the remaining intersections, and installing sensing technology such as appropriately designed and positioned inductive coil sensing, should be considered for the remaining intersections. Signal timing should be adapted to take into account the needs of on-road and off-road cyclists. Additional cyclist facilities, such as off-road cycling paths and well-placed cyclist lanes, should also be considered. The intersections identified consist of a mixture of both state and local roads, so both Main Roads Western Australia and the relevant local government authorities need to be consulted when considering any changes.

The future of cyclist safety may lie in communication between vehicles and infrastructure (connected vehicles). However, currently connected and autonomous motor vehicles struggle to detect bicycles (Richards, 2018). Technologies which can be attached to bicycles are developing to enable sensing of vehicles. These may provide options for individual cyclists who travel during higher volume times, such as commuter cyclists, to improve their safety. However, long-term solutions are developing which enable the detection of bicycles by motor vehicles and communication between these vehicle types and road infrastructure (V2X or vehicle-to everything).

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