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Safer cycling and the urban road environment: A case control study

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ABSTRACT

This study aimed to identify features of the road environment that increased the risk of on-road bicycle crashes in Perth, Australia between 2014-2017. This case-control study used a combination of an in-depth crash study and naturalistic study to compare the road environment characteristics of 100 case (crash) sites and 300 control sites where no crash occurred using conditional logistic regression. For intersection sites, roundabouts (adjusted OR: 2.98, 95% CI: 1.18, 7.56) and traffic lights (adjusted OR: 3.86, 95% CI 1.29, 11.63) significantly increased the risk of a bicycle crash, compared to priority control/uncontrolled intersections. For midblock (non-intersection) sites, roads with an incline (upwards/downwards) significantly increased the risk of a crash (adjusted OR: 3.39, 95% CI: 1.02, 11.22), compared to level roads. This study highlighted the risk of roundabouts, traffic lights and roads with an incline for bicycle crashes. Treatments that reduce vehicle speeds and encourage cyclists to claim the lane at roundabouts, as well as careful road design and road maintenance at traffic lights, may reduce the risk of crashes for cyclists. While it is impossible to remove hills and slopes from the topography, it is possible to select routes to target for bicycle infrastructure which are predominantly level.

1. Introduction

Cycling is being promoted as a method of active transport in Europe, North America and Australia in response to dealing with rising congestion, and to encourage more physical activity in increasingly sedentary populations. While several OECD countries have seen decreasing numbers of bicycle crashes, this decrease is lower than for crashes involving other road users (OECD/ International Transport Forum, 2013). In addition, countries like Australia and New Zealand have seen increases in cyclist injuries over the last decade (Henley and Harrison, 2012; OECD/ International Transport Forum, 2013; Henley and Harrison, 2015). This trend suggests that cycling safety improvements are lagging behind the improvements occurring in other areas of road safety. Previous research has reported that most bicycle crashes occur in urban areas (Watson and Cameron, 2006) with crashes involving motor vehicles resulting in the most serious injuries among cyclists (Haileyesus et al., 2007; Chong et al., 2010) however, this may be due to the under-reporting of bicycle crashes to Police which do not involve a motor vehicle (Shinar et al., 2018). Other studies using hospitalisation data in Australia have found that injuries associated with on-road single-vehicle bicycle crashes were as severe as multi-vehicle crashes (Boufous et al., 2013).

There has been a plethora of research examining crashes involving cyclists, however many studies have focused on behavioural characteristics. The majority of studies examining road environment-related risk factors for bicycle crashes have been conducted in Europe which has quite different cycling road environments to Australia or North America. Many cities in Europe, where cyclists are fully separated from traffic in higher speed environments and lower speed roads function as shared spaces designed with cyclists in mind, have much higher cycling participation rates than Australia. However, the United States is more similar to Australia in that there is a dominant 'car culture' with minimal infrastructure provided for cyclists. Perth has a warm climate and generally flat topography, making commuter and recreational cycling popular. It has a network of off-road bicycle paths (shared with pedestrians) located largely on commuter routes however on-road riding (in traffic) is still common due to issues with the connectivity of bicycle paths.

Previous research has consistently reported that a greater number of bicycle crashes occur at intersections (Kaplan and Prato, 2013; Poulos et al., 2015). However there has been mixed findings regarding injurious bicycle crashes at an intersection in the presence of signalisation

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(traffic lights). One Canadian study found nearly five times greater risk for an injury at signalised intersections compared to non-signalised intersections (Strauss et al., 2014), while other research reported higher crash risk at priority control intersections (Harris et al., 2013; Rash-ha Wahi et al., 2018). A large study in Belgium, using a decade of crash data found that the crash risk for cyclists at roundabouts was even worse than at signalised intersections (Daniels et al., 2009). A Danish study also reported an increase of 65% and 40% in the number of crashes and cyclist injuries respectively, after intersections were converted to roundabouts (Jensen, 2013). While roundabouts may be associated with increased vehicular safety (Jurewicz et al., 2015), the opposite seems to be true for cyclists. Consistent research also suggests that the presence of on-road cycling facilities (bicycle lanes), whilst not as safe as dedicated off-road facilities, may in fact be a compromise to the riskier option of shared off-road facilities (De Rome et al., 2014; Poulos et al., 2015). Bicycle lanes in combination with roundabouts however are associated with a significant increase in bicycle crashes, with additional conflict points and reduced visibility created by the roundabout design (Jensen, 2013; Mulvaney et al., 2015). A recent Cochrane systematic review of road environment factors and cycling injuries concluded that there is a lack of high-quality evidence upon which to draw inferences on the effect of infrastructure on bicycle crashes (Mulvaney et al., 2015). Further investigation is required into the association between intersection control type and bicycle crashes in countries outside of Europe. Importantly, other road environment elements need to be examined in order to provide insights for designers and engineers who are increasingly having to deliver road environments that accommodate, safely, vulnerable roads users such as cyclists. Therefore the aim of this study was to identify features of the road environment that increased the risk of an on-road bicycle crash in Perth, Western Australia (WA).

2. Materials and methods

2.1. Study design

A case-control study was undertaken which examined the association between road environemnt factors at sites where cyclists had experienced a bicycle crash resulting in hospitalisation, compared to sites where cyclists had not been involved in a bicycle crash, in Perth, Western Australia.

Ethics approval was obtained from Curtin University and the four recruiting hospitals. All participants provided written consent.

2.2. Case participant recruitment

Recruitment for case participants occurred between September 2014 and December 2016. Eligible cyclists were identified through the trauma registries of four public hospitals and were recruited consecutively while in hospital or shortly after discharge. Inclusion criteria stipulated: involvement in an on-road cycling crash (on a road shared with motor vehicles, not an off-road path/ sidewalk or dirt track), involvement in a single cyclist, cyclist/cyclist or cyclist/ motor vehicle crash; admitted to hospital for at least 24 h and aged 18 years or older. Exclusion criteria included: involvement in an off-road crash, severely disabled in the crash, unable to recall the crash events and non-English speaking.

In total, 624 patients were reviewed for eligibility with 439 being excluded due to: involvement in an off-road crash (n = 189), admitted to hospital for less than 24 h (n = 120), crash occurred outside the Greater Perth area (n = 56), unable to recall the events of the crash (n = 28), aged less than 18 years (n = 23), killed or severely disabled in the crash (n = 16) and non-English speaking (n = 7). An additional 58 patients were unable to be contacted. Of the remaining 127 cyclists, 100 agreed to participate (78.7%).

2.3. Control participant recruitment

Control participants consisted of 100 randomly selected cyclists who had not been involved in a hospitalisation bicycle crash in the previous three years. They were recruited between March 2015 and January 2017 near the on-road location where each of the 100 cases crashed. Potential control participants were intercepted by a researcher as they stopped at traffic lights, and were offered a slap-band for their wrist which had the study website printed on it. Cyclists then completed an online questionnaire and were asked to leave their contact details if they were willing to be contacted by phone about participating in the study. If they agreed to participate an appointment was then made to attach cameras to their bicycle. Inclusion criteria were: aged 18 years or older, lived in the Perth area; cycled at least once per week. Exclusion criteria were non-English speaking people.

In total, 752 slapbands were offered to cyclists at the 100 sites and 664 cyclists accepted the slapband (88.3%). Of those who accepted, 279 completed the online survey (42.0%) and 205 of these (73.5%) agreed to be contacted. 109 cyclists needed to be contacted to achieve the 100 controls (9 declined, 8.3%).

2.4. Data collection: cases

Case data collected included a researcher-administered questionnaire, crash information from the Integrated Road Information System (IRIS) database and a virtual inspection of the crash site.

2.4.1. Researcher-administered questionnaire: cases

The majority of participants completed the questionnaire by phone (77.8%) which was administered, on average, 18 days (SD: 11.6) after the crash (range: 1–52 days). The questionnaire elicited information on demographics, health condition(s) and medication use; cycling exposure; bicycle crash history; risky cycling behaviours; crash information and a participant sketch of the crash location and circumstances which cyclists emailed, faxed or posted back to the researcher.

2.4.2. Crash site inspections: cases

A virtual inspection of each of the 100 crash sites was undertaken electronically using Nearmap and Google Maps. Nearmap is a provider of high-resolution aerial imagery. Google Maps is a web mapping service offering satellite imagery, street maps and Street View. The variables obtained from viewing the maps included: intersection approaches; intersection control; number of lanes in the direction of travel; speed limit, on-road bicycle lane; and motorised traffic volume. Variables collected for midblock sites were: left lane width; median type; adjacent parking; speed limit; lanes in the direction of travel; road incline (either upwards or downwards); traffic calming (speed humps or slow points); on-road bicycle lane; and motorised traffic volume.

The Main Roads WA Road Information Mapping System was also used to determine the posted speed limit at the crash site (Main Roads Western Australia, 2016). Motorised traffic volume information was obtained from a Main Roads WA database of annual average daily traffic (AADT). Volumes were obtained for the direction of travel of the cyclist only and expressed as vehicles per day (vpd). To validate the site inspection data, a second experienced researcher inspected a random sample of crash sites (n = 22). Inter-rater reliability was calculated for all variables using Cohen's kappa and Pearson's correlation coefficients. Overall, 91% of kappa coefficients were 0.8 or above. Median type (κ = 0.51) and left lane width (r = 0.7) showed lower inter-rater reliability and these variables were treated with caution.

2.4.3. Crash information from the Integrated Road Information System (IRIS) Database: cases

The IRIS database which is maintained by Main Roads WA contains information on all crashes in WA which are reported to the Police or through the Online Crash Reporting Facility (Insurance Commission of

WA/ WA Police, 2017). The IRIS database only contained a small number of the variables collected in the in-depth questionnaire. Data also only appeared in the IRIS for those crashes which were reported to Police (40% of crashes in the study). Therefore, the IRIS was used simply to confirm the accuracy of specific self-reported data (e.g. crash location and single or multi-vehicle crash) and consistency was excellent.

2.5. Data collection: controls

Control data collection consisted of an online questionnaire, video recorded by the cyclist using bicycle mounted cameras over a 2-week period and GPS data, mapping of recorded routes and selection of three control road sites per control participant.

2.5.1. Online questionnaire: controls

This questionnaire elicited information on demographics; cycling exposure; previous bicycle crash history; and risky cycling behaviours.

2.5.2. Cycling video footage and GPS data: controls

Up to six hours of cycling video footage and GPS data was collected per control participant over a two week period. Contour brand video cameras were attached to participants' bicycles. The cameras provided high quality HD video, filmed at 720pixels at 60 frames per second, with a field of view of 170 degrees. The researcher attached two Contour cameras to each bike where possible to capture forward and rear footage (Fig. 1). One camera also had an inbuilt GPS receiver and GPS data was extracted and saved as gpx and csv files using the Contour Storyteller software, version 3.6.2.

2.5.3. Route mapping: controls

Every trip recorded on the cameras was manually mapped in ARCMap 10.2 based on the extracted GPS data and video footage. Each section of the mapped route was coded using ARCMap attribute tables to indicate whether the cyclist was riding on-road or off-road and all off-road riding was excluded. Each participant's most common route/s were identified. Participants had an average of 2.3 (SD: 1.7) most common routes, ranging from 1 to 7 routes. One Masterfile was also created in ARCMap which mapped every section of road or path travelled on for every control cyclist (Fig. 2). The most common route data consisted of a total of 1680 km of path and road. The 280 km of path riding were excluded (16.7%) resulting in 1400 km of eligible on-road riding for inclusion in the study.

2.5.4. Selection of control sites

The ARCMap Masterfile containing all participant routes was used to randomly select 300 control sites where no crash involving the control cyclist occurred. For each participant, their most common route/s were combined into a single line. Then the 'create random points' tool was used to select 12 random locations along this line, at least 100 m apart from one another. Each location was checked and if the cyclist was riding off-road, the location was excluded. This process was continued until three valid control sites were identified for each control participant. Approximately half of the corresponding case sites occurred at midblocks (49%) and half at intersections (51%). Therefore, if the corresponding case site for a control was located at a midblock, then the nearest midblock to each of the three locations was selected as the control sites. If the corresponding case site was at an intersection, then the closest intersection to each of the three locations was selected as the control sites. Fig. 3 shows the location of the 100 case and 300 control sites.

Fig. 1. Contour cameras fitted to a bicycle.

2.5.5. Control site inspections

Virtual inspections of each of the 300 control sites (147 midblock sites and 153 intersection sites) were undertaken by the researchers. These followed an identical protocol to the site inspections performed for case sites.

2.6. Statistical analysis

The demographics, road environment characteristics and cycling exposure of case (n = 100) and control (n = 100) participants were summarized and unadjusted odds ratios (ORs) and 95% confidence intervals (CI) were calculated for each variable using conditional logistic regression. The crash characteristics of the cases were described using percentages or means and standard deviations.

Two multivariate conditional logistic regression models were constructed to examine road environment factors associated with crash risk, while controlling for confounding factors. Logistic regression is used to analyse case-control studies which have a binary outcome, however it assumes that each observation is independent. For this study, three control sites were chosen from each control participant's routes and matched to one case site, meaning the assumption of independence was violated. Conditional logistic regression takes into account this lack of independence.

The first model examined all intersection sites whilst the second model included all midblock sites. Variables included in the final most parsimonious conditional logistic regression model for intersection sites were: intersection control (priority control/ uncontrolled, roundabout, traffic signals); university degree (no, yes); nationality (Australian: current citizens, other: not Australian citizen); frequency of riding (≤ 3 times per week, > 3 times per week) and; percentage of on-road riding (≤ 50%, > 50%). Variables in the final most parsimonious conditional logistic regression model for midblock sites were: road gradient (level, incline); traffic calming (none, speed hump or slow point); on-road bicycle lane (no formal bicycle lane, formal bicycle lane); lanes in direction of travel (1 lane, ≥ 2 lanes); and university degree (no, yes). All data were analysed using Statistical Package for the Social Sciences (SPSS), version 22 (SPSS Inc, Chicago, USA).

3. Results

3.1. Participant demographics and cycling exposure

The majority of cases (58%) and controls (75%) had university degrees. Those who had university degrees were about half as likely to be involved in a crash (unadjusted OR: 0.43, 95% CI: 0.23, 0.83, $P = 0.012$). The majority of controls (88%) and cases (70%) were Australian. Crash risk was 3 times greater for those who were of a different nationality, compared to those who were Australian (unadjusted OR: 3.00, 95% CI: 1.41, 6.38, $P = 0.004$). The majority of controls (84%) and cases (60%) were in full time employment. Those who did not have full time employment had a greater crash risk (unadjusted OR: 3.67, 95% CI: 1.76, 7.67, $P = 0.001$). The majority of controls (77%) and cases (85%) were male. The majority of controls

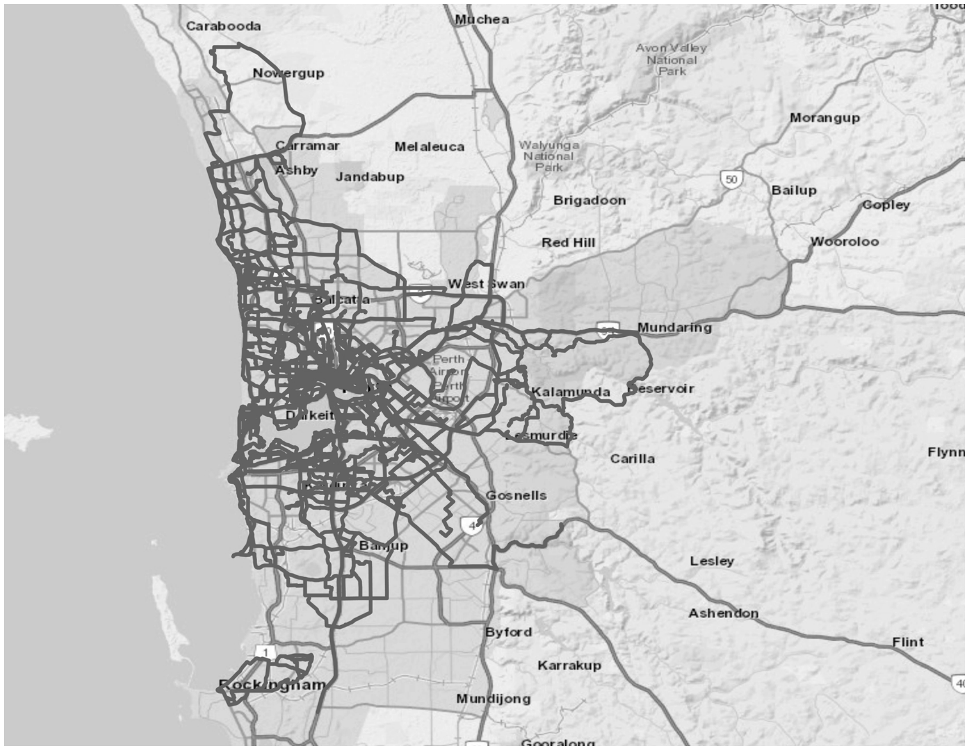

Fig. 2. Map of all roads travelled on by control cyclists in the Perth, WA area.

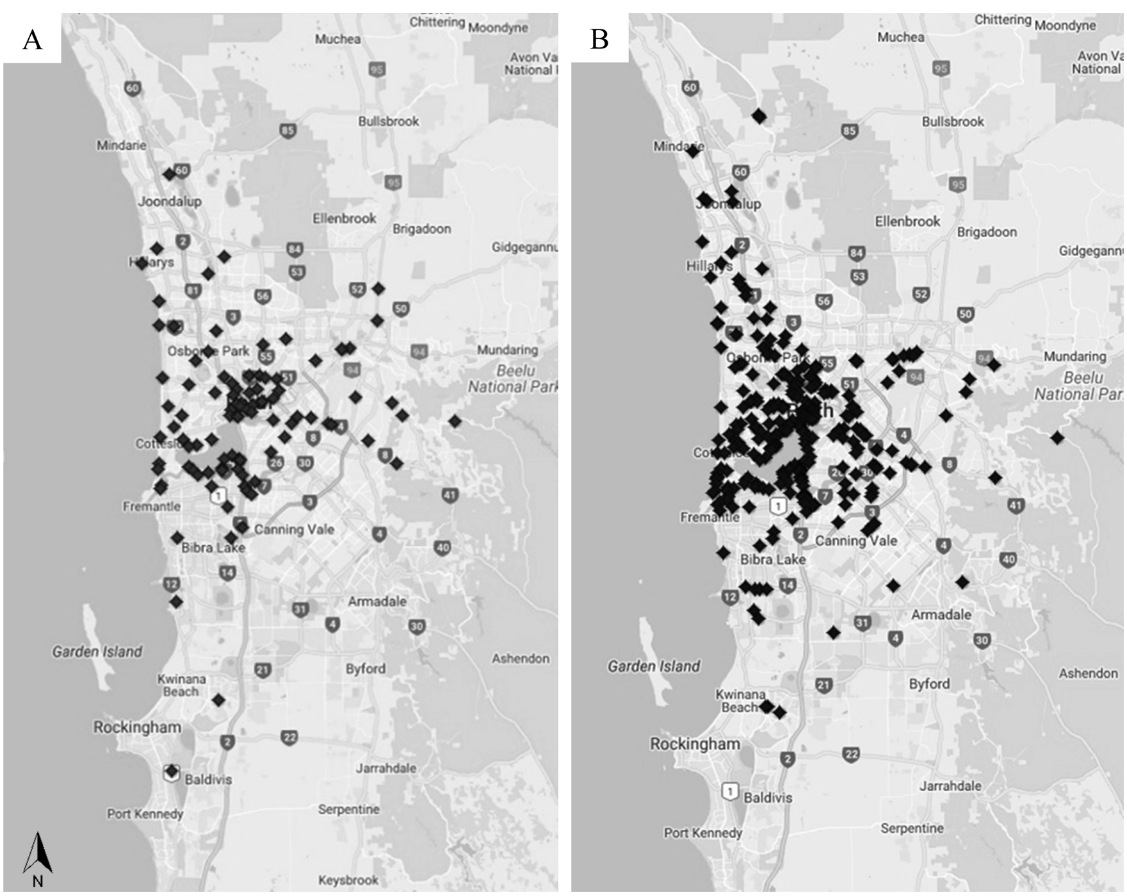

Fig. 3. Location of case and control sites in the Greater Perth area, Western Australia. A) 100 case sites. B) 300 control sites.

Table 1
Demographic and Cycling Exposure Characteristics for Case and Control Cyclists.

	Controls (n = 100)		Cases (n = 100)		OR[b]	95% CI	*P*- value
	N	%	N	%			
Gender							
Male	77	77.0	85	85.0	1.00		
Female	23	23.0	15	15.0	0.56	0.26, 1.20	0.136
Age (years)							
≤ 50	55	55.0	46	46.0	1.00		
> 50	45	45.0	54	54.0	1.36	0.81, 2.3	0.243
University Degree							
No	25	25.0	42	42.0	1.00		
Yes	75	75.0	58	58.0	0.43	0.23, 0.83	0.012[a]
Nationality							
Australian	88	88.0	70	70.0	1.00		
Other	12	12.0	30	30.0	3.00	1.41, 6.38	0.004[a]
Employment							
Full time work	84	84.0	60	60.0	1.00		
Other	16	16.0	40	40.0	3.67	1.76, 7.67	0.001[a]
Cycling experience							
< 20 years	49	49.0	53	53.0	1.00		
20+ years	51	51.0	47	47.0	0.86	0.50, 1.48	0.579
Cycling frequency (previous year)							
≤ 3 times/ week	41	41.0	39	39.0	1.00		
> 3 times/ week	59	59.0	61	61.0	1.09	0.61, 1.95	0.768
On-road riding							
≤ 50%	26	26.0	40	40.0	1.00		
> 50%	74	74.0	60	60.0	0.58	0.33, 1.01	0.055

Abbreviations: CI, confidence interval; OR, odds ratio.
[a] significant at $P < 0.05$.
[b] Unadjusted odds ratios calculated using conditional logistic regression.

were under the age of 50 years (55%), however the majority of cases were over the age of 50 years (54%). There were no significant differences in crash risk for gender or age. There were no significant differences for years of cycling experience, cycling frequency per week and percentage of on-road riding between cases and controls (Table 1).

3.2. Crash types

Overall, 42% of the cases' cycling crashes involved conflict with a motor vehicle and 58% did not involve a crash with a motor vehicle. For those crashes not involving a motor vehicle, 18% involved another cyclist, 21% were due to loss of control, 18% involved an object and one involved a pedestrian. Approximately half of the crashes occurred at an intersection (51%) and half at a midblock (non-intersection) site (49%).

3.3. Road environment characteristics

Fig. 3 presents the locations of the 100 case and 300 control sites in the Perth metropolitan area. The majority of intersection sites were priority control/ uncontrolled intersections for both controls (69%) and cases (51%), followed by roundabouts (16% of control and 28% of case sites) and traffic signal intersections (14% of control and 22% of case sites). Roundabouts had more than twice the risk of crashes compared to priority control/ uncontrolled intersections (unadjusted OR: 2.44, 95% CI: 1.06, 5.60). Half of the crashes occurring at roundabouts involved a motor vehicle (n = 7) and half did not involve a motor vehicle (n = 7). A larger proportion of intersection case sites involving a motor vehicle were located at roundabouts (n = 7, 24.1%), compared to corresponding control sites (n = 13, 14.9%). In addition, a larger proportion of intersection case sites not involving a motor vehicle were located at roundabouts (n = 7, 31.8%), compared to corresponding control sites (n = 12, 18.2%). The highest proportion of intersections had a speed limit of ≤50 km/h for both controls (72%) and cases (57%). Compared to intersection sites with a speed limit of under 60 km/h, sites with speed limits of 60 km/h or higher had over twice the risk of a crash (unadjusted OR: 2.33, 95% CI: 1.11, 4.89). There were no significant differences between cases and controls for intersection approach, lanes in the direction of travel or traffic volume (Table 2).

While the majority of control (94%) and case (84%) sites were located on level roads, roads with an incline significantly increased the risk of a crash by over three times (unadjusted OR: 3.34, CI: 1.13, 9.90). Seventy-five percent of crashes occurring on sloped roads did not involve a motor vehicle (n = 6) and 25% involved a motor vehicle (n = 2). A larger proportion of midblock case sites not involving a motor vehicle were located on sloped roads (n = 6, 16.7%), compared to corresponding control sites (n = 8, 7.4%). In addition, a larger proportion of midblock case sites involving a motor vehicle were located on sloped roads (n = 2, 15.4%), compared to corresponding control sites (n = 1, 2.6%). There were no significant differences between cases and controls for left lane width, median type, adjacent parking, posted speed limit, lanes in the direction of travel, traffic calming (speed hump or slow point), on-road bicycle lane or traffic volume (Table 2).

3.4. Multivariate analysis of intersection sites

Intersection control was the only significant road environment-related variable in the intersection sites model. Roundabouts significantly increased the risk of an intersection crash by nearly three times (adjusted OR: 2.98, 95% CI: 1.18, 7.56) and intersections with traffic lights had a significantly increased risk of almost four times (adjusted OR: 3.86, 95% CI 1.29, 11.63), compared to priority control/ uncontrolled intersections. Higher education (i.e. university degree) was also associated with a significantly reduced the risk of a crash (adjusted OR: 0.13, 95% CI: 0.03, 0.50) and people whose nationality was not Australian had over three times the risk of a crash (adjusted OR: 3.25, 95% CI: 1.10, 9.66). Participants who usually rode on roads more than 50% of the time also had a significantly decreased risk of a crash (adjusted OR: 0.28, 95% CI: 0.11, 0.72) (Table 3).

Table 2
Road Environment Characteristics for Case and Control Sites by Intersection and Midblock.

	Control sites		Case sites		OR[b]	95% CI	*P*-value
INTERSECTION SITES (n = 153 controls, 51 cases)							
Intersection Control							
Priority control/ uncontrolled	106	69.3	26	51.0	1.00		
Roundabout	25	16.3	14	27.5	2.44	1.06, 5.60	0.036[a]
Traffic signals	22	14.4	11	21.6	2.35	0.92, 5.97	0.074
Intersection approaches							
T-intersection	103	67.3	30	58.8	1.00		
Cross-intersection	46	30.1	20	39.2	1.52	0.77, 3.00	0.224
Multi-intersection	4	2.6	1	2.0	0.86	0.09, 7.38	0.858
Lanes in direction of travel at intersection							
One lane	113	73.9	33	64.7	1.00		
Two lanes	20	13.1	6	11.8	1.13	0.41, 3.14	0.814
Three or more lanes	20	13.1	12	23.5	2.25	0.93, 5.41	0.071
Intersection Speed Limit							
≤ 50 km/h	110	71.9	29	56.9	1.00		
≥ 60 km/h	43	28.1	22	43.1	2.33	1.11, 4.89	0.026[a]
On-road bicycle lane at intersection							
None	125	81.7	38	74.5	1.00		
Continuous through intersection	18	11.8	8	15.7	1.48	0.58, 3.81	0.412
To intersection entry	4	2.6	3	5.9	2.38	0.52, 10.77	0.262
Stop prior to intersection	6	3.9	2	3.9	1.14	0.21, 6.23	0.881
Traffic volume at intersection (vpd)							
< 1500	61	39.9	16	31.4	1.00		
1500 – 10 000	45	29.4	18	35.3	1.60	0.70, 3.64	0.265
> 10 000	47	30.7	17	33.3	1.46	0.62, 3.44	0.385
MIDBLOCK SITES (n = 147 controls, 49 cases)							
Left Lane Width							
< 3.0m	17	11.6	5	10.2	1.00		
3.0-3.5m	63	42.9	24	49.0	1.31	0.40, 4.31	0.654
> 3.5m	67	45.6	20	40.8	1.02	0.30, 3.48	0.970
Median Type							
No median	101	68.7	32	65.3	1.00		
Non-physical median	13	8.8	6	12.2	1.53	0.50, 4.68	0.456
Physical median	33	22.5	11	22.5	1.08	0.47, 2.50	0.861
Adjacent Parking							
No	111	75.5	36	73.5	1.00		
Yes	36	24.5	13	26.5	1.13	0.51, 2.48	0.761
Midblock speed limit							
≤ 50 km/h	100	68.0	33	67.3	1.00		
≥ 60 km/h	47	32.0	16	32.7	1.04	0.49, 2.20	0.924
Lanes in direction of travel							
1 lane	116	78.9	41	83.7	1.00		
≥ 2 lanes	31	21.1	8	16.3	0.70	0.28, 1.74	0.439
Road gradient							
Flat	138	93.9	41	83.7	1.00		
Sloped	9	6.1	8	16.3	3.34	1.13, 9.90	0.030[a]
Traffic calming							
None	139	94.6	45	91.8	1.00		
Speed hump or slow point	8	5.4	4	8.2	1.63	0.43, 6.13	0.479
On-road bicycle lane at midblock							
None	113	76.9	32	65.3	1.00		
Formal bicycle lane	30	20.4	13	26.5	1.56	0.71, 3.46	0.269
Unmarked bicycle lane	4	2.7	4	8.2	3.26	0.81, 13.18	0.098
Traffic volume (vpd)							
< 1500	70	47.6	21	42.9	1.00		
1500-4000	27	18.4	12	24.5	1.52	0.64, 3.61	0.343
> 4000	50	34.0	16	32.7	1.09	0.50, 2.37	0.829

Abbreviations: CI, confidence interval; OR, odds ratio; VPD, vehicles per day.
[a] significant at $P < 0.05$.
[b] Unadjusted odds ratios calculated using conditional logistic regression.

3.5. Multivariate analysis of all midblock sites

Road gradient was the only significant variable in the model. At midblock sites, roads with an incline increased the risk of a crash by over three times, compared to level roads (adjusted OR: 3.39, 95% CI: 1.02, 11.22). Possession of a university degree also significantly reduced the risk of a midblock crash (adjusted OR: 0.21, 95% CI: 0.09, 0.52) (Table 4).

4. Discussion

This is one of the first in-depth crash studies to examine the road-environment related risk factors for bicycle crashes resulting in hospitalisation in Perth, Australia. Several road-environment related factors were associated with an increased risk of bicycle crashes resulting in a hospitalisation which included roundabouts and traffic lights at intersections and roads with an incline at midblock sites.

This study found that roundabouts increased the risk of a crash compared to priority control/ uncontrolled intersections. Previous

Table 3
Conditional Logistic Regression Model of Crash Risk for Intersection Sites (n = 51 Case and 153 Control Sites).

Variable	Adjusted OR	95%CI	*P*-value
Intersection control			
Priority control	1.00		
Roundabout	2.98	1.18, 7.56	0.021[a]
Traffic lights	3.86	1.29, 11.63	0.016[a]
University degree			
No	1.00		
Yes	0.13	0.03, 0.50	0.003[a]
Nationality			
Australian	1.00		
Other	3.25	1.10, 9.66	0.033[a]
Frequency of riding			
≤ 3 times per week	1.00		
> 3 times per week	2.01	0.76, 5.30	0.159
Percentage of on-road riding			
≤ 50%	1.00		
> 50%	0.28	0.11, 0.72	0.009[a]

Abbreviations: CI, confidence interval; OR, odds ratio.
[a] significant at $P < 0.05$.

Table 4
Conditional Logistic Regression Model of Crash Risk for Midblock Sites (n = 49 Case and 147 Control Sites).

Variable	Adjusted OR	95%CI	*P*-value
Road gradient			
Flat	1.00		
Sloped	3.39	1.02, 11.22	0.046[a]
Traffic calming			
None	1.00		
Speed hump or slow point	2.99	0.692, 12.96	0.142
On-road bicycle lane			
No formal bicycle lane	1.00		
Formal bicycle lane	1.37	0.58, 3.20	0.473
Lanes in direction of travel			
1 lane	1.00		
≥ 2 lanes	0.83	0.31, 2.19	0.703
University degree			
No	1.00		
Yes	0.21	0.09, 0.52	< 0.001[a]

Abbreviations: CI, confidence interval; OR, odds ratio.
[a] significant at $P < 0.05$.

research has similarly reported this increased risk (Reynolds et al., 2009; Cumming, 2010; Harris et al., 2013; Wilke et al., 2014; Jurewicz et al., 2015). The findings also suggest that roundabouts may increase the risk of both crashes involving a motor vehicle and those not involving a motor vehicle. Possible reasons for this include the increased number of conflict points on roundabouts, motorists failing to see and give way to cyclists and increased risk of single cyclist crashes due to the cyclist interacting with the road environment (e.g. kerbs) or sliding while negotiating a turn (Cumming, 2011; Harris et al., 2013). Roundabouts are also associated with severe crash outcomes for cyclists, especially when approach and entry speeds are high (Turner et al., 2009; Jurewicz et al., 2015). In Australia, tangential design roundabouts are typically used which have smooth curves and triangular shaped splitter islands, increasing vehicle speeds and traffic capacity. Radial roundabouts, which have increased deflection and reduced operating speeds are more typically used in Europe (Patterson, 2010; Wilke et al., 2014). Therefore, treatments which may lower vehicle speeds on approach to roundabouts such as radial roundabouts (Wilke et al., 2014), reducing sight distances at roundabouts (Turner et al., 2009) and signage (Cumming, 2011) should be tested and considered on routes used by cyclists. If the design of a roundabout is unable to achieve low vehicle speeds of less than 30 km/h, then it is recommended that cyclists should be completely separated from motorised traffic (Woolley et al., 2018).

Previous research has also reported that the risk of crashes decreases if cyclists claim the lane (position themselves to the right instead of the left side of the lane in Australia) at a roundabout (Cumming, 2011). This increases the cyclist's visibility to adjacent motorists, reduces conflict points and prevents motor vehicles travelling in the same direction overtaking cyclists on entry to the roundabout (Cumming, 2011; Wilke et al., 2014). Treatments which encourage cyclists to claim the lane may include low speed environments, advisory lane markings or *'sharrows'*, bicycle merge signage, ending bicycle lanes well before the roundabout entry and narrow approach lanes not exceeding three metres (Cumming, 2011; Wilke et al., 2014). Treatments encouraging cyclists to claim the lane are only safe when vehicle speeds are less than 30 km/h however, otherwise cyclists should be separated (Woolley et al., 2018).

This study also found that intersections with traffic lights increased the risk of a hospitalisation crash compared to priority control/ uncontrolled intersections. Previous research has reported mixed findings on the risk of bicycle crashes at traffic lights (Harris et al., 2013; Strauss et al., 2014; Rash-ha Wahi et al., 2018). However, these studies examined only bicycle crashes involving a motor vehicle. In the current study, eight of the 11 crashes at traffic lights (73%) did not involve a motor vehicle but were due to cyclists losing control while performing a manoeuvre or hitting a hazard on the road. This demonstrates the importance of maintaining road surfaces, clearing hazards and careful design of kerbs at traffic light intersections in order to reduce bicycle crashes which do not involve a motor vehicle.

Roads with an incline increased the risk of a crash compared to level roads at midblock sites. The findings also suggest that roads with an incline may increase the risk of both crashes involving a motor vehicle and those not involving a motor vehicle. A case-crossover study in Canada also reported that downhill grades increased the risk of a bicycle crash at both intersections and non-intersections (Teschke et al., 2012) and this is likely due to the higher speed of cyclist travel downhill, which can exceed 50 km/h (Harris et al., 2013; Johnson and Chong, 2015). While it is impossible to remove hills and slopes from the topography, it is possible to select routes to target for bicycle infrastructure which are predominantly level and minimise changes in elevation.

A strength of this study was the in-depth information collected on bicycle crashes resulting in hospitalisation including crash and road environment characteristics. However there were several limitations. The insignificance of some results and wide confidence intervals may be due to limited power resulting from the small sample size. The sample size of the study was also not large enough to perform multivariate analyses of crash risk separated by intersection/ midblock crashes as well as by crash type (motor vehicle/ non motor vehicle) and this is an area for further research. While the self-reported information collected on crash circumstances from the cyclists may be subject to reporting bias, the focus on road infrastructure characteristics collected through objective site inspections in this study, minimises this effect. The findings may also be subject to selection bias since the control sites were selected from the routes of different cyclists to those who had crashed (cases). These effects were minimised by recruiting control cyclists nearby to the crash site, restricting the study to on-road case and control sites only and controlling for differences in demographic and cycling characteristics in the models. Finally, this study only included crashes that were severe enough to result in hospitalisation. The inclusion of only hospitalisation crashes in the study may have resulted in more intersection crash sites and sites with higher speed limits than lower severity crashes not requiring hospitalisation. Therefore, the findings of this study are not generalizable to crashes resulting in fatal or extremely severe injuries, or minor injuries.

5. Conclusion

This study highlighted the risk of roundabouts, traffic lights and roads with an incline for bicycle crashes. Treatments that reduce vehicle speeds and encourage cyclists to claim the lane at roundabouts as well as careful road design and road maintenance at traffic lights may reduce the risk of crashes for cyclists. While it is impossible to remove hills and slopes from the topography, it is possible to select routes to target for bicycle infrastructure which are predominantly level.

In conclusion the results of the study provide clear directives into how cyclist safety can be improved through creating a safer road environment for cyclists while using the urban road network.

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