SAFETY AT TRAFFIC SIGNALS FOR CYCLISTS AND PEDESTRIANS

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INTRODUCTION

The New Zealand Government and most of the Australian State Governments have developed transport strategies that emphasise the importance of walking and cycling as an alternative to use of the motor vehicle, especially for shorter journeys. Investment has been provided to road controlling authorities over recent years to promote more walking and cycling, particularly through travel demand management initiatives, such as safe routes to school and workplace and community travel plans. To complement the promotion of cycling, investment has also been made in cycle friendly streets and intersections in many cities and cycling facilities, including on-road cycle lanes, approach and storage cycle lanes at intersections and off-road paths, along motorways and through parks and reserves. While these promotional programs and infrastructure improvements are still developing they are being effective in reversing the decline in cycle numbers, and in many cities there has been an increase in cycling over the last five or more years.

While an increase in walking and cycling is a positive outcome from a sustainability and public health perspective, in terms of road safety there is a higher risk of a crash when cycling and walking, compared to being a driver or passenger in a motor vehicle. Turner et al. (2006) showed, using safety performance functions (or crash prediction models), that in New Zealand the crash risk while on a bicycle was indeed higher than when in a motor-vehicle. He also showed, however, that there is a 'safety in numbers' effect, with a significant drop in the individual crash risk as cycle and pedestrian numbers increased. While the crash risk was still higher than while in a motor-vehicle the individual risks were much lower at higher cycle and pedestrians flows. The safety in numbers effect has also been found by other researchers, including Jacobson (2003) and Robinson (2005) at the macro (city-wide) level, and Leden et al. (2000) and Ekman et al. (2001) at the micro (road element level). It appears that once cycle and pedestrian volumes reach a critical mass, there are safety benefits for all cyclists and pedestrians.

Transport professionals, and road safety engineers in particular, are of course interested in what else can be done to lower the risk faced by cyclists and pedestrians, and how the risks can be better managed at the high-risk lower volumes. The (UK) Department of Transport (2004) hierarchy of provision is perhaps a good place to start. The hierarchy promotes the introduction of the following improvements in priority order (the first design considerations being favoured ahead of latter ones);

1. Reduction of traffic speeds and volumes,
2. Provision of intersection treatment, hazard site treatment and traffic management,
3. Redistribution of carriageways (road and footpath/sidewalk surface), including wider kerb-side lanes,
4. Provision of cycle lanes, segregated cycle paths by reallocating carriageway space,
5. Conversion of footpaths to un-segregated shared-use cycle paths

While this list of improvements would appear on the face of it to be effective in improving safety for cyclists and pedestrians, there is limited research on how effective each level of the hierarchy is in improving safety. A key motivation of the research that has been undertaken in New Zealand, and reported here, is to quantify the reduction in crashes that might be achieved for each type of improvement in each element of the hierarchy. It is also important to understand what works well. For example, whether a 1m cycle lane is effective in reducing cycle crashes, or whether it is better to provide a wider kerb-side lane when space does not allow the standard 1.6m wide cycle lane (Austroads, 1999).

There are relatively few studies internationally that have directly quantified the relationship between cycle and pedestrian crashes and various road/intersection features, including cycle facilities and signal phasing (compared with studies focused on motor-vehicle only and total crash models). Many of the studies available on cycle safety are focused on safety surrogate measures, rather than crashes, such as traffic conflict methods.

There is limited data available on the impact on crashes of various cycle facilities and speed reduction measures. Elvik and Vaa (2004) have brought together research on cycle and pedestrian safety. For example, they found that mid-block cycle lanes reduced cycle crashes by around 10% and all crashes by 30%. Advanced limit lines for cyclists (or storage boxes) reduced cycle crashes by around 27% and all crashes by 40%. They also found that adding cycle lanes through an intersection reduced cycle crashes by 12%, but increased all crashes by 14%.

This paper presents the findings of two key studies that have been undertaken on the safety impacts of cycle facilities and other intersection features on the crash risk faced by cyclists and pedestrians at traffic signals. The first study (Austroads Effectiveness and Selection of Intersection Treatments for Cyclists, Turner et al., 2010), referred to as Study 1 in this paper, has focused on cycle safety at traffic signals, with a specific focus on the safety benefits that might be achieved from installing approach and storage cycle facilities. The most recent study (NZTA Crash Prediction Models for Signalised Intersections – Draft Report, 2011), referred to as Study 2 in this paper, looks at the effects of signal phasing and geometry on the crash risk faced by various user classes at traffic signals. The paper provides details on cycle and pedestrian crash relationships that were developed as part of Study 1 and 2 respectively,

MODELLING METHODS

The models developed in this paper have been produced using generalized linear modelling methods. Generalized linear models were first introduced to road crash studies by Maycock and Hall (1984), and extensively developed in Hauer, Ng and Lovell (1989). These models were further developed and fitted by Turner (1995), using crash data and traffic counts for motor vehicle crashes in New Zealand.

The aim of the modelling exercise is to develop relationships between the mean number of accidents (as the dependent variable flows) and traffic flows, cycle flows and variables indicating qualities of the cycle installation (such as whether the cycle lane is coloured). Typically the models are of the following multiplicative form:

$$A = \beta_0 {x_1}^{\beta_1} {x_2}^{\beta_2} \ldots {x_i}^{\beta_i} e^{\beta_{i+1} x_{i+1}} \ldots e^{\beta_p x_p} \qquad (1)$$

where:

A is the annual mean number of crashes

x_1 is the average daily flow of vehicles and x_2 the average daily flow of cycles or pedestrians

x_3 to x_i are remaining measurement predictor variables

x_{i+1} to x_p are categorical predictor variables, such as the presence of a cycle installation, and

β_i are the true model coefficients.

In the modelling process, these models are first transformed to an additive form by taking logarithms, as shown in Equation 2. This is why the models are called log-linear models even though the final model form above is multiplicative.

$$\eta = \log A = \log \beta_0 + \beta_1 \log x_1 + \beta_2 \log x_2 + \ldots + \beta_i \log x_i + \beta_{i+1} x_{i+1} + \ldots + \beta_p x_p \qquad (2)$$

For given values of the predictor variables (e.g. when we consider a set of arms with common properties) accidents are assumed to follow either a Poisson or, more generally, a negative binomial, distribution. The Poisson distribution is used where the variance in crash numbers is roughly equal to the mean over most of the explanatory variable range. Generally, however, the variability is higher than the mean and hence the negative binomial model is more commonly used. (The negative binomial model is a mixture of Poisson distributions by a gamma distribution; the gamma distribution models the Poisson parameter across similar intersections.) The fitted model is described using two parameters, k and μ, where k, μ and the coefficients $\beta_0, \ldots, \beta_p$ must be estimated from the data.

Care must be exercised to include in the model all important predictor variables. Failure to do this can result in a distortion of the importance of those that are included. At the other extreme, care must be exercised to avoid selection of “overlapping” variables, variables with high correlation. Inclusion of a pair of highly correlated variables can similarly provide a confusing message from a fitted model; the sign of a fitted parameter can reverse when a competing correlated variable is added to the model. (A helpful analogy is to consider assembling the ingredients for baking a cake. If you forget the sugar, the result will be unpalatable; on the other hand, if you include sugar, and honey as well, the result may be equally unappetizing)

A criterion is needed to decide when the addition of a new variable is worthwhile; this balances the inevitable increase in the likelihood L of the data upon the inclusion of a new variable against over-fitting (inclusion of an excess of predictor variables). The popular Bayesian Information Criterion (BIC) was chosen in this case. We stop adding variables when the BIC reaches its lowest point. The BIC is given by:

$$\mathrm{BIC} = (-2\ln(L) + p\ln(n))/n \qquad (3)$$

(where p is the number of variables included in the model and n is the total number of observations in the sample set). The model with the lowest BIC is typically the preferred model form.

The BIC provides us with a model, but the model may still not fit the data well. The usual methods for testing goodness of fit of generalized linear models involve the scaled deviance G^2 (twice the logarithm of the ratio of the likelihood of the data under the larger model, to that under the smaller model). This test is not valid in the current situation because of the “low mean value” problem (i.e. the models are being fitted to data with very low means). This difficulty was first pointed out by Maycock and Hall (1984).

In Wood (2002) a “grouping” method has been developed which overcomes the low mean value problem. The central idea is that sites are clustered and then aggregate data from the clusters is used to ensure that a grouped scaled deviance follows a chi-square distribution if the model fits well. Evidence of goodness of fit is provided by a p-value. For the scaled deviance a low value of ‘p’, of below 0.05, is evidence that the model does not fit well. Middling p-values indicate a satisfactory fit. Software has been written in the form of Minitab macros in order to run this procedure. A more detailed explanation of the models is given in Wood and Turner (2008).

SAMPLE SELECTION

Study 1: Austroads Safety of Intersection Treatments for Cyclists Study, 2010

The sample set for Study 1 consisted of 102 four-arm intersections and 383 approaches drawn from Christchurch, New Zealand and Adelaide, Australia. These sites were selected from a larger sample set of well over 200 intersections across the two cities. Using maintenance records and local knowledge, sites were selected having cycle facilities for at least 6 years (before 2003) and no major changes during this period. Most intersections only had cycle facilities on two arms, normal as part of a route treatment. Intersections with no cycle facilities were also included in the study set. Details on the number of approaches with and without cycle facilities at each site are shown in Table 1.

Table 1: Selected Traffic Signal Sites: Study 1

City	Number of Study Sites	Number of Approaches	
		With Cycle Facilities	Without any Cycle Facilities
Christchurch	56	118	100
Adelaide	46	91	72
Total	102	209	172

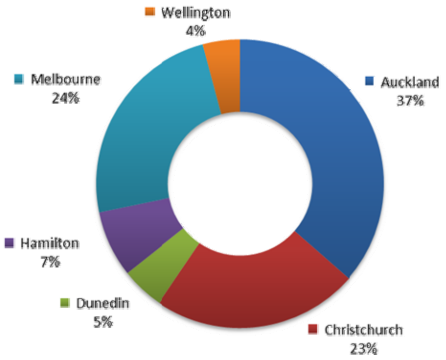
Study 2: NZTA Crash Prediction Models for Signalised Intersections Study, 2011

Study 2 utilised data from a much larger set of 238 three-arm and four-arm intersections (corresponding to 889 approaches) from Auckland, Wellington, Christchurch, Hamilton and

Dunedin in New Zealand and from Melbourne in Australia. Both low-speed and high-speed intersections were selected, including those that were known to lie along coordinated corridors.

Table 2: Selected sites: Study 2

Location	Low Speed Sites	High Speed Sites	Total selected intersections	Number of approaches
Auckland	81	8	89	324
Christchurch	53	0	53	205
Dunedin	11	0	11	43
Hamilton	17	0	17	66
Melbourne	37	21	58	214
Wellington	8	2	10	37
Total	**207**	**31**	**238**	**889**



DATA COLLECTION

Crash data

Injury crash data for New Zealand sites (those reported to police) was obtained from the New Zealand Crash Analysis System (CAS), a national crash database covering all New Zealand roads. Crash data is available by crash type and can be broken down by vehicle involved. Crash data has also been obtained from South Australia and VicRoads, for the cities of Adelaide and Melbourne respectively. Crashes occurring in Australian cities were converted to the New Zealand crash type coding, to be consistent.

Motor vehicle, cycle and pedestrian volumes

Study 1 (the Austroads Study) utilised motor vehicle and cycle count data, by vehicle movement, for traffic signals in Christchurch, New Zealand and Adelaide, Australia. Midblock cycle counts were also available in Christchurch. These two cities were chosen because of the significant numbers of cyclists and the widespread availability of manual movement cycle and motor-vehicle counts. Christchurch also has a specific cycle counting program. While cycle counts are also collected at the same time as motor-vehicle counts, analysis indicates that there is undercounting in such situations.

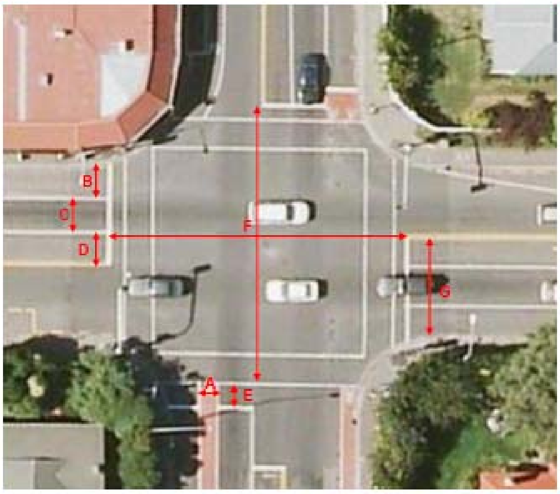
The manual turning movement counts were collected on weekdays and during the school term. Motor vehicle counts were typically collected for a one hour period during the morning (7:00am – 9:00am) and evening (4:00pm – 6:00pm) peak periods. Cycle counts were collected for a one hour period (and 1.5 hours in some cases) over the morning peak (7:30am to 9:00am) and the evening peak (4:15pm to 5:45pm). In Christchurch manual and automated mid-block link counts (motor-vehicles and cyclists) are available. Continuous cycle count data at some of the automated counts sites was used to study daily and weekly trends in cycle flows.

Study 2 (the NZTA Study) involved collection of motor vehicle counts from the SCATS system for the 238 selected intersections. These counts were also adjusted to reduce the error that is inherent in SCATS detector loop data. In addition, short duration (15 minute) manual turning counts were also simultaneously undertaken at approaches where lanes with shared movement were present, to identify turning volume proportions for that lane. Manual traffic counts were also undertaken for free left turns, in cases where SCATS detector loops were not present. Since the purpose of the manual counts was solely to identify the proportion of traffic turning on shared lanes (and of free left turn lane turning volumes where required), the use of short duration counts was considered satisfactory.

The frequency of activation of the pedestrian phase, a metric available from SCATS, was used to classify intersections according to the level of pedestrian volumes. Intersections were classified on a five-point scale, with 1 representing low pedestrian volumes and 5 representing high pedestrian volumes.

Signal Geometry and Layout

Both studies also involved collection of intersection geometry data by approach. This included the type of traffic lane configuration (e.g. whether the left turn lane is exclusive or shared), traffic and cycle lane widths, intersection depth and the type of cycle facilities installed. Figure 1 shows the layout data that was collected. Cycle treatments were classified according to type, i.e. whether transition, approach, through or departure, as shown in Figure 2. In addition, additional layout data regarding the presence of bus bays, upstream parking, right turn bay offsets and presence of exit lane merges was collected as part of Study 2.



A: Cycle lane width;
B: Kerbside lane width;
C: Total through lane width (exclude shared left turn or right turn lanes);
D: Total right turn lane width;
E: Depth of advanced cycle lane or bike box;
F: Intersection depth;
G: Total approach width;

Figure 1: Intersection Layout Variables (Luo, 2010)

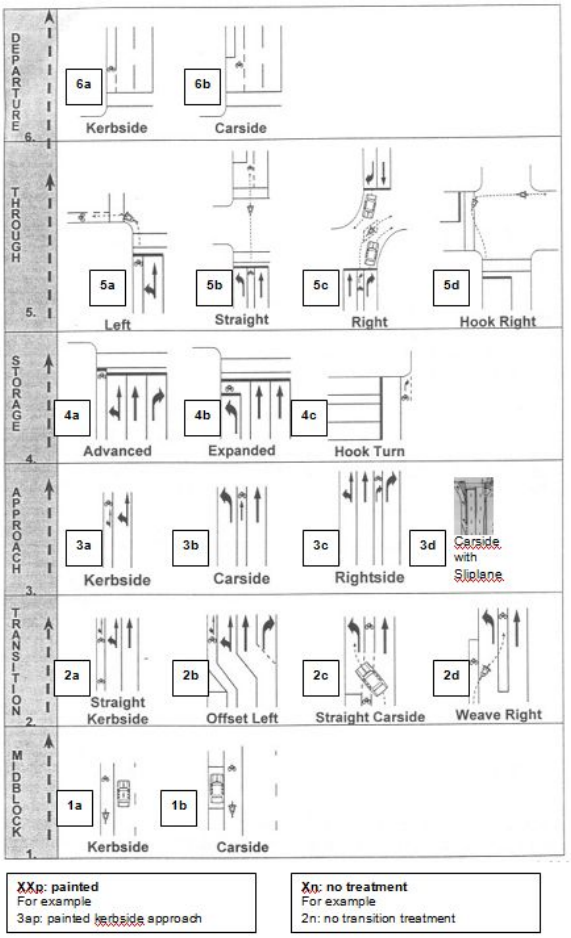


Figure 2: Types of Cycle Facilities (Cummings, 2000)

Signal phasing and signal coordination

Information on signal phasing and signal coordination was extracted from the SCATS system for the sites selected in Study 2. SCATS IDM data and signal layout diagrams were used to extract information on variables such as green, amber and all-red times, presence of split phasing, fully/partially protected right turn phasing, cycle time and coordination with upstream intersections.

Figure 3 illustrates the various sources that were utilised during data collection for Study 2.

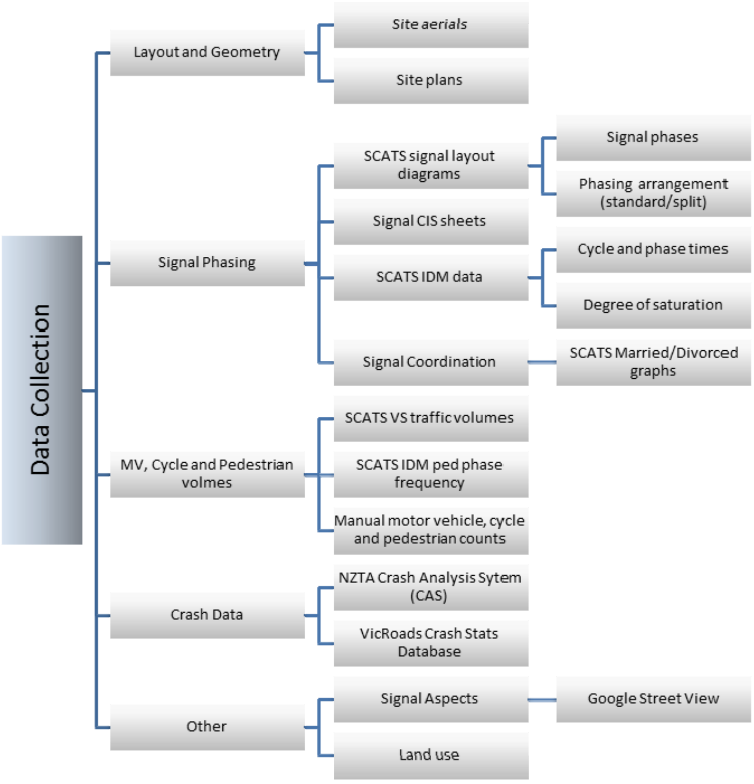


Figure 3: Data Collection: NZTA Crash Models for Signalised Intersections Study

RESULTS

Cycle crashes

Two types of analysis were undertaken for cycle crashes at traffic signals and mid-blocks; a before-after control-impact analysis and construction of safety performance functions. In the Austroads study (Study 1) the before-after analysis was undertaken to provide an initial assessment of the effects of cycle facilities (any facilities) on cycle crash rates, for total crashes and the main crash types. The effect of coloured cycle lanes and the application of cycle facilities when applied next to shared and exclusive left turning lanes were also examined for Christchurch. In both studies the ‘before-after analysis’ was also used to search for any bias in the application of cycle facilities to higher crash sites.

The safety performance functions (SPFs) allow a more detailed analysis of specific variables, including cycle lane width and storage box depth. It also enables the interaction of variables to be examined. Correlation is a key matter to consider when building SPFs; inclusion of highly correlated variables must be avoided. A major limitation of SPFs is also that they can be influenced by bias in the selection of sites that are treated using a specific countermeasure, such as the installation of cycle lanes.

The influence of bias in the selection of sites that received cycle lanes is illustrated in the results of the study of mid-block arterial roads in Christchurch. One of the SPFs developed includes a variable for ‘with cycle lane’, in addition to the volume of motorists and cyclist and the length of the route. This model is shown later in this paper (Table 6). The value for ‘with cycle lane’ in the SPF was 1.21, which indicates that there are 20% more cycle crashes when cycle lanes are installed. To check this outcome a before-after study was undertaken using the Empirical Bayes method for sites with cycle lanes (for at least five years). The analysis showed that at treated sites there had been a 10% reduction in cycle crashes, indicating there is bias in the sites that are selected for treatment.

a) Before-After Study of Cycle Facilities at Traffic Signals

A 'before-after' analysis was undertaken for the major cycle crash types at traffic signals, for five years before and after cycle facilities (of any type) were installed. Analysis was also undertaken of the effect on all cycle crashes of applying cycle facilities on approaches with shared and exclusive left turn lanes and free left turn. In both cases, the expected crashes in the 'after' period were calculated based on historic crash rates from a control group comprising of all urban intersections (for Christchurch) and all signalised intersections (for Adelaide).

The key finding from the analysis, as shown in Table 3, is that the overall effect on cycle safety of installing cycle lanes is similar in most respects between Christchurch and Adelaide for the main crash types, where changes were statistically insignificant. The apparent differences in the totals almost disappear when the "other" crash types are removed. A close look at the data revealed, that in Adelaide a significant increase in "other crashes" was due to an increase in footpath riding. The "other" crashes in Christchurch involved car doors opening within 50 metres of the intersections located near the CBD. Wide cycle lanes almost eliminated these.

Table 3: Results of before-after analysis at Traffic Signals

	Number of approaches in case group	Total observed crashes in the before period	Total expected crashes in the after period if no cycle treatment was installed	Total observed crashes in the after period	Ratio	% reduction after installation of cycle facility
All sites, all crashes						
Adelaide	90	18	19.24	26	1.37	**-37%**
Christchurch	104	30	28.8	23	0.80	**20%**
By crash type						
Crossing, both straight (HA) – at 90 degrees from each other						
Both Cities	194	8	7.90	5	0.63	**37%**
Right Turn against - cyclist through (LB) and vehicle turning right - at 180 degrees from cyclist						
Both Cities	194	13	12.80	17	1.33	**-33%**
Same direction, rear end, sideswipe (A*FG*) – both straight through						
Both Cities	194	13	13.02	13	1.01	**-1%**
Left turn sideswipe – cyclist through (GB+AC) and motor vehicle left turning						
Adelaide	90	3	3.21	7	2.03	**-103%**
Christchurch	104	5	4.80	2	0.42	**58%**
Other (all other cycle crashes)						
Both Cities	194	10	9.92	10	1.02	**-2%**
All sites by lane layout						
Sites with shared left turns (left and through together)						
Adelaide	31	5	5.34	8	1.40	**-40%**
Christchurch	45	14	13.43	8	0.60	**40%**
Sites with exclusive left turn (lanes)						
Adelaide	55	13	13.90	19	1.36	**-36%**
Christchurch	55	15	14.39	14	0.97	**3%**
Sites with coloured facilities (only used in Christchurch)						
Christchurch	38	9	8.64	5	0.61	**39%**

[#] the 'Other' category includes all crashes not included in the four main crash types

There are apparent differences in the effects of cycle lanes on left turn side swipe crashes, although the number of crashes is quite low and the results are thus more prone to statistical variation. There are also apparent differences in the effects of cycle lanes on both shared left turn lanes and exclusive lanes.

There were significant differences in the type of intersections being treated in Adelaide. Adelaide sites had more exclusive left turn lanes, including free left turns which the SPF analysis shows are much safer to start with and, have less potential for improvement by cycle lanes. They also mostly had part time cycle lanes leading to them, which only provide full benefits during peak times on the approaches and departures within the 50 metre distance used in the analysis. Christchurch had more shared left turns which the SPFs suggest pose higher risks to cyclists and which benefit most from treatment. However Christchurch sites also had more room to provide wider cycle lanes, had deeper advanced storage areas, and about a third of the approaches had a coloured surface. The SPFs suggest that all these are beneficial – especially colour which consistently shows as very beneficial in nearly all the models. .

b) Safety Performance Functions for Cycle Crashes at Traffic Signals

Safety performance functions were developed for the major cycle crash types. A number of continuous and discrete variables were used in the modeling for each crash type. The preferred models for each crash type contain the more important predictive variables. Three different model types were developed for each crash type (see Table 4) to build up a picture of what variables were important and what the difference was between the two cities. The variables used are described in Table 5.

The first model uses data from the two cities together, but allowing the constant value (covariate) only to vary for each city. The second model developed was for Christchurch data only, which enabled the researchers to assess whether the exponents of the variables also varied between the cities (this was expected for some crash types, given the variability in the before-after studies). The first two models contained variables that recorded the presence or absence of features such as approach lanes and storage but also separately included the dimensions of some of those features. These are highly correlated, and while better fitting, they are difficult to interpret in practice.

The last model looked at approaches with cycle treatment only so that the design parameters, such as cycle lane width could be examined independently. The two city models have the best goodness-of-fit, as they are based on the largest sample sets. The variability observed between the two cities in the before-after studies, however, and our concerns around having correlated variables in this first model, have lead to the development of the other two models to enable a better understanding of the most important variables.

The benefit of coloured surfacing is very apparent, as is the available width of the near kerb-side lane irrespective of whether a cycle lane was marked within it. Wider cycle lanes (1.6m) are better than narrower ones (1m). In some cases the effect of variables, such as presence of a storage box, is not clear, though once installed deeper is clearly better. The high correlation between the presence of transition treatments and storage treatments confuses the picture.

Table 4: Safety Performance Functions for Crashes involving Cyclists

Crash Type	Equation (crashes per approach)	B_0	Model Parameters	Error Structure, P-Value
Crossing, (HA)				
Two City Model	$A_{UXHA} = B_0 \text{ X } C_2^{0.269} \text{ X } (Q_5 + Q_{11})^{0.878} \text{ X (Total Approach Width)}^{2.267} \text{ X (Intersection Depth)}^{-1.699} \text{ X X } F_{\text{Storage}} \text{ X } F_{\text{Approach facility}} \text{ X } F_{\text{Painted}} \text{ X } F_{\text{shared LT}}$	$B_{0\,\text{(Adelaide)}}$ 2.81E-06 $B_{0\,\text{(Christchurch)}}$ 7.37E-06	$F_{\text{Approach facility}}$ 2.020 F_{Storage} 0.820 F_{Painted} 1.281 $F_{\text{shared LT}}$ 0.928	Poisson p-value = 0.0024
Christchurch Model	$A_{UXHA\,\text{(Christchurch)}} = B_0 \text{ X } C_2^{0.232} \text{ X } (Q_5 + Q_{11})^{0.681} \text{ X (Total Approach Width)}^{2.340} \text{ X (Intersection Depth)}^{-2.108} \text{ X (1+Through cycle lane width)}^{0.721} \text{ X } F_{\text{Storage}} \text{ X } F_{\text{Approach facility}} \text{ X } F_{\text{Painted}} \text{ X } F_{\text{shared LT}}$	$B_{0\,\text{(Christchurch)}}$ 1.10E-04	F_{Storage} 2.430 $F_{\text{Approach facility}}$ 0.845 F_{Painted} 0.874 $F_{\text{shared LT}}$ 1.081	
Cycle treatment approaches	$A_{UXHA\,\text{(treatments)}} = B_0 \text{ X } C_2^{0.694} \text{ X } (Q_5 + Q_{11})^{0.963} \text{ X (Total Approach Width)}^{3.142} \text{ X (Intersection Depth)}^{-3.857} \text{ X (1+Through cycle lane width)}^{3.986} \text{ X (1+Depth of Advanced Cycle Box)}^{-0.298} \text{ X } F_{\text{Painted}} \text{ X } F_{\text{shared LT}}$	$B_{0\,\text{(Adelaide)}}$ 1.37E-06 $B_{0\,\text{(Christchurch)}}$ 4.28E-06	F_{Painted} 1.119 $F_{\text{shared LT}}$ 0.407	
Right Turn against - cyclist through				
Two City Model	$A_{UXLB} = B_0 \text{ X } C_2^{0.308} \text{ X } Q_7^{0.297} \text{ X exp(-0.572 X No. of through traffic lanes) X (Intersection depth)}^{0.890} \text{ X } F_{\text{Painted}} \text{ X } F_{\text{Approach facility}} \text{ X } F_{\text{Storage}} \text{ X } F_{\text{SharedRT}} \text{ X } F_{\text{RTphasing}}$	$B_{0\,\text{(Adelaide)}}$ 1.54E-04 $B_{0\,\text{(Christchurch)}}$ 1.42E-04	$F_{\text{Approach facility}}$ 0.517 F_{Storage} 1.306 F_{Painted} 0.613 SharedRT 0.522 $F_{\text{RTphasing}}$ 0.522	Negative Binomial p-value = 0.0082

Crash Type	Equation (crashes per approach)	B_0	Model Parameters	Error Structure, P-Value
Christchurch Model	$A_{UXLB\ (Christchurch)} = B_0$ X $C_2^{0.079}$ X $Q_7^{0.550}$ X exp(-0.436 X No. of through traffic lanes) X (1+Through cycle lane width)$^{-1.336}$ X (1+Depth of Advanced Cycle Box)$^{0.023}$ X (Intersection depth)$^{1.397}$ X $F_{Painted}$ X $F_{Approach\ facility}$ X $F_{SharedRT}$ X $F_{RTphasing}$	$B_{0\ (Christchurch)}$ 2.38E-05	$F_{Painted}$ 0.553 $F_{Approach\ facility}$ 3.388 SharedRT 0.933 $F_{RTphasing}$ 0.987	
Cycle treatment approaches	$A_{UXLB\ (treatments)} = B_0$ X $C_2^{0.396}$ X $Q_7^{0.617}$ X exp(-0.158 X No. of through traffic lanes) X (1+Through cycle lane width)$^{-2.596}$ X (1+Depth of Advanced Cycle Box)$^{-0.483}$ X (Intersection depth)$^{3.904}$ X $F_{Painted}$ X $F_{SharedRT}$ X $F_{RTphasing}$	$B_{0\ (Adelaide)}$ 2.23E-10 $B_{0\ (Christchurch)}$ 2.42E-09	$F_{Painted}$ 0.372 SharedRT 0.482 $F_{RTphasing}$ 1.343	
Same direction, rear end, sideswipe				
Two City Model	$A_{UXA*FG*} = B_0$ X $C^{0.033}$ X $Q^{0.416}$ X Total Approach Width$^{0.425}$ X (kerbside lane width)$^{-0.898}$ X $F_{Storage}$ X $F_{Transition\ facility}$ X $F_{Painted}$ X $F_{shared\ lanes}$	$B_{0\ (Adelaide)}$ 3.23E-05 $B_{0\ (Christchurch)}$ 5.54E-05	$F_{Storage}$ 1.392 $F_{Transition\ facility}$ 0.374 $F_{Painted}$ 3.101 $F_{shared\ lanes}$ 3.534	Poisson p-value = 0.0001
Christchurch Model	$A_{UXA*FG*\ (Christchurch)} = B_0$ X $C^{-0.062}$ X $Q^{0.655}$ X Total Approach Width$^{-1.30}$ X (Cycle lane width + kerbside lane width)$^{-3.236}$ X $F_{Storage}$ X $F_{Transition\ facility}$ X $F_{shared\ lanes}$	$B_{0\ (Christchurch)}$ 4.72E-05	$F_{Storage}$ 1.502 $F_{Transition\ facility}$ 4.304 $F_{shared\ lanes}$ 3.365	
Cycle treatment approaches	$A_{UXA*FG*\ (treatments)} = B_0$ X $C^{0.381}$ X $Q^{-0.051}$ X Total Approach Width$^{1.065}$ X (Cycle lane width + kerbside lane width)$^{-0.666}$ X (1+Depth of Advanced Cycle Box)$^{-0.220}$ X $F_{Painted}$ X $F_{shared\ lanes}$	$B_{0\ (Adelaide)}$ 1.60E-03 $B_{0\ (Christchurch)}$ 1.64E-03	$F_{Painted}$ 1.620 $F_{shared\ lanes}$ 1.961	
Left turn sideswipe – cyclist through				
Two City Model	$A_{UXGBAC} = B_0$ X $C_2^{0.223}$ X $Q_3^{0.369}$ X $F_{shared\ LT}$ X $F_{Painted}$ X $F_{Storage}$ X $F_{Transition\ facility}$	$B_{0\ (Adelaide)}$ 2.58E-03 $B_{0\ (Christchurch)}$ 1.06E-03	$F_{shared\ LT}$ 2.410 $F_{Painted}$ 0.375 $F_{Storage}$ 2.353 $F_{Transition\ facility}$ 0.739	Negative Binomial p-value = 0.059
Christchurch Model	$A_{UXA*FG*\ (Christchurch)} = B_0$ X $C_2^{-0.055}$ X $Q_3^{0.328}$ X (1+Through cycle lane width)$^{1.753}$ X $F_{shared\ LT}$ X $F_{Painted}$ X $F_{Storage}$ X $F_{Transition\ facility}$	$B_{0\ (Christchurch)}$ 2.32-03	$F_{shared\ LT}$ 2.632 $F_{Painted}$ 0.332 $F_{Storage}$ 2.997 $F_{Transition\ facility}$ 0.150	
Cycle treatment approaches	$A_{UXGBAC\ (treatments)} = B_0$ X $C_2^{0.509}$ X $Q_3^{0.198}$ X (1+Through cycle lane width)$^{5.742}$ X (1+Depth of Advanced Cycle Box)$^{-0.023}$ X $F_{shared\ LT}$ X $F_{Painted}$	$B_{0\ (Adelaide)}$ 3.91E-05 $B_{0\ (Christchurch)}$ 5.68E-06	$F_{shared\ LT}$ 1.994 $F_{Painted}$ 0.417	
Others				
Two City Model	$A_{UXOther} = B_0$ X $C^{0.247}$ X $Q^{0.128}$ X (Total Approach Width)$^{-0.631}$ X $F_{Storage}$ X $F_{Transition\ facility}$ X $F_{Painted}$ X F_{FLT} X $F_{sharedRT}$	$B_{0\ (Adelaide)}$ 5.72E-03 $B_{0\ (Christchurch)}$ 1.34E-03	$F_{Storage}$ 3.264 $F_{Transition\ facility}$ 0.412 $F_{Painted}$ 0.475 F_{FLT} 1.490 SharedRT 1.434	Poisson Goodness of fit testing not undertaken
Christchurch Model	$A_{UXOther\ (Christchurch)} = B_0$ X $C^{0.508}$ X $Q^{0.064}$ X (Total Approach Width)$^{-0.995}$ X $F_{Storage}$ X $F_{Transition\ facility}$ X $F_{Painted}$ X F_{FLT} X $F_{sharedRT}$	$B_{0\ (Christchurch)}$ 3.83E-04	$F_{Storage}$ 2.597 $F_{Transition\ facility}$ 0.468 $F_{Painted}$ 0.561 F_{FLT} 0.636 SharedRT 0.877	
Cycle treatment approaches	No significantly converging model			

Table 5: Variables for Cycle SPFs for Traffic Signals

Variable	Description
$B_{0\ (Adelaide)}$	Constant for Adelaide
$B_{0\ (Christchurch)}$	Constant for Christchurch
Q_1 to Q_{12}	Volume for each vehicle movement, starting with right turn on crash approach and going clockwise
C_1 to C_{12}	Volume for each cycle movement, starting with right turn on crash approach and going clockwise
1 + through cycle lane width	Cycle lane width in meters plus 1m
1 + depth of advanced cycle box	Depth of advanced cycle box in meters plus 1m
Kerb-side lane width	Width in meters of lane closest to kerb
$F_{Approach\ facility}$	Presence of approach cycle facility
$F_{Transition\ facility}$	Presence of transition cycle facility on approach
$F_{Storage}$	Storage treatments present on approach
$F_{Painted}$	Coloured treatments
$F_{shared\ lanes}$	Presence of shared lanes on approach
$F_{SharedRT}$	Shared right-turn lane on motor vehicle movement approach (RT motor vehicles)

Variable	Description
$F_{shared\ LT}$	Shared LT lane on approach
F_{FLT}	Presence of free left turn on approach
$F_{RTphasing}$	Fully / partially protected phasing arrangement at intersection

Pedestrian Crashes

Table 6 shows the SPFs that have been developed for predicting the two most prominent crashes involving pedestrians, namely right angle (NZ types NA and NB) and right turning/pedestrian crossing (NZ types ND and NF). A separate SPF was built for right angle crashes in Auckland and Melbourne sites, since these two cities displayed similar rates of right angle crashes involving pedestrians.

Table 6: Safety Performance Functions for Crashes involving Pedestrians

Crash Type	Equation (crashes per approach)	B_0	Model Parameters	Error Structure, P-Value
Right angle (NZ types NA and NB)	$A_{NA,NB} = B_0 \times q^{0.314} \times p^{0.364} \times \exp(0.16 \times \text{Number of approaching lanes}) \times (\text{All-red time})^{0.61} \times (\text{Cycle time})^{0.810} \times F_{Cycle\ facilities} \times F_{Shared\ turns} \times F_{Split\ phasing} \times F_{Med\ island}$	B0 (Auckland) 3.84E-05 B0 (Wellington) 1.28E-05 B0 (Christchurch) 5.30E-05 B0 (Hamilton) 5.94E-05 B0 (Dunedin) 8.90E-05 B0 (Melbourne) 3.39E-05	FCycle facilities 0.513 FShared turns 1.321 FSplit phasing 0.741 FMed island 0.767	Negative Binomial p-value = 0.036
Right angle (Auckland and Melbourne sites only)	$A_{NA,NB} = B_0 \times q^{0.188} \times p^{0.406} \times \exp(0.275 \times \text{Number of approaching lanes}) \times (\text{All-red time})^{0.444} \times (\text{Cycle time})^{0.646} \times F_{Cycle\ facilities} \times F_{Shared\ turns} \times F_{Split\ phasing} \times F_{Med\ island}$	B0 1.84E-04	FCycle facilities 0.673 FShared turns 1.414 FSplit phasing 0.550 FMed island 0.710	Negative Binomial p-value = 0.29
Right turning/pedestrian crossing (NZ types ND and NF).	$A_{ND,NF} = B_0 \times q_1^{0.093} \times p^{0.172} \times (\text{Cycle time})^{-0.579} \times (\text{Yellow time})^{0.837} \times F_{Full\ RT\ Protection} \times F_{Residential} \times F_{Coordinated} \times F_{Med\ island}$	B0 (Auckland) 3.10E-02 B0 (Wellington) 1.03E-01 B0 (Christchurch) 1.09E-01 B0 (Hamilton) 1.93E-02 B0 (Dunedin) 2.24E-01	FFull RT Protection 0.63 FResidential 0.57 FCoordinated 1.24 FMed island 0.99	Negative Binomial p-value = 0.056

Table 7: Variables for Pedestrian SPFs for Traffic Signals

Variable	Description
$B_{0\ (city)}$	Constant for the respective city
q, q_1	Total vehicle volume on approach, right turning vehicle volume respectively
p	Pedestrian volume bin on the approach (On a scale of 1 to 5, with 1 being low and 5 being high)
$F_{Cycle\ facility}$	Presence of cycle facility on the approach
$F_{Split\ phasing}$	Presence of split phasing arrangement on approach
$F_{Med\ island}$	Presence of raised median/central island on approach with pedestrian movement
$F_{Full\ RT\ Protection}$	Fully protected right turn phasing
$F_{Residential}$	Residential land use
$F_{Coordinated}$	Coordination with upstream intersection
$F_{shared\ lanes}$	Presence of shared lanes on approach

Increasing the length of the signal cycle is shown to result in more pedestrian crashes. Operation of intersection approaches using split phasing and full right turn protection also appear to reduce the number of pedestrian crashes. The models also indicate that wider approaches have more right angle crashes. Presence of a raised median/central island results in a reduction in right angle crashes, but does not have an effect on the number of right turning crashes.

CONCLUSIONS

The provision of cycle facilities at intersections, especially traffic signals, is becoming more common across Australia and New Zealand, particularly in cities that are popular for cyclists. At the same time, conflicts between motor vehicles and pedestrians continue to be a significant concern at signalised intersections. Cycle lanes and paths (off-road) are also being installed in most major cities. There is currently very little research locally on the effectiveness of these facilities, in terms of safety and cycle perceptions.

This paper presents results from two research studies which quantify the impacts of various facilities on cyclist and pedestrian crash rates. The study of cycle safety has focused on the safety impacts of various cycle facilities, in combination with a number of other features, such as width of approach kerbside lane and whether left lane is shared or exclusive. Based on a review of cycle facilities provided across each of the Australian States and New Zealand, Christchurch and Adelaide were selected, due to the widespread use of cycle lanes and intersection facilities and the availability of manual movement counts for cyclists and motor-vehicles. In total 102 signalised cross-roads were included in the analysis, with 383 approaches (some approaches were excluded due to tram tracks and other unusual layouts). The major crash types were right turn against (right turning vehicle hitting opposing through cycle), right angle (both travelling straight through), same direction (on the approach), left turn side-swipe (left turn vehicle cutting off straight through cyclists) and ‘other’ (most of the remaining crash types).

The pedestrian crash models presented in this paper were developed as part of a wider study looking at the effects of signal phasing and geometry on crash rates of various user classes at traffic signals. The pedestrian models utilise data from 238 sites located in Auckland, Wellington, Christchurch, Hamilton, Dunedin and Melbourne. The key crash types involving pedestrians were those of right angle (through moving vehicles hitting crossing pedestrians) and right turning (right turning vehicle hitting crossing pedestrians).

Crash prediction models were developed for each crash type, relating crashes to a number of intersection features and exposure. Key predictor variables used included cycle, pedestrian and motor vehicle volumes, total intersection approach width, signal cycle time, phasing arrangement, cyclist facility type, depth of advanced stop boxes, intersection depth, number of through lanes, cycle lane width and kerbside lane width. A before-after study of a smaller sample set was also undertaken for all cycle crashes and each of the major crash types involving cyclists.

Combining the results of the before and after studies for cycle crashes with the cycle crash prediction models leads to the following conclusions:

- The overall effect of cycle lanes was neutral. Cycle lanes built to high standards improve cyclist safety. Those built to lesser standard can reduce cyclist safety.
- Sites with coloured cycle lanes (all within Christchurch) decreased by 39% in the before and after studies and for most crash types produced modelled safety performance factors less than 0.5. This conclusion provides evidence that the better driver behaviour observed at coloured cycle lanes in previous studies, results in substantially safer outcomes.
- Sites with shared left-turn and through lanes, have higher initial crash rates, but also benefit the most from coloured cycle lanes and advanced storage boxes.
- Sites with exclusive left turn lanes are much safer for cyclists than those with a shared through and left turning lane. Any intersection design should first aim to provide them. They benefit from coloured transition cycle lanes marked across the diverge area to the limit line.
- For rear end crashes the provision of adequate total width in the near kerbside approach lane is more important than the marking or width of a cycle lane within this space.

The crash prediction models developed for pedestrians offer more direct results:

- Longer cycle times result in more pedestrian crashes.
- Approaches with a raised median/central island are safer for crossing pedestrians, although this treatment does not have an effect on collisions with right turning traffic.
- Split phasing and full right turn protection prove to be safer for pedestrian crashes as compared to filter turns.

Future research will take into account bicycle exposure before and after treatments are installed and in particular whether bicycle volumes are higher in the after period at treated sites. This will involve modifying the current before and after modelling methods. The use of different model forms and methods, as considered in the literature on motor-vehicle only safety performance functions, also needs to be explored. The pedestrian crash relationships also hint at the need for conducting before and after analysis to determine the effects of factors such as upstream coordination on pedestrian crashes.

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