Safety performance functions for traffic signals: phasing and geometry

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Abstract

A significant proportion of urban crashes, especially serious and fatal crashes, occur at traffic signals. Many of the black-spots in both Australia and New Zealand cities occur at high volume and/or high speed traffic signals. Given this, crash reduction studies often focus on the major signalised intersections. However, there is limited information that links the phasing configuration, degree of saturation and overall cycle time to crashes. While a number of analysis tools are available for assessing the efficiency of intersections, there are very few tools that can assist engineers in assessing the safety effects of intersection upgrades and new intersections. Safety performance functions have been developed to help quantify the safety impact of various traffic signal phasing configurations and level of intersection congestion at low and high-speed traffic signals in New Zealand and Australia.

Data from 238 signalised intersection sites in Auckland, Wellington, Christchurch, Hamilton, Dunedin and Melbourne was used to develop crash prediction models for key crash-causing movements at traffic signals. Different variables (road features) effect each crash type. The models indicate that the safety of intersections can be improved by longer cycle times and longer lost inter-green times, especially all-red time, using fully protected right turns and by extending the length of right turn bays. The exception is at intersections with lots of pedestrians where shorter cycle times are preferred as pedestrian crashes increase with longer wait times. A number of factors have a negative impact on safety including, free left turns, more approach lanes, intersection arms operating near or over capacity in peak periods and higher speed limits.

Keywords:

crash prediction models, generalised linear models, traffic signal layout and phasing, pedestrian safety and safety performance functions

Introduction

The majority of urban crash black-spots (or hot-spots) occur at major signalised intersections. While crash reduction studies often focus on such intersections there is limited information that links the phasing configuration, degree of saturation of each movement and overall cycle time to crashes. Most changes to the signal phasing, other than right turning phases, occur for efficiency reasons. Safety improvements often focus on other factors like conspicuousness of the signals, the amount of inter-green time and approach skid resistance.

Many traffic signal and road safety engineers/professionals have anecdotal experience that signal phasing and traffic congestion (and the resulting driver frustration) has an effect on road safety. However this effect has not been well quantified and there is only limited research on what the safety effects are, both good and bad, of changes to signal phasing and congestion relief. The result is that many changes to traffic signal phasing are being made without a good understanding of the safety implications of these changes.

While there is some international research on this topic, including before and after studies of the safety of various intersection features, there is a lot of variety in the layouts of traffic signals between different countries, and in the case of large countries, like the USA, from State to State and even city to city. This does mean that such studies are not directly transferable to New Zealand and Australia, which typically have similar traffic signal lay-outs, with some local variations. The overseas research does however help in identifying the key features that impact safety at traffic signals, and should be included in the models.

Some of the earliest accident prediction models (or safety performance functions) for traffic signals were produced by TRL in the United Kingdom. Hall [1] analysed four years of crash data from 1979 to 1982 at 177 four-leg urban intersections on 30 mile/h roads throughout the United Kingdom. The report divided intersections into eight groups based on the presence (or lack thereof) of Urban Traffic Control, pedestrian stages, and right turn stages (or more or less than two stages). Hall derived significant crash prediction models for total crashes, vehicles only, pedestrian crashes and 11 specific types of crashes. The best fitting models (and the simplest) were functions of all 12 vehicular flows into the intersection (three movements on each leg) and the total vehicular and pedestrian flows.

Hall further tested geometric variables at the intersections and found significant models correlating crashes with approach width, number of approach lanes, approach horizontal curvature, sight distance and gradient on the approach, horizontal displacement across the intersection (when approaches are not exactly opposite one another), the angle of intersecting roadways, yellow box "no stopping" markings, the position of the secondary signal and the presence of a pedestrian refuge island. Operational variables that had a significant correlation with crashes included the sequencing of the right turn (leading vs. lagging), the number of stages, the length of the cycle time, the degree of saturation, the inter-green time and the presence of a pedestrian stage.

In the United States, Poch and Mannering [6] carried out similar research on 63 intersections in Bellevue, Washington, US where intersection improvements had been carried out between 1987 and 1993; not all of these intersections were signalised. Poch and Mannering used a negative binomial model to correlate crashes with intersection variables. Significant variables at the signalised intersections included the number of phases (e.g. whether left turns (or right turns in New Zealand) were given their own phase), protection of left (right in New Zealand) turns, restricted sight distance, approach gradient, horizontal curvature and the approach speed limit.

Interestingly, Poch and Mannering found an increase in the crash rate when the approach had two or more lanes and a shared left-through lane (right and through lane in New Zealand) because "(1) Left-turning vehicles that must stop and wait for a gap to complete the manoeuvre cause a high potential for rear-end crashes as through vehicles approach in the same lane at prevailing speed; and (2) stopped left-turning vehicles that face stopped left-turning vehicles in the opposing approach must overcome the sight restriction to the opposing through vehicles to successfully complete the manoeuvre." This arrangement (or rather, combined right-through lanes) is employed in a number of locations in New Zealand, normally due to space restrictions at the intersection.

Kumara and Chin [3] evaluated signalised intersections in Singapore. They used a modified Poisson under-reporting model on a sample size of 104 three-legged intersections with nine years of crash data to identify crash causal factors and take into account the traditional under-reporting of crashes to the police. Kumara and Chin specifically highlighted unprotected left-turn slip roads, the number of signal phases per cycle, the use of permissive right turning phases, and restricted sight distances less than 100m as variables that increase crash rates, while right turn channelisation, left turning acceleration lanes, obvious camera surveillance, anti-pedestrian median railing, obtuse intersection angles and approach gradients greater than 5% reduce crash rates. The report expressed some surprise at the reduction in crashes from uphill approaches, noting that "an uphill grade into an intersection may lead to reduced vehicle speeds, while obtuse angles require reduced turning speeds in order to navigate right turns."

Mitra et al. [5] also looked into crashes at four-legged signalised intersections in Singapore, specifically at side-impact and rear-end crashes, which account for 84% of all crashes in Singapore, at such intersections. This research involved the development of zero-inflated probability models, which account for data from intersections during intervals where there are no recorded crashes. This research highlighted that closely adjacent intersections and bus bays will decrease the rate of side-impact crashes, whereas greater sight distance, the presence of pedestrian refuge islands and higher approach speeds increase the rate. Rear-end crashes appear to decrease with adaptive signal control and increase with camera surveillance. Crashes of all kinds increased with the presence of uncontrolled channelised left turns, wider medians, higher approach volumes and an increase in the number of signal phases.

At signalised crossroads, Roozenburg and Turner [7] found that all crash types decreased per vehicle with increasing conflicting flows except rear-end crashes, which increased with increased traffic volumes through an intersection. Data on three-leg intersections showed similar trends for rear-end, loss-of-control, and catchall "others" crashes but there were conflicting conclusions for right-turn-against and crossing crashes. These models were further refined with the addition of non-volume variables to help quantify right turn phasing impacts: number of opposing through lanes, right turn bay offset, intersection depth, right-turn signal phasing (e.g. filtered turns or protected turns) and visibility to opposing traffic. However, only the number of opposing through lanes was deemed to improve the above models. The small data set may have limited some of the variables' influence.

The objective of this research was to quantify the effect that signal phasing has on various crash types at traffic signals in New Zealand and Australia, taking into account the speed limits (and where available, operating speeds), the intersection geometry and the surrounding land-use, be it industrial, commercial (e.g. shopping) or residential, or a combination. Factors such as horizontal and vertical approach alignment have also been factored into the evaluation, along with the duration and configuration of the lost time between signal phasing. Data has been collected in several cities, in order to pick-up the safety impacts of variations in traffic signal set-up.

Modelling methodology

Safety Performance Functions (SPFs) are mathematical models that relate crashes to road user volumes and other road layout and operational features. SPFs are cross-sectional regression models. With crashes being discrete events, and typically following a Poisson or negative binomial distribution, traditional regression analysis methods such as linear regression are not suitable. The models used in crash prediction are developed using generalised linear modelling methods.

Generalised linear models were first introduced to road crash studies by Maycock and Hall [4], and extensively developed in Hauer et al. [2]. These models were further developed and fitted using crash data and traffic counts in the New Zealand context for motor-vehicle-only crashes by Turner [8]. While more advanced modelling methods have been examined in the literature, generalised linear models, with a negative binomial error structure, continue to be preferred by many researchers as in most studies these other modelling methods do not result in a significant improvement in the model fit.

The aim of this modelling exercise is to develop relationships between the mean number of crashes (as the response variable), and traffic flows, as well as non-flow predictor variables. Typically the models take the multiplicative form,

$$A = b_0 x_1^{b_1} \ldots x_i^{bi} e^{b_{i+1} x_{i+1}} \ldots e^{b_n x_n}$$

where A is the mean annual crashes, the x_1 to x_i are measurement variables, such as average daily flows of vehicles, and the x_{i+1} to x_n are categorical variables, recording the presence, for example, of a cycle installation, and the $b_1, \ldots, b_n$ are the model coefficients.

Software has been developed in Minitab in order to fit such models (i.e. to estimate the model coefficients). The popular Bayesian Information Criterion (BIC) has been used as the preferred criterion to decide when the addition of a new variable is worthwhile.

Goodness of fit testing of all models (using the scaled deviance) has also been undertaken by using software that has been written in the form of Minitab macros. This method is based on the work by Wood [11], which takes into account the low mean value problem. The low mean value problem can influence the accuracy of the scale deviance statistic and often occurs when the crash data is disaggregated into various crash types and by time of day. A detailed description of the modelling methodology adopted is given in Wood and Turner [12].

Like all analysis methods there are a number of limitations to the models including; the quality of the data collected for each intersection (given the large sample size there are bound to be errors in the data collected), correlation between predictor variables (this has been minimised) and systematic endogeneity bias (where some features might be introduced only at high crash sites – this is unlikely to be a factor in most if not all predictor variables).

Sample selection and data collection

Signalised intersection sites were selected primarily from a desktop assessment of road maps and aerials, in the six cities. Only three-arm and four-arm traffic signals were included in the sample set, with all arms being two-way and with few turning restrictions. All intersections were on the cities SCATS signal control system (so SCATS signal phasing and traffic count data could be collected) and a significant proportion were on a coordinate traffic signal route. Both low and high speed signals were included in the sample set.

It was recognised that some of the intersections initially selected during the desktop assessment may have undergone significant changes over the five year (crash) study period (2004-2008). Major changes can have an impact on the annual crash frequencies at intersections and introduce error into the modelling. None of the cities had a comprehensive database of changes that had occurred at their traffic signals during this time period. In some cases it was not possible even to confirm the date the traffic signals were installed. In all cities we did have access to experienced and knowledgeable traffic signal engineers that were able to identify those traffic signals that had had significant changes and improvements in this period. The following changes were deemed to be significant; changes to intersection geometry (e.g. addition of traffic lanes), changes to signal phasing (e.g. addition of protected turning phases) and addition of signal aspects or mast arms.

Table 1 shows the number of intersections and approaches selected in each city and the number of intersections that were excluded because of significant changes over the five year study period. Only 31 sites were classified as high speed (13% of the sample). These are intersections where at least one of the intersecting roads has a speed limit equal or greater than 80kph. The majority of the traffic signals had four arms (181).

Data was collected on a wide range of physical and operational characteristics of the signalised intersections. The data was collected for each individual approach of the selected signalised intersection sites. Figure 1 presents a summary of the different categories of data that was collected at each site and the source of the data.

A large number of geometric variables were included in the data set, including facilities for pedestrians, cyclists, buses, motor-vehicles and parking. Key variables included intersection width and depth, number of approach lanes, presence of pedestrian crossings, cycle storage and approach lanes, bus bays and parking in the vicinity of the intersection, offset of right turn bays and distance to the upstream intersection.

Table 1. Selected traffic signals by location

Location	Initial number of selected intersections	Exclusions	Final number of selected intersections	Number of approaches at selected intersections
Auckland	127	38	89	324
Christchurch	66	13	53	205
Dunedin	14	3	11	43
Hamilton	27	10	17	66
Melbourne	69	11	58	214
Wellington	44	34	10	37
	Total		238	889

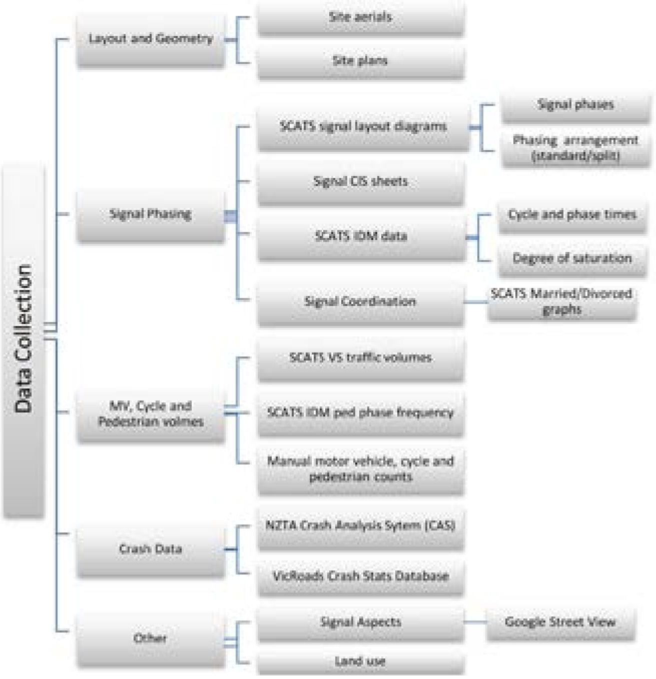


Figure 1. Categories of variables used in the study

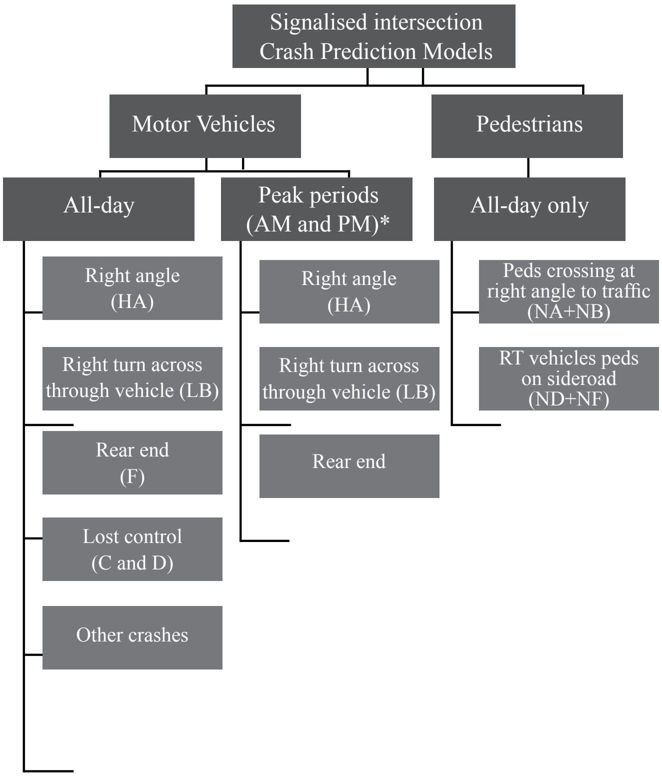


Figure 2. Safety Performance Function Categories

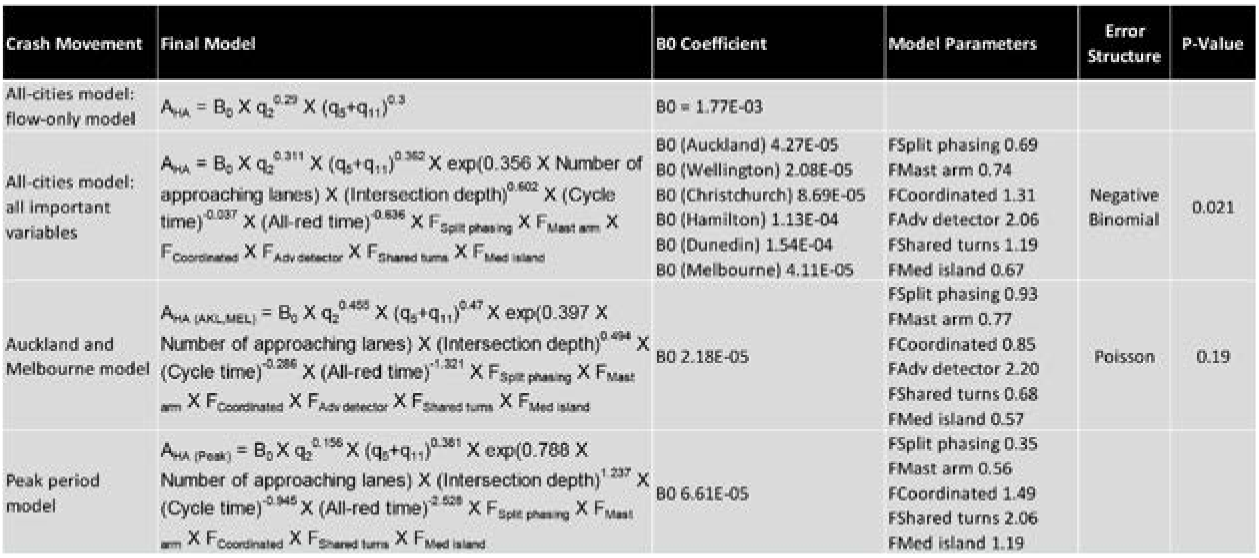
Traffic signal layout variables include height of signal poles, presence of mast arms, number of signal aspect per approach and the layout of the signal aspects. Signal operational variables include cycle time, standard and split phasing, type of right turn phase (filtered, partially and fully protected) and signal coordination (i.e. whether linked with other signals).

Modelling results

Figure 2 presents the various categories of safety performance functions that have been developed in this study. Models were developed for the main crash types for motor-vehicle only and pedestrian versus vehicle crashes and for peak periods only. Appendix A shows the movement coding diagram used in New Zealand. Appendix B includes a description of each of the variables used in the models. It should be noted that the models show the association between each variable and crashes and this does not necessarily mean causation. When key variables are missing or where there is correlation between variables the relationship between a variable and crashes may be unclear, and represent a number of factors. While this is not generally the case here, we suggest readers are cautious in interpreting the results of the modelling.

Models for cycle versus motor-vehicle crashes were not developed as there were insufficient intersections where cycle counts were available. Turner et al. [9] does look at bicycle crashes at traffic signals, using data from Christchurch and Adelaide, where cycle counts are readily available.

Table 2. Right angle crashes models (Type HA)



Crash Movement	Final Model	B0 Coefficient	Model Parameters	Error Structure	P-Value
All-cities model: flow-only model	$A_{HA} = B_0 \times q_2^{0.29} \times (q_5+q_{11})^{0.3}$	B0 = 1.77E-03			
All-cities model: all important variables	$A_{HA} = B_0 \times q_2^{0.311} \times (q_5+q_{11})^{0.362} \times \exp(0.356 \times \text{Number of approaching lanes}) \times (\text{Intersection depth})^{0.602} \times (\text{Cycle time})^{-0.037} \times (\text{All-red time})^{-0.636} \times F_{\text{Split phasing}} \times F_{\text{Mast arm}} \times F_{\text{Coordinated}} \times F_{\text{Adv detector}} \times F_{\text{Shared turns}} \times F_{\text{Med island}}$	B0 (Auckland) 4.27E-05 B0 (Wellington) 2.08E-05 B0 (Christchurch) 8.69E-05 B0 (Hamilton) 1.13E-04 B0 (Dunedin) 1.54E-04 B0 (Melbourne) 4.11E-05	FSplit phasing 0.69 FMast arm 0.74 FCoordinated 1.31 FAdv detector 2.06 FShared turns 1.19 FMed island 0.67	Negative Binomial	0.021
Auckland and Melbourne model	$A_{HA\ (AKL,MEL)} = B_0 \times q_2^{0.455} \times (q_5+q_{11})^{0.47} \times \exp(0.397 \times \text{Number of approaching lanes}) \times (\text{Intersection depth})^{0.494} \times (\text{Cycle time})^{-0.286} \times (\text{All-red time})^{-1.321} \times F_{\text{Split phasing}} \times F_{\text{Mast arm}} \times F_{\text{Coordinated}} \times F_{\text{Adv detector}} \times F_{\text{Shared turns}} \times F_{\text{Med island}}$	B0 2.18E-05	FSplit phasing 0.93 FMast arm 0.77 FCoordinated 0.85 FAdv detector 2.20 FShared turns 0.68 FMed island 0.57	Poisson	0.19
Peak period model	$A_{HA\ (Peak)} = B_0 \times q_2^{0.156} \times (q_5+q_{11})^{0.361} \times \exp(0.788 \times \text{Number of approaching lanes}) \times (\text{Intersection depth})^{1.237} \times (\text{Cycle time})^{-0.945} \times (\text{All-red time})^{-2.528} \times F_{\text{Split phasing}} \times F_{\text{Mast arm}} \times F_{\text{Coordinated}} \times F_{\text{Shared turns}} \times F_{\text{Med island}}$	B0 6.61E-05	FSplit phasing 0.35 FMast arm 0.56 FCoordinated 1.49 FShared turns 2.06 FMed island 1.19		

Right angle crashes

Table 2 shows the models that were developed for right angle crashes (HA type). This crash type involves straight through vehicles on one approach (q2) colliding with a straight through vehicle on an approach to the left (q5) or right (q11) of the first approach (refer to Appendix A for coding conventions used in New Zealand crash data and coding description for each traffic movement). For this crash type a 'flow-only' model and full variable model was developed for all sites for all-day crashes. A separate model was also developed for the peak periods during the working week.

The magnitudes of the constant term (B_0) for the different cities in this model points to a significant variation in the number of HA crashes between cities. This is also likely to be the primary cause of the large variation seen in model results and the resulting low goodness of fit. However, the model does indicate the factors that have a significant effect on safety. Both intersection traffic flow volumes are observed to have similar coefficients. Larger intersections - those having more approach lanes and larger intersection depths - also have more crashes. Split phasing and presence of a mast arm or raised median/central island on the approach are seen to reduce the number of crashes, while approaches having shared turns and traffic signals lying along a coordinated route generally tend to have more crashes. Surprisingly, approaches with an advance SCATS detector appear to have twice the number of crashes as compared to those where these detectors are not present.

Due to the similarities observed between Auckland and Melbourne within this crash group (with similar B0s), a separate model was developed specifically for these two (large) cities. This model had a Poisson error structure and a p-value of 0.19, which indicates that the model is a satisfactory fit. Larger intersections have more crashes, although reduction in cycle time and all-red time has a greater positive effect on safety. Presence of split phasing, mast arms and raised medians reduces crashes, although the magnitude of reduction for split phasing is lower than that predicted by the first model. Presence of an advance SCATS detector is again observed to have a large negative effect on safety. However, in contrast to the model for all cities, presence of shared lanes and signal coordination is seen to result in a decrease in crashes for Auckland and Melbourne.

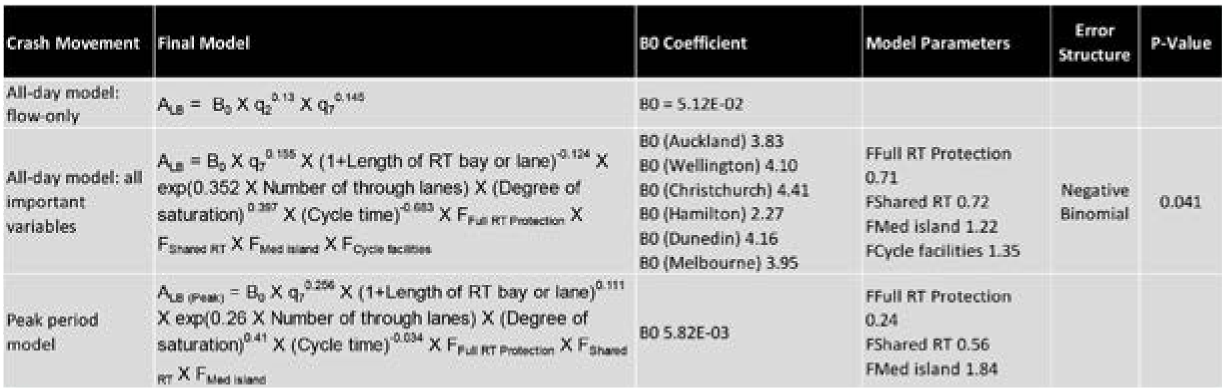
The models for peak periods show some differences in the importance of variables. Interestingly, the conflicting traffic flow from the left and right side of the main vehicle is significantly more important in the morning and evening peak periods as compared to the whole day. The effect of larger intersection size (more crashes), split phasing (fewer crashes) and shared turns (more crashes) is also seen to be more significant in the peaks. Presence of advance detectors is not seen to have an effect in this model.

Right turn against models

Table 3 shows the models that were developed for right turn against crashes (LB type). This crash type involves a vehicle turning right (q7) colliding with an opposing straight through vehicle (q2). This can occur at four different conflict points at a signalised crossroads. Flow only and full variable models were developed for all-day crashes and a model was developed for the peak periods.

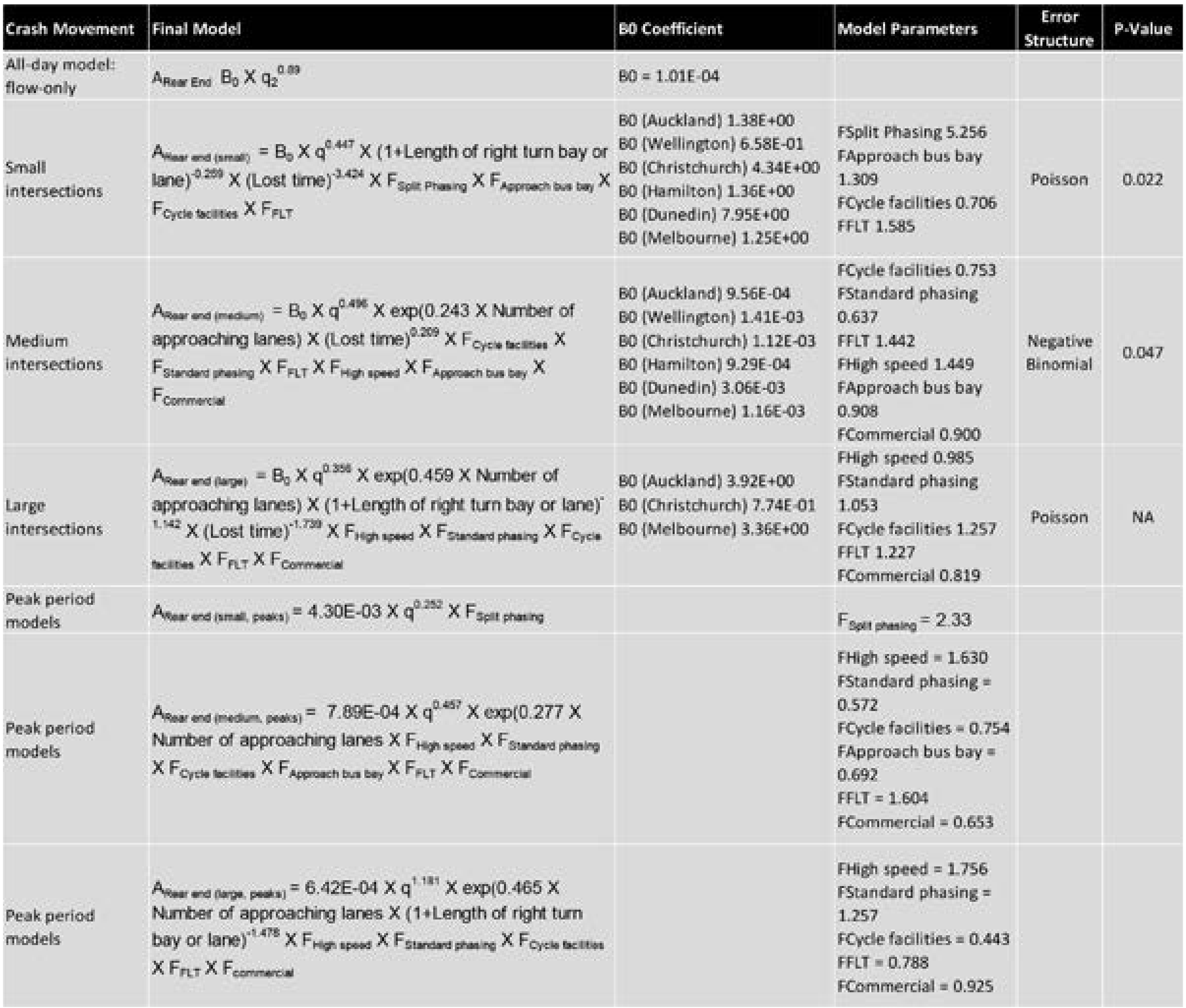
The all-day model for right-turn-against crashes suggests that the right turning traffic volume is a more significant contributor in these crashes than the through traffic volume. Wider approaches (i.e. those having more lanes for through traffic) are more prone to these crashes. Extending the length of the right turning bay or lane results in fewer

Table 3. Right turn against models (Type LB)



Crash Movement	Final Model	B0 Coefficient	Model Parameters	Error Structure	P-Value
All-day model: flow-only	$A_{LB} = B_0$ X $q_2^{0.13}$ X $q_7^{0.145}$	B0 = 5.12E-02			
All-day model: all important variables	$A_{LB} = B_0$ X $q_7^{0.155}$ X (1+Length of RT bay or lane)$^{-0.124}$ X exp(0.352 X Number of through lanes) X (Degree of saturation)$^{0.397}$ X (Cycle time)$^{-0.683}$ X $F_{Full\ RT\ Protection}$ X $F_{Shared\ RT}$ X $F_{Med\ island}$ X $F_{Cycle\ facilities}$	B0 (Auckland) 3.83 B0 (Wellington) 4.10 B0 (Christchurch) 4.41 B0 (Hamilton) 2.27 B0 (Dunedin) 4.16 B0 (Melbourne) 3.95	FFull RT Protection 0.71 FShared RT 0.72 FMed island 1.22 FCycle facilities 1.35	Negative Binomial	0.041
Peak period model	$A_{LB\ (Peak)} = B_0$ X $q_7^{0.256}$ X (1+Length of RT bay or lane)$^{0.111}$ X exp(0.26 X Number of through lanes) X (Degree of saturation)$^{0.41}$ X (Cycle time)$^{-0.034}$ X $F_{Full\ RT\ Protection}$ X $F_{Shared\ RT}$ X $F_{Med\ island}$	B0 5.82E-03	FFull RT Protection 0.24 FShared RT 0.56 FMed island 1.84		

Table 4. Rear-end models (F Type)



Crash Movement	Final Model	B0 Coefficient	Model Parameters	Error Structure	P-Value
All-day model: flow-only	$A_{Rear\ End}$ B_0 X $q_2^{0.89}$	B0 = 1.01E-04			
Small intersections	$A_{Rear\ end\ (small)} = B_0$ X $q^{0.447}$ X (1+Length of right turn bay or lane)$^{-0.209}$ X (Lost time)$^{-3.424}$ X $F_{Split\ Phasing}$ X $F_{Approach\ bus\ bay}$ X $F_{Cycle\ facilities}$ X F_{FLT}	B0 (Auckland) 1.38E+00 B0 (Wellington) 6.58E-01 B0 (Christchurch) 4.34E+00 B0 (Hamilton) 1.36E+00 B0 (Dunedin) 7.95E+00 B0 (Melbourne) 1.25E+00	FSplit Phasing 5.256 FApproach bus bay 1.309 FCycle facilities 0.706 FFLT 1.585	Poisson	0.022
Medium intersections	$A_{Rear\ end\ (medium)} = B_0$ X $q^{0.496}$ X exp(0.243 X Number of approaching lanes) X (Lost time)$^{0.209}$ X $F_{Cycle\ facilities}$ X $F_{Standard\ phasing}$ X F_{FLT} X $F_{High\ speed}$ X $F_{Approach\ bus\ bay}$ X $F_{Commercial}$	B0 (Auckland) 9.56E-04 B0 (Wellington) 1.41E-03 B0 (Christchurch) 1.12E-03 B0 (Hamilton) 9.29E-04 B0 (Dunedin) 3.06E-03 B0 (Melbourne) 1.16E-03	FCycle facilities 0.753 FStandard phasing 0.637 FFLT 1.442 FHigh speed 1.449 FApproach bus bay 0.908 FCommercial 0.900	Negative Binomial	0.047
Large intersections	$A_{Rear\ end\ (large)} = B_0$ X $q^{0.356}$ X exp(0.459 X Number of approaching lanes) X (1+Length of right turn bay or lane)$^{-1.142}$ X (Lost time)$^{-1.739}$ X $F_{High\ speed}$ X $F_{Standard\ phasing}$ X $F_{Cycle\ facilities}$ X F_{FLT} X $F_{Commercial}$	B0 (Auckland) 3.92E+00 B0 (Christchurch) 7.74E-01 B0 (Melbourne) 3.36E+00	FHigh speed 0.985 FStandard phasing 1.053 FCycle facilities 1.257 FFLT 1.227 FCommercial 0.819	Poisson	NA
Peak period models	$A_{Rear\ end\ (small,\ peaks)}$ = 4.30E-03 X $q^{0.252}$ X $F_{Split\ phasing}$		$F_{Split\ phasing}$ = 2.33		
Peak period models	$A_{Rear\ end\ (medium,\ peaks)}$ = 7.89E-04 X $q^{0.457}$ X exp(0.277 X Number of approaching lanes X $F_{High\ speed}$ X $F_{Standard\ phasing}$ X $F_{Cycle\ facilities}$ X $F_{Approach\ bus\ bay}$ X F_{FLT} X $F_{Commercial}$		FHigh speed = 1.630 FStandard phasing = 0.572 FCycle facilities = 0.754 FApproach bus bay = 0.692 FFLT = 1.604 FCommercial = 0.653		
Peak period models	$A_{Rear\ end\ (large,\ peaks)}$ = 6.42E-04 X $q^{1.181}$ X exp(0.465 X Number of approaching lanes X (1+Length of right turn bay or lane)$^{-1.478}$ X $F_{High\ speed}$ X $F_{Standard\ phasing}$ X $F_{Cycle\ facilities}$ X F_{FLT} X $F_{commercial}$		FHigh speed = 1.756 FStandard phasing = 1.257 FCycle facilities = 0.443 FFLT = 0.788 FCommercial = 0.925		

crashes. Degree of saturation is also observed to have a significant negative effect on safety for this crash type. As was the case with HA crashes, longer cycle times also result in a reduction in LB crashes. Fully protected right turn phasing, and shared right/through lanes improve safety, while presence of a raised median and cycle facilities results in higher crash rates.

The right turning traffic volume is observed to have a greater effect on crashes in the peaks as compared to the all-day period. Interestingly, longer right turning bays/lanes results in a slight increase in crashes. Longer cycle times still reduce crashes, although the effect is quite diminished. The effect of full right turn protection (fewer crashes), shared right/through lanes (fewer crashes) and presence of raised median or central island (more crashes) is more pronounced as compared to the all-day period.

Rear-end models

Table 4 shows the models developed for rear-end crashes (F Type). Models that utilised data from all selected intersections were initially developed for rear end crashes. However, a large degree of variation due to intersection size was observed in these model results. It was thus felt necessary to develop models based on the size of the signalised intersection. Intersections were split into three size categories, and crash prediction models were built for each. These categories are: small intersections (those having one or two approaching lanes and intersection depth of 25m or less), large intersections (those having three or more approaching lanes, and an intersection depth of 40m or greater) and medium intersections (those not lying in either of the other two categories). Table 5 shows the number of approaches that fall within each size category, along with the total number of rear end crashes.

Table 5. Number of approaches and crashes by intersection size classification

Intersection size	Number of approaches	Number of crashes
Small	201	36
Medium	611	184
Large	77	93

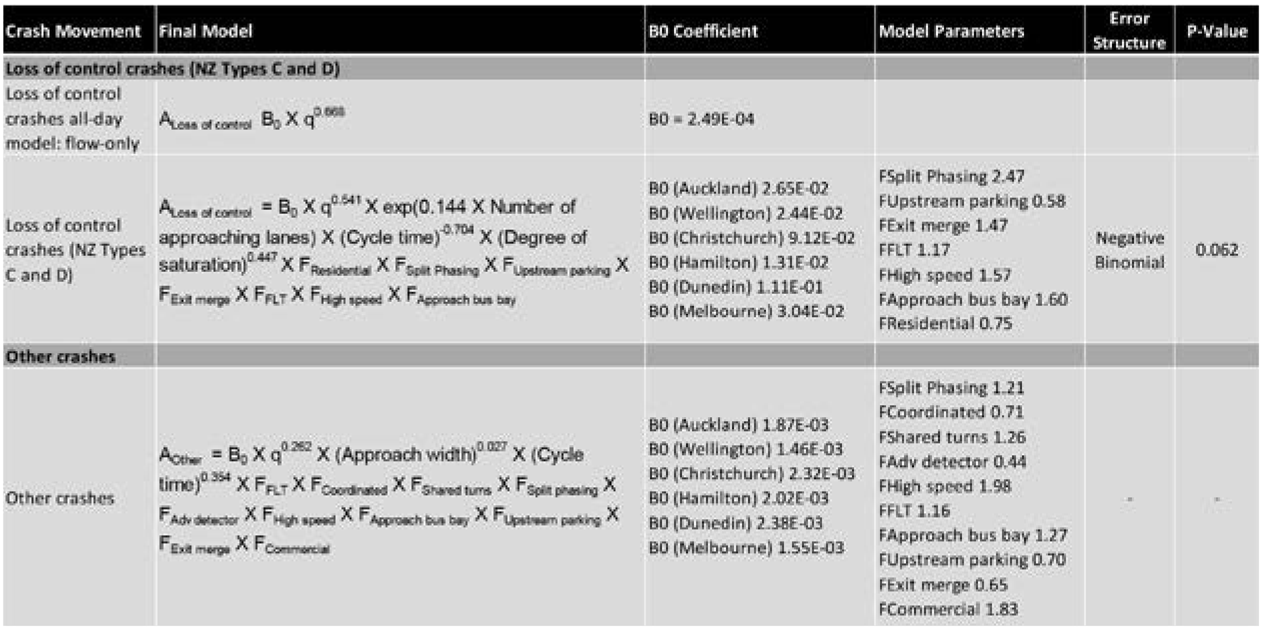
The all-day rear-end crash model for medium sized intersections shows a strong relationship between crashes and the total approach traffic volume. Intersections with more approach lanes also have increased crash numbers. Although lost time has a positive coefficient, this is likely to be the result of variation within the sample set (the non city-covariate model showed a reduction in crashes with longer lost times). The model results also indicate that intersections that operate using a 'standard' phasing arrangement and approaches having cycle facilities, have fewer rear-end crashes. A high speed environment and presence of a free left turn for motor vehicles is seen to negatively affect safety. Presence of an approach bus bay within 100m upstream of the approach limit line and commercial land use environment also appears to lead to slight reductions in rear-end crashes. There was some variation in results at small and large intersections.

The total approach traffic volume during peak periods is observed to show a significant relationship with crashes for medium intersections, while the effect for smaller and larger intersections is less pronounced in comparison. The 'standard' phasing arrangement improves safety at small and medium sized intersections, but not at large intersections where split phasing is more common. The model coefficients also indicate that higher speeds on approaches are a more important factor during the peaks as compared to the all-day period, with more crashes occurring in high speed environments. In contrast to the results of the all-day model, the presence of free left turn lanes at larger intersections is shown to reduce rear-end crashes during peak periods.

Loss of control and other crashes

Table 6 shows the all-day loss of control (Type C and D) and a general model of all other crash types. This Table shows that that more loss of control crashes occur on intersection approaches that have higher volumes, wider approaches and are close to or over-saturated. Increasing

Table 6. Loss-of-control and 'other' crash models



Crash Movement	Final Model	B0 Coefficient	Model Parameters	Error Structure	P-Value
Loss of control crashes (NZ Types C and D)					
Loss of control crashes all-day model: flow-only	$A_{Loss\ of\ control}\ B_0 \times q^{0.668}$	B0 = 2.49E-04			
Loss of control crashes (NZ Types C and D)	$A_{Loss\ of\ control} = B_0 \times q^{0.541} \times \exp(0.144 \times \text{Number of approaching lanes}) \times (\text{Cycle time})^{-0.704} \times (\text{Degree of saturation})^{0.447} \times F_{Residential} \times F_{Split\ Phasing} \times F_{Upstream\ parking} \times F_{Exit\ merge} \times F_{FLT} \times F_{High\ speed} \times F_{Approach\ bus\ bay}$	B0 (Auckland) 2.65E-02 B0 (Wellington) 2.44E-02 B0 (Christchurch) 9.12E-02 B0 (Hamilton) 1.31E-02 B0 (Dunedin) 1.11E-01 B0 (Melbourne) 3.04E-02	FSplit Phasing 2.47 FUpstream parking 0.58 FExit merge 1.47 FFLT 1.17 FHigh speed 1.57 FApproach bus bay 1.60 FResidential 0.75	Negative Binomial	0.062
Other crashes					
Other crashes	$A_{Other} = B_0 \times q^{0.262} \times (\text{Approach width})^{0.027} \times (\text{Cycle time})^{0.354} \times F_{FLT} \times F_{Coordinated} \times F_{Shared\ turns} \times F_{Split\ phasing} \times F_{Adv\ detector} \times F_{High\ speed} \times F_{Approach\ bus\ bay} \times F_{Upstream\ parking} \times F_{Exit\ merge} \times F_{Commercial}$	B0 (Auckland) 1.87E-03 B0 (Wellington) 1.46E-03 B0 (Christchurch) 2.32E-03 B0 (Hamilton) 2.02E-03 B0 (Dunedin) 2.38E-03 B0 (Melbourne) 1.55E-03	FSplit Phasing 1.21 FCoordinated 0.71 FShared turns 1.26 FAdv detector 0.44 FHigh speed 1.98 FFLT 1.16 FApproach bus bay 1.27 FUpstream parking 0.70 FExit merge 0.65 FCommercial 1.83	-	-

the cycle time can result in improved safety. Fewer loss of control crashes are observed at approaches with parking within 100m of the limit line, suggesting more caution on the part of drivers approaching the intersection. Use of split phasing results in a large increase in crashes, while the presence of an exit merge, free left turn lane, upstream bus bay (within 100m) and speed limit of 80kph or more also cause more loss of control crashes. Sites located in residential areas were observed to have fewer crashes as compared to those in commercial or industrial zones.

A range of factors appear to be important in the 'other' model, which is to be expected given the variety of crash types included in this model. Some of the key results of this model suggest that longer cycle times, split phasing, shared left/through or through/right lanes, high speed environments and upstream bus bays within 100m increase crashes, while signal coordination, parking within 100m of the limit line and exit merges reduce crashes.

Pedestrian crashes

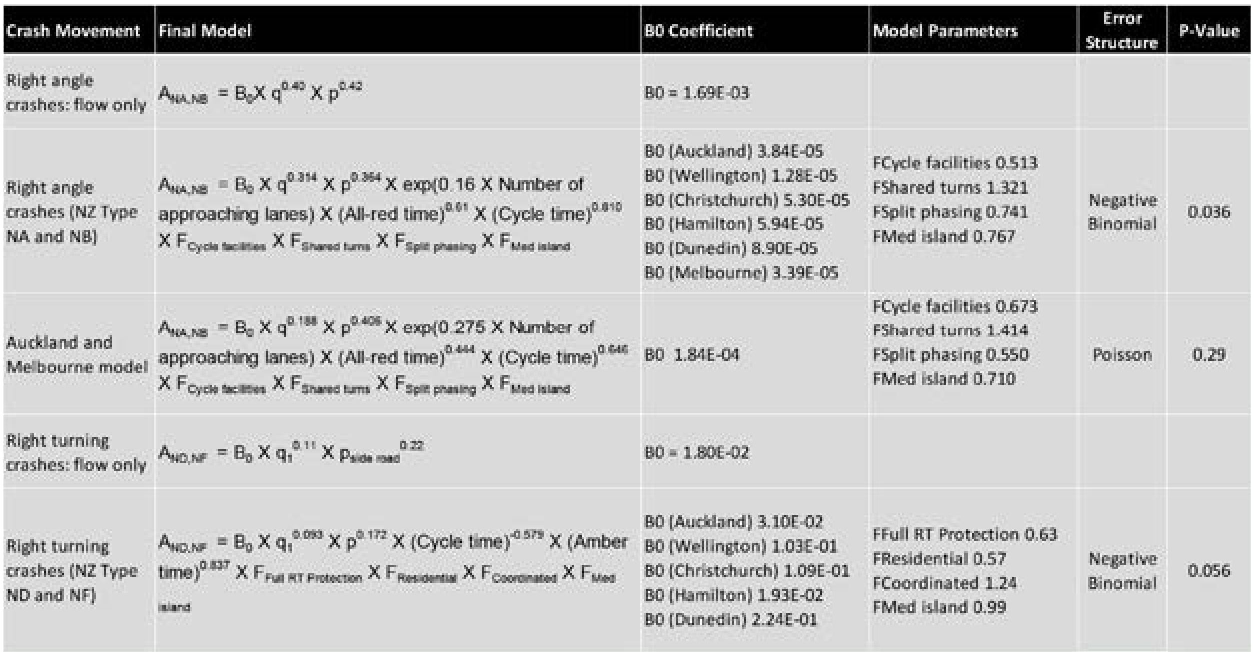
Table 7 shows the models that were developed for crashes between pedestrians and motor-vehicles at traffic signals. There are two key types, right angle crossing (Type NA and NB) and right turn crossing (Type ND and NF). Right angle crashes involve a straight through vehicle hitting a pedestrian crossing at ninety degrees, either from left or right. It is not possible with the New Zealand crash coding to distinguish between nearside and far-side crashes at intersections. Right turn crossing crashes involve a right turning driver hitting a pedestrian crossing the road into which they are turning.

The coefficients for traffic volume and pedestrian volume are similar. Wider approaches are predicted to have more right angle crossing crashes. The variable coefficients for cycle time and all-red time suggest that increasing the length of the signal cycle results in more pedestrian crashes, possibly as a result of pedestrian frustration. A split signal phasing arrangement, presence of a raised median and cycle facilities on the approach result in reduced crash numbers.

The variation in B_0 values for Auckland and Melbourne are observed to be similar. A separate model for the Auckland and Melbourne sites was thus developed to limit some of the variation that is apparent in the all-city model. The coefficient of total approach volume, q, is observed to be lower for the Auckland/Melbourne model as compared to the model for all cities. A split phasing arrangement also shows a higher benefit at the Auckland and Melbourne intersections. The values of the other variables are similar to those found in the model for all cities.

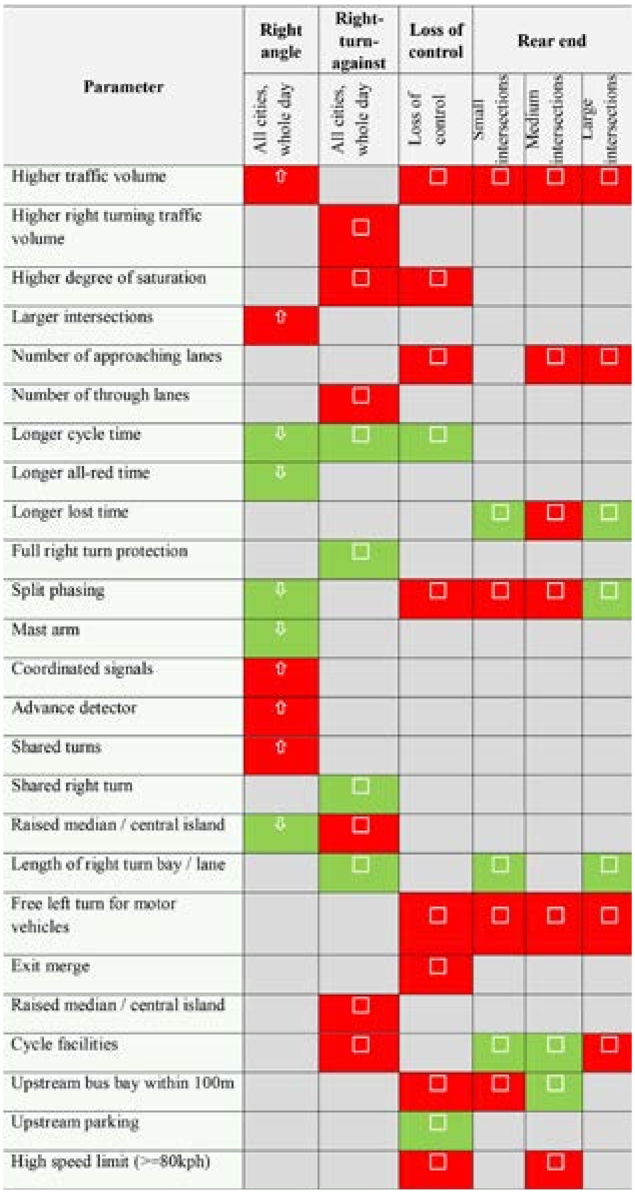
The right turning crossing model shows that the pedestrian volume is a more important factor than motor vehicle volume in crashes. Longer cycle times are observed to reduce crashes, however longer amber times result in an increase in crashes. Fully protected right turns are quite beneficial from a safety perspective, while coordinated signals usually have more crashes. The presence of a median for crossing pedestrians was not found to have a significant effect on safety.

Table 7. Pedestrian crash models



Crash Movement	Final Model	B0 Coefficient	Model Parameters	Error Structure	P-Value
Right angle crashes: flow only	$A_{NA,NB} = B_0 X q^{0.40} X p^{0.42}$	B0 = 1.69E-03			
Right angle crashes (NZ Type NA and NB)	$A_{NA,NB} = B_0 X q^{0.314} X p^{0.364}$ X exp(0.16 X Number of approaching lanes) X (All-red time)$^{0.01}$ X (Cycle time)$^{0.810}$ X $F_{Cycle\ facilities}$ X $F_{Shared\ turns}$ X $F_{Split\ phasing}$ X $F_{Med\ island}$	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	0.036
Auckland and Melbourne model	$A_{NA,NB} = B_0 X q^{0.188} X p^{0.406}$ X exp(0.275 X Number of approaching lanes) X (All-red time)$^{0.444}$ X (Cycle time)$^{0.646}$ X $F_{Cycle\ facilities}$ X $F_{Shared\ turns}$ X $F_{Split\ phasing}$ X $F_{Med\ island}$	B0 1.84E-04	FCycle facilities 0.673 FShared turns 1.414 FSplit phasing 0.550 FMed island 0.710	Poisson	0.29
Right turning crashes: flow only	$A_{ND,NF} = B_0 X q_1^{0.11} X {p_{side\ road}}^{0.22}$	B0 = 1.80E-02			
Right turning crashes (NZ Type ND and NF)	$A_{ND,NF} = B_0 X q_1^{0.093} X p^{0.172}$ X (Cycle time)$^{-0.579}$ X (Amber time)$^{0.837}$ X $F_{Full\ RT\ Protection}$ X $F_{Residential}$ X $F_{Coordinated}$ X $F_{Med\ island}$	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	0.056

Table 8. Effect of intersection parameters on motor vehicle crashes



Parameter	Right angle	Right-turn-against	Loss of control	Rear end		
	All cities, whole day	All cities, whole day	Loss of control	Small intersections	Medium intersections	Large intersections
Higher traffic volume	🟥 ⇧		🟥 ☐	🟥 ☐	🟥 ☐	🟥 ☐
Higher right turning traffic volume		🟥 ☐				
Higher degree of saturation		🟥 ☐	🟥 ☐			
Larger intersections	🟥 ⇧					
Number of approaching lanes			🟥 ☐		🟥 ☐	🟥 ☐
Number of through lanes		🟥 ☐				
Longer cycle time	🟩 ⇩	🟩 ☐	🟩 ☐			
Longer all-red time	🟩 ⇩					
Longer lost time				🟩 ☐	🟥 ☐	🟩 ☐
Full right turn protection		🟩 ☐				
Split phasing	🟩 ⇩		🟥 ☐	🟥 ☐	🟥 ☐	🟩 ☐
Mast arm	🟩 ⇩					
Coordinated signals	🟥 ⇧					
Advance detector	🟥 ⇧					
Shared turns	🟥 ⇧					
Shared right turn		🟩 ☐				
Raised median / central island	🟩 ⇩	🟥 ☐				
Length of right turn bay / lane		🟩 ☐		🟩 ☐		🟩 ☐
Free left turn for motor vehicles			🟥 ☐	🟥 ☐	🟥 ☐	🟥 ☐
Exit merge			🟥 ☐			
Raised median / central island		🟥 ☐				
Cycle facilities		🟥 ☐		🟩 ☐	🟩 ☐	🟥 ☐
Upstream bus bay within 100m			🟥 ☐	🟥 ☐	🟩 ☐	
Upstream parking			🟩 ☐			
High speed limit (>=80kph)			🟥 ☐		🟥 ☐	

Discussion, conclusions and findings

An advantage of building crash prediction models for the different crash types at traffic signals is that this provides a holistic overview of safety at such intersections. The effects of various intersection features and treatments have a positive effect on safety of certain crash types, while negatively affecting other crash types. Table 8 provides a summary of results from the models that have been developed. It lists all factors that were found to be significant in one or more of the models and whether the factor led to an increase (red), decrease (green) or no effect (grey) on the rate of crashes of the respective crash types. The table shows those features that always have a positive or negative effect on crashes and those which can be either depending on the crash type.

A number of intersection parameters such as all-red time, shared turns and signal coordination were observed to affect a specific crash type. However, the model results also highlight the safety benefits obtained from longer cycle times and longer right turning bays across multiple crash types. On the other hand, free left turns for motor vehicles, more approaching lanes and near-saturated or over-saturated intersections were found to increase the risk of having a crash.

Phasing arrangements also figured prominently in the models. Presence of full right turn protection reduced right-turn-against crashes. Split phasing arrangements led to a reduction in right angle crashes and rear end crashes at larger intersections (those with three or more approach lanes and an intersection depth of 40m or greater), but an increase in loss of control crashes, other crashes and rear end crashes at small (one or two approach lanes, less than 25m) and medium intersections (all those not covered in the previous categories).

In addition to the models shown in Table 8, a combined Auckland and Melbourne model was developed for right-angle crashes, while peak period models were built for right angle, right-turn-against and rear end crashes. Coordinated signals showed mixed trends in Auckland and Melbourne (fewer right angle crashes) as compared to all cities together, where they were associated with more right angle crashes. This may be an outcome of drivers in larger cities being used to driving along coordinated corridors.

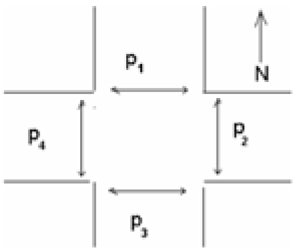
The presence of shared turns (i.e. both shared left/through or right/through lanes) had mixed effects, with an increase in right angle crashes for all cities taken together and in peak periods, but a reduction at the Auckland and Melbourne sites.

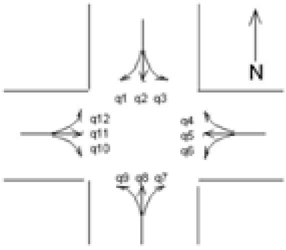
The cycle data collected as part of this study proved insufficient for developing crash prediction models for the prominent cycle crash types. There is a need for more and better quality cycle data from signalised intersections in New Zealand. Future studies should ideally consider a larger sample set for the analysis of cycle crashes. Data from 102 signalised intersections is already available as part of research conducted for Austroads by Turner et al. [10]. There is scope for building upon this data to include additional sites as well as intersection phasing information for the existing intersections. This will enable a more comprehensive dataset to be built which can be drawn upon for future studies.

Appendix A – New Zealand crash coding diagram

Appendix B – Data dictionary (variable names and units)

The two figures below show the four pedestrian phases around a four leg (approach) intersection (P_1 to P_4) and the 12 traffic flow movements at a cross-roads (q_1 to q_{12}). A similar approach can be used to define the pedestrian and traffic flows at T-junctions.





The following table presents each of the variables used in the models and their units. This includes continuous variables and dummy variables (those which are either on or off).

Unit Type	*Variable Description*	*Units*
Continuous Variables	Number of approach lanes	1,2,3 etc..
	Intersection depth	m
	Approach width (entry only)	m
	Length of right turn (RT) bay	m
	Cycle time	seconds
	Lost time (or inter-green – red and amber)	seconds
	All-red time	seconds
	Amber time	seconds
	Degree of saturation – during peak period	Ratio
Dummy Variables	Split phasing (or standard)	Type
	Mast arm	Present
	Coordinated signals (or not)	used
	Advanced (adv) detectors (or not)	Present
	Shared turns (left with through or right with through)	Present
	Median (med) island	Present
	Shared right turn (with through)	Present
	Full right turn (RT) protection (phase) on approach	Present
	Cycle facilities provided	Present
	Bus bay on approach	Present
	Free left turn provided	Present
	Standard phasing (nor coordinated)	used
	High speed approach (above 70kph)	or low
	Commercial development (or other development type)	Type
	Residential development (or other development type)	Type
	Upstream parking provided within intersection	Present
	Exit Merge	Present

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Use of Kloeden et al's relative risk curves and confidence limits to estimate crashes attributable to low and high level speeding

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Abstract

Kloeden et al.'s relative risk relationships have been used in conjunction with vehicle speed measurements to estimate the relative frequency of casualty crashes associated with each speed range. Risks associated with high speeds had generally been ignored because of uncertainty about the relationships. This study estimates the relative crash frequencies using the confidence limits for the relative risks on urban 60 km/h limit roads. The estimated relative risks were also adjusted to reflect the increased probability of serious injury outcomes associated with increased speed. The concept of "population attributable risk" was used to estimate the fraction of crashes attributable to speeding in each illegal speed range. The estimated attributable fraction of casualty crashes was found to be higher for speeds above 80 km/h than speeds in the 60 to 70 km/h range, and higher again when the attributable fractions for serious casualty crashes were estimated. However, the results need to be tempered by the wide confidence limits associated with Kloeden et al's relative risk relationship at high speeds on 60 km/h limit roads.

Keywords

Speeding, Relative risk, Population attributable risk, Attributable fraction

Introduction

Estimates of the relative risk of a casualty crash related to the travel speed of vehicles provide a valuable link between speed observations and crashes in the same road environment. It is possible to predict the crashes associated with each speed range on road and thus consider countermeasures focused on the speeds that make the highest contribution to road trauma. This study made use of Kloeden et al.'s [1] relative risk relationship for urban 60 km/h limit roads in a way that allowed the full range of on-road speeds to be analysed for the first time, including very high speeds. Previous researchers have generally not analysed very high speeds in this way.