Minimum design parameters for cycle connectivity
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Andrew Macbeth and Axel Wilke are acknowledged and thanked for their critical assessment of the drafts of this document. The efforts they undertook significantly influenced and shaped the final form of this work and it is a better work for that critical assessment. ViaStrada does not necessarily support the recommendations of this report nor does their involvement in the research represent agreement with any particular outcome of the project. Indeed, the partnership with ViaStrada might have always been anticipated to bring different views on a problem into a single programme of research without the need for agreement and it is sufficient that process of critical reflection on the outcomes of the work was genuinely undertaken.

The burden of the errors or any criticism that might come from the presentation of this material will fall to its authors.

Abbreviations and acronyms

ANOVA	analysis of variance
ANCOVA	analysis of co-variance
CAS	crash analysis system
CI	confidence interval
df	degrees of freedom
GSM	global system for mobile communications
M	mean
n	the number of cyclists included in a given table or statistical test (sample size)
ns	non-significant
NZTA	New Zealand Transport Agency
RRPM	reflective raised pavement markers
SD	Standard deviation
SPARC	Sports and Recreation New Zealand
USB	universal serial bus

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Executive summary

This research used video surveillance of 1245 cyclists passing pinch points in cycle lanes and road shoulders to determine the relationship between the width of available space for a cyclist and the likelihood of a cyclist traversing the edge line and moving into the motorised vehicle stream. Twenty sites in total were selected in two regions: 10 in Wellington and 10 in Christchurch (although one Christchurch site was eventually excluded). Sites were selected on the criteria of available widths between 0.2m and 1.2m, varied relative heights of adjacent objects and traffic conditions. Objects included storm water drains, kerb extensions and parked cars, and are also referred to as 'obstacles' in this report. Remote camera equipment was installed to observe cyclists riding through the site and to capture their behaviour immediately before and after traversing the site. The video surveillance system used an active pixel monitoring computer that recorded images of cyclists at 0.2 to 0.5 second intervals and was activated when a cyclist approached the object. Each of the 20 sites was monitored from 1.5 to 4 hours in Christchurch and 20 to 40 hours in Wellington to collect on average around 64 cyclist 'events', each consisting of multiple images, per site. These events were classified and coded and the inter-rater reliabilities checked by cross comparison of a subset of the total image sets. Cyclist characteristics and traffic conditions were rated consistently at 91% and 96% in the compared images, and 95% of the estimates of cyclist position were within acceptable bounds of variability.

The images were analysed to establish the effect site characteristics had on cyclists' path trajectories. The most important consideration was to determine the influence of lane narrowings on cycle position and to use this to determine the minimum width at which a cyclist would maintain a course where their wheels were left of the line demarcating the motorised traffic lane.

We found a set of factors (including vehicle speeds, traffic volumes and the position of traffic) that had no significant influence on cycle position at pinch points. Seven other factors were significant in influencing rider position: the height of the object, width available to cyclists at the object, distance from the edge line to the centre line, width available to cyclists downstream of the object, width available to cyclists upstream of the object, width of the traffic lane adjacent to the object and type of bicycle. These results were generally in line with the outcomes of overseas research examining perceptions of level of service (or the quality of the infrastructure provided for cyclists). In particular, other researchers found that perceived level of service was less concerned with cycle lane or shoulder width than with other factors.

The available guidelines (as at December 2010) for the design of a cycle-friendly infrastructure (Austroads 1999; NZTA 2008) were critically examined and reviewed against the idea of recognising a minimum space requirement. The ergonomics of cycle/rider design are acknowledged as providing sensible input into the design constraints for cycle infrastructure but they do not establish the very important component of how the intended design is actually used. This study demonstrated how design and use can be mismatched, that is, the actual design of cycle lanes might fail to match the intent of the design criteria (see Parkin and Meyers 2010). In particular, the observations in this study did not support the contention that 'cycle lanes may offer a greater degree of separation between the cyclist and the motorist' (Parkin and Meyers 2010, p150).

The investigation was supported by presentations to the Greater Wellington Region Active Transport Forum which gave valuable feedback on how to represent the significance of the findings from the observations. It is important to emphasise that the intention of the research was to determine the *minimum* space a cyclist might tolerate without moving into conflict with the motorised vehicle stream. The recommendations set the 'minimum' width at the point most cyclists can maintain a path without moving into conflict because it was observed that this is the threshold at which 'most cyclists do' stay left of the line. Not all cyclists will operate within that space but it would be difficult to accommodate the very wide individual differences in cycling behaviour in any one design recommendation. Cyclists were observed riding outside the line (ie in the motorised traffic stream) even when the available space exceeded 1.8m.

The final sample of observations of 1245 cyclists allowed us to recommend a minimum space requirement at pinch points, recognising that those who currently tolerate occlusions may be experienced cyclists and that the population of 'future cyclists' may require an even greater minimum distance. Putting aside these limitations, a designed space of 0.4m to 0.5m of clear, debris-free pavement will allow a cyclist to ride to the left of the white line and continue past an object without deviating across the edge line into the vehicle stream. This minimum space is recommended, recognising that much of the current road network design provides less than 0.4m of clear space at bridges, kerb extensions, on clear shoulders, at corners etc. When the far left road edge has an object height exceeding pedal height then the minimum should be 0.5m; when the far left edge is flat, 0.4m is the recommended space. For situations where the object may intrude on a cyclist's handle bars (eg fences or hedges) an additional 0.5m of space needs to be provided, resulting in a total space requirement of 1.0m. Parked cars, although handle bar height, require a different treatment due to the risk of car doors being opened into a cyclist's path.

The research has provided evidence to support the idea that natural riding behaviour balances 'maintaining a presence to motorists' and keeping left of the motorised traffic. Our observations of cyclists making a long gradual run up to the objects show that cyclists keep the variation in their trajectory to a minimum in front of other vehicles. The important concern is cyclists are actively maintaining that 'presence' or 'owning the lane'. A consequence is cyclists naturally ride close to the edge line, with the most typical distance being 40mm inside the edge line. Designers, when designing cycle paths, should take into account the natural riding behaviour of cyclists rather than attempt to use design to alter cyclists' behaviour.

This study did not address the cause or reasons for riding further out from the left edge than is objectively thought to be necessary. There must be a reason why cyclists ride close to the edge line when there is space to ride further left and increase their distance from the motorised vehicle stream. Some cyclists and cycling advocate groups are concerned about cyclists riding unnecessarily close to the vehicle stream. This is the wrong interpretation to take from the typical riding position results. There may be exceptionally good reasons for cyclists to ride where they do which we can only speculate on. This research provides clear evidence riders of mountain bikes are around seven times more likely to stay left of the edge line than road cyclists. Again, the co-linearity of variables relating to rider types (speed of cyclists, location and motor vehicle traffic speeds) limited our ability to draw conclusions as to why this pattern of cycling behaviour occurred. Other researchers (eg Parkin and Meyers 2010) have demonstrated methods which could be used to address the issue and we recommend further research is undertaken.

The research drew six conclusions for the future design of cycling infrastructure:

1. Cyclists need at least 0.4m of clear space to the left of the edge line at a pinch point which will afford a continuous trajectory or path continuity. When provided with 0.4m to 0.8m almost all cyclists will ride left of the white line despite the presence of a pinch point.

2. If the far left of the roadside has an object higher than 0.1m then the minimum space to preserve a cycle trajectory is 0.5m. Where objects encroach on a cyclist's handlebars (eg fences) there should be 1m of clear space for the cyclist. Although the risk of doors opening from parked cars was not studied

specifically, with only one site having parked cars as an obstacle, these will require additional site-specific design considerations when accounting for cyclist space.

3 In narrow lanes or shoulders, cyclists will often keep just to the left of the lane line or edge line, despite having extra clear, well-maintained space further to the left in which to ride. When provided with 1.1m of space, most (around 80%) cyclists remain within 40mm of the edge line.

4 Cyclists anticipate pinch points and will minimise the angle of approach, given available space and forewarning of the narrow point. Any pinch point with a sight line of at least 20m will allow the cyclist to negotiate the site and give the perception of maintaining a steady course.

5 1.5m of space or more (eg to match design guidance) is preferred by cyclists. However, there is evidence from this research that at pinch points extending over short distances (eg 5m, the approximate length of the longest pinch point in the study) there is a continuity advantage in providing cycling space down to a width of 0.5m.

6 Cyclists on mountain bikes are considerably more variable in their behaviour and much less likely to be influenced by the presence of roadside objects.

The researchers wish to draw a distinction between what is usable and what is acceptable. The findings of this research represent the *minimum* width of usable space that should be provided at pinch points to ensure most cyclists will pass a pinch point without entering into conflict with the motorised vehicle stream. The recommendations do not represent an acceptable or comfortable level of service provision for cyclists, nor should the recommendations be taken as good design practice for cycle lanes.

Abstract

This research used video surveillance of 1245 cyclists in New Zealand at pinch points to determine the relationship between the remaining lane or shoulder width and the likelihood of cyclists traversing the edge line into the motorised vehicle stream. Ten sites were observed in Wellington and nine in Christchurch. Sites were selected on the criteria of retained cycle space widths at short pinch points between 0.2m and 1.2m wide, variable relative heights of the objects and traffic conditions. Remote camera equipment was installed to capture cyclist behaviour immediately before and after the site. Results established that at 0.4m most cyclists could retain a course inside the edge line and navigate the pinch point without needing to enter the motorised vehicle stream. It was observed cyclists appeared to anticipate pinch points and move to avoid them gradually in a way to minimise lateral movement. The results support recommendations that set minimum path widths of 0.4m for flat objects, 0.5m for pedal height and 1.0m for handlebar height objects. This report contributes a theoretical understanding of the natural riding style of cyclists and proposes a set of recommendations for future research that would support investment in the design of infrastructure to better accommodate cyclists.

1 Introduction

Road cycling is the fifth most popular recreational activity in New Zealand (SPARC 2009). Participation in recreational cycling has increased over the last 10 years, from 15% of the adult population (SPARC 2002) to 22.7% (SPARC 2009). However, when cycling for transport is also considered, there has been an overall decrease in cycling (Ministry of Transport 2009a). One factor which influences the decision not to cycle is a perception of a lack of safety (Federal Highway Administration 1992; Hunt and Abraham 2007). When safety is considered in research it is usually discussed in terms of general, rather than specific, safety concerns and therefore little detail accompanies an understanding of what features of the cycling environment influence cyclists' actual safety or perception of safety.

Accident data indicates that collisions between a motor vehicle and the rear of a bicycle result in a disproportionately high number of fatalities. Stone and Broughton (2003) reported that 10% of collisions where the cyclist was hit from the rear were fatal, compared with 2.9% when the cyclist was hit at the front. In a data subset looking specifically at collisions involving the front of a vehicle and the rear of a cycle, the percentage of cyclist fatalities increased to 17%. Crashes where cyclists were hit from behind were more common in higher-speed zones, with fatality rates for these collisions increasing from 5% in 30mph (48km/h) zones to 31% in 70mph (113km/h) zones. Kim et al (2007) found that of five crash types (bicyclist turning/merging, motorist overtaking, motorist turning/merging, motorist backing and head-on collision), those involving a motorist overtaking were the second most severe type of collision (25.8% serious or fatal injuries) with only head-on crashes being more severe (26.8% serious or fatal injuries). However, head-on collisions represented only 6.6% of the total studied crashes, compared with 23% for those caused when a motorist was overtaking.

An examination of 2008 to 2009 data from the NZTA crash analysis system (CAS) revealed that of the 2225 recorded cyclist accidents, 2071 (93%) occurred on straight roads or roads with easy curves. At least 14% of these crashes occurred when the cyclist was either hit by an overtaking vehicle (8%) or collided with the open door of a parked car (6%). This subset covered crashes where a cyclist's behaviour may have been influenced by a roadside object, eg a cyclist moving towards the traffic lane to avoid a drainage grate and being hit by an overtaking vehicle. Almost 40% of all fatalities were accounted for by this subset of crashes. In contrast, the proportions of severe and minor injuries related to the crash subset were 13.8% and 14.6% respectively. These findings indicated that a disproportionate number of fatal crashes involved roadside obstacles. Additionally, Collins et al (1993) found that collisions with motor vehicles accounted for most cyclist fatalities and about a third of cyclist hospitalisations in New Zealand.

1.1 The problem

Avoidance of obstacles by cyclists has been poorly studied, yet 20% (Munster et al 2001) to 58% (Olkkonen et al 1990) of reported cycle accidents resulting in hospitalisation were due to the collision of a cycle with a road feature. In a New Zealand survey of injured cyclists (Munster et al 2001), 28% of cyclists attributed their crash to road features, with loose gravel most commonly cited as a cause (34%), and other surface irregularities, such as potholes and uneven surfaces (39%), also regularly identified as problematic. Previous overseas work also found that a collision with the kerb or an object on the ground was the most common type of cycling crash, together with falling on a slippery road. These two types of accidents when combined were twice as frequent as a collision with a motor vehicle (Bjornstig and Naslund 1984).

One situation that has received some attention is road narrowing, as a result of creating pedestrian safety features such as kerb extensions and pedestrian islands. Inadequate lane width for cyclists has been identified as a key cyclist safety issue (Austroads 2000). In some cases where sufficient space is not available for cyclists it has been suggested that cycle bypasses be constructed (eg McClintock and Cleary 1995). Uneven quality and width of cycle spaces can also discourage potential cyclists (Stinson and Bhat 2003).

Figure 1.1 shows a cycling refuge, which was created to avoid a significant kerb extension but will possibly be avoided by cyclists because of debris or having to stop for a car that approaches on the side street and severs the natural path. The alternative is to cycle around the kerb extension, still giving right of way to the possible car on the side street and maintaining a visible presence to other motorists. The decision comes at the cost of losing road space and negotiating the reflective raised pavement markers (RRPMs). A redesign could provide sufficient space to allow the cyclist a natural path between the far most right line and the kerb extension.

Figure 1.1 Cycling refuge

In figure 1.2 the cycle lane terminates because of the road narrowing before the bridge. The site was investigated for possible inclusion in the study but pilot observations revealed no cyclist would use it to cross the bridge. The cycle lane is effectively severed, with access to the footpath normally achieved some 50m ahead of the bridge bringing cyclists and pedestrians into conflict on the bridge. The sightlines for cycles and pedestrians are not good over the shared space.

The key to providing more suitable infrastructure for cyclists under these circumstances is determining what exactly defines ‘sufficient space’, and what downstream influence this has on cyclist behaviour when it is not provided. For example, if cyclists tend to follow the path to avoid the lowest level of service then the benefits of any dedicated cycleway can be negated by a single instance of path occlusion. Understanding the minimum space required for cycle connectivity is a key parameter of road design to establish new, empirically based guides for the provision of road space for cyclists.

Figure 1.2 A cycle lane severed by a bridge

1.2 Definitions

This report has adopted terminology from the *New Zealand supplement to Austroads guide to traffic engineering practice part 14-bicycles* (New Zealand supplement) (NZTA 2008), with one exception as explained in the final paragraph of this section. As in the New Zealand supplement, we have used the words 'cycle' and 'bicycle' interchangeably, recognising these include road bikes, mountain bikes, children's bicycles and tandems, but exclude motorised bicycles. The terminology for describing the relative position of cyclists is not straightforward. The international literature uses various terms to describe where cyclists ride: cycle lanes, edge lines, cycle paths, parking lanes, road shoulders, kerbs, footpaths, safety shoulder and the like. In our research we excluded all situations where a cyclist might be separated from motorised traffic by some physical infrastructure. We also excluded recreational off-road cycling on tracks, on dedicated cycle paths through parks, forests or town centres, or on footpaths. The term 'cyclist' may refer to anyone riding a bicycle for any purpose and therefore include those riding for purpose, recreation or sport. While we observed cyclists avoiding narrow bridges by riding down footpaths we were forced to exclude these from the research. Our focus was on the space between the edge line of the carriageway and the gutter, verge, fence, guardrail etc. Concurrently we wished to understand this space and the space in which a cyclist might be found riding, and whether or not the latter space extended over the line into the motorised vehicle traffic stream. Two terms from the New Zealand supplement (NZTA 2008) describe cyclist-specific facilities:

1. Cycle lane: The lane designated generally for the exclusive use of cyclists, except that motor vehicle drivers may use this lane in certain circumstances such as to access parking or to turn at intersections or driveways. A cycle lane is defined in the Traffic Control Devices Rule. See New Zealand supplement, section 4.4.1 Cycle lanes.

2. Cycle path: A path within the road reserve that is physically separated from the roadway (including a cycle track formed under section 332 of the Local Government Act 1974) that is intended for the use of cyclists, but which may also be used by pedestrians. It may not necessarily be within the road reserve (such as in a park or alongside a river, lake or railway line).

The report needs the term 'path' to describe the future position of the cyclist relative to their current position so it cannot be abandoned altogether without some unnatural replacement for the expression 'a cyclist's path'. It should be clear that in this report any reference to a cycle path does not relate to a cycle path as defined in the New Zealand supplement.

1.3 Best practice guidance for cycle lanes and shoulders

The New Zealand supplement (NZTA 2008) is a companion document to Austroads (1999) *Guide to traffic engineering practice (GTEP) part 14 bicycles* for New Zealand designers of cycle facilities.

The New Zealand supplement was developed in recognition of New Zealand legislation and conditions being, in some cases, different from Australia. In addition, the New Zealand supplement provides different advice from the original Austroads guide. In particular, the advice on cycle lane and road shoulder width is considered superior.

Austroads has more recently moved to a new format for technical guidance. It replicates much of the advice provided in the original Austroads series. But advice for cycling, previously covered in one document, is now contained in at least three documents (including the *Guide to road design*, *part 4* and *part 6A,* and the *Guide to traffic management*), making it less accessible. Many consultancies do not yet carry the full range of new Austroads guides as they have only recently been published and are expensive.

The researchers recommend using the advice of the New Zealand supplement (NZTA 2008) which is based on Austroads (1999). It is freely available on the NZTA website and elsewhere. Key advice on cycle lane and shoulder width is as follows. Please note that table and figure numbering are from the New Zealand supplement and hence do not match the rest of this report. Only tables have been reproduced as part of this report.

> ***Part of Section 4.4.1 Cycle Lanes***
>
> ***Application Details – Cycle Lanes Next to the Kerb or Road Edge***
>
> *Cycle lanes next to the kerb or road edge should be implemented in accordance with the details shown in Table 4-1 and its associated notes.*
>
> *The width of road gutters/channels (comprising a different surface medium) should be less than 0.4 m. The widths of cycle lanes in Table 4-1 presume that surface conditions adjacent to the gutter or road edge are of a high standard. Where there are poor surface conditions at the road edge (see Section 8.5 Surfaces for Cycling), then the width of cycle lanes should be based on usable road space available to cyclists.*
>
> *When using Table 4-1, the following key width requirements of cycle lanes where no parking exists, are:*
>
> 1. *At least 2.0 m is desirable where the adjacent motor traffic is moving at high speed (e.g. 100 km/h) and there are few large vehicles, or where speeds are moderate (e.g. 70 km/h) and the volume of large vehicles is substantial. This is also the minimum width that will enable cyclists to overtake each other without encroaching into the adjacent traffic lane;*
> 2. *A space of 1.2 m is the absolute minimum width and should only be used in low speed environments (85th Percentile speed of 40 km/h and below) and when it is not possible to achieve a wider cycle lane*
> 3. *If cycle traffic flows exceed 150 in the peak hour, then additional width to accommodate overtaking manoeuvres should be considered.*

	Lane Width[2] (m)		
Speed Limit[1] (km/h)	**≤50**	**70**	**100**
Desirable Minimum Width	**1.5**	**1.9**	**2.5**
Acceptable Range	1.2-2.2	1.6-2.5[3]	2.0-2.5[3]

Table 4-1: Cycle Lane and Sealed Shoulder Widths

Notes:

1. *The speed limit is used unless the 85th percentile speed is significantly higher.*
2. *Interpolation for different speed limits is acceptable.*
3. *When greater than 2.5 m of shoulder exists, chevron pavement markings should be provided to suggest a cycling area of between 1.5 m and 2.0 m in width and to separate the cycling area from the general traffic lane. In such cases, the chevron markings should be at least 1.0 m wide.*

Typical cross-sections of a cycle lane next to the kerb are shown in Figure 4-4.

Application Details – Cycle Lanes Next to Parallel Parking

Cycle lanes next to parking should be installed in accordance with the details shown in Table 4-2 and its associated notes.

	Cycle Lane Width in Metres[2]		Parking Width
Speed Limit[1] (km/h)	**≤50**	**70**	
Desirable Minimum Width	**1.8**	**2.2**	**2**
Acceptable Range	1.6[3]-2.5	2.1-2.5	1.9 -2.5

Table 4-2: Cycle Lane and Parking Space Widths

Notes:

1. *The speed limit is used unless the 85th percentile speed is significantly higher.*
2. *Interpolation for different speed limits is acceptable*
3. *1.6 m is the absolute minimum width and should only be used in low speed environments (85th Percentile speed of 40 km/h and below) and when it is not possible to achieve a wider cycle lane.*

   Other important aspects of cycle lanes next to parking are:

4. *The absolute minimum width for a cycle lane plus parking should be 3.7 metres. This width requires cyclists to ride close to the adjacent traffic lane to avoid potential collisions with car doors. This width is only acceptable where the mean traffic speeds are no more than about 50 km/h, most parked vehicles are cars, and parking demand and turnover are low. Similarly, where mean vehicle speeds are 70 km/h, the absolute minimum combined width of cycle lane and parking should be 4.2 m.*

5. *Cycle lanes next to parking should not use a "buffer strip" as suggested in GTEP Part 14 (Section 9.6.1.2) to separate cyclists from parked cars. Any extra width should be provided in the cycle lane.*

6. *The width of cycle lane required should be considered in relation to the width of the adjoining traffic lanes and parking spaces. In urban areas it is often preferable to narrow traffic lanes to a width less than 3.5 m to facilitate desired widths for cycle lanes. The extent of such narrowing depends upon the likely presence of large or heavy vehicles. Minimum width cycle lanes adjacent to narrow traffic lanes should be avoided* (NZTA, 2008, pp7–8).

Cycle lanes or shoulders next to the kerb (urban) or road edge (rural) should have a 'desirable minimum width' of 1.5m for roads with speed limits of 50km/h or less, with an absolute minimum of 1.2m in low-speed environments and where it is not possible to achieve a wider cycle lane. Greater widths are required for higher-speed roads.

The locations tested in this research were considerably narrower than this. Accordingly, they should not be thought of as desirable cycle lanes.

For bridges and structures, Austroads (1999) has this to say:

> ***7.2.1 Exclusive Bicycle Lanes***
>
> *If an exclusive lane exists on the approach to the bridge it is desirable that the same width be carried across the bridge. However, if this is not possible the desirable bicycle lane width of 1.5 metres or absolute minimum bicycle lane width of 1.2 metres should be provided (sect. 4.4.1). Additional width is required if the kerb on the bridge is fairly high, greater than 150 mm for example. Assuming 3.4 metre lanes are required for motor traffic this necessitates a bridge width of 9.8 metres or 9.2 metres respectively for a two lane two way bridge.*
>
> *On roads where motor vehicle speeds are above 75 km/h, the volume of commercial vehicles is greater than 400 vehicles per day, or the gradient on the bridge is greater than 5% it is desirable that the bicycle lane be at least 2.0 metres wide.*
>
> *In many cases, particularly in rural and outer urban areas, a sealed shoulder on the bridge and approaches will provide the same level of service to cyclists as an exclusive bicycle lane without the costs of signs associated with the latter* (Austroads, 1999).

The guidance here, when read in conjunction with the New Zealand supplement, suggests that bridges should have shoulders matching the approaches to the bridge – as covered in table 4-1 of the supplement. It is a little more permissive of lower standards ('if this is not possible…') so less ideal widths (1.5m) could be provided on higher-speed bridges. Accordingly, the advice in table 4-1 is supported for bridges. In addition, the New Zealand supplement notes that:

> *However, extra width is desirable to compensate for the "shy space" that is needed by cyclists and drivers when travelling alongside the edges of bridges or tunnel walls*
>
> *Where bridges have significant gradients or are subject to strong winds, extra width for cyclists will be necessary. High traffic volumes and proportions of truck traffic also increase stress levels for cyclists on bridges and in tunnels and require extra facility width. On these*

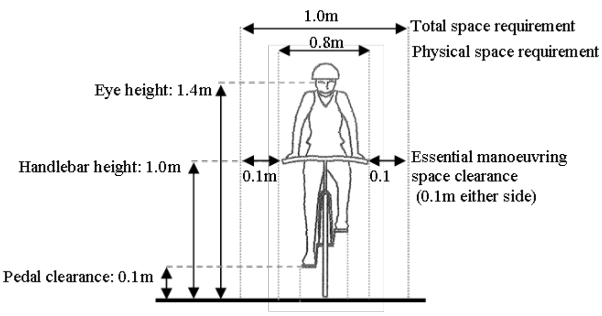
facilities, cyclists usually do not have an escape option to the side as is usually the case on roads.

Where insufficient width is available (typically on existing bridges and tunnels), provision of alternate facilities such as "clip-on" bridges or alternate routes for cyclists may also be required. In some situations, proportionate reductions in all lane widths (both for general traffic lanes and cycle lanes/road shoulders) should be considered to provide an appropriate level of safety for all road users (NZTA 2008, p8).

1.4 Existing cycle lane width guidelines

In summary, existing guidelines recommend that a lane or shoulder between 1.2m–3.0m wide should have a smooth, debris-free surface so that cyclists do not swerve out into the path of traffic (Austroads 1999; NZTA 2008). In practice, cycle lanes are often disrupted by secondary uses including car parking, the provision of utilities or poor road maintenance such as pot holes, debris and loose gravel. The cost of creating cycle lanes means they are not common, and when they are provided they are often not continuous, being broken by pedestrian refuges, bridges, intersections and other road features. Construction guidelines recommend tolerances to account for irregularities of existing surfaces (Austroads 1999), but even when these are provided they relate poorly to cyclists' perceptions of comfort (Cairney 2003) whose behavioural response is to ride in and out of the general traffic lane. Figure 1.3 presents a representation of the space required by cyclists.

Figure 1.3 Approximate cyclist space requirements (adapted from Transit NZ ((2005)), this figure has been updated for NZTA ((2008)) but the updated figure is not as detailed as the one presented here)



The New Zealand supplement (NZTA 2008) provides clear guidelines for the provision and design specification of dedicated cycle lanes. The supplement states that 1.2m is the 'absolute minimum' cycle lane width and this is only to be used on low-speed roads (ie 50km/h speed zones) where no vehicle parking exists (NZTA 2008). International guides also suggest minimum cycle lane widths of 1.0m (Devon County Council 1991) and 1.2m (AASHTO 1999), and typically recommend 1.5m for cycle lanes next to the kerb. Table 1.1 gives the space requirements of different vehicles, showing that a truck travelling alongside a cyclist requires a 4m space.

Intuitively, the lateral clearance between cyclist and motorist increases with the width of the traffic lane. Loder and Bayly (1989) found that average lateral clearances ranged from about 0.3m for 3.0m traffic lanes (as measured from the edge of the kerb) to clearances of 0.8m for 4.0m traffic lanes.

Table 1.1 Actual physical space requirements of bicycles, cars and heavy vehicles compared with design allowances in New Zealand and the United Kingdom

Vehicle type	Actual physical space occupied (Davies et al 1997b)	Carriageway occupied (Devon County Council 1991)	Physical space allowance in New Zealand (NZTA 2008)
Bicycle (with cyclist)	0.75m	1.00m	1m*
Car	1.70m	2.00m	1.80m
Heavy vehicle (eg bus or truck)	2.55m	3.00m	2.40m

* This value includes a buffer of 0.1m of essential manoeuvring space on either side of the cyclist.

The width of cycle lanes, according to current New Zealand standards, varies depending on speed zone and provision for parking (Austroads 1999; NZTA 2008), shown in table 1.2. This is very similar to international recommendations, which state there is ideally an additional space requirement when a motor vehicle passes a cyclist of 0.40m in slower speed zones, and 0.75m–1.00m in faster speed zones (Devon County Council 1991).

Table 1.2 Desirable cycle lane widths across different speed limits and environmental conditions. Values drawn from Austroads (1999) and NZTA (2008)

Additional width requirements	Cycle lane width (m)		
	50km/h	70km/h	100km/h
Minimum allowed space	1.5 (1.2–2.2)	1.9 (1.6–2.5)	2.5 (2.0–2.5)
Additional space for parking	3.8 (3.5–5.0)	4.2 (4.0–5.0)	NA
Additional allowance for heavy vehicles	Not known	Not known	Not known

Note: Acceptable ranges in parentheses.

In the case of roads without cycle lanes, guidance is less specific for space considerations that would naturally assist the cyclist to keep left of the road traffic lane, especially where there are obstructions or a narrowing of available space. (Note that New Zealand is a left-hand traffic country.) Despite a lack of specific guidance, the problem is recognised:

> *When cyclists use sealed shoulders care must be taken to ensure that the continuity of cycling facilities is maintained and any narrowing of the shoulder does not put cyclists at risk* (NZTA 2008, p11).

Roadside bottlenecks from tunnels and bridges are often provided as ‘worst-case’ examples of situations where discontinuity in the road shoulder causes cyclists to enter the traffic lane (eg Federal Highway Administration 1992), and have been linked to a reduction in use of the shoulder.

1.5 Previously identified problem obstacles

Previous research by Walton et al (2006) suggested cyclists would avoid almost all obstacles by moving towards the right; that is, towards the motorised vehicle stream. The observed exception is a flat aluminium utility cover for telephone cable access that is cycled over without difficulty. Walton et al (2006) found raised obstacles (ie obstacles at bicycle pedal height or higher) which clearly narrowed the cycleway, including a pedestrian island, parked motor vehicle or a bridge, were observed to induce cycle/vehicle conflict (meaning sharing the same road space) as was expected. Walton et al (2006) also found lower obstacles, including utility access covers, drainage grates, rough and smooth sections of pavement, roadside debris and gravel also caused avoidance behaviour and consequently potential conflict with motor vehicles. Examples of guidelines for dealing with roadside obstacles and in-road obstacles (eg manhole covers) are provided in tables 1.3 and 1.4.

Table 1.3 Current road design guideline recommendations for minimum cycle lane width allowances past roadside obstacles (eg drainage grates, pedestrian refuges)

Obstacle	Recommended width allowance
Bridges (where alternative footbridges are not available) and tunnels	Minimum of 1.2m (Austroads 1999) at 50km/h or less; greater width for higher-speed roads as in New Zealand supplement, table 4-1. Where bridges have high gradients or are exposed to high winds 'extra width' is recommended, but a recommendation is not given for the amount of additional space. In the case of insufficient lane width, it is recommended that a 'clip-on' bridge or alternative path be provided (NZTA 2008).
Drainage grates and utility covers	Austroads (1999, table 1.4, below) specifies that the height of a step (such as a utility cover) should not be more than 10mm.
Pedestrian crossing refuges (where raised refuges interfere with the road shoulder in the cycle path)	NZTA recommends that pedestrian refuge islands should not be spaced closer than about 4.5m from the kerb in a 50km/h area to allow room for cyclists or a cycle lane (NZTA 2007, pp15–19).

Table 1.4 Maximum dimensions of non-flush obstacles (eg manhole covers and driveway edges) in a new cycle lane. Adapted from table 8.1 in Austroads (1999)

	Not to exceed (mm):	
	Width of groove	Height of step
Parallel to direction of travel	12	10
Perpendicular to direction of travel	–	20

Several traffic calming measures implemented for pedestrian safety have been identified as hazardous for cyclists and can discourage cycling, for example, pedestrian kerb extensions (where there is insufficient space between the extension and the kerb) and rough or textured surfaces (such as coloured pavers) (McClintock and Cleary 1995).

The literature acknowledges that road narrowing can adversely affect cyclist behaviour and safety. For instance, while pedestrian refuges can improve pedestrian safety (LTSA 1994), these refuges can push cyclists into the traffic lane, thereby increasing the danger for cyclists (McClintock and Cleary 1995). Parked cars are another common cause of disruption to the cyclist's path (Hunter et al 1998; Wood 1999). Researchers have proposed different recommendations to mitigate the risks of cyclist course disruptions.

Davies et al (1997b) recorded videos of cyclists passing through 15 different sites where the road narrowed. The main purpose was to observe whether cyclists stayed on the road or chose another option such as cycling on the footpath when passing through a road narrowing. Based on these observations Davies et al (1997b) provided two main recommendations. First, they indicated that road narrowing should be avoided wherever possible through improved enforcement or scheme design. If the road had to be narrowed they recommended either providing a 4.5m space for vehicles to pass the cyclists or installing separate cyclist facilities. Second, speed reduction measures were recommended if space was limited. General comments included altering the US Highway Code to set a minimum distance before narrowings within which vehicles could not overtake cyclists. Davies at al (1997b) recommended further research into the behaviour of car drivers when overtaking cyclists on 2.5m–3.5m wide roads.

Daff et al (1989) provided guidelines on the minimum kerbside lane widths for cyclist safety, with inadequate kerbside lanes being associated with an increase in crash risk (Austroads 2000). Daff et al (1989) recommended a kerbside lane with parking should be between 3.7m and 4.2m wide. This width reduced the opportunity for other vehicles to share the lane with the cyclist, while providing space for the cyclist to pass the parked cars. The research underlying these guidelines was based on observing 49 cyclists: 29 cycling in a kerbside lane free of parking and 20 cycling in a kerbside lane with parking. As there is significant individual variation in cyclist behaviour (Walton and Thomas 2007), the sample may have been too small to produce robust guidelines.

Wood (1999) made suggestions for different narrowing conditions, many of them based on the Dutch standards (CROW 1993). For bus stops Wood recommended positioning a cycle path on the left or right of the bus stop. The only suggestion for narrow bridges was to add a clip-on section to provide cycle facilities, although he did not discuss the costs of this. Narrow streets could have the traffic lane width reduced to add a cycle lane, or speed limits could be reduced. Wood's main suggestions concerned resolving disruptions caused by parked cars. Recommendations included adding cycle paths, better enforcement of drivers parking on cycle paths, or kerb build-outs to restrict vehicle parking at intersections. Wood's research was based on an analysis of New Zealand fatal crash data, and did not take into account actual cyclist behaviour.

To ensure traffic calming measures are cycle friendly, McClintock and Cleary (1995) outlined seven guidelines, four of which related to disruptions of the cycle space. Cyclists could be excluded from the traffic calming measure (such as a cycle path through a speed hump), which was similar to Davies et al's (1997b) suggestion to provide separate cycle facilities where possible. If a separate path was not possible, they recommended leaving a 3.5m space from the kerb to a central refuge. Parking should be avoided where it increased the risk to cyclists. Finally, the road surface should be suitable for the users, so cobbles and similar roading materials should be avoided where there were cyclists. The recommendations in this paper were theoretically derived rather than based on experimental work.

These recommendations provide a basic outline of how to account for cyclists in roading projects. However, there is limited research on the specific location on the road chosen by cyclists when passing roadside obstacles that cause lane narrowing. Davies et al's (1997b) research indicated that some cyclists avoided a narrowing by choosing routes other than the main carriageway. From a cyclist safety perspective, the concern would have to be for those who ride in the traffic lane to avoid a road obstacle. To produce robust guidelines the behaviour of cyclists who could come into conflict with traffic needs to be observed in detail.

1.6 Attitudes to cycle lane or shoulder discontinuity

Anything that forces cyclists into conflict with motor vehicle traffic is likely to cause anxiety and may discourage cycling. For example, in an examination of new cycle owners, Davies and Hartley (1998) reported that a quarter of cyclists said they cycled less as a consequence of their experiences with motor vehicle traffic on busy roads.

Davies et al (1997b) interviewed cyclists at selected road narrowing sites where traffic calming measures had created 'squeeze' points. They found that cyclists reported a higher sense of anxiety; about half the cyclists disliked the narrowing and about a third felt less safe at the narrowing. A quarter of cyclists believed that the nearest vehicle would pass them at the narrowing, which was probably a low estimate, as driver overtaking did not reduce noticeably at these points. About 16% of the cyclists also believed that 'assertive' cycling (ie cycling faster, holding their line and pulling into the middle) was the safest approach to the road narrowing.

Landis et al (1997) found that wider sealed surfaces increased perceived level of service for cyclists. Cycleways with a painted strip separating cyclists from traffic were perceived to have a 50% higher level of service, despite having higher volumes of traffic. Striped cycleways were also perceived as safer and less hazardous. Poor pavement surfaces had a strong negative effect on perceived level of service; however, good quality surfaces had a smaller effect on positive perceptions.

Drivers are critical of cyclist behaviour and commonly cite cyclists not signalling their intentions, cyclists getting in the way, and the unpredictability of cyclists as among the most annoying cycling behaviour (eg Basford et al 2002). More specifically, in a driving simulation study Basford et al (2002) found that scenarios with a road narrowing (caused by a pedestrian kerb extension) significantly reduced driver ratings of confidence in a cyclist's behaviour and their perception of how considerate a cyclist was.

1.7 Actual cyclist behaviour

Cyclists do not typically use the kerb to select their lane position. Bell and Dolphin (1990) found that two-thirds of cyclists travelled between 0.3m and 2.1m from the kerb (depending on the road conditions, cf Davies et al 1997b). Most cyclists tend to ride 0.3m–0.5m inside the edge line even when the road shoulder is more than 1.5m wide (Walton and Thomas 2007). Therefore, cyclists choose not to keep further left and away from traffic. Further, approximately 10% of cyclists prefer to ride on the road with the traffic despite the presence of an adequate shoulder (Walton and Thomas 2007).

Cyclists are thought to ride according to a perceived minimum standard of service so a disruption of the cycle lane may generate riding behaviour downstream that is consistent with their perception, but at odds with the level of service provided by the road (Davies et al 1997a). That is, even with a clear and adequate path, cyclists avoid keeping left, and this desire to avoid the road shoulder is based on the worst level of service encountered during their overall trip or that section of their trip. Walton and Thomas (2007) found that a discontinuity to the cyclists' path had a larger carry-on effect, where 61% of cyclists who were forced to move into the traffic lane maintained their riding position after the 'squeeze' point.

Davies et al (1997b) observed that even when cycle bypasses were in place, actual cyclist use of these varied between 25% and 92%. Walton and Thomas (2007) examined cyclist behaviour when travelling in locations with specific obstacles such as rough ground, utility access covers and pedestrian facilities. They found three sites which, when compared with a smooth asphalt surface, had the same low likelihood of encouraging cyclists to move into the traffic lane. Two characteristics these sites had in common were a lack of vertical features (eg raised guttering) and a road shoulder space greater than 0.45m. At the other 'obstacle' sites cyclists were at least 11 times more likely to move into the traffic lane.

Cairney (2003) surveyed cyclists about typically encountered deficiencies in the cycle network, and asked them to rate the seriousness of these deficiencies. Respondents reported that rough surfaces and narrow cycle lanes were serious problems which were encountered frequently, whereas potholes and slippery surfaces were relatively more serious, but encountered less frequently. Pavement surface cracking was frequently encountered, but not viewed as a serious problem.

1.8 Purpose of this research

Our interest was in cyclists who encounter naturally occurring roadside objects due to the design of the road (eg encroaching pedestrian kerb extensions), or due to a function of its maintenance (eg intruding bushes) as these are features that can be managed by a change in practice. In a previous work, Walton and Thomas (2007) organised a group of cyclists to ride a route with naturally occurring objects in their path. The intention of this study was to observe cycling behaviour as naturally as possible, or at least without the overt presence of an observer. Remote camera equipment captured images of cyclists riding past the obstacles and each 'event' became the basis for inclusion in the study; the events became the objects of interest, not the cyclists per se.

The research described in this report studied the minimum design parameters for cycle connectivity on urban roads that did not have special provision for cyclists. The primary outcome of the research was to determine the minimum space conditions that allowed cyclists to stay outside the normal traffic lane (ie within the cycle lane or road shoulder) while cycling on urban roads.

1.9 Hypotheses

The research, which was based on the belief that cyclists could and would maintain a straight course given sufficient space, had a central aim of determining the threshold at which this proposition became false. From this, three hypotheses were developed:

1. The probability of a cyclist crossing the edge line when confronted with a partial obstruction to the cycle path is a function of the starting position and the size of the obstruction. Conversely, the probability of a cyclist staying within the lane is a function of the width of available space and the initial starting position of the cyclist.
2. The observed starting position is a function of the type of cycle, traffic flow, speed of the cyclist, gender and age.
3. Whether conflict with traffic continues is a function of the nature of the obstacle and the characteristics of the route prior to the obstacle, and the amount of obstruction of the obstacle.

End user groups such as the Wellington Region Active Transport Forum encouraged us to consider a wider set of observations than would be strictly necessary within our original brief or to address the basic hypotheses. There are few reported observation studies of cyclists and core statistics are not common, nor are they frequently updated. We have also included in our results a set of descriptive statistics for wearing cycle helmets, riding two-a-breast and carrying luggage. This data is provided recognising that the sample is not strictly random but any design effect resulting from the method of sampling is likely to be insignificant or clear to those who may rely on the data.

2 Methodology

2.1 Participants/cyclist observations

A total of 1301 cyclist event observations were made between 5 September 2009 and 2 February 2010: 622 in Christchurch and 679 in the Wellington region. Nine cyclist events were removed from consideration as they involved cyclists on the footpath. These events were important but were so dwarfed by the usual cycling activity that they were not considered further. Cyclist gender (table 2.1), cycle type (table 2.2) and age category (table 2.3) were estimated from the camera images and hence include subjective error (see section 3.1). Different types of cyclists were observed at the locations and this was reflected in differences across the two centres and across sites. The primary reason was that Christchurch has a wider demographic of cyclists riding for a wider set of travel purposes, using predominantly mountain bikes. In Wellington observations were typically, though not exclusively, made at sites which captured recreational cyclists on road bikes.

Being a natural experiment no control was made on whether a cyclist might reappear through the observation points on different days. It bears reminder that our concern was with cycling events, not cyclists, and it is conceivable, and likely, that the same person appeared in different sites or across the same site at different times.

Table 2.1 Percentages of estimates of gender by site number and city. A higher proportion of female cyclists were observed in Christchurch than Wellington

Christchurch					Wellington			
Estimated gender (%)					Estimated gender (%)			
Site	Female	Male	n		Site	Female	Male	n
1	24	74	50		11	9	91	43
2	33	62	55		12	14	84	44
3	36	64	76		13	13	88	40
4	37	63	71		14	9	91	44
5	20	80	90		15	5	95	103
6	47	53	45		16	13	85	91
7	24	71	59		17	27	70	143
8	36	62	47		18	15	80	66
9	16	84	43		19	18	80	61
10	28	72	86		20	23	77	44
Total	**30**	**69**	**622**		**Total**	**16**	**83**	**679**

Note: Values have been rounded to the nearest whole percentage. Observations where gender could not be estimated have been excluded from the table and hence the percentage may not sum to 100%.

In cases where it was not possible to judge either gender or age, for instance if the participant was facing away from the camera, then the data was coded as missing. The type of bicycle was easier to judge from the images and hence there was no missing data for bicycles.

Table 2.2 Percentage of bicycle types by site and city. For Christchurch mountain bikes were most common, while road bikes were most common for Wellington

Christchurch						Wellington				
Type of bicycle (%)						Type of bicycle (%)				
Site	**Mountain**	**Road**	**Other**	**n**		**Site**	**Mountain**	**Road**	**Other**	**n**
1	56	44	0	50		11	0	100	0	43
2	62	38	0	55		12	0	100	0	44
3	84	16	0	76		13	5	95	0	40
4	85	15	0	71		14	7	93	0	44
5	84	13	2	90		15	4	96	0	103
6	67	33	0	45		16	3	97	0	91
7	59	41	0	59		17	7	93	0	143
8	70	28	2	47		18	6	94	0	66
9	63	37	0	43		19	59	39	2	61
10	59	41	0	86		20	57	43	0	44
Total	**70**	**29**	**0**	**622**		**Total**	**13**	**87**	**0**	**679**

Note: Values have been rounded to the nearest whole percentage

Table 2.3 Percentages of estimates of age category by site and city. The age trends for both Christchurch and Wellington were very similar

Christchurch							Wellington					
Estimated age category (%)							Estimated age category (%)					
Site	**Under 15**	**16–35**	**36–50**	**51+**	**n**		**Site**	**Under 15**	**16–35**	**36–50**	**51+**	**n**
1	0	80	18	2	50		11	0	100	0	0	43
2	0	91	9	0	55		12	2	68	18	0	44
3	3	74	21	3	76		13	0	68	30	3	40
4	3	66	31	0	71		14	0	82	9	0	44
5	1	69	30	0	90		15	0	77	10	0	103
6	2	80	18	0	45		16	2	82	7	0	91
7	0	80	15	0	59		17	0	68	27	0	143
8	15	77	6	0	47		18	0	95	5	0	66
9	0	74	26	0	43		19	2	74	21	0	61
10	1	78	21	0	86		20	0	73	27	0	44
Total	**2**	**76**	**21**	**0**	**622**		**Total**	**1**	**78**	**16**	**0**	**679**

Note: Values have been rounded to the nearest whole percentage. Observations where age could not be estimated have been excluded from the table and hence the percentage may not sum to 100%.

2.2 Site selection

Sites were selected based on the distance between a roadside obstacle (eg edge of seal or storm water drains) and a line delineating the edge of the traffic lane. The main criterion was that the space available to cyclists between the obstacle and the traffic lane should be less than the minimum recommendation of

1.2m at 50km/h (see Austroads 1999; NZTA 2008). Only naturally occurring obstacles were used due to the inherent risks of placing objects in the path of cyclists.

Twenty sites in total were selected for study, 10 in the Wellington region and 10 in Christchurch. For each site the available space upstream and downstream of the obstacle, the height of the obstacle, and the width of the adjacent vehicle lane were measured. The width of the site at the pinch point was measured considering the usable space to the immediate inside edge of the shoulder line, edge line or extrapolated demarcation line (if the line was not exactly present at the pinch point but was present immediately before it). All sites were located on predominantly straight sections of road to avoid the influence of corners on cyclist positions, and most had similar quality surfaces (predominantly chip seal with some asphalt). Within each site there were no substantial changes in surface quality; using sites where the surface quality changed would have introduced a confounding factor that might have influenced the cyclist's position. Therefore, within each site all cyclists were riding on the same quality surface, regardless of their lane position.

Traffic speed limits were either 50km/h or 100km/h. All sites in Christchurch were 50km/h and all but two sites in Wellington were 100km/h. Site characteristic and observation point measurements for Christchurch and Wellington are presented in tables 2.4 and 2.5 respectively. More information on the sites is provided in the appendices. Due to concerns about site 9 because of the nature of the obstacle[1] and the lack of reliable height information, this site was not included in the remaining analyses, resulting in a final sample of 1245 observations.

For this project the term 'kerb' referred to both the edge of the footpath near the gutter on urban roads and a concrete edge next to a rural road. The before and after measurements were taken approximately 10m either side of the obstacle as this represented where the cyclist observations were made from the camera images. This distance represented around one to two seconds of travel time for cyclists travelling at 30km/h and 20km/h respectively.

Table 2.4 Road and site measurements for the Christchurch sites. These were the specific measurements used in the data analysis. The applicable width of the marked cycle lane is the before pinch point lane width

Location	Obstacle details	Marked cycle lane	Speed limit (km/h)	Cycle lane width			Traffic lane width	Object height
				Before pinch point	During pinch point	After pinch point		
Site 1	Storm water drain	NU	50	0.70m	0.30m	0.40m	3.20m	0m
Site 2	Storm water drain	Yes	50	1.35m	0.70m	1.30m	3.23m	0m
Site 3	Vehicle parking	NU	50	0.74m	0.74m	2.50m	3.50m	1.55m
Site 4	Kerb	Yes	50	1.50m	0.63m	1.3m	2.90m	0.10m
Site 5	Storm water drain	Yes	50	1.15m	0.63m	1.15m	3.00m	0m
Site 6	Kerb	WU	50	1.40m	0.55m	1.40m	3.65m	0.14m
Site 7	Pedestrian crossing kerb extension	Yes	50	1.50m	0.84m	1.45m	3.15m	0.12m

[1] The obstacle for site 9 was a bush intruding into the shoulder. The bush differed from the other obstacles in two key ways. First, unlike the other obstacles the bush was not solid. Second, the remaining 19 obstacles all had a presence at the level of the road, whereas the bush did not. The other obstacles higher than 0.1m could have interfered with the cyclists' pedals, while this was not the case for the bush. These two differences meant that the bush might have had a qualitatively different effect on cyclist behaviour than the other obstacles.

Location	Obstacle details	Marked cycle lane	Speed limit (km/h)	Cycle lane width			Traffic lane width	Object height
				Before pinch point	During pinch point	After pinch point		
Site 8	Kerb	WU	50	1.17m	0.40m	1.30m	3.7m	0.11m
Site 9	Intruding bushes	Yes	50	1.03m	0.50m	1.03m	3.00m	NA[(a)]
Site 10	Kerb	Yes	50	1.10m	1.10m	1.05m	3.10m	0.14m

Note: NU = shoulder less than 0.8m wide and no marked cycle lane (narrow unmarked); WU = shoulder wider than 0.8m and no marked cycle lane (wide unmarked).

[(a)] For site 9 the original object height measurement was incorrect and therefore no height was recorded.

Table 2.5 Road and site measurements for the Wellington sites. These were the specific measurements used in the data analysis. The applicable width of the marked cycle lane is the before pinch point lane width

Location	Obstacle details	Marked cycle lane	Speed limit (km/h)	Cycle lane width			Traffic lane width	Object height
				Before pinch point	During pinch point	After pinch point		
Site 11	Edge of seal	WU	100	1.85m	1.0m	2.05m	3.4m	-0.08m
Site 12	Kerb	WU	100	0.94m	0.85m	0.75m	3.4m	0.10m
Site 13	Edge of seal	NU	100	0.65m	0.20m	0.25m	3.3m	-0.08m
Site 14	Kerb	WU	100	1.10m	0.70m	0.40m	3.8m	0.12m
Site 15	Kerb	NU	100	0.50m	0.40m	0.35m	4.7m	0.12m
Site 16	Edge of seal	NU	100	0.35m	0.50m	0.35m	6.8m	-0.05m
Site 17	Edge of seal	NU	100	0.50m	0.30m	0.45m	7.3m	-0.08m
Site 18	Traffic island	WU	100	0.80m	0.80m	2.77m	3.6m	0.12m
Site 19	Pedestrian crossing kerb extension	Yes	50	1.10m	0.45m	1.00m	5.2m	0.13m
Site 20	Storm water drain	Yes	50	1.15m	1.00m	1.15m	5.7m	0m

Note: NU = shoulder less than 0.8m wide and no marked cycle lane (narrow unmarked); WU = shoulder wider than 0.8m and no marked cycle lane (wide unmarked)

The widths referred to in tables 2.4 and 2.5 are not necessarily clear widths. That is, there might have been temporary or permanent obstructions in the cycle lane that reduced the usable width. Temporary obstructions included broken glass, stones and loose foliage (eg fallen branches), while the main permanent obstructions were reflective raised pavement markers (RRPMs). During the study no temporary obstructions were observed, but RRPMs were noted for some sites (see appendix B, sites 12 and 13). As the study focused on obstructions on the far left of the road, RRPMs were not studied in detail. However, their influence on cyclist behaviour should be noted, such as causing the cyclist to avoid them by travelling further to the left or into the traffic lane, as cycling over RRPMs has been shown to reduce cyclists' stability (eg Cleland et al 2005).

2.3 Equipment

The core equipment consisted of a computer running video monitoring software, and three water-resistant cameras. The computer was stored inside a locked steel box and was powered by a portable battery. The cameras were mounted at the top of a 3m-high pole, with one focused on the obstacle, one focused upstream and one focused downstream. The software was configured to capture the upstream and downstream images when motion was detected on the obstacle camera. More details about the functioning of the software are provided in section 2.4. Figure 2.1 presents the computer equipment and figure 2.2 shows the equipment in the field. The custom-built computer system included a specialised graphics card to manage the volume of data, a GSM-linked USB data card for real-time configuration of settings and another cellular phone system to remotely turn the system on and off to conserve the main battery. The original set-up of the video monitoring equipment required the site to have a pole in close proximity to which the cameras could be attached. As these sites were difficult to find the portable pole was added to the design.

Figure 2.1 The custom-built computer system

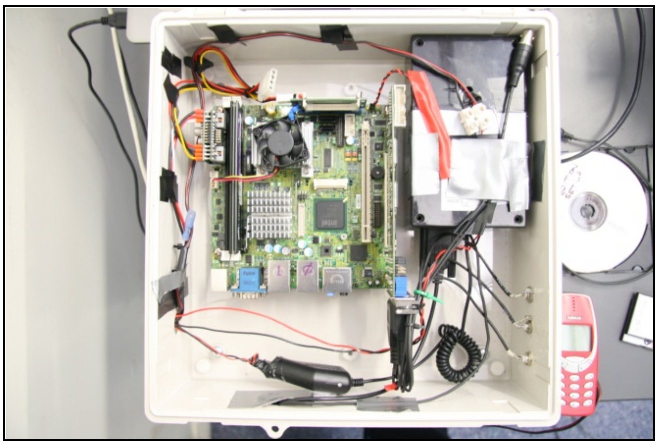


Figure 2.2 Video monitoring equipment in Wellington, site 18, State Highway 2

ZoneMinder open-source software was used for video monitoring. The software monitors user-defined *activation zones*, and records images if movement is detected within a zone. An example activation zone is presented in figure 2.3. When there was an alteration to the pixels in the activation zone (ie any movement in the space) a series of images were recorded, and these were referred to as an 'event'.

Figure 2.3 shows an example activation zone (red, bottom) and exclusion zone (blue, top) as used at a pilot site. If a vehicle passed through both the activation zone and the exclusion zone no images were recorded. Cyclists were more likely to only pass through the activation zone, thereby triggering the recording of images.

Figure 2.3 Example activation zone (red, bottom) and exclusion zone (blue, top) at a pilot site

The cameras could be functionally linked to enable motion detected on one camera to trigger events on the other two cameras. For this project the camera focused on the obstacle in the activation zone, and when a cyclist was detected passing the object, which was the main interest, both upstream and downstream images were also recorded. Upstream images were taken from an image buffer, which enabled images prior to the cyclist passing the obstacle to be recorded. In essence the computer was constantly recording images from each of the three cameras but when a cyclist triggered an object site event the computer 'selected' the appropriate images from its stored record and placed them in an 'event folder'. An example of the object, together with upstream and downstream images from site 2 in Christchurch is shown in appendix A.

2.3.1 Technical issues and resolutions

The cameras were originally mounted on an existing power pole or structure adjacent to the site (eg a lamp post or pedestrian crossing pole). This method was favoured because of concerns for camera security but it unduly narrowed site selection. To overcome this we developed a frangible pole that was secured to the steel box housing the computer equipment. A concern was that the pole might wobble and the pixel monitoring would be corrupted. This was overcome by adjusting camera sensitivity and by employing techniques within the design of the pixel monitoring software that required a significant change in the image to trigger an event.

Initial testing meant many false events were triggered by passing vehicles, vehicle shadows, buses, trucks, trailers, reflections, insects, birds, litter and even a police car, which parked under the camera zone to issue an infringement notice to a motorist. Given the relative frequency of vehicles to cyclists, it was necessary to develop methods of filtering out non-cyclist causes of events. The first method trialled was the use of exclusion zones. When movement was detected within an exclusion zone the activation zones were deactivated. An example of an exclusion zone can be seen in figure 2.3. The second method was modifying the camera configuration to reduce the likelihood of the movement of fast objects, such as cars, being detected. The use of exclusion zones was tested at a pilot site (see section 2.3.2), while the logic behind the camera configuration was first developed in a controlled laboratory setting then trialled on site.

For the first two Wellington sites only the exclusion zones were used. Due to a concern regarding the possibility of recording all passing vehicles, the activation zones and exclusion zones were set conservatively. This is likely to have resulted in cyclists being missed by the system, especially those who were cycling in the vehicle lane. Through experience the two methods were used to effectively reduce the number of false hits while detecting cyclists both within the shoulder and in the vehicle lane.

2.3.2 Motion detection validation at a pilot site

A pedestrian island site (pilot site) was used to validate the proportion of hits (correctly identifying the cyclist) under different cyclist behaviours. A confederate cycled through the site at different speeds and at different lane widths.

In the initial cycle runs, where cyclists rode in line with the edge line marking, there were 90% hits (n=10). When cyclists rode a further 15cm out from the edge line (ie 15cm into the traffic lane) there were 100% hits (n=3), but when cyclists rode 30cm out from the edge line there were 0% hits (n=3). The inclusion zone was increased to 1.2m wide (from the object) and was approximately 2.0m long. The sensitivity on the exclusion zone was decreased (so that the head or shoulders of a passing cyclist did not exclude the cyclist). After these alterations the confederate cycled through at a width of between 1.0m and 1.2m with a hit rate of 80% (n=10).

2.4 Experimental measures

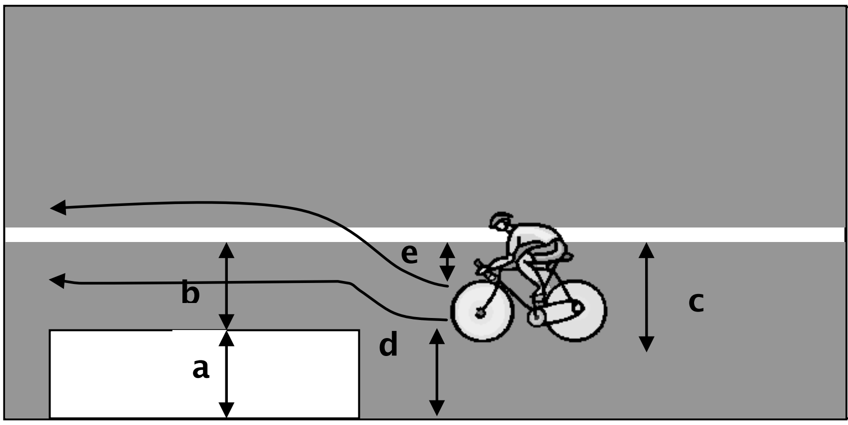
The key dependent variables were the likelihood of conflict with other vehicles (ie the proportion of cyclists who chose to move into the vehicle lane), the likelihood of return behaviour (ie the proportion of cyclists who returned to the left of the vehicle lane) and look backs (ie the proportion of cyclists who looked back to check for traffic). The presence and position of motor vehicles in relation to the cyclist were also recorded.

Key independent variables assessed the relationship between conflict, available space and starting position (see figure 2.4). Cyclist characteristics (age, gender, speed), bicycle type (mountain bike, road cycle), discontinuity characteristics (bridge, drainage grate, object height), weather conditions (dry or wet), and time of day were also examined, with the key variables shown in table 2.6. The presence of a vehicle was likely to influence a cyclist's behaviour, and was coded in general terms as judging the distance between a vehicle and a cyclist from the camera images was too difficult due to the quality of the images.

Table 2.6 Primary observational measures taken from the recorded images

Measure	Description
Cyclist characteristics	
Gender	Estimated from images: male or female
Age group	Broadly categorised into: 5–15 years, 15–35 years, 36–50 years, and 50 years and over
Cycle type	Mountain bicycle, road bicycle, BMX/child's bicycle
Speed	The approximate speed of cyclists (slow, medium, fast)
Width maintenance behaviour	
Lane position	The lane position of the cyclist 1) before 2) during and 3) after the narrowing
Conflict	Whether cyclists are in conflict (in the traffic lane) 1) before and 2) during the narrowing
Traffic interaction	
Motor vehicle	The presence of a motor vehicle: none, ahead of the cyclist, adjacent to the cyclist, behind the cyclist.

Figure 2.4 Variables related to the cyclist position passing a roadside object. The position of the cyclist past the object (d and e) is predicted to be based on the space available next to the object (b) and the starting position (c)



a Object creating discontinuity

b Available space (cm)

c Starting position (cm)

d Path avoiding 'conflict' with vehicle stream

e Path entering vehicle stream

3 Results and analysis

3.1 Inter-rater reliability

A list of all coded measures (eg bicycle type, cyclist position) is included in table 2.6. A subset of 210 images was coded by a second coder to assess inter-rater reliability. For the cyclist characteristics, the two coders agreed 91% of the time for cyclist age and 94% for cyclist gender. The presence of motor vehicles was rated consistently by the two coders at 96%.

The riding position data was coded as a proportion of the gap between the white line marking the edge of the traffic lane and the far left of the road. A rating of 0.5 meant the cyclist was riding in the middle of the gap, 1 indicated the cyclist was to the far left of the gap, 0 indicated they were on the white line, and negative numbers indicated the cyclist was in the traffic lane. Estimates were made using units of 10% of the gap rather than absolute distances. For coding the riding position data the two coders' estimates were the same at 52%, with 83% of the estimates being within 1 unit of each other and 95% within 2 units. Differences between the two coders did not show any systematic bias (ie the first coder's estimates were not always or usually higher or lower than the second coder's estimates).

These inter-rater reliabilities are considered to be of an acceptable level.

3.2 Baseline riding behaviour

The concept of 'cycle/vehicle conflict' is for the most part a conceptual aid to understanding the relationship between vehicles occupying road space. Here the opportunity exists to quantify the position of the cyclist as a function of the various measures described above. However, whether the positions constitute 'conflict' depends on the way the observed measures are construed. Please note that not every cyclist observed at the object was also observed upstream and/or downstream, so the sample sizes vary based on the observation position being discussed.

Our general approach was to consider the road edge line or cycle lane line as the demarcation of the lane, and any cyclist with their cycle wheels to the right of this point was defined as being in conflict with other types of vehicles, thus recognising a person riding inside the line may still overhang the line. Considered this way, our observations yielded 528 (n=1245) cyclists (42.4%) riding in conflict with the vehicle stream across a range of pinch points from 0.2m to 1.1m.

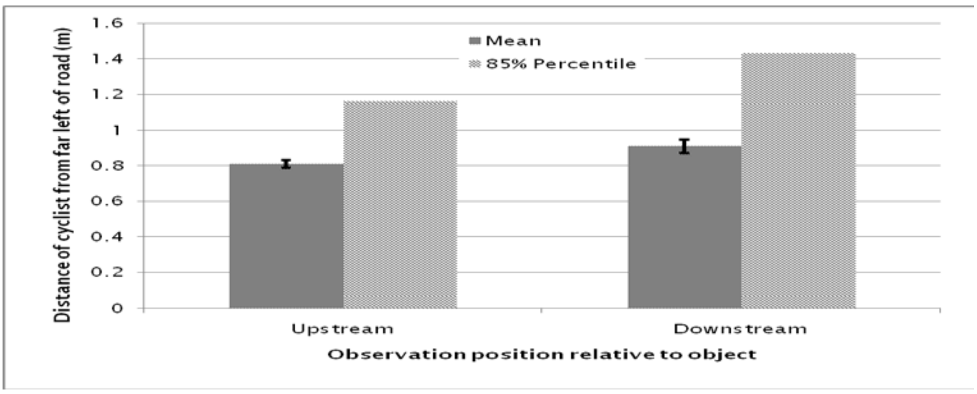
The position of the cyclist ahead of the pinch point was of critical importance. When the pinch points were all conceptualised as arising from a continuous 1.2m road shoulder narrowing to the various object sizes it was reasonable to record those cyclists who were outside the line as being 'in conflict' before the object. These physical conditions were rare and not well represented in the data. Widths before sites ranged from 0.35m to 1.85m, and in at least one case the pinch point actually expanded the available space for the cyclist (site 16 in Wellington). Considered simply, 431 (n=1115) cyclists (38.6%) would be deemed to be 'in conflict' prior to the object.

The usual riding position prior to the object was found to be on average 40mm inside the edge line (standard deviation (SD)=335mm). After the object, the mean riding distance was 55mm inside the edge line with around the same variation (SD=360mm). These findings should be considered in recognising a wide variation in the available space prior to and after the pinch point.

Across all sites (N=1115), cyclists rode with a mean distance of 0.81m (SD=0.36m) from the shoulder edge or kerb face (whether or not they were inside or outside an edge line) prior to encountering the object. The 85th percentile distance was 1.16m (see figure 3.1).

Across all sites, (N=1173) cyclists were found to ride a mean distance of 0.91m (SD= 0.67m) from the edge after encountering the object. The 85th percentile distance was 1.43m (see figure 3.1). Again, these observations were simple and made across all site conditions and did not account for any variations in object height, speed zone, lane width and type of cycle. Most importantly, the fact that cyclists tended to ride between 0.8m–1.3m from the extreme left of the road shoulder did not mean that this behaviour defined where they would ride under different conditions. However, most riders were within a 0.5m envelope around the reference point, the line of demarcation of the cycle lane or shoulder.

Figure 3.1 Differences in cyclists' mean and 85th percentile riding position relative to the far left of the road for observations made upstream and downstream of the object



The basic test of whether the objects had any effect on cyclists' behaviour was achieved by comparing the observations of each cyclist's position prior to, adjacent to, and after each obstacle, F (2, 2012)=11.019 p. <.001. In both Christchurch and Wellington, encountering the object led to some change in the cyclists' positions relative to the white line demarcating the shoulder or cycle lane. The results established riding behaviour did vary according to a site's characteristics but as these differed depending on the site the results merely showed that our observations included variations which needed explanation.

3.3 Type of bicycle

Tables 2.4 and 2.5 show the Christchurch sites were urban areas with 50km/h speed limits and the Wellington sites were predominately 100km/h road sections. There was a strong correlation between road speed limit and bike type, r(1246)=.65, p <.001, indicating that road bikes were more common in 100km/h zones while mountain bikes were more common in 50km/h zones (see table 2.2). Rather predictably, cyclists on road bikes were more often observed riding fast compared with cyclists on mountain bikes χ^2 (2, n=1240) =325.27, p<.001.

3.4 The influence of a pinch point on riding behaviour

Sites were chosen with a range of conditions to help identify what influenced riding behaviour. However, to develop a model showing the influence of road design on cycling behaviour, a range of site variables were required to explain the variation in riding behaviour at the object. In ideal conditions we would have experimented with adjusting a single variable, such as available path width at the obstacle. Doing this would have posed an obvious risk to the cyclist and made the result artificial through the presence of observers and the efforts of cyclists.

A stepwise regression was undertaken considering three variables:

1 Rider characteristics, including behaviour

2 Road design characteristics

3 Traffic conditions as represented in table 3.1.

The number of cyclists analysed at the 19 sites was reduced by excluding those who were observed in highly aberrant positions (such as on the footpath n=9). The main dependent variable was the cyclist's position relative to the edge line. Table 3.1 outlines the correlation between the individual variables and the cyclist's lane position at the object (the main dependent measure).

Table 3.1 Influence of rider, road and traffic factors on the rider's position at the object. Higher or lower numbers indicate more influence, while numbers close to 0 indicate no influence

Factor	r		Factor	r
Rider characteristics				
Rider's position upstream of object[(a)]	.93***		Rider's age[(b)]	.01
Rider's position downstream of object[(c)]	.91***		Rider's gender[(de)]	.08*
Estimated speed of rider[(f)]	.29***		Rider was wearing a backpack[(g)]	.39***
Bicycle type [(h)]	.40***		Cycle had pannier/saddle bags[(g)]	.11***
Riders travelling two abreast[(g)]	.06*		Rider was not wearing a helmet[(g)]	.07**
Leading and following riders' wheels overlap[(g)]	-.05		Rider looked over their shoulder when passing object[(g)]	.02
Road design characteristics				
Cycle path width at object (cm)	.53***		Width of traffic lane at object (m)	-.65***
Cycle path width upstream of object (cm)	.71***		Height of object (cm)	.05
Cycle path width downstream of object (cm)	.38***		Speed limit (50km/h or 100km/h)	-.51***
Traffic conditions				
Vehicle parked in cycle lane[(g)]	-.02		Leading car as well as following car[(g)]	.04
Vehicles stopped in lane next to cyclists[(g)]	.08**			

Note: n=1245 except where specified.

[(a)] n=1115, [(b)] n=1202, [(c)] n=1130, [(d)] n=1226, [(e)] male =1, female =2, [(f)] n=1239, [(g)] factor coded 1 if true, 0 if false, [(h)] mountain bike =1, road bike =2.

*** p<.001, ** p<.01, * p<.05.

The regression of cycle position at the object against the various conditions excluded a surprising set of variables. This should be recognised against the possible contribution of a range of excluded factors, such as whether or not traffic was present, the speed of the cyclist and the speed of the traffic. For example, the road speed limit co-varied with the location (Christchurch had only 50km/h zones) but this was not found to be a significant predictor of cycle position in the regression analysis so was excluded from further consideration. Other variables excluded were personal factors such as the estimated age and gender of the cyclists which had no significant influence in the model.

The final model contained the cyclist's position before the object, the width of the shoulder before and after the object, the width of the traffic lane, the height of the object and, importantly for our main concern, the width of the point where the available space narrowed. The model explained an impressively high 87.5% of the variation in cycle positions, with an adjusted R^2=.875, F (7, 1106) = 1114.2, p.<.001 using seven predictor variables. Put another way, knowing five characteristics of the environment, the type of bike and the cyclist riding position more than 20m before encountering the object, the position of the cyclist in relation to the object could be predicted accurately about 85% of the time. Table 3.2 outlines the contribution of each predictor to the overall equation.

Table 3.2 Relative influence of the main predictors on estimates of cyclist position. Higher or lower beta values indicate more influence

	Unstandardised coefficients		Standardised coefficients	t	Sig.
	B	Std error	Beta		
Intercept	-0.11	0.03	NA	-4.03	0.00
Cycle lane width at object	0.11	0.02	0.08	5.08	0.00
Cyclist position before obstacle	0.85	0.02	0.80	49.96	0.00
Downstream cycle path width	0.04	0.01	0.07	4.38	0.00
Upstream cycle path width	0.03	0.02	0.03	1.53	0.13
Width of the traffic lane adjacent to the obstacle	-0.01	0.00	-0.05	-3.36	0.00
Height of the obstacle	-0.05	0.02	-0.04	-2.68	0.01
Type of bicycle (coded)	0.03	0.01	0.04	3.49	0.00

Standard error of the estimate =.126.

If the two types of bicycle were considered separately then the set of variables in the combined model was better at predicating the position of road bikes (R^2 = .894, F (6, 690) = 979.73, p.<.001) than mountain bikes (R^2 = .706, F (6, 410) = 164.29, p.<.001). This recognised that riders of mountain bikes showed more variability in their movement in relation to the objects they encountered than road bikes which displayed a more predictable movement to the right (χ^2 (1, n = 1114) = 191.60. p.<.001). Indeed, the odds ratio demonstrated that road bikes were seven times more likely than mountain bikes to either maintain or enter into a conflict position on encountering an object (OR = 7.21, 95% CI 5.35, 9.71). Clearly, road bikes are more sensitive than mountain bikes to variation in the pavement width or to an obstruction.

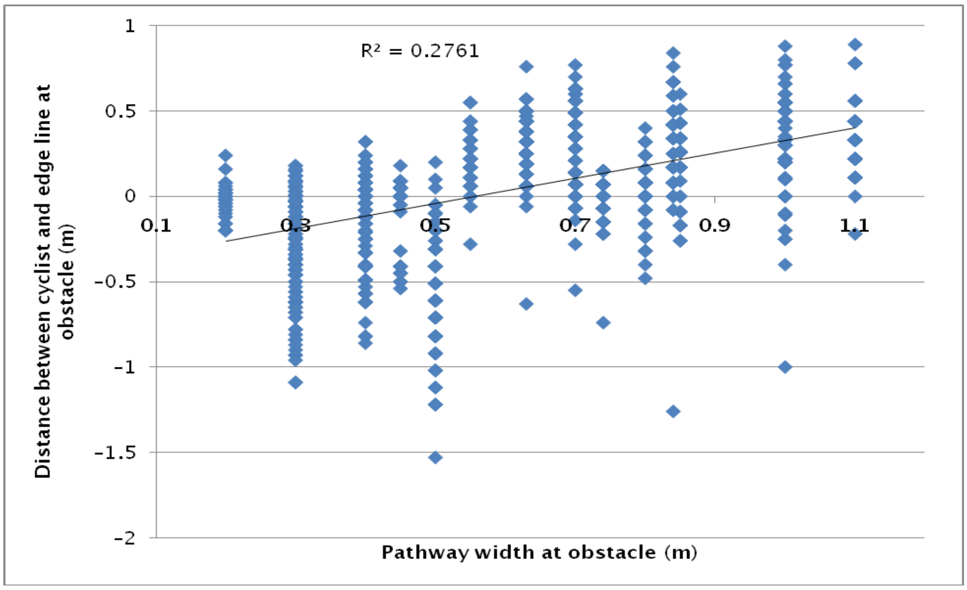
3.5 The influence of 'available space'

We have demonstrated above that a variation in road width affected the position of cyclists: specifically, when the available space narrowed, cyclists moved further out towards the general traffic stream or the road centre line. The influence of the cyclists' 'prior' position on their position at the object was not due to cyclists maintaining a straight line past the object. However, knowing the 'prior' position was the dominant predictor of where the cyclist would be at the object (see table 3.2) and, as there was little a road designer could do about normal riding behaviour, the hierarchical regression analysis deliberately excluded the 'rider behaviour' characteristics and focused on those features of the road that could be redesigned.

The five road design variables were entered into the model where it was seen that the downstream cycle path width and object height were not significant predictors. When these two variables were removed, the three remaining variables collectively explained that approximately 57% of the variation related to the cycle position when passing the object ($R^2 = .57$, F (5, 1238 = 334.43, p.<.001).

Figure 3.2 shows a cyclist's position on the road relative to the edge line against the width of space for the cycle for each observation. The point 0 on the y-axis represents the edge line. Negative numbers indicate when the cyclist is in the motorised traffic lane, and positive numbers indicate that the cyclist is within the space to the left of the demarcation line. Figure 3.2 illustrates a linear trend where cycling in the motorised traffic lane is more likely in narrower spaces, and cyclists become more likely to stay within the edge line as more space is available and the shoulder widens.

Figure 3.2 The influence of cycle lane width on the cyclist's position at the object relative to the edge line. Positive numbers indicate the cyclist was inside the edge line, while negative numbers indicate the cyclist was in the traffic lane



The width available to the left of the demarcation line was divided into three categories of equal size: narrow (0.2m to 0.5m), medium (0.5m to 0.8m) and wide (0.8m to 1.1m). Cyclists' distance from the edge line was categorised into six groups in bands of 0.4m. The effect of cycle lane width on cyclists' riding position is shown in figure 3.3.

The proportion of cyclists within the cycle lane increased from 35% for narrow cycle lanes up to 90% for the widest cycle lanes. As the cycle lane width increased cyclists were also more likely to stay further left. The proportion of cyclists 0.4m–0.8m from the edge line increased from 0% to almost 40%. However, it is important to note that the cycle lanes included in the 'narrow' category were not wide enough to accommodate riders in a position more than 0.5m from the edge line. Therefore, the increase in cyclists riding further left from the edge line was due to the provision of extra space that nearly 40% of the cyclists decided to use. Cyclists were 11.1 (95% CI from 8.2 to 15.0) times more likely to be within the cycle lane than outside it in medium-width cycle lanes compared with narrow-width cycle lanes, Mantel-Haenszel χ^2 (1, N = 973) = 277.91, p<.001. The odds ratio comparing narrow cycle lanes with wide lanes was greater at 21.0 (95% CI from 14.0 to 31.6), Mantel-Haenszel χ^2 (1, N = 804) = 282.5, p<.001. The percentage of cyclists more than 0.4m outside the edge line decreased from 28% to about 2% when the width of the cycle lane increased from narrow to medium.

Figure 3.3 Area plot showing the position of cyclists relative to the edge line across narrow, medium and wide cycle lanes

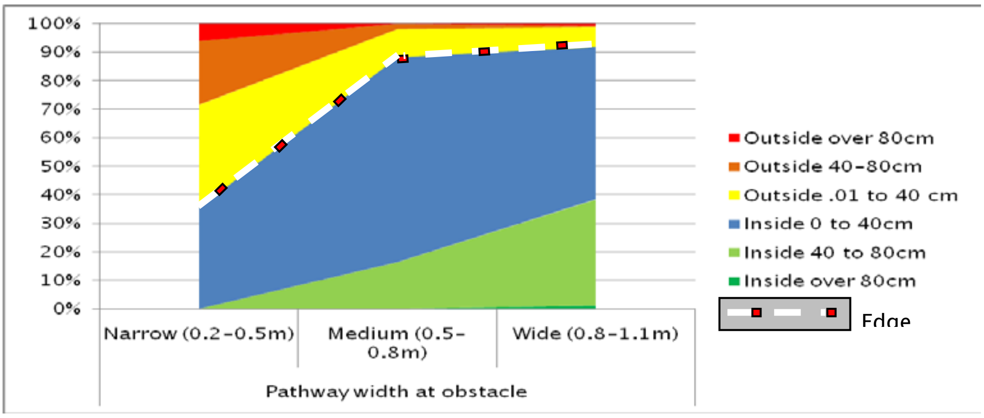
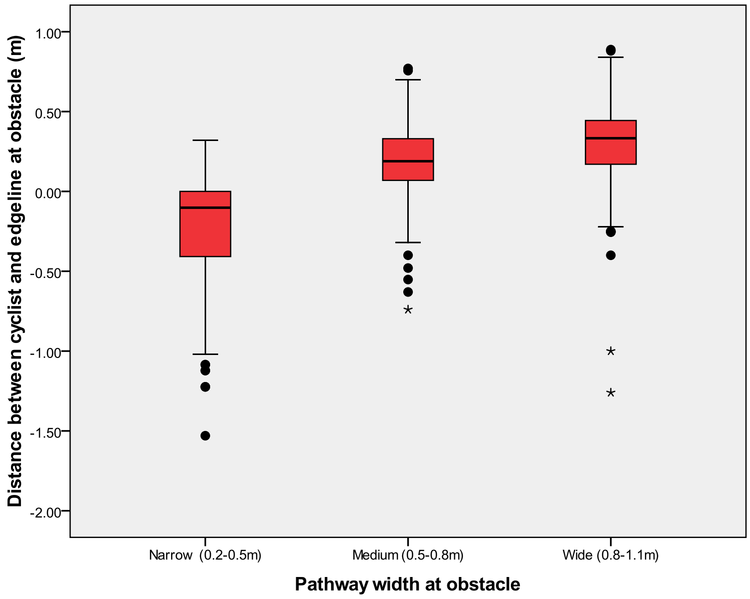


Figure 3.4 presents boxplots of the raw data of cyclist position for each cycle lane width category. The figure demonstrates that the greatest variability in lane position was found for the narrow lane category. The medium and wide categories had a similar level of variability, although the most extreme scores in relation to the category mean were found for the wide category. The plot for the narrow lanes demonstrates a floor effect. As all the narrow cycle lane sites were less than 0.5m wide no cyclist could be more than 0.5m inside the line.

Figure 3.4 Box plot of cyclists inside and outside of the edge line across narrow (0.2 to 0.5m), medium (0.5 to 0.8m) and wide (0.8 to 1.1m) cycle lane widths. Negative numbers are in the traffic lane and positive numbers are in the cycle lane. Solid circles are outliers, while extreme scores are shown with an asterisk



3.6 The influence of object height

The regression equation presented in table 3.2 indicates that the height of an object has a small but significant effect on cyclists' lane position when passing the object. The unstandardised regression coefficient of -0.05 indicates that every one-unit increase in object height will alter a cyclist's position by 0.05 units to the right. For instance, increasing the height of an object by 1m will result in cyclists moving only 0.05m further to the right. It is possible that the reason object height appears to have such a small effect on cyclist position is due to the range in observed object heights. Of the 19 sites, only one had an object higher than 0.14m, with the heights at the remaining sites ranging between -0.08m and 0.14m. The object for site 3 was 1.55m high, over 10 times larger than the next highest object and therefore potentially skewing the apparent influence of object height. In addition, the object here was a parked car and cyclists may have had the additional concern of avoiding opening doors and may have kept a wider berth of parked vehicles than of passive objects.

Re-running the regression excluding site 3 resulted in no substantial changes to the regression model presented in table 3.2 (see table 3.3), nor to the predicted mean riding position (40mm for both models). However, the unstandardised regression weight for object height changed to -0.41m. Repeating the example given above, this value indicates that increasing the height of an object by 1m will result in the cyclists moving nearly 0.5m to the right. While the model including site 3 is suitable overall, site 3 needs to be excluded to determine the influence of object height on cyclist position.

Table 3.3 Relative influence of the main predictors on estimates of cyclist position excluding site 3. Higher or lower beta values indicate more influence

	Unstandardised coefficients		Standardised coefficients	t	Sig.
	B	Std error	Beta		
Intercept	-0.06	0.03	.	-2.18	0.03
Cycle lane width at object	0.12	0.02	0.08	5.60	0.00
Cyclist position before obstacle	0.87	0.02	0.81	52.13	0.00
Downstream cycle path width	0.03	0.01	0.06	4.39	0.00
Upstream cycle path width	0.02	0.02	0.02	1.17	0.24
Width of the traffic lane adjacent to the obstacle	-0.02	0.00	-0.08	-5.16	0.00
Height of the obstacle	-0.41	0.05	-0.10	-7.95	0.00
Type of bicycle (coded)	0.03	0.01	0.04	3.11	0.00

Based on figure 1.3 there are three key object heights ranges to consider: flat objects (0m high); pedal-height objects (0.1m to 0.2m); and handlebar height (about 1m). Using the model excluding site 3, flat objects are expected to have no influence, pedal height objects are expected to move cyclists approximately 0.1m to the right, and handlebar height objects will move cyclists approximately 0.5m to the right.

3.7 Predicting where a rider is normally positioned

Means on the following comparisons represent upstream measures of cyclist position in metres relative to the edge line. Negative numbers indicate the cyclist was in the traffic lane, and positive numbers indicate the cyclist was within the available space to the immediate left of the demarcation line.

Cyclists were significantly more likely to ride in the traffic lane in Wellington (M = 0.10m) than in Christchurch (M = 0.22), where cyclists were more likely to ride in the cycle lane, $t(1112) = 16.82$, $p<.001$. Related to this are the findings for bike type and speed limit, given the difference between Wellington and Christchurch on these factors (see tables 2.2, 2.4 and 2.5). Cyclists on road bikes, most common in Wellington, were more likely to be in the traffic lane (m = -0.06m) whereas mountain bikers, more common in Christchurch, were more likely to be on the left side of the white line (M = 0.21m), $t(1112) = 14.63$, $p<.001$. In this survey, 100km/h zones were used only in Wellington, and cyclists in this speed zone were more likely to be in the traffic lane (M = 0.13m) than cyclists in 50km/h zones (M = 0.20m), $F(1, 1112) = 19.35$, $p<.001$.

Cyclists travelling faster were more likely to be in the traffic lane (M = -0.06m) and cyclists travelling at medium (M = 0.16m) and slow speeds (M = 0.13m) were more likely to be in the cycle lane, $F(2, 1108) = 60.78$, $p<.001$. No significant effects were found for estimated age or gender.

3.8 The influence of a marked cycle lane versus a marked shoulder on cyclist lane position

Certain sites were divided into one of three lane marking categories: sites with marked cycle lanes (*marked,* eight sites); sites without a marked cycle lane but where the shoulder was more than 0.8m wide (*wide unmarked,* two sites*)*; and sites without a marked cycle lane and with a shoulder narrower than 0.8m (*narrow unmarked,* two sites*)*. One-way analyses of variation (ANOVAs) were used to test differences in cyclist lane position across the three categories. Only 50km/h sites were used as there were no marked cycle lanes on the 100km/h sites.

Table 3.4 presents the results of the ANOVA tests for cyclist position before the obstacle, at the obstacle, and past the obstacle. In all cases for the 50km/h sites the position of the cyclist was further within the edge-line for the marked cycle lane sites than for the wide unmarked or narrow unmarked sites. When controlling for cycle path width using an analysis of co-variance (ANCOVA) these differences remained. Controlling for the cyclist's lane position before the obstacle resulted in the lane marking category becoming non-significant for lane position at the obstacle, $F(2, 574) = .84$, ns, and reduced the F statistic for position past the obstacle, $F(2, 481) = 3.8$, $p<.05$. Controlling for the cyclist's position at the obstacle reduced the F statistic for the past the obstacle test, $F(2, 566) = 12.0$, $p<.001$, but not to the same extent as controlling for position before the obstacle.

Table 3.4 The influence of lane marking on cyclist position (m) in relation to the edge line before passing, when passing, and after passing a roadside obstacle. Standard deviations are presented in parentheses

Cyclist position (m)	Marked	Wide unmarked	Narrow unmarked	df	F
Before obstacle	$0.269^{(a)}$ (0.21)	$0.11^{(b)}$ (0.13)	$0.005^{(c)}$ (0.02)	2, 575	66.7***
At obstacle	$0.27^{(a)}$ (0.25)	$0.14^{(b)}$ (0.16)	$0.02^{(c)}$ (0.12)	2, 667	68.2***
Past obstacle	$0.30^{(a)}$ (0.22)	$0.13^{(b)}$ (0.24)	$0.13^{(b)}$ (0.12)	2, 567	33.0***

Note: Marked site has marked cycle lane; wide unmarked site has no marked cycle lane but the shoulder is over 80cm wide; narrow unmarked site has no marked cycle lane and the shoulder is less than 80cm wide. The mean for the narrow unmarked sites past the obstacle only includes one site as there was no data for the other site.

Means with different superscripts differ at the .05 level (Tukey post-hoc test). A negative mean indicates the cyclist was riding in the traffic lane.

*** p<.001

These findings suggest the key influence of the type of lane (as categorised here) in which a cyclist is riding is on the prior to object (or baseline) riding position. The type of lane has no significant effect on the cyclist's position when passing the obstacle once the baseline position is accounted for. While the F statistic was reduced for the two ANCOVAs on position past the obstacle, compared with the original ANOVA, the baseline position had the greater effect.

3.9 Other descriptive measures

The most frequently observed cycling behaviour was riding side by side which occurred in 1.8% (n=23) of all observed cases. All cyclists who rode side by side were on road bikes, and the observations indicated that the cyclists were riding together rather than one overtaking another. These observations were made from the obstacle images. For instance, if two cyclists were riding side by side on the approach to the obstacle but cycled passed the obstacle in single file they would not have been recorded as cycling side by side.

The base rates for all other cycling behaviours measured in the study were 0.5% or lower, as shown in table 3.5.

The national rate of helmet use is 92%, measured by the national survey of helmet use by cyclists (Ministry of Transport 2009b), which is 7.5% lower than found in this study. The proportion of helmet use in the survey was higher in Christchurch (96%) than in Wellington (86%). This study targeted vulnerable road users in commonly cycled areas, as opposed to short recreational trips, which may explain the higher rate of helmet use observed here.

Table 3.5 Overall percentage of cyclists observed performing rare behaviours

	Proportion of cyclists displaying each behaviour			
	Observed		Not observed	
Observed cyclist behaviour	**%**	**n**	**%**	**n**
Carrying child in child seat	0.3	4	99.7	1241
Holding an object	0.4	5	99.6	1240
Looking over shoulder at cars	0.5	6	99.5	1239
Not wearing a helmet	0.5	6	99.5	1239
Riding with one hand	0.4	5	99.6	1240
Riding side by side[a]	1.8	23	98.2	1222
Riding the wrong way down road	0.2	2	99.8	1243

Note: n = 1245

[a] Includes instances where front and rear riders' wheel positions slightly overlapped (n=5)

4 Discussion

The current *Government policy statement on land transport funding 2009/10–2018/19* (Ministry of Transport 2009c) indicates around $50 million has been allocated to walking and cycling facilities over the next three years, which is about 0.58% of the total funding for road and transport infrastructure. In contrast, management of the funding allocation system is valued at $100 million over the same three years. Some funding for cyclists will be contained in other activity classes, such as 'New and improved infrastructure for local roads' and 'Renewal of local roads', but the contribution of this funding to improved cycling infrastructure cannot be determined.

Despite a substantial investment in new cycling and walking infrastructure, cycling is still taking place on roads, not on dedicated cycle paths or even marked cycle lanes on roads. An obvious result of the present study that might be overlooked because it is so basic is that the position of the cyclist in relation to vehicle traffic is a function of road design. Poor design leads to poor positioning of the cyclist, which means a relative increase in exposure to the risk of a crash.

The idea that roads are designed for cycling is at odds with both an effort to develop specialised cycling infrastructure, such as cycle lanes, and an effort to develop roads for motorised traffic. Cycling is an activity that is not necessarily routinely considered in road asset development or management and significant additional effort is required by cycling advocacy groups and enthusiastic supporters of cycling to ensure cycling remains recognised within these activities (Jackson and Ruehr 1998).

A pragmatic approach must be taken to reduce the risk of a crash involving a cyclist. The safe system approach endorsed by *Safer journeys,* New Zealand's road safety strategy 2010–2020 (Ministry of Transport 2010) adopts the view that the cyclist's behaviour is one component of the risk exposure and that we ought not to blame the cyclist for establishing this risk but rather recognise it within a broader systems approach. Thus, based on the safe system approach and the evidence gathered from our observations, it would not be good practice to suggest cyclists ought to keep left because they might, or should or can. The fact is, they do not naturally keep left, even when they can, meaning even where there is available space in which they could ride they will not use it.

In our survey, cyclists did not, in general, ride in conflict with traffic. However, the findings demonstrated a tendency for cyclists to avoid the extreme far left (even when there was clear space) and this should be considered together with the fact that around three-quarters of all cyclists adjusted their riding position according to the obstacle they encountered. Those who were riding outside the line tended to move further outside the line (towards motorised traffic) to avoid the object, even when the move was not necessary. This finding further reinforces the need to ensure available space is provided in the design or maintenance of the roadside if the intention is to keep cyclists in a clear, predictable space.

The road surface may influence the cyclist's position if there are changes in the quality of the surface, either in the path of the cyclist or from the far left edge to the centre of the road. During site selection, if any site showed a substantial variation in the quality of the road surface it was rejected as the change in quality would have introduced a potentially confounding factor. The result of this decision was that the road surface quality was consistent for all sites, regardless of whether the cyclist was riding on the far left of the cycle path or in the traffic lane. The only section of the road surface that might have been smoother was the vehicle tyre paths, but this is an area unlikely to be used by cyclists. Additionally, all sites were well trafficked by cyclists, indicating the road surfaces were perceived to be of a suitable quality for cycling. Although seemingly a circular argument, the best indicator that a road is perceived to be suitable for cycling is that cyclists actually use it.

In general, cyclists riding in officially designated cycle lanes kept further to the left than those in wide or narrow undesignated shoulders. The benefit of the marked cycle lane appeared to be due to its influence on the cyclist's original position; it did not appear to have any effect on the cyclist's position at the object once the pre-object position was taken into account. This result occurred despite some of the undesignated shoulders being wider than the marked cycle lanes. It needs to be noted that the study was not designed to test the differences between marked cycle lanes and other shoulders. The number of sites fitting into the marked, wide unmarked and narrow unmarked categories was not balanced or matched according to specific physical characteristics such as road width. The impact of the marked cycle lane, therefore, needs further research before the differences in cyclist behaviour for the lane categories is understood. However, it may be beneficial to use marked cycle lanes leading up to pinch points if this encourages cyclists to keep further to the left.

Walker (2007) found that cyclists who rode further into the carriageway received significantly less space from vehicles overtaking them, although Walker did not take into account available widths of the carriageway or the presence of cycle lanes. Drivers may consider that cyclists riding further out on the carriageway are less likely to make erratic movements to the right and can be negotiated with less space than those who ride on the side of a cycle lane with a less variable-width road shoulder. However, this finding needs to be considered with other observations that motorists give less space to helmeted cyclists than to those without helmets. Basford et al (2002) found that helmeted cyclists were considered by drivers to be more sensible and serious. Basford et al also found evidence that drivers had less confidence passing a 'wobbling' cyclist than one maintaining a straight course on the left. Driver confidence decreased significantly when the cyclist was passing a pedestrian kerb extension.

The findings of Walker (2007) and Basford et al (2002) present a general concern that there is a relationship between motorists' perceptions of cyclists and how they negotiate overtaking them. There is a relationship between the cyclist and the features of the road design that causes the cyclist to move further out into the vehicle lane. The result is that a feature of road design becomes a feature for the motorist to negotiate in the presence of a cyclist; the roadside feature has a kind of ripple effect from the edge of the road to the centre of the carriageway.

The height of the object affects the cyclist's position and requires a predictable extension to the baseline left buffer zone maintained by cyclists when passing road-level objects (eg maintenance covers). The buffer zone for different object heights can be estimated from the object height regression weight for the model excluding site 3 (table 3.3, section 3.6). Different buffer zone extensions can be set separately for all object heights, but doing this makes little sense. For instance, a 3m high object is likely to influence a cyclist to the same extent as a 1.5m object. To this end there are three key object heights that need to be considered (see figure 1.3); lower than pedal height (under 0.1m); pedal height (0.1m to 0.2m); and handlebar height (greater than 0.9m). Given that the two main points of contact on the sides of a bicycle are the handlebars and the pedal, objects between pedal height and handlebar height can be treated as pedal height.

Objects lower than pedal height (eg drainage grates) will have a minimal effect (less than 25mm movement) on the cyclist's position and therefore no additional buffer needs to be provided. A caveat to this recommendation is that a drainage system should be approximately level with the road. Drainage systems below road level, such as drainage gullies, are likely to require additional space. However, as no systems of this type were included in the study sites no specific recommendation is made. Pedal height objects (such as a 0.14m high kerb) should have a 0.1m buffer added to the basic 0.4m buffer zone. Objects that are at handlebar height (approximately 1m high) or higher, such as fences, should have an additional 0.5m buffer zone added to the pedal-height zone. This distance is similar to the recommendation made in the *New Zealand cycle trail design guide* (Ministry of Tourism 2010), although the specifications in the design guide are for off-road cycle trails. Parked cars could be included in the handlebar-height category, but need site-specific attention due to the risk of doors being opened into a cyclist's path.

In our results we found differences between road bikes and mountain bikes that indicated cyclists on more robustly designed bikes, such as the latter, were less likely to move out as far as those on road bikes. Some of this effect might have been due to riding style, as road bikes tend to be ridden by recreational cyclists who probably have more riding experience than others. These bikes were also estimated to be travelling faster. The data supported this with the regression model showing much more variability for mountain bikes than for road bikes. Road bikes moved more consistently to the right past the object than did mountain bikes. An alternative explanation is that mountain bikers can traverse the debris or other features of the roadside with more confidence so they are more comfortable riding further left. In general, bicycle research conducted elsewhere has not separately considered different types of bicycle and so there is no supporting literature on the contribution of bicycle type to crash rates.

A longer viewing distance upstream of the object would have assisted in determining the relationship between the 'prior-to' and 'at-object' cycling behaviour. The strength of the correlation was impressive but it was not as well correlated with the 'after-object' position observations. It is probable that cyclists anticipated the objects well in advance of our observation upstream and therefore moved to negotiate the occlusion to their continued path with a very long run-up. We can theorise that cyclists attempted to minimise their potential to be seen doing an 'erratic wobble'. If true, the cyclist's normal riding position (or even their preferred riding position) was not directly observed in this experiment; rather it could only be inferred from the 'after position' the rider returned to. The changes we observed in a cyclist's position before, at and after reaching the object indicated the influence of the object at each of these points, as well as its impact on the normal riding style of the cyclist.

Parkin and Meyers (2010) offer a methodological solution to the problem of determining 'normal riding position', although they used the method for a different purpose. It is possible to place a small camera on a bike and point it to the roadside to monitor the cyclist's course over many more points. Parkin and Meyers used only a single cyclist, pointed the camera toward the traffic and held the rider position constant so they would not have been able to determine the 'normal riding position'. However, their method could be adopted to determine usual rider position relative to other points of reference and could have valuable application in determining the benefits of cycle lanes.

Parkin and Meyers (2010) offer four reasons why cycle lanes keep cyclists safe. Cycle lanes:

1 create a greater degree of separation between the cyclist and the motorist
2 usefully direct cyclists to the most appropriate position in the carriageway
3 create a legal means for the cyclist to undertake (ie pass on the left) queued motor vehicle traffic
4 provide a degree of continuity and conspicuity of the route of cycle traffic.

Even so, in their research Parkin and Meyers (2010) found motorists actually gave more space to passing a cyclist riding at a constant distance 0.5m from the kerb when there was no cycle lane, even though a road with a cycle lane allowed for greater available space. The finding is supported by research elsewhere. Against expectation, Landis (1997) also found that lane width, (meaning the entire carriageway width) made only a negligible contribution to the perceived level of service reported by cyclists.

This research found evidence against two of the four claims made by Parkin and Meyers (2010). First, even given the opportunity, cyclists did not stay left and therefore the presence of adequate lane width did not in itself create a separation between the motorist and the cyclist. There were considerable individual differences but it appeared that cyclists tended to travel around 40mm inside the edge line and large numbers remained outside the edge line even when they could cycle within it. It was also observed that motorised vehicle traffic regularly entered the shoulder or cycle lanes. Thus, there was little evidence to suggest an appropriate width of a cycle lane would be an effective mechanism for separating cyclists from motorised traffic.

The second assumption of Parkin and Meyers (2010) that the cycle lane may indicate the most 'appropriate position' for the cyclist on the carriageway was not supported by the data in this survey or elsewhere despite a number of studies examining the features of road design that influenced perceived safety (eg Parkin et al 2007). Riding close to the edge line was found to be the modal riding position despite the fact that the edge line could also be a hazard, especially in the case of audio-tactile edge markings (Brucko et al 2001; Cleland et al 2005; Plant 1995). Edge lines may not be free of debris, ponding of water or cracks and one ubiquitous feature of the edge line is the presence of hazardous RRPMs (Walton et al 2005). One reason why the white line might be regarded as a safer position by the cyclist is a belief that in order to install the edge line the road marker must ensure the area is clear of obstruction, clean and free from loose debris, even if this is not the case. Anecdotally, broken glass may be more visible on the white line compared with the regular road surface and hence be easier to avoid. However, these perceptions, even if widespread, do not necessarily coincide with the actual risks of different lane positions or riding styles. Evidence is required to prove there is a lower crash rate associated with riding on the edge line than further to the left of it.

Third, the idea that a cycle lane makes cyclists clearly visible involves understanding cyclists' behaviour and how this is perceived by motorists who overtake them. This is recognised by Basford et al (2002) and Walton and Thomas (2004) and is in agreement with the findings of this research. It is hard to reconcile the position of the cyclist at the edge line with any principle of self-preservation or risk reduction unless a mechanism of being collectively 'visible', serious and steady operates *better* when the rider is at the edge line than when negotiating the cycle lane in a position further left of the line. It is this principal that must be understood and is best revealed by naturalistic observation rather than by asking the cyclists themselves.

It is important to emphasise that the problem at the objects we investigated was not exclusively roadside maintenance. The study here considered several objects which were clearly roadside design features, including pedestrian kerb extensions that severally restricted the available space for the cyclist. Only one object was the result of a lack of maintenance and this was a bush that intruded into a cycle lane.

4.1 Peripheral findings

Observing helmet use was not central to our report and the findings reflected a sampling procedure based on a methodology designed for another purpose. The rate of helmet use in this study was 7.5% higher than the national rate of helmet use of 92% (Ministry of Transport 2009b) where the sample size was too small to make comparisons at a regional level. The number of cyclists in the Wellington sample in this study (n=679) was just over double that of the national helmet use survey (n=330). Differences in the rate of cycle helmet use were probably due to the different groups of cyclists being measured. This study selected targeted areas with high levels of cycling, rather than attempting to get a representative sample of all cyclists as in the national cycle use helmet survey. The higher rate of cycle helmet use found in this study suggests that cyclists are more likely to wear helmets in high-density cycling areas than on shorter urban trips.

4.2 Cyclist factors

Only 1.8% of all riders were found to cycle side by side. No other observational study reports the rate at which this occurs, although the rate would be expected to be higher based on informal observations. This lower than expected rate was probably due to the classification of whether cyclists were riding two abreast occurring at the point where the cycle lane narrowed. The proportion of cyclists riding two abreast in the upstream image would probably be higher than at the object image, but testing this hypothesis was beyond the scope of this study.

4.3 Limitations

This study was the first to attempt to quantify the thresholds of design that influence cycling behaviour and because of this it makes a number of methodological contributions. It has also made a number of methodological errors, but further work should be able to benefit from a refinement of the method used.

The present study assumed it was desirable to keep cyclists left of the motorised traffic stream in a clear predictable course that avoided occasional sudden movements of the cyclist into the motorised vehicle stream. This assumption need not be true. A major and unanticipated finding was the planned negotiation of the pinch point by cyclists well in advance of reaching it. It was possible our camera alerted cyclists to the site of interest, although this was not obvious from the images captured.

The method of data collection may not have caught very aberrant behaviour. The cameras were positioned to capture extreme events, such as cyclists riding more than 1m into the motorised vehicle lane, but not all instances were necessarily captured. The cameras also observed pedestrians, animals, cyclists on the footpath, joggers, cyclists travelling in the opposite direction and other usual events. The datasets represented hundreds of hours of automated observations, and the specific events required by the study were a filtered set of those hours based on algorithms contained within the pixel monitoring system. The operation of the camera system was trialled, piloted, assessed and validated by observations so there was sufficient confidence that it obtained an appropriate dataset. Even so, observers trawled through thousands of images to extract those that featured cyclists.

4.4 Design recommendations

A group of expert end users was invited to assess the findings and establish a recommended level to set a threshold where, 'most cyclists stay outside the general traffic lane, most of the time'. The problem is that a reasonable threshold cannot be determined empirically. There is considerable variability in riding styles so that even with 1.5m of available clear pavement, cycles are found in the motorised vehicle lane. The acceptable threshold could be defined statistically, for example, as a point on the distribution of observed position relative to available width where 85% of all cyclists are to the left of the white line. However, whether this is reasonable is not for the researchers to decide. Some groups might say 100% of people all the time; other might be comfortable with 60% of people 60% of the time.

The threshold recommendations were put forward, along with other key findings, to inform the development of future guidelines to set minimum design parameters for cyclists. It is important to emphasise these *minimum* design parameters respond to the need to define the minimum space required *to afford cyclist course continuity*. These design principles must be seen as assisting design to achieve a minimum standard and invite designers to exceed the threshold a cyclist will tolerate. The threshold need not, and probably does not, meet the expectations of what cyclists want, prefer, or are comfortable with.

This research contributes to an increasing body of research concerned with developing an understanding of cyclists' natural behaviour and recommends design should meet the expectation of natural behaviour rather than attempt to adjust cyclist behaviour.

1 Cyclists need at least 0.4m of clear space to the left of the edge line at a pinch point which will afford a continuous trajectory or path continuity. When provided with 0.4m to 0.8m almost all cyclists will ride left of the white line despite the presence of a pinch point.

2 If the far left of the roadside has an object higher than 0.1m then the minimum space to preserve a cycle trajectory is 0.5m. Where objects encroach on a cyclist's handlebars (eg fences) there should be 1m of clear space for the cyclist. Although the risk of doors opening from parked cars was not studied specifically, with only one site having parked cars as an obstacle, these require additional site-specific design considerations when accounting for cyclist space.

3 In narrow lanes or shoulders, cyclists will often keep just to the left of the lane line or edge line, despite having extra clear, well-maintained space further to the left in which to ride. When provided with 1.1m of space, most (around 80%) cyclists remain within 40mm of the white line.

4 Cyclists anticipate pinch points and will minimise the angle of approach, given available space and forewarning of the narrow point. Any pinch point with a sight line of at least 20m will allow the cyclist to negotiate the site and give the perception of maintaining a steady course.

5 1.5m of space or more (eg to match design guidance) is preferred by cyclists. However, there is evidence from this research that at pinch points extending over short distances (eg 5m, the approximate length of the longest pinch point in the study) there is a continuity advantage in providing cycling space down to a width of 0.5m.

6 Cyclists on mountain bikes are considerably more variable in their behaviour and much less likely to be influenced by the presence of roadside objects.

The design of road infrastructure would benefit from further investigation of cyclists' natural behaviour to prevent developing cycling facilities which cyclists choose not to use because of unintended disincentives or because they potentially create a hazard (Parkin and Meyers 2010). Examples include unused cyclist paths through pedestrian kerb extensions, buttons a cyclist has to activate to cross a busy section of road or travel across a narrow bridge, and cycle lanes that terminate suddenly. The collective lobby of cyclists does not benefit when road designers and traffic engineers develop infrastructure that cyclists do not use. Parkin et al (2007) found a similar resistance to the provision of on-road cycling facilities, which while clearly intended to reduce risk to cyclists, were not perceived in this way by cyclists. Davis et al (1997a) found it impossible to reconcile that cyclists' concerns for safety were not overcome or even lessened by methods to reduce risk, including changes to the infrastructure. Asking cyclists to respond to questionnaires or videos does not seem to address what remains a complex relationship between cyclists and the road environment. Observations of cyclists' natural behaviour in negotiating hazards revealed the nature of their engagement with the infrastructure and demonstrated a basic mismatch between the intended design of cycling infrastructure and its actual use.

5 Conclusions

We have previously discussed in chapter 4, the four reasons according to Parkin and Meyers (2010) why cycle lanes keep cyclists safe.

From an ecological[2] perspective the design of cycling infrastructure does not accord with its observed use. In the research, cyclists were sensitive to minor variations in path width and prepared to make adjustments to their riding position even when objectively they had clear space in which to continue along a straight path. Cyclists were observed to have some aversion to keeping to the far left, with the most common position being the cycle's wheels just to the left of the white edge line, therefore leaving much of the available cycle lane space or shoulder width free. The influences on the cycle position were the width of the adjacent traffic lane, the height of the object the cyclist encountered and the type of bicycle (mountain bike compared with road bike). Factors previously reported to influence cyclist comfort, namely traffic volume and traffic speed (eg Landis et al 1997), were not found to influence their position.

The supposition that cyclists' riding positions were related to a concern for debris was unsupported by the data collected here. It is more likely cyclists actively maintained a visible presence for motorists by positioning themselves inside the white line and keeping variation in lateral movement to a minimum. This report supports design principles which extend the sightlines to objects cyclists might encounter and provide a minimum space of 0.4m at a narrowing, with 0.5m being optimally desired if the intention is to keep the cyclist in a predictable course along their natural riding position, approximately 40mm inside the white edge line. The condition, design and alteration of the edge line are more of a concern for cyclists than may have been previously recognised and the widespread use of RRPM and audio tactile markings should be assessed against the likely effect they could have on cyclists, despite the clear space in which to ride. NZTA guidelines acknowledge that audio tactile markings are of concern, with recommendations indicating that these markings should not be used if the space available to cyclists is reduced to less than 1m (NZTA 2009). However, Walton et al (2005) make the point that a hazardous line is likely to be more important than an apparent lack of space: '[Dividing the cyclists' space from the motorists' space by a close-spaced raised pavement marker] will mean the common method of avoiding hazards within the cycle space by entering into the vehicle lane would require the negotiation of an even more significant hazard' (p28).

The research illustrated the need to design for cyclists' riding behaviour rather than attempting to change their natural behaviour through design. Further research is needed to determine the separate influences of the cyclist's sources of 'perceived risk' of a position further left than the position they naturally use. In particular, it would be helpful to determine the balance of concern between collision with debris and the 'loss of presence' to motorists that arises when moving to a more variable lateral position left of the current path. Road designers can accommodate this natural riding style by providing a sight line for cyclists that is inside the edge line. A trial of such a change would establish the benefits of what might be a simple alteration that optimises the available width and reduces the competition and demand for wider road space.

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[2] Ecological in this context refers to the interaction of humans with the environment.

6 Recommendations for future research

1. Further investigate cyclists' natural riding behaviour and consider developing this into a set of evidence-based principles to be placed into the next road design guide for cycling infrastructure. Despite the availability of numerous design guides there is a tendency for observed use of cycling facilities to be different from expected use or design intentions.
2. Special consideration should be directed towards the use of a solid white line for marking the lane. This is also recognised by Parkin and Meyers (2010). Alternatives to the white line include coloured surfaces and broken white lines (used in the UK to indicate an advisory cycle lane). Consider the benefits of lines or RRPMs buttressed against the main edge line at regular intervals to discourage the 40mm average separation maintained by cyclists.
3. Consider establishing a 'guide line' for cyclists more than 40mm inside the edge line and evaluate it to determine whether this encourages cyclists to move further left.
4. Investigate the reasons why cyclists prefer to ride close to the edge line, including understanding the influence of debris, stone chip, surfacing etc.
5. Investigate the situations where cyclists make erratic movements to the right, perhaps using the Parkin and Meyers (2010) method, as described in chapter 4, p42. Use this methodology to gain a better understanding of the wide variation in rider positions prior to reaching the object.
6. Determine the extent to which cycle routes are affected by pinch points and establish the cost/benefit of removing the points or increasing them to a minimum of 0.4m in size.

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Appendix A: Extended descriptions and photos of the Christchurch sites

Site 1

Location: Moorhouse Avenue, just west of intersection with Ferry Road

Observation date: 10 November 2009

Cyclist direction: eastbound

Obstacle: storm water drain

Obstacle height: 0m

Width at obstacle: 0.3m

Upstream image	Object image	Downstream image
		No downstream images were recorded for this site

Site 2

Location: Ferry Road, just west of intersection with Moorhouse Avenue

Observation dates: 10 and 11 November 2009

Cyclist direction: eastbound

Obstacle: storm water drain

Obstacle height: 0m

Width at obstacle: 0.7m

Upstream image	Object image	Downstream image
		
		

Site 3

Location: Oxford Terrace, between Montreal Street and Durham Street South, north side

Observation date: 17 November 2009

Cyclist direction: eastbound

Obstacle: parked car

Obstacle height: 1.55m

Width at obstacle: 0.74m

<table>
<tr><th>Upstream image</th><th>Object image</th><th>Downstream image</th></tr>
<tr><td></td><td></td><td></td></tr>
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</table>

Site 4

Location: Fendalton Road, approximately 20m north-west of Harper Avenue intersection

Observation date: 17 November 2009

Cyclist direction: north-westbound

Obstacle: narrowing by bridge

Obstacle height: 0.1m

Width at obstacle: 0.63m

Upstream image	Object image	Downstream image
		

Site 5

Location: Gasson Street, between Kingsley Street and Byron Street

Observation date: 18 November 2009

Cyclist direction: northbound

Obstacle: storm water drains

Obstacle height: 0m

Width at obstacle: 0.63m

Upstream image	Object image	Downstream image
		
		

Site 6

Location: Kilmore Street, just east of Cranmer Square, south side

Observation date: 19 November 2009

Cyclist direction: eastbound

Obstacle: edge of kerb

Obstacle height: 0.14m

Width at obstacle: 0.55m

Upstream image	Object image	Downstream image
		
		

Site 7

Location: Ferry Road, south-east of Hopkins Street

Observation date: 26 November 2009

Cyclist direction: north-westbound

Obstacle: pedestrian crossing kerb extension

Obstacle height: 0.12m

Width at obstacle: 0.84m

Upstream image	Object image	Downstream image
		
		

Site 8

Location: Briggs Road, opposite Clearbrook Street

Observation date: 23 November 2009

Cyclist direction: south-westbound

Obstacle: edge of kerb

Obstacle height: 0.11m

Width at obstacle: 0.4m

<table>
<tr><th>Upstream image</th><th>Object image</th><th>Downstream image</th></tr>
<tr><td></td><td></td><td></td></tr>
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</table>

Site 9

Location: Avonside Drive

Observation date: 3 December 2009

Cyclist direction: eastbound

Obstacle: foliage intruding into cycle lane

Obstacle height: Unclear. Height was incorrectly recorded and likely to have changed since testing.

Width at obstacle: 0.5m

Upstream image	Object image	Downstream image
		
		

Site 10

Location: Waltham Road rail-crossing bridge

Observation dates: 2 and 3 February 2010

Cyclist direction: northbound

Obstacle: edge of kerb

Obstacle height: 0.14m

Width at obstacle: 1.15m

Upstream image	Object image	Downstream image
		
		

Appendix B: Extended descriptions and photos of the Wellington sites

Site 11

Location: River Road (State Highway 2), approximately 200m north-east of Silverstream turnoff.

Observation dates: 5 and 6 September 2009

Cyclist direction: north-eastbound

Obstacle: raised seal edge next to safety barrier

Obstacle height: 0.08m

Width at obstacle: 1.0 m

Upstream image	Object image	Downstream image
		
		

Site 12

Location: River Road (State Highway 2), approximately 2km south-west of Moonshine Road

Observation dates: 19 and 20 September 2009

Cyclist direction: south-westbound

Obstacle: raised concrete edge marking

Obstacle height: 0.1m

Width at obstacle: 0.85m

Upstream image	Object image	Downstream image
		

Site 13

Location: River Road (State Highway 2), approximately 2km south-west of Moonshine Road

Observation dates: 26 and 27 September 2009

Cyclist direction: south-westbound

Obstacle: edge of seal produced by gutter

Obstacle height: 0.08m

Width at obstacle: 0.2m

<table>
<tr><th>Upstream image</th><th>Object image</th><th>Downstream image</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3"></td></tr>
</table>

Site 14

Location: River Road (State Highway 2), approximately 200m north-east of Silverstream turnoff.

Observation dates: 4 and 5 October 2009

Cyclist direction: south-westbound

Obstacle: raised concrete edge marking

Obstacle height: 0.12m

Width at obstacle: 0.7m

<table>
<tr><th>Upstream image</th><th>Object image</th><th>Downstream image</th></tr>
<tr><td></td><td></td><td></td></tr>
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</table>

Site 15

Location: River Road (State Highway 2), approximately 175m north-east of Silverstream turnoff.

Observation dates: 10 and 11 October 2009

Cyclist direction: south-westbound

Obstacle: raised concrete edge marking

Obstacle height: 0.12m

Width at obstacle: 0.4m

Upstream image	Object image	Downstream image
		
		

Site 16

Location: River Road (State Highway 2), approximately 150m north-east of Silverstream turnoff.

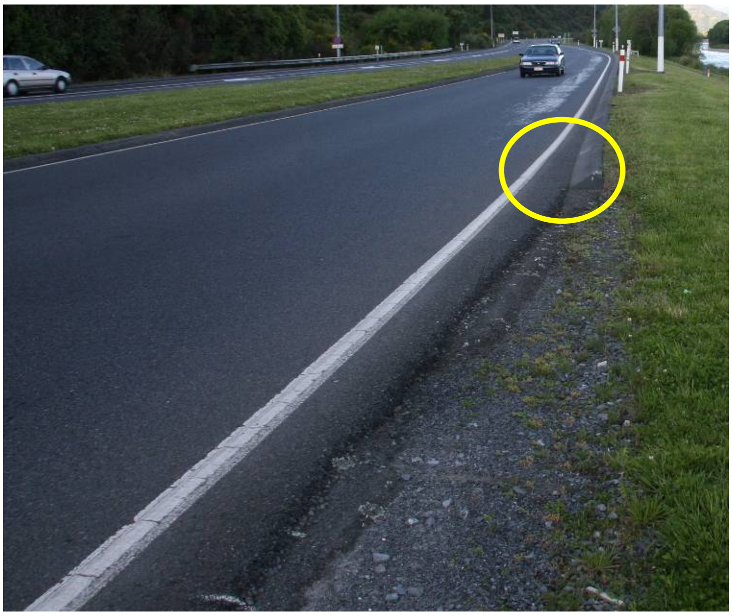
Observation dates: 17 and 18 October 2009

Cyclist direction: south-westbound

Obstacle: edge of seal

Obstacle height: 0.05m

Width at obstacle: 0.5m

Upstream image	Object image	Downstream image
		
		

Site 17

Location: River Road (State Highway 2), approximately 150m north-east of Silverstream turnoff.

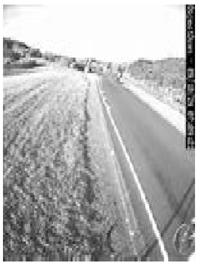
Observation dates: 24 and 25 October 2009

Cyclist direction: south-westbound

Obstacle: edge of seal

Obstacle height: 0.08m

Width at obstacle: 0.3m

<table>
<tr><th>Upstream image</th><th>Object image</th><th>Downstream image</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3"></td></tr>
</table>

Site 18

Location: Intersection of Western Hutt Road (State Highway 2) and Haywards Hill Road (State Highway 58)

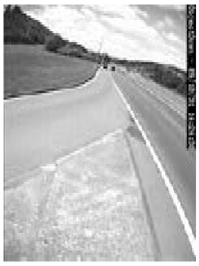
Observation dates: 31 October and 1 November 2009

Cyclist direction: north-eastbound

Obstacle: edge of raised traffic island

Obstacle height: 0.12m

Width at obstacle: 0.8m

Upstream image	Object image	Downstream image
		
		

Site 19

Location: The Esplanade, Petone, opposite Patrick Street

Observation dates: 11 and 12 November 2009

Cyclist direction: north-westbound

Obstacle: raised pedestrian kerb extension

Obstacle height: 0.13m

Width at obstacle: 0.45m

<table>
<tr><th>Upstream image</th><th>Object image</th><th>Downstream image</th></tr>
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</table>

Site 20

Location: The Esplanade, Petone, opposite William Street

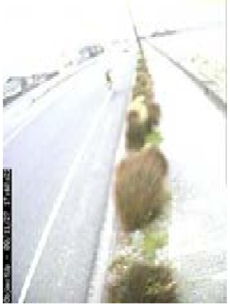
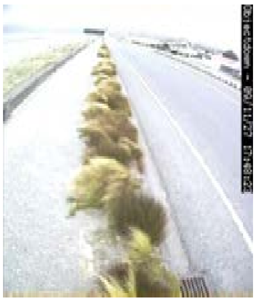
Observation dates: 27 to 30 November 2009

Cyclist direction: north-westbound

Obstacle: storm water drains

Obstacle height: 0m

Width at obstacle: 1m

Upstream image	Object image	Downstream image
		
		

Appendix C: Glossary

Activation zone	A user-defined section of the video image that is used to record images when movement is detected within the zone.
Austroads	Association of Australian and New Zealand road transport and traffic authorities.
Available path width	The distance between the edge of the obstacle and the inside edge of the edge line.
Cycle connectivity	Maintaining the path continuity so that cyclists are not forced to move into the traffic lane when passing obstacles.
Cycle lane	The lane designated generally for the exclusive use of cyclists, except that motor-vehicle drivers may use this lane in certain circumstances such as to access parking or to turn at intersections or driveways, for example.
Cycle path	The future position of a cyclist relative to their current position. Note that this definition differs from the one given in the *New Zealand supplement to Austroads guide to traffic engineering practice part 14: bicycles*.
Cycle/vehicle conflict	A situation where the cyclist is sharing the same road space as motor vehicles, that is the cyclist is to the right of the edge line.
Edge line	The white line separating the road shoulder from the traffic lane.
Event	A series of images of a cyclist passing the roadside obstacle and their approach and departure from the obstacle.
Exclusion zone	A user defined section of the video image that stops an event being recorded if movement is detected within the zone.
Level of service	The quality of the infrastructure provided for cyclists (eg surface quality, road crossing facilities, width).
Mountain bicycle	A type of bicycle that is usually fitted with wide tyres and shock absorbers, and is used for both on-road and off-road cycling.
Pinch point	(See roadside object).
Reflective raised pavement markers	Devices used to delineate road edge lines or centre lines, and are also known as cat's eyes in New Zealand.
Road bicycle	A type of bicycle that is usually fitted with narrow tyres and which is designed specifically for on-road cycling.
Roadside object	A naturally occurring obstacle on the side of the road that narrowed the available space for cyclists, eg a pedestrian kerb build out, drainage grate, or intruding bushes.
Zoneminder	Open-source video monitoring software (www.zoneminder.com).