A method for understanding conflicts between cyclists and other road users at urban intersections

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Final REPORT

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Revision History

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1	Final report following minor comments from client	Hamish Mackie and Jared Thomas	28/10/2016
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Contents

1. Background and Purpose

A key component of the government's investment in cycling is ensuring that cycling safety can be improved and not worsened by increased participation. Accordingly, the Cycling Safety Panel, among its recommendations, seek to ensure that intersections are designed so that they are safe for cyclists. Key to this is understanding the factors that are associated with cyclist casualties at intersections. Thus, an approach needs to be developed to understand near misses and other behaviours that are likely to be associated with poor actual and perceived safety for cyclists at intersections. The comfort of all road users is also important and so a method to better understand cyclist near misses needs to consider both motorist and cyclist comfort.

The AA Research Foundation, in partnership with the Transport Agency, is embarking on feasibility research to develop a method for this. Further to the scoping document presented by the AA Research Foundation and the initial scope of work offered by Mackie Research and OPUS, a discussion with key stakeholders has been useful in helping to refine the scope of the feasibility work. This document presents the proposed method for assessing cyclist near misses and behaviours that are likely to indicate motorist and cyclist risk or discomfort. The focus will be on commuter cycling at urban intersections.

2. Scope

The overall goal of this pilot project is to provide sufficient information to determine whether a full cycling intersection conflict study would be feasible and the likely costs of doing so. The follow stages set out the deliverables for this project.

1) A very brief review of literature
2) Development of an indicative draft framework based on literature and previous work of the researchers
3) An approach to identify intersection sites
4) A detailed method for the next stages of work
5) A review of benefits and limitations of this approach (to inform a robust decision on whether to proceed)

3. Brief summary of the literature

Academic and other literature that describes methods for analysing safety aspects of road user interactions (i.e. traffic conflicts, near misses) was reviewed, with a particular focus on studies involving intersections. Interactions of interest included motorist-motorist, motorist-bicycle, and motorist-pedestrian conflicts. Within the studies reviewed, three main methodological approaches were identified.

Manual methods: Where human observers code video footage manually, or directly observe and code up their observations in the absence of video footage.

Automated computer vision methods: Where video footage is automatically processed by software designed to identify conflict events.

Hybrid methods: Where there is a combination of automated and manual methods (or semi-automated methods).

Manual approaches include those where video recorders capture the data, as well as those where human observers capture the data. Both rely on people to manually code and analyse the video footage, including recording any physical measurement parameters and target behaviours. The advantage of the former technique lies in the ability to re-appraise the video footage multiple times, and by different observers, in order to gain a thorough appreciation of the wider, potentially complex contextual components around the interactions. Pre, during and post event factors can be analysed, including the contribution of driver / rider behaviours, infrastructure, road side and road rule factors. While this allows the creation of a full and detailed picture of the circumstances around the event, the main disadvantage to this approach is the considerable amount of time, and therefore cost required to review the video footage, code up the measurement parameters and then analyse them. There is also the possibility that human error may result in some events being missed, or inaccurately coded, particularly where there is no video footage to review.

Automated approaches rule out the human error component, by identifying all events within the video footage that meet a pre-determined set of criteria. The data processing time is fast and efficient, since it targets only the footage that contains certain measurement parameters or criteria. The parameters and criteria used during the automated data processing allow critical events to be shortlisted and levels of conflict and / or near-miss prioritised according to the spatial and temporal criteria imposed. However, where the automated approaches benefit from efficiencies of time and hence cost, they are disadvantaged by their inability to identify and analyse the wider contextual information and contributing factors mentioned above and how these contribute to the event. Difficulties with automated processing can also arise where there are multiple road users interacting simultaneously, with different behaviours and trajectories adding layers of complexity that an automated system will find hard to differentiate and attribute accurately.

Hybrid approaches aim to maximise the benefits of the both the manual and automated approaches, while minimising their limiting factors. Thus an automated approach can be used to detect, shortlist and prioritise critical events / interactions based on a set of pre-defined temporal and spatial parameters, or set of criteria, following which the human observer can manually review the target footage, and examine the wider context, and associated contributing factors, before, during and after the event.

3.1. Conclusion from the literature

Overall, we recommend a hybrid approach, which is complementary in that the shortcomings of the automatic method are overcome by the manual method and vice versa. Automated systems are cost efficient if capturing a lot of data or doing longitudinal studies, and can have up to an 85% correct conflict detection rate, and allow for easier monitoring of speed and distance metrics. Then for interpreting the severity and context of the behaviour leading up to an event, a Manual Evaluation by a human observer overcomes the typical interpretation errors where the automated systems still have reliability issues, and allows subtle measurement of behaviours to determine variation in severity assessments. See Appendix 1 for more detail on the advantages, disadvantages and metrics used with studies examined.

This approach is also world-leading, in that there are very few studies that combine disciplines (human factors and information technology) to take a hybrid approach, so this also fills a large research gap.

4. Hybrid approach methodology

4.1. Overview

Monitoring road users' movements by camera is non-intrusive and does not alter their behaviour. The literature, along with our previous experience suggest that there are two feasible options for cycle conflict analyses at intersections – a completely manual approach or a hybrid approach. For the manual approach all aspects of the analysis are carried out manually. For the hybrid approach, cyclist identification and possibly conflict identification may be carried out automatically using 'machine vision' technology. Realistically, at this stage, to fully code road user behaviours, a manual approach is needed for at least some aspects of the analysis.

The hybrid approach will be a 4 phase process: firstly, video recordings of the intersection will be collected; secondly applying computer vision software processing to the video footage to automatically identify cyclists; thirdly potentially categorise cyclist – motorist interactions; and lastly, engaging a researcher to examine the wider contextual, behavioural and situational factors impacting on the event.

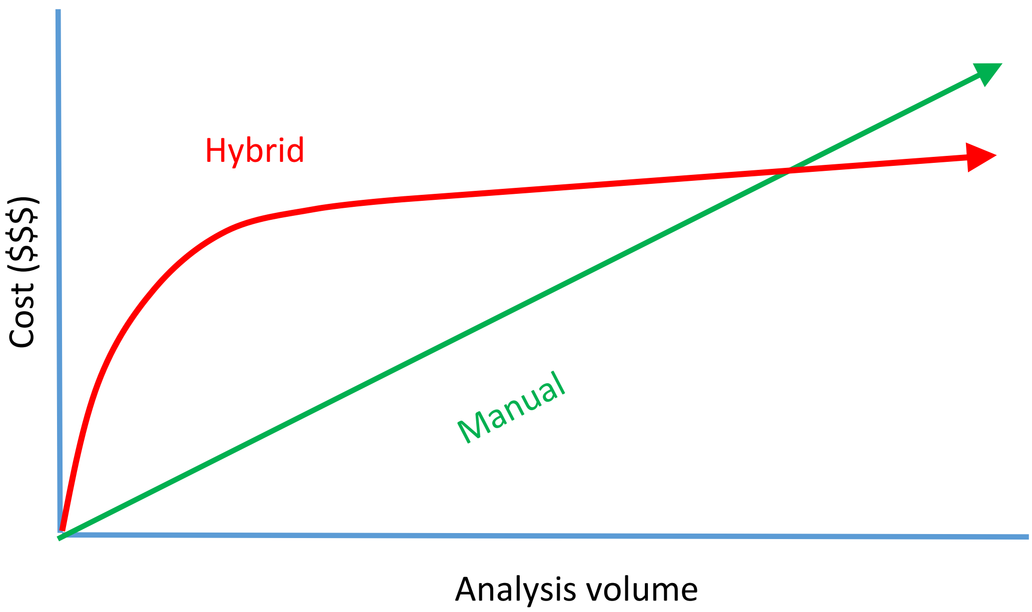
4.2. Better value approach

We believe that the use of a hybrid approach is the most cost effective solution to having the best of both worlds in the video-recorded data collection arena. It will allow us to collect a large amount of targeted data, over a longer period of time, for more statistically robust results. The automated identification of critical events involves considerably less time and labour cost than where a person is tasked with having to identify all instances when a bicycle is present within the hours of video footage.

The human component is optimised through the automated short-listing process, such that the researchers time is spent as efficiently as possible eliciting the rich contextual information surrounding the identified events that the automated process will fail to appreciate. In short, the automated data processing will provide a list of critical events which the researcher will then manually review to gain an appreciation of the wider context and layers of complexity created by the contributing infrastructure, behavioural and situational factors.

The table below shows the possible approaches to each stage and the following figure shows the likely differences in cost for manual vs a hybrid approach.

	Phase 1 Data collection	Phase 2 Cyclist identification	Phase 3 Conflict identification	Phase 4 Behavioural coding
Manual approach	Intersection selection and video camera placement	Manual	Manual	Manual
Hybrid approaches		Computer	Manual	Manual
		Computer	Computer	Manual



4.3. Phase 1: Data collection

- Four intersections (two in Auckland and two in Wellington) will be selected for data collection. Initially, one intersection will be filmed as a trial site. This will help to establish a data analysis framework that can then be effectively applied to multiple intersections;
- Data will be collected using a high-quality video camera (30 frames per second) overlooking the selected intersections. The camera may be attached to a light pole, sign, or be placed in an office window. Ideally, the camera will be in a location where it will not be obscured by high passing vehicles, cannot be interfered with, and where its stability is not affected (i.e. by wind). It will be equipped with a timing device and appropriate storage capacity to enable data capture during peak traffic periods over a 3-day period;
- In terms of perspective, the automatic detection software works best from an aerial (or birds-eye) view (typically from a building, so may work best in urban setting), which requires greater height and has the benefit that it could capture a larger part of the intersection from one camera (and so capture more interactions and also provide geolocation of conflicts). The trade-off here is the higher up, the less detailed view of for manual coding of behaviour;
- One camera will be positioned at each intersection. It will not be necessary to use multiple cameras due to the simple nature of the selected intersections;
- Video will be taken during morning and afternoon peak periods (7:30-9:30am and 3:30-6:30pm) in an effort to capture the times that cyclists most frequently use the intersections. Earlier and later times will be avoided due to the camera's poor sensitivity in low light conditions;
- The video will be captured over a period of 2-3 non-rain week days. Wet weather and night conditions may eventually be of interest, but not for this initial study. Importantly, we can potentially collect more footage on more days if we use the hybrid method. So another advantage of the hybrid method is it can potentially increase our data set for a lower cost;
- The computer vision software can run off standard video footage from an aerial view, and then is calibrated using real-world features to ensure the distance measurements are accurate.

4.4. Phase 2: Cyclist identification

Once video footage is collected, cyclists can be identified either manually or automatically. Manual identification simply involves an analyst playing video footage (either in real time or fast forward), visually identifying a cyclist and then initiating the coding process. For automatic cyclist identification, software detects a cyclist and makes an entry in a database, noting the time, or possibly even recording a relevant segment of video. One example of technology that could be useful is the FLIR System which is currently used to activate electronic cycle signs using a thermal imaging camera. This system currently dumps activations into a spreadsheet and an associated camera (such as Rasberry PI) could be used in conjunction with it to only capture video with cyclists in it. A drawback of this technology is that motorcyclists are typically also captured with this system. However, given that motorcyclists also suffer from some crash types that cyclists typically experience (e.g. looked but didn't see by motorist from side road), there may be an opportunity to analyse both cyclist and motorcyclist conflicts using a single system.

4.5. Phase 3: Conflict identification

Following the process of identifying cyclists, instances where some sort of 'conflict' exists then need to be determined. Various levels of conflict are explained further in Phase 4, but a system needs to capture lower-level conflicts (Avoiding or negotiated behaviour) as well as more serious conflicts or near misses. Lower level avoiding behaviour is important to capture as it helps to understand not only safety risk but also occasions where cyclists (and motorists) may feel discomfort.

A manual approach to conflict identification would simply involve an analyst assessing any interactions with other road users and categorising the level of conflict accordingly (as proposed in the next section). Taking an automated approach, measures such as Time to Collision (TTC) or Post Encroachment Time (PET) may be used. For this a 'machine vision' system would be needed to automatically identify and track users in the field of view. Typically, a PET of less than 1.5 seconds between a cyclist and another road user would be used to identify any potential conflicts.

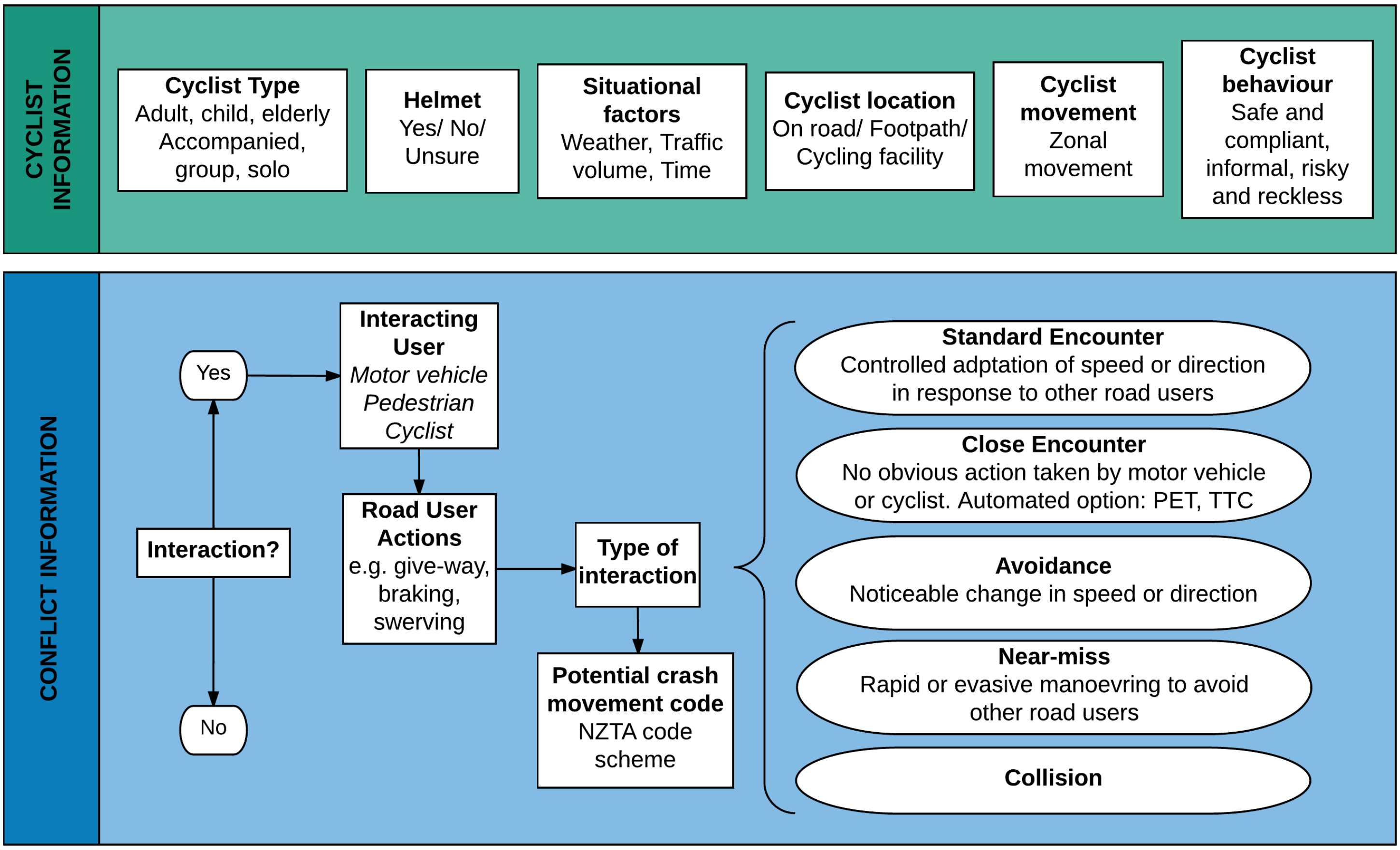
4.6. Phase 4: Behavioural coding

From the initial automated (or manual) sorting of the video data to identify important events, a human will then be used to code the characteristics of the interactions. The coding for this phase provides sufficient information to understand the nature of the interaction so that solutions can be designed and effectively evaluated. The human coder would be more adept at identifying subtle and nuanced behaviour than a computer program, so it is accepted that this last phase will require manual coding.

This approach would initially utilise two independent analysts to code cyclist behaviour. Once an acceptable inter-rater reliability score has been established, then one analyst could code the main dataset, with periodic auditing by a second coder.

For this phase, we have started with our Future Streets coding framework, as significant effort has already gone into developing it, including determining an acceptable inter-rater reliability. However, it required modification to meet the specific purpose of analysing cycle intersection conflicts. Discussion between Mackie and Opus identified areas where modifications were needed.

A summary of the coding framework for phase 4 is presented in the diagram below:



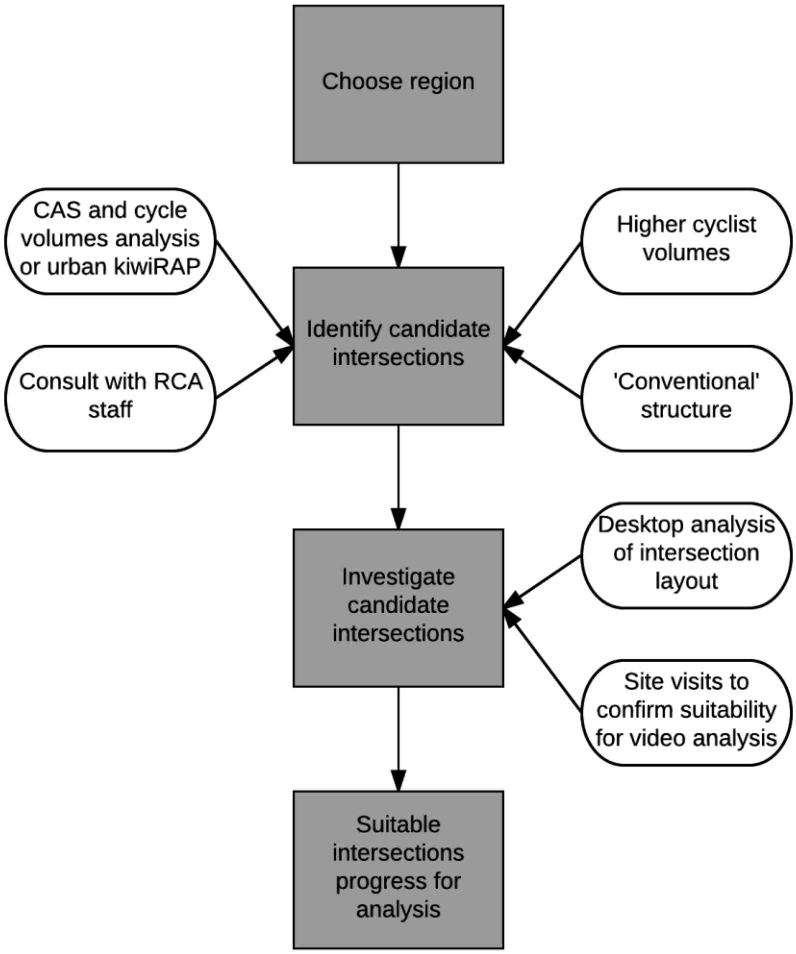
A more detailed description of the NZTA movement codes can be found in Appendix 2, and a more detailed description of the coding options for each item can be found in Appendix 3.

5. An approach to identify intersection sites

Initially, a convenience approach to selecting intersections of interest is suggested to test and refine a video analysis method. Consultation with RCA staff will be used to determine sites that are of mutual interest. Criteria for intersection inclusion may include intersections that:

- are relatively 'conventional' and therefore will allow the method to be scaled up around the country to similar intersections if successful. We are not including roundabouts at this stage.
- have higher volumes of cyclists, so that sufficient data can be collected from them
- are known hotspots for cyclist conflicts and/or crashes
- Include cyclist movements that are typically problematic
- have obvious locations where video cameras could feasibly be located (or have existing video cameras which provide a useful field of view)

Beyond pilot work, the following process might be used to select intersections for analysis:



6. Suggested method

6.1. Pilot Study (1 intersection, 2 days of data collection, data processing)

Once selected, there will be a preliminary site investigation to examine infrastructure and other features of the site, observe road user behaviours through the site, identify any potential risks that could impact on data capture, record any health and safety considerations for installing the equipment, and identify the best structure / location to install the camera that offers the best overall perspective of the intersection. Permission to locate the camera in this chosen location will then be sought.

Data will be collected over 2-3 days (taking into account traffic flow through the site, battery life, memory capacity).

Camera footage will be calibrated for the specific site, to match real world features that enable accurate calculations of distance and therefore speed data to be made. Following calibration, a selection of the footage will be processed automatically using baseline identification rules and the identical footage will then be corroborated manually by a human coder. The algorithms used during the automated processing will then be further calibrated / moderated to minimise misses and false detections in the data.

All cyclist-motorist interactions captured will then be time-stamped and binned if they occur within 1.5s of each other in terms of PET. This short-listed 'binned' group will then be prioritised based on 0.5s increments (i.e. from collisions at 0s, 0.5s, 1.0s, 1.5s), where the smaller PET in seconds reflects the greater severity of the event. Automatic processing of these interactions will also include calculations of the speed of the cyclist and motorist (including braking), location and trajectory of the vehicles. The short-listed events will then be processed in greater depth and within the wider context by a human coder, starting with the most serious conflicts first. The human coder will take a systems approach to the coding, that includes a thorough appraisal of the range of contributory factors, (infrastructure, driver/rider and environmental) impacting before, during and after the event, and in terms of conflict severity, as outlined in the framework shown in earlier in Section 4.5.

The results will be written up in a short report highlighting summary statistics and recommended refinements for the full study.

6.2 Main Study: 3 additional intersections

After a hold point and review, we will proceed onto the main study. A refined methodology based on the steps outlined in the pilot above will be applied to examine the final intersections. The findings will be analysed, including comparative statistical analyses between intersections and examining novel and common factors relating to cyclist-motorist conflict.

6.3 Findings

There are three main components to the findings of this innovative research. First, the findings will provide new lessons and knowledge about computer vision using a hybrid methodology. Second, the intersection data captured will reveal cyclist/motorist interaction factors that may be generalisable to a wider set of intersections to inform engineering and education practice and recommendations. Third, and most importantly, the study will provide unique cycle/motorist interaction data on four important intersections where informed interventions could be put in place (working with the local road authority). The method could then be employed to test success immediately and cost-effectively. So this provides the opportunity to move beyond research and into reporting real-world safety benefits.

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Glossary/Definitions

Traffic conflict: Defined as “an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged” (Amundsen and Hyden 1977, cited by Van de Horst et al 2014)

Near miss: Defined as “the time between the moment that the first road-user leaves the path of the 2nd road-user, and the 2nd road-user reaches the path of the 1st” (Allen et al 1977, cited by Van de Horst et al 2014)

PET: Pose-Encroachment Time is a common conflict measure that examines the difference in time between a first road user leaving a common spatial location and a second road user arriving at that same location (Ismail et al., 2009).

TTC: Time-to-Collision is a common conflict measure that examines the time before two road users (or objects) collide if they were to continue on the same trajectory with no change in speed or direction (Sayed et al., 2013).

Conflict monitoring success metrics

Collective Risk = Events/hour

Individual Risk = Conflict rate/interaction

Severity = Typically examine a combination of TTC or PET (but do not typically attempt to combine this with speed, which would be a nice addition)

Appendices

Appendix 1

	Collection method	Author/ title	Method	Method - Comments	Manual Analysis	Manual Analysis - Comments
Manual study		*Application of automated video analysis for behavioural studies: concept and experience (Laureshyn, Ardo et al. 2009)*	Manual observations at the same time as video observations Attached cameras to balconies on apartment buildings. Issues with permission to use balcony, being able to contact building owner, source of power nearby etc.	Ensure accuracy. Might gather more behavioural information (if the cyclist shouted, facial expressions etc.)		
	Two observers positioned at each location (intersection)	*Manual Conflict observation Technique DOCTOR (Kraay, Van der Horst et al. 1986)*	Two observers located near intersection.	Careful to position observers so they are not noticeable by road users and do not disrupt naturalistic behaviour. Not having video means the researchers are unable to review an event.	Developed a coding system to analyse the behaviour of all road users and determine the seriousness of conflicts.	The coding system can be used regardless of if the method of collection is by observation, or video. Although the system can effectively code movement, it does not provide a qualitative understanding behind movement-based behaviour

				Having two observers means you are less likely to miss an event. Can clarify the details of an event. Physical observers capture 'in the moment' data. Researcher may have a better 'feel' for the event than if it was on video.		
			Paper-based observation form			
	Video cameras positioned on poles overlooking an intersection. One camera per intersection.	*Future Streets*	Video taken two days a week (Wednesday and Saturday) from 6am-6:30-7pm for four days.		Two analysts used to code the video.	More accurate, avoids coding bias
			Traffic tube counters	Tubes: limited lifespan of 2 weeks. Can count all vehicles, including cyclists	Zones were created on the video analysis screen	The analyst could then record how the road user moved through the intersection, and what manoeuvre they had made.
					Developed an analysis framework for all road users. Here, we outline cyclist analysis: Type: adult, child, elderly, accompanied, group (2 or more adults), group of children helmet (yes/no) cyclist movement (1-4-5-6) cycling location: on-road, footpath, on cycling facility **Cyclist behaviour**: safe & compliant. Mostly follows road rules and demonstrates awareness of traffic, cycling as a vehicle either mid-block or whilst turning. **Informal**: mixture of road and footpath, opportunistic crossing or gap selection. Cyclist may not demonstrate formal head checks or signalling, but demonstrates some awareness of	

					other road users. **Risky/reckless**: Riding heedless of traffic or pedestrians, demonstrating risky manoeuvres (e.g. diagonal crossing at intersections regardless of traffic, darting out).
					Coding system to determine severity of encounter: Adapted from (Kraay, Van der Horst et al. 1986, Johnson, Charlton et al. 2010, Hunter, Srinivasan et al. 2012) **Standard encounter**: A traffic situation in which two road users approach each other in time and space and may influence each other's behaviour. For the majority of encounters, a controlled adaption of course or speed will be sufficient to realise a normal settlement of encounter. This includes giving way or 'courtesy' give-way behaviour, where user does not legally have to give-way. Behaviour is controlled. **Avoidance**: a noticeable change in speed or direction by either the pedestrian or interacting user to avoid the other (e.g. minor braking by the vehicle). Less severe avoiding behaviour compared to a near-miss/conflict. **Near-miss**: Rapid or evasive manoeuvring (Johnson et al., 2010) to avoid each other, evident by a sudden change in speed or direction by the pedestrian or interacting user to avoid the other (or both users) (e.g. major braking by the vehicle or swerving).
	Video cameras were positioned on commuting cyclists' helmets. Their regular commute over a 4-week period was recorded. A survey of participants was also included	*Naturalistic cycling study: identifying risk factors for on-road commuter cyclists (Johnson, Charlton et al. 2010)*	Video recordings captured cyclists' perspective of the road and traffic behaviours including head checks, reactions and manoeuvres.	Helmet-mounted camera: Only from the point-of-view of cyclists. Can't get the bigger picture of the intersection. Can't see what is happening behind them. Oregon Scientific ATC3K Action Camera. Footage recorded at 640 x 480 VGA resolution, 30 frames p/s	Data analysis was conducted in four stages: an initial footage review; identification of events, classification of event characteristics and; statistical analysis. The classification of events was adapted from 100-car study (Neale et al. Blacksburg, Virginia: Virginia Tech Transportation Institute; 2002. The 100 Car Naturalistic Driving Study, Phase 1 - Experimental Design.) "Three event severities were identified: collision, near-collision and incident. A *collision* involved contact between the cyclist and another road user with kinetic energy transference. A *near-collision* required rapid, evasive manoeuvring from the cyclist and/or the driver to avoid a collision, e.g. sudden braking or swerving. An *incident* required some collision avoidance, but was less sudden than the near-collision event and included close vehicle proximity which results when drivers did not allow sufficient space when overtaking cyclists."
			Each participant recorded 12 hours of their	Footage when participants rode off-road including bike paths and footpaths	

			commuter cycling trip over a 4-week period.	and; footage recorded during low light hours as the camera had poor light sensitivity was excluded		
			Participant inclusion criteria: over 18 years, regularly cycle commuted to and from work, travelled the majority of trip (70%) on-road and able to film 12 hours of footage over a 4-week period.	The study was conducted during warmer months from October to December 2009, commencing with the start of daylight savings (summer time).		
			Participants completed a survey about their driving/cycling experiences	Provided weekly updates. Completed an exit interview about their study experience, cycling safety and general topics including helmets, headphones and registration.		
	Video camera placed on a roof overlooking a crossing.	*Reduction in car–bicycle conflict at a road–cycle path intersection: evidence of road user adaptation*	28.25 hours of recordings were made on weekdays between 7-9am and 3-		Two analysts coded the video data	Two people rated these situations independent of each other. 86% in agreement. In cases where there was disagreement, reclassification occurred by discussing the situation between the two people rating them.
					Zones on the video were coded	The analyst could then record how the road user

		(Phillips, Bjørnskau et al. 2011)	5pm		i.e. A, B, G, H	moved through the intersection, and what manoeuvre they had made.
					"Yielding event: The cyclist and/or driver yields in a controlled manner in order to avoid a collision with the other party. Conflict event: The cyclists and/or driver stops or brakes suddenly in order to avoid a collision with the other party" p.90	It was noted who yielded first. Uneventful cases involving cyclists were also recorded
	Purpose of study to investigate the rate, associated factors, and behaviour characteristics of two-wheeler red light running	The red-light running behavior of electric bike riders and cyclists at urban intersections in China: an observational study (Wu, Yao et al. 2012)	Observational study with two synchronised video cameras at three four-armed signalised intersections in Beijing.	Tripod next to the roadway. The other faced the other direction. Weekdays during daylight hours. Avoided rain and extreme temperatures.	Coding restricted to e-bikes and cyclists entering an intersection on a red light. Only those riders travelling through the intersection.	Coded for: age group, gender, traffic light status, type of bike (electric, pedal), crossing behaviour (law-obeying, risk-taking, opportunistic), situational factors (cross traffic volume, group size)
					1h of video was coded by two independent research assistants to avoid potential coding bias	
	Video of an urban intersection in Copenhagen for 12 hours from an office window.	The Bicycle Choreography of an Urban Intersection (Colville-Andersen, Madruga et al. 2013)	The empirical data is collected from 7 am to 7 pm on 11 April 2012. It consists of bicycle user and motorist counts, recording the 'Desire Lines' of the bicycles and the	Recorded 16,631 bicycle users and 27,644 motorists passing through the intersection from 07:00 to 19:00.	When determining whether behaviour was "good" or "bad" we used the current Danish traffic laws as a rough guideline. However, as the traffic laws are car-centric in nature and do not priortise pedestrians or bicycles, we divided the laws into two categories and created three categories for bicycle users.	**Conformists** - Bicycle users who ride by the book. **Momentumists** - Bicycle users who interpreted the current rules creatively whilst following their Desire Lines. Our rule of thumb was that if something is legal in The Netherlands or in another cycling nation or city, then we regarded it as Momentumism. Right turns on red for bicycle users, for example are now legal in Paris and Brussels. In addition, bicycles are not excluded from pedestrian crossings in many cities around the world like Japan, Spain, etc. **Recklists** - Bicycle users who flouted what we think to be rather sensible traffic rules; running a red or yellow light, riding on a sidewalk or ignoring the bicycle infrastructure.

			number of legal and illegal acts - according to the Danish traffic laws - as well as general behavioural observations.		We classify the bicycle users' paths according to the Desire Lines they follow. The Lines range from basic movements that follow the planners' intentions for movements through the intersection, to the more complex methods such as U-Turns and multiple turns. They use these lines to optimize their ride and make the best use of the bike's efficiency as transport mode. Most traffic users orient themselves according to the choreography of other users, as opposed to the existing traffic rules.	
	Cyclists wore helmet-mounted video cameras. Aim of the study was to assess the speed of cyclists in different situations	Faster than the speed of bikes (Johnson and Chong 2015)	Helmet-mounted cameras	Only from the point-of-view of cyclists. Can't get the bigger picture of the intersection. Can't see what is happening behind them Good-quality cameras used Oregon Scientific ATC9K camera mounted on helmet to measure daily commute (in the ACT).		
	'think aloud' and video	*Using on-road study data to explore the sequence of behaviours and factors involved in cyclists' near collisions with other road users (Goode, Salmon et al. 2014)*	On-road trial of cyclists on a pre-defined urban route. Cyclists provided concurrent 'think aloud' verbal protocols, while being video recorded by a following		Near misses were identified using manual observation of the video footage and classified according to; a) type of conflict (single, multiple vehicles) b) sequence of behaviours (awareness, pre-event manoeuvre, precipitating factor, evasive manoeuvre) c) contributory factors (road layout, road furniture, driver behaviour, cyclist behaviour,	**Advantages**: Verbal protocols allowed researchers to extract cyclists decision-making and thought processes in real-time. Cyclist verbal protocols could be used to compare with and validate analysis of video footage / classification of interactions captured. They could also be used as a complementary measure to the fixed camera approach, where a small number of riders could ride through the target intersections providing verbal protocols about their

			researcher on a bicycle.		pedestrian behaviour, road rules) Stanton and Salmons 2009 taxonomy of driver error causal factors was adapted for cycling. Guo et al's 2010 model of vehicle crashes/near misses was applied to cyclist crash/near miss events.	experience interacting with the intersection and perceptions of safety / discomfort in relation to particular infrastructure, motorist or other features. **Disadvantages**: Labour intensive reviewing video footage and associated cyclist verbal protocols. Possible mismatch between cyclist verbal identification of critical event / near-miss and researcher classification of these using the video footage. Verbal protocols based on cyclists personal perspective, and could therefore introduce variation related to age, experience, confidence etc.
	Video were captured over a week (location?)	*Traffic conflicts on bicycle paths: A systematic observation of behaviour from video (van der Horst, de Goede et al. 2014)*	Used 2 or 3 CCD (charge-coupled device) video cameras and a close up camera, recording for 24 hours a day over a 7-day period.		Analysis was undertaken using the DOCTOR (Dutch Objective Conflict Technique for Operation and Research) conflict observation method. A critical situation was identified when the space available for manoeuvring was less than that needed for a normal avoidant reaction. Conflict severity based on probability of collision and likely outcome of a collision.	**Advantages**: Overcomes some of the limitations of automated methods, such as detection error due to lighting and the presence of shadows, occlusion by other vehicles in heavy traffic, and requirements on camera angles for specific feature detection (e.g. bicycle wheels). Manual coding allows for repeated viewing of the video footage to specifically score different aspects of the conflict. This follows the safe system approach through the analysis of events, behaviours and infrastructure features that are evident before during and after the conflict. It allows for the analysis of contextual information about the amount of space available vs amount of space needed – which might provide an indicator for

						infrastructure change. This safe system method of analysis is similar to the AustRoads risk assessment calculator, in that they both utilise the likelihood of an event occurring and the likely injury severity following a crash to assess the impact of an actual conflict. **Disadvantages**: High cost as the task is labour intensive, both in identifying a conflict event (especially if cycling is less frequent), and in coding a conflict event (which requires repetition of the same conflict event several times to code it, often going through it frame-by-frame). Identification of conflict events relies on a focussed human observer watching footage that is typically running at higher than real-time speed (between events). Thus introducing the possibility for some conflict/ near miss situations to be missed. Particularly difficult to accurately capture microscopic changes in road user position and speed. Also, this takes the longest to code. Some of the metrics used would be difficult to repeat by other researchers due to the subjective nature of the assessment criteria used for the conflict events.
	Video footage of an intersection, used two cameras to film	A study on cyclist behavior at signalized intersectons (Ling and Wu 2004)	Positioned two synchronised cameras to view the entire intersection	May miss subtle movement, don't necessarily understand decision-making process	Manual video analysis: Within the data-reduction process, the speeds of traffic entities were determined by noting the time required to traverse a known distance (usually about 15–20 m), which is defined by a set of fixed objects (i.e. the width of roadways or the distance between stop lines).	

	it. Aim to understand cyclist behaviour and movements at signalised intersections		Used two cameras Pedestrian overpass over an intersection	Limited battery life Monitoring road users' movements by camera is non-intrusive and does not alter their behaviour.	The time required to traverse the section was obtained by noting the number of frames during the traverse. The time can be calculated by multiplying the number of frames by 0.04 s. The speed was computed by dividing the reference distance by the elapse time for each entity. In this method, the error of speed data is estimated less than 0.15 km/h. The duration of a gap is measured from the number of pictures between the beginning and end of the gap. The gap begins when the bicycle front wheel reaches the conflict point; at this moment, the opening gap vehicle arrived at point A and the gap ends when the closing gap vehicle reaches point A. Likewise, we can measure an accepted lag in this way; the only difference is that point A locates at the conflict point in this case.	
	Video was collected of roads and intersections pre- and post a change in the design of the road	Road user behaviour changes following a self-explaining roads intervention (Mackie, Charlton et al. 2013)	Video was collected over nine separate days, at nine different locations, both before and after SER construction	Cameras mounted on tripods	Video data used to count pedestrians and cyclists. For each road user that appeared within the video frame, numerical codes were assigned to descriptors that were developed. Firstly, the data were broadly categorised by road type (local, collector or both in the case of threshold intersections), location (mid-block or intersection) and then by road user (e.g. car, pedestrian etc.). Descriptors were chosen for their relevance to the SER modifications. While they needed to give sufficient information to allow subtle changes in road user behaviour to be detected, they also needed to be easily subjectively categorised. After the descriptor codes were developed, they were tested to determine whether they provided sufficient information to be useful and also whether they were agreeable between analysts. Two analysts independently coded an initial sample of data. Any discrepancies in subjective interpretation were then addressed to clarify the requirements for each road user behaviour code, prior to the main data coding	
	Collection method	**Author/ title**	**Method**	**Method- Comments**	**Hybrid analysis**	**Hybrid analysis - comments**
Hybrid study	Analysis of contra-flow cycling on a one-way street using video	*Application of automated video analysis for behavioural studies: concept and experience (Laureshyn, Ardo et al. 2009)*	Attached cameras to balconies on apartment buildings.	Issues with permission to use balcony, being able to contact building owner, source of power nearby etc	Developing automated video analysis system. Uses a point-tracker. Measures trajectories (foreground – background segmentation), and speed (shape analysis of interest points). Manual observations of the video were also conducted	The video analysis system that was used was most effective at picking-up movement going in the counter direction. In general, the video system picked up fewer cyclists than the human observers did, but there were cases when the system found cyclists that the human observer had not observed.

	Video of a 'scramble-phase' intersection in California. Aim: to demonstrate pedestrian-vehicle conflicts in the context of a scramble-phase intersection	*Automated pedestrian safety analysis using video data in the context of scramble phase intersections (Ismail, Sayed et al. 2009)*	Similar analysis techniques are presented in (Ismail, Sayed et al. 2009) "Automated analysis of pedestrian-vehicle conflicts using video data"		Used automated computer vision techniques to detect and analyse the severity of pedestrian-vehicle conflicts at an intersection, using positional, spatial and temporal data parameters. While the system was automated, this was one of the only studies to explicitly highlight the benefit of using the automated system to identify important events, for the purpose of relaying these events to a human observer for further examination (as opposed to validation). Hence, we have labelled this as a hybrid system, as it is one of the only studies to recommend this approach.	**Advantages**: Automated systems can identify, shortlist and prioritise important events. About 7000 vehicle turning events and 2100 pedestrian crossing events were identified during 20 hours of footage. The authors recommend PET over TTC as the most reliable approach for detection of important events. However, PET has limitations in accurately capturing conflict severity. Once identified, critical conflict events can then be analysed in more depth by a human observer, to provide thorough contextual analysis of events, including severity confirmation. **Disadvantages**: Still requires accurate identification of conflict events taking into account error around lighting effects, limited video angle, and occlusion.
	Comparison of methods	*Cross-comparison of three surrogate safety methods to diagnose cyclist safety problems at intersections in Norway (Laureshyn, Goede et al. 2016)*			Compared two semi-automated methods using 1) the Swedish traffic conflict technique (Swedish TCT), 2) the Dutch conflict technique (DOCTOR). Object identification and Time-to-Collision. This was also compared to a Canadian probabilistic surrogate measures of safety (PSMS), which used open source software developed from the "Traffic Intelligence" project.	**Advantages**: The semi-automated methods use supplementary tools to assist manual coding via semi-automated video processing (using T-Analyst: http://www.tft.lth.se/en/research/video-analysis/co-operation/software/). This allows a manual setup of a 3D model that can calculate elements that are difficult to manually code, such as speed, road user position, and Time-to-Collision. Some evidence of external validity with crash data. The type and location of conflicts were similar to that reported in the crashes (although the crash numbers were small, n = 7 crashes). High correlation between the two semi-automated

						methods indicating high reliability. The Swedish TCT develops a conflict severity ranking by combining time-to-accident (the time at which an evasive action is taken) and the conflicting speed (the speed of travel at the time of the evasive maneuver) **Disadvantages**: Used experts to initially identify the “conflict” events, meaning it is still a labour intensive approach initially (but faster than manual coding once set up). Far fewer conflict events than automated methods (although arguably fewer false detections).
	Grid-based camera calibration	*Camera calibration for urban traffic scenes: practical issues and a robust approach (Ismail, Sayed et al. 2010)*			This method paper outlines an approach for grid-based camera calibration that is used prior to the use of automated computer vision techniques. This helps overcome error due to the visual angle of the camera, by placing an even grid over the 2-D image it can map it to real-world geometric road user positions.	**Advantages**: A grid-based overlay could be used as another semi-automated approach, adding another tool to help with the more difficult metrics related to manual coding. Often manual coders will make evenly spaced temporary markings in real-world scenes to provide distance cues when determining speed, distance and conflict. This method provides a more accurate version of this. **Disadvantages**: This method would still require manual coding that would be resource intensive

	Video of intersection to understand movement of cyclists. Water drip on cyclists’ front wheel to better see travelled path. Note, this is a PhD, so only some methods have been commented on here.	*Innovative Techniques for Analyzing Cyclist Behaviour and Predicting Cyclist Safety* *(Kassim 2014)*	Positioned camera on 12th floor of a building to view the entire intersection	Static high-definition commercial grade video camera (1920 × 1080 pixels at 30 frames/second). Good-quality camera ensures high-quality video footage. Monitoring road users’ movements by camera is non-intrusive and does not alter their behaviour. May miss subtle movement, don’t necessarily understand decision-making process Limited battery life	Video analysis technique to measure cyclist speed.	Measuring wheel was used on the road to mark out areas. This helped get true information on the computer screen to determine true lengths of segments which appeared on the video.
			Cyclist water trail	Not naturalistic It rains a lot in Auckland, might not show up. To show the path that the bike took. Dripper system installed onto front wheel. Useful for mapping desire lines	Tracking algorithm to identify moving objects	Saves time looking through hours of video. Differentiate between different road users and the environment Cost Expertise to develop it. Is something like this already available?
	Collection method	**Author/ title**	**Method**	**Method comments**	**Automated analysis**	**Automated analysis - comments**

Automated study	Videoed an intersection. Traffic conflicts were automatically identified by computer analysis	*Automated safety diagnosis of vehicle–bicycle interactions using computer vision analysis (Sayed, Zaki et al. 2013)*	Vide of an intersection using multiple, synchronised cameras. Careful about deciding the placement and angles. One intersection camera was used, with the camera angle altered to pick up three different views or locations on three different days (for 8 hours each).	Get the whole view of the intersection, can better understand and interpret the movement and behaviours as you get the 'whole picture'	Automated safety diagnosis approach for evaluating vehicle–bicycle conflict situations using video analysis. Countermeasures were also recommended based on the analysis (but no post-implementation trial was run to evaluate this). Automatic detection of; traffic conflicts and ranking of severity (using TTC), different vehicle types, vehicle road rule violations	Produced a cyclist-vehicle conflict heat map for the intersection. Good way of showing 'hot spots', the dangerous points for cyclists at intersections. **Advantages**: Object detection allows automatic coding of variables like vehicle type, and space-based object detection can automatically code frequency and location of risk maneuvers (like failure to yield at intersections), providing additional data at relatively low cost. Tracking accuracy of movements was over 85%, and classification of objects was above 90%. Conflict and severity rates could be automatically evaluated, with 28% of cyclist-motorist interactions with a TTC of 3s or less, and 14% with a TTC of 1s or less. Including a breakdown by location, and visual hot spot spatial techniques, to look at conflict density by exact location (e.g. conflicts/m2). **Disadvantages**: Overall false detection rates are very high. Some conflicts are missed through automation. Noise in the image and errors such as classification errors meant that about 13% of conflicts were missed (when compared with those classified manually by a human observer). Accurate detection of cyclists can mean that the camera position needs a good viewing angle on the wheel of the bicycle (as this is the most consistent feature detection component, especially if distinguishing a bicycle from a motorcycle or pedestrian).

	Used eight cameras to film an intersection	*A comparison between PARAMICS and VISSIM in estimating automated field-measured traffic conflicts at signalized intersections (Essa and Sayed 2016)*			This study used automated video-based computer vision techniques to capture vehicle trajectory data to predict conflict using vehicle trajectory data. Microsimulation models (PARAMICS and VISSIM) were evaluated to predict conflict at a signalised intersection, validated against manual observer data. The Kanade–Lucas–Tomasi feature tracker algorithm was used to track movement and audit the data. The focus was vehicle-vehicle interactions, specifically looking at rear end conflict.	**Advantages**: The length of the observation period can be extended, as the resource cost of analysing the footage is low (once the data is collected). The most severe events can then be identified and prioritised for examination. High reliability of conflict prediction. A two-phase calibration of the data meant a very strong relationship with manual expert observations of conflict for these models. Compared with manual observation the PARAMICS model provided a 0.60-0.75 correlation at lower Time-to-Collision (TTC) thresholds (between 1.0s and 1.5s respectively). Lower TTC thresholds are more relevant to safety, as they represent closer conflicts or near misses. The benefit of 8 cameras for each intersection is that the closer the camera (or the higher the resolution of the footage) the more accurate the measurements are regarding speed, position, and likelihood of conflict **Disadvantages**: The 8 camera approach is a higher resource approach compared with some automated methods. Also, the practicalities of setup may be difficult at some intersections (i.e. locating positions for the 8 cameras and syncing the cameras). This study only examined rear end collisions using only trajectory data, so other proxy measures of conflict, or other relevant behaviours were not captured. Still required manual coding by a human observer to determine validity, and even after calibration both PARAMICS and VISIM overestimate the number of conflicts (i.e. false detections).

	Used pole-mounted GoPro cameras (with a resolution of 15 frames/s).	*Are signalized intersections with cycle tracks safer? A case–control study based on automated surrogate safety analysis using video data (Zangenehpour, Strauss et al. 2016)*	This research examined multiple intersections using a case-control study approach to determine the efficacy of cycle tracks (defined as cycles lanes that are physically separated by infrastructure like concrete medians or bollards) in improving safety when they cross over with intersections.	Automated video-based method for analysis of post-encroachment time (PET) at intersections. **Advantages**: Automated conflict prediction allows automated processing of larger data sets, in this case more than 90 hours of data from 23 intersections. This is beneficial in assigning relative risk between intersections or monitoring change in risk over time. In this case it has indicated that intersections with cycle tracks vs no cycle tracks have about half the "dangerous" interaction rate (which was calculated based on exposure to PET of less than 1.5s). The classification accuracy of conflicts (compared with manual) was high at 88%. **Disadvantages**: A before-after approach with more data on fewer intersections would have greater control.

Appendix 2

NZ TRANSPORT AGENCY
WAKA KOTAHI

VEHICLE MOVEMENT CODING SHEET

For use with crash data from CAS (Version 2.8 May 2010)

	TYPE	A	B	C	D	E	F	G	O
A	OVERTAKING AND LANE CHANGE	PULLING OUT OR CHANGING LANE TO RIGHT	HEAD ON	CUTTING IN OR CHANGING LANE TO LEFT	LOST CONTROL (OVERTAKING VEHICLE)	SIDE ROAD	LOST CONTROL (OVERTAKEN VEHICLE)	WEAVING IN HEAVY TRAFFIC	OTHER
B	HEAD ON	ON STRAIGHT	CUTTING CORNER	SWINGING WIDE	* BOTH OR UNKNOWN	LOST CONTROL ON STRAIGHT	* LOST CONTROL ON CURVE		OTHER
C	LOST CONTROL OR OFF ROAD (STRAIGHT ROADS)	OUT OF CONTROL ON ROADWAY	OFF ROADWAY TO LEFT	OFF ROADWAY TO RIGHT					OTHER
D	CORNERING	LOST CONTROL TURNING RIGHT	LOST CONTROL TURNING LEFT	MISSED INTERSECTION OR END OF ROAD					OTHER
E	COLLISION WITH OBSTRUCTION	PARKED VEHICLE	CRASH OR BROKEN DOWN	NON VEHICULAR OBSTRUCTIONS (INCLUDING ANIMALS)	WORKMANS VEHICLE	OPENING DOOR			OTHER
F	REAR END	SLOWER VEHICLE	CROSS TRAFFIC	PEDESTRIAN	QUEUE	SIGNALS	OTHER		OTHER
G	TURNING VERSUS SAME DIRECTION	REAR OF LEFT TURNING VEHICLE	LEFT TURN SIDE SIDE SWIPE	STOPPED OR TURNING FROM LEFT SIDE	NEAR CENTRE LINE	OVERTAKING VEHICLE	* TWO TURNING		OTHER
H	CROSSING (NO TURNS)	RIGHT ANGLE (70° TO 110°)							OTHER
J	CROSSING (VEHICLE TURNING)	RIGHT TURN RIGHT SIDE	OPPOSING RIGHT TURNS	TWO TURNING					OTHER
K	MERGING	LEFT TURN IN	RIGHT TURN IN	TWO TURNING					OTHER
L	RIGHT TURN AGAINST	STOPPED WAITING TO TURN	MAKING TURN						OTHER
M	MANOEUVRING	PARKING OR LEAVING	"U" TURN	"U" TURN	DRIVEWAY MANOEUVRE	ENTERING OR LEAVING FROM OPPOSITE SIDE	ENTERING OR LEAVING FROM SAME SIDE	REVERSING ALONG ROAD	OTHER
N	PEDESTRIANS CROSSING ROAD	LEFT SIDE	RIGHT SIDE	LEFT TURN LEFT SIDE	RIGHT TURN RIGHT SIDE	LEFT TURN RIGHT SIDE	RIGHT TURN LEFT SIDE	MANOEUVRING VEHICLE	OTHER
P	PEDESTRIANS OTHER	WALKING WITH TRAFFIC	WALKING FACING TRAFFIC	WALKING ON FOOTPATH	CHILD PLAYING (INCLUDING TRICYCLE)	ATTENDING TO VEHICLE	ENTERING OR LEAVING VEHICLE		OTHER
Q	MISCELLANEOUS	FELL WHILE BOARDING OR ALIGHTING	FELL FROM MOVING VEHICLE	TRAIN	PARKED VEHICLE RAN AWAY	EQUESTRIAN	FELL INSIDE VEHICLE	TRAILER OR LOAD	OTHER

* = Movement applies for left and right hand bends, curves or turns

New Zealand Government

Appendix 3

Draft coding protocol

Code site and date.

Code time for each cyclist for when they appear in the frame.

Code the cyclist for each time they cross the road under the same site reference (specific to a site and specific to a user).

If a cyclist crosses the road twice at different roads, code the cyclist twice under same site reference and the same time on the row below (highlighted in yellow).

For the cyclists it is very important to code everything e.g. if they signal or have, or do not have lights on when it is dark, this should be coded in the comments box to the left in the spreadsheet.

If a cyclist is riding mid-block and a car passes them – but there is no visible change in direction or speed by either road user – this is a no interaction.

Cyclist type:

- Adult
- Child (definition: Wearing a school uniform, obviously under 18 years of age)
- Elderly (definition: obviously elderly)
- Accompanied
- Group (2 or more adults on bikes)
- Group of children

Helmet:

- Yes (wearing a helmet)
- No (not wearing a helmet)
- Unsure

Cycling location:

- On road
- On footpath
- Mixture (mixture between riding on footpath and road). If a cyclist only rides on the road to cross but otherwise rides only on the footpath, it should be classified as *on footpath.* If during riding they swap between footpath and road and vice versa, it should be classified as mixture.
- On cycling facility

Cyclist movement:

- Between zones ascribed to the intersection.

Cyclist behaviour:

- **Safe and compliant** (definition: generally following road rules and demonstrating awareness of traffic (cycling as a vehicle either mid-block or whilst turning). Cycling on the road and showing awareness of other road users, head checks, may be signalling.
- **Informal**: Riding on the footpath, mixture of road and footpath, opportunistic crossing or gap selection. Cyclist may not demonstrate formal head checks or signalling, but demonstrates some awareness of other road users.
- **Risky or reckless**: Riding heedless of traffic or pedestrians, demonstrating risky manoeuvres (e.g. diagonal crossing at intersections regardless of traffic, darting out)

Interaction type:

- **No interaction** Definition: No cars present or no evidence of an intersecting movement, or road users adapting their behaviour in response to the other.
- **Standard encounter** (definition: a traffic situation in which two road users approach each other in time and space and may influence each other's behaviour. For the majority of encounters, a controlled adaption of course or speed will be sufficient to realise a normal settlement of encounter)
- **Close encounter** (definition: no obvious action taken by either road user. Automated option: PET, TTC)
- **Avoidance** (definition: a noticeable change in speed or direction by either the cyclist or interacting user to avoid the other (e.g. minor braking by the vehicle). Less severe avoiding behaviour compared to near-miss/conflict)
- **Near-miss** (definition: Rapid or evasive manoeuvring to avoid each other, evident by a sudden change in speed or direction by the pedestrian or interacting user to avoid the other (or both users) (e.g. major braking by the vehicle or swerving).
- **Collision** (definition: physical contact between users)

Interacting user:

- Motor vehicle
- Pedestrian
- Motorbike

Interacting user movement:

- Between zones ascribed to that intersection

Standard encounter cyclist action:

- No action – maintains course
- Passes parked vehicle
- Gives-way
- Negotiates traffic/RU (road user)

Standard encounter pedestrian action:

- No action – maintains course
- Gives-way
- Negotiates cyclist

Standard encounter vehicle (or motorbike) action:

- No action – maintains course
- Gives-way (courtesy)
- Vehicle non-compliant

Avoidance cyclist action:

- No action – maintains course
- Passes parked vehicle
- Brakes or slows
- Accelerates
- Changes path/swerves
- Priority

Avoidance pedestrian action:

- No action – maintains on course
- Stops or slows runs
- Changes path or swerves

Avoidance vehicle (or motorbike action):

- No action – maintains course
- Vehicle non-compliant
- Brakes
- Overtakes cyclist (<1m)
- Overtakes cyclist (>1m)
- Accelerates
- Swerves