Evaluation of evidence-based infrastructure for safer cycling

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Thesis Summary

Cyclists are one of the most physically vulnerable road user groups, particularly when they share the road with motorised vehicular traffic. Their vulnerability as road users stems from their limited protection in the event of a collision and their low tolerance to the forces associated with collisions with motor vehicles.

In Australia, there is significant scope to increase the mode share of cycling with both a large proportion of the population living within a serviceable riding distance from their place of work or education and a large proportion of private motor vehicle trips being made over relatively short distances. However one of the key concerns of cyclists is their vulnerability when riding on road in mixed traffic and this discourages many people from riding a bicycle or riding more often. One proven measure to improve the safety of cyclists is the provision of high quality continuous cycling infrastructure that provides separation from adjacent motor vehicle traffic, particularly in higher speed road environments.

This thesis presents an innovative approach to investigating cycling infrastructure and thereby addressing some of the most frequent and high severity mid-block collision types that occur within urban road environments throughout Australia. The centrepiece of this thesis, that represents both a unique and significant contribution to the field of road safety research, is the development and validation of a purpose-built bicycle simulator, designed specifically for the task of evaluating on-road infrastructure design concepts. Subsequent to the development and validation of the bicycle simulator, the research presented in the later chapters of this thesis utilised simulator-based research methods to investigate cycling infrastructure designs selected to address high priority and common cyclist crash types in Australia. The research identified various bicycle lane design concepts with the potential to encourage safer cycling by increasing the spatial separation between cyclists and motor vehicles. The research also identified various design concepts that participants perceived were beneficial compared to commonly used Australian bicycle lane designs.

The findings provide new insight into the benefits of innovative bicycle lane designs that adhere to the principles of the “Safe System” approach to road safety. The findings will directly inform best practice bicycle facility design, helping to improve the safety of cyclists and thereby helping to increase cycling participation.
Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

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Chapter 1: Introduction

Cycling is gaining renewed popularity as a mode of transportation (Garrard 2009, Australian Bicycle Council 2015) resulting in increased research related to cycling (Handy et al. 2014); particularly, a focus on factors that influence participation and the risk associated with on-road cycling (Wardman et al. 2007, Xing et al. 2008, Geller 2009, Fishman et al. 2012). Research suggests that in-order to facilitate increasing growth in cycling participation there is a need to address the issues surrounding cycling safety (Fishman et al. 2012), particularly if on-road mode share is to increase (Bauman et al. 2008, Garrard 2009, Garrard et al. 2010, Fishman et al. 2012).

There are a variety of methods that can be utilised in isolation or in combination to improve road safety. Historically these were considered to include, education, enforcement and engineering (Noland 2013). These concepts are further developed within the “Safe System” framework for road safety which comprises a systems based approach to road safety by considering the interactions amongst roads and roadside environments, road user speeds, road users and their behaviours (Chen & Meuleners 2011). The primary focus of the research presented in this thesis is on engineering based road safety solutions which were formulated to investigate and evaluate cycling infrastructure to address a range of high prevalence and high injury risk cyclist collision types, with a predominant focus on ways to change the road and roadside environment to influence road user behaviours and speeds.

In order to achieve this objective, a bicycle simulator was developed and validated as part of this research program. This simulator was then used to evaluate infrastructure concepts that target key collision types involving cyclists. The development and application of the simulator form the key components of this research, however, firstly in order to address cyclists safety there is a need to better understand the context within which cycling occurs.

The remainder of this chapter presents an introduction to cycling within an Australian context, including a discussion of the benefits of cycling, risks associated with on-road cycling and a discussion of current cycling participation levels. The chapter concludes with a statement of the research objectives, research questions and presentation of the structure for the remainder of the thesis.

1.1 The benefits of cycling

Bicycles are a versatile vehicle that are well suited to a range of recreation, commuting and utilitarian trips (Organisation for Economic Co-operation and Development (OECD)/ International Transport Forum (ITF) 2013). Cycling is also considered to be a sustainable mode of transportation as it provides “transport that meets the needs of the present without compromising the ability of future generations to meet their own need” (World Commission on Environment and Development 1987, p. 43). The sustainability of cycling is apparent when bicycles are used as a mode of transport and particularly when cycling trips replace private motorised transport. When this occurs cycling generates a range of social, environmental, economic and health benefits, both for the

In Australia, it is recognised that there are a range of benefits associated with increased cycling participation, and there is significant scope to increase the mode share of cycling, particularly for the forty percent of Australians who commute less than ten kilometres to their place of work or study and also for those making short local trips (Infrastructure Australia 2009). Increasing cycling mode share and participation has the potential to reduce traffic congestion and improve the quality of life in cities (Lusk et al. 2011, Handy et al. 2014). In Australia, the Bureau of Transport and Regional Economics (BITRE) estimate that the annual avoidable cost of traffic congestion in Australia will rise to over $20 billion AUD by 2020 (BITRE 2007) representing a substantial economic cost to society through lost productivity and resources. Compared to private motor vehicles, bicycles are a much more spatially efficient mode of transport (Botma & Papendrecht 1991, Dekoster et al. 2000). A typical three and a half metre wide traffic lane has a maximum capacity for approximately 2,000 private vehicles per hour. Comparatively, it is estimated that 14,000 cyclists per hour could theoretically utilise the same space (Hickman et al. 2011). These values show that inner urban areas can be more efficiently serviced by cycling and that increasing cycling mode share could reduce congestion of the roadway and potentially reduce the amount of space allocated to and required for transportation infrastructure.

Bicycles are not only spatially efficient, especially within urban environments, cycling also provides a viable alternative to private motorised vehicles in terms of travel time (Dekoster et al. 2000, Ellison & Greaves 2011). When travel time is measured from door to door a person riding a bicycle can comfortably travel distances of up to ten kilometres in the same time as someone using private or public transport vehicles. Bicycles also provide much greater freedom and flexibility compared to public transportation (OECD/ITF 2013).

Reducing motorised transport use in favour of cycling also generates significant environmental benefits. In Australia, the transport sector is responsible for approximately seventeen percent of total carbon dioxide equivalents (CO2e) emissions (Commonwealth of Australia 2016). Cycling as a mode of transport produces practically zero carbon emissions apart from negligible emissions associated with respiration. Other environmental benefits associated with cycling include, reduced noise pollution, compared to private vehicles (Litman 2013), and a reduction in other pollutants associated with the use of fossil fuels, including carbon monoxide, methane, nitrous oxide and particulate matter (Litman 2013).

Cycling is also a much more cost effective mode of transport for the individual compared to private motorised and public transport. There are no fuel, parking, ticketing or registration costs associated with cycling and generally speaking, bicycles are cheaper to purchase and maintain than motorised vehicles. Average transport costs for Australian households are estimated to be $323.36 AUD per week, which is equivalent to approximately 13.3 percent of an average household’s budget (Australian Automobile Association 2016) and 43.3 percent of these costs are related to fuel, maintenance and toll road fees for private motor vehicles. Therefore switching trips from car to bicycle has the potential to significantly reduce a household’s transport and total expenditure.
Riding a bicycle is associated with a range of health benefits for riders of all ages. Cardiovascular diseases, type 2 diabetes and obesity are some of most significant public health issues in modern society (Australian Institute of Health and Welfare (AIHW) 2014). These non-communicable diseases are associated with an increasingly sedentary lifestyle and the risk of developing these conditions can be reduced through regular physical activity (AIHW 2014), which benefits not only the individual cyclist, but also reduces the burden of disease on the public health system. Cycling as a mode of transport offers an excellent opportunity to swap sedentary time in a motor vehicle for exercise. Physical exercise is shown to have other benefits including improved, mental health (Penedo & Dahn 2005), wellbeing (Whitaker 2005, Daley et al. 2007) and productivity (Penedo & Dahn 2005).

1.2 Cycling risks

Despite the range of benefits generated by cycling, riding a bicycle is not without risk (OECD/ITF 2013, Stevenson et al. 2015). Compared to motor vehicles, bicycles offer very limited protection to the rider. The limited protection results in exposure to adverse weather conditions and increased exposure to air pollutants, particularly as a result of tailpipe emissions (Woodcock et al. 2009, De Hartog et al. 2010). However, these risks are relatively minor compared to the increased risk of being seriously or fatally injured due to a collision when riding on a road, particularly when compared to other motorised road users and vehicle occupants (Hillman & Morgan 1992, Woodcock et al. 2009, De Hartog et al. 2010). Cyclists are one of the most physically vulnerable road user groups, particularly when they share the road with motorised vehicle traffic (Chong et al. 2010, OECD/ITF 2013, Stevenson et al. 2015). Their vulnerability stems from their limited protection in the event of a collision and their low tolerance to the forces associated with collisions with motor vehicles, in particular as a result of the transfer of kinetic energy that occurs during a collision (OECD/ITF 2013).

1.3 Cycling participation

Despite the risks associated with cycling, research suggests that the benefits of cycling outweigh the risks (Hillman & Morgan 1992, Woodcock et al. 2009, De Hartog et al. 2010) and it is for this reason that the need to increase cycling participation is recognised through numerous cycling strategies and public policies at various levels of government in Australia and Internationally (Australian Bicycle Council 2010, City of Portland Bureau of Transportation 2010, Victorian Government 2012, City of Copenhagen 2013, Greater London Authority 2013).

Cycling participation is influenced by a number of diverse factors including demographic, social, economic, cultural, political, infrastructure and environmental (Wardman et al. 2007, Handy & Xing 2011). These factors contribute to the varying rates of cycling participation observed throughout the world. Figure 1 illustrates that European countries, particularly those in Northern Europe, have some of the highest rates of cycling participation in western society, with some countries and cities having up to a quarter of their urban trips made using active transportation (Pucher & Dijkstra 2000).
High level political decisions to encourage cycling have resulted in many European cities making significant investments in cycling infrastructure. For example, in the Netherlands it is estimated that approximately $25 per head per annum is invested in cycling infrastructure. This compares to less than $10 per head across most Australian states, territories and local government areas (Parker 2013). The significant investment in cycling infrastructure is justified due to the economic benefits that the mode generates, particularly when compared to private motorised travel. For example, a recent study conducted in Germany determined that a 10 percent increase in active transport modal split could increase the German GDP by 1.1 percent, equivalent to an economic benefit of 29 billion euros (Doll 2013).

Apart from government commitments to develop cycling infrastructure, another key reason for high levels of cycling mode share in European cities is the compact land-use pattern (Stevenson et al. 2016). Many European cities have average densities that are approximately three times that of Australian and North American cities, resulting in average trip lengths that are approximately half the distance (Pucher & Dijkstra 2000). High population densities in many European cities has resulted in urban design that is oriented towards people and not private vehicles, with pedestrian and bicycle access prioritised ahead of other modes of transport and cycling being viewed as a utilitarian goal of urban designers (Pucher & Dijkstra 2000). This has also contributed to a less car centric culture in many European cities compared to other western societies (Pucher & Dijkstra 2000). Other design factors that influence increased cycling participation in Europe include the provision of traffic calming measures to lower vehicle speeds, provision of end-trip facilities, and integrating cycling with public transport (Martens 2007).
As opposed to many European countries, North America has typically had low levels of cycling participation. This is partly attributed to the low cost of private motor vehicle ownership, high levels of mobility typical of North American lifestyles, the perceived danger associated with cycling, road infrastructure primarily set up for motor vehicular travel, and the very low levels of funding that have historically been made available for bicycle infrastructure (Pucher 1988, Pucher & Dijkstra 2003). Many of these issues are shared with Australian cities. However, despite these trends, cycling participation is slowly growing in parts of North America, with many major cities beginning to construct cycling infrastructure networks over the past decade (Dill & Carr 2003, Pucher et al. 2011). There are also several examples of smaller cities re-designing infrastructure to accommodate cyclists, typically associated with University campuses with strong cycling cultures and mode shares (Handy & Xing 2011).

While in many European countries, a great deal of research has been conducted investigating factors surrounding cycling participation (Pucher & Dijkstra 2000, Bassett et al. 2008, Pucher et al. 2010). In Australia there is currently a limited understanding of cycling participation, with very few comprehensive surveys available to quantify participation levels and trends. Furthermore, with no requirements for licencing or registration and minimal barriers to participation, it is a difficult task to accurately measure the number of people who ride bicycles for commuting and recreational purposes or verify any travel pattern information. Estimates from the Australian Cycling Participation Survey suggest that in a typical week four million Australians ride a bicycle and a little over a third of the population ride a bicycle each year (Australian Bicycle Council 2015). Furthermore the results from the survey indicate that cycling participation is primarily focused in inner urban areas, approximately within ten kilometres of city centres (Australian Bicycle Council 2015).

Estimates of commuter cyclist volumes from the Australian Census show that, in Melbourne cycling mode share represents approximately 1.5 percent of commuter trips to work. This figure is marginally above the Australian average at approximately 1.2 percent (Australia Bureau of Statistics 2011). Analysis of trips to work in Melbourne reveal that the majority of cycling trips (75%) originate within inner and middle local government areas, with some areas close to the Melbourne Central Business District (CBD) recording up to twenty percent of journey to work trips being made by bicycle. The census data also highlights that commuter cycling trips are predominantly focused on travelling to (and from) the CBD, with almost half of all trips made by bicycle in metropolitan Melbourne ending in the City of Melbourne (Australia Bureau of Statistics 2011). While these data provide some indication of cycling participation, there are limitations with the use of journey to work data, particularly for cycling trips (Pucher et al. 2011). These limitations include the fact that the census data do not consider recreational or utility cycling trips, or any information on child cyclists (Oxley et al. 2016). Furthermore the data is collected on just one day in the middle of winter, which is a time when cycling participation is typically at its lowest rate throughout the year, resulting in significant under-reporting of total cycling. Notwithstanding, the results from various cycling data sources suggest that the demand for cycling in Australia is increasing, albeit at a relatively slow rate. In Melbourne, commuter cyclists are largely concentrated in the inner urban areas within 10 kilometres of the CBD and the majority of cycling trips are towards and from the CBD.
In Australia there has been a marginal increase in cycling participation in recent years, however, cycling has not been adopted as a common mode of transport to the extent that it has in many European cities (Pucher & Dijkstra 2003). There may be many reasons for these differences, including cultural and environmental factors and the fact that many European cities were designed pre automobile dependence unlike Australia (Stevenson et al. 2016).

It has been established that countries and cities with high levels of cycling participation and low cyclist collision rates tend to have extensive cycling infrastructure, traffic calming measures where there is a mix of vehicles and cyclists, and policies and programs that are supportive of cycling and discourage the use of private transport, while the opposite is generally true for cities with low cycling rates (Pucher & Dijkstra 2003). These findings suggest that the use of appropriate cycling infrastructure can both improve cyclist's safety while at the same time encourage increased participation. However there is a need to further understand cycling infrastructure within an Australian context in order to understand how infrastructure can be developed, enhanced and in many cases retrofitted to encourage increased cycling participation, and more importantly to improve safety.

1.4 Research objectives

The overarching objective of this research is to evaluate evidence-based on-road cycling infrastructure designs that have the potential to significantly reduce injury risk to cyclists when engaging with the urban road and traffic environment and which may ultimately help to encourage increased and safer cycling participation. Furthermore it is intended that the evaluation of cycling infrastructure will be conducted using a newly developed bicycle simulator, developed as part of this research. In order to meet these aims, the specific objectives of the research were to:

- Develop and validate a bicycle simulator suitable for evaluating on-road infrastructure designs from a cyclist's perspective;
- Develop an evidence base to guide the development of on-road cycling infrastructure designs to address the most prevalent serious and fatal cyclist collision types in Australia;
- Apply best-practice design principles to select on-road cycling infrastructure that addresses the most prevalent cycling collision types that result in a fatal or serious injury outcome;
- Evaluate the effect of on-road cycling infrastructure designs on cyclist behaviour using the bicycle simulator; and
- Translate the findings into best-practice road design and infrastructure treatments to create a safer road environment for cyclists.
1.5 Research questions

Based on the research objectives, two overarching research questions were developed to guide the research:

- What changes can be made to on-road cycling infrastructure in the urban road environment that can reduce the prevalence of serious and fatal cyclist injury collisions?
- How do cyclists perform and interact with alternate infrastructure treatments?

A secondary aim of the research was to develop and validate a bicycle simulator for use in the evaluation process. In relation to this process two secondary research questions were proposed:

- What is required to develop and validate a high fidelity bicycle simulator to evaluate road design for improved cyclist safety?
- What cyclist performance measures can be accurately assessed in a bicycle simulator?

The following section details the structure of this thesis and provides an overview of each of the remaining chapters in this thesis. The research in the remaining chapters were guided by the research questions and with the intention of meeting the research objectives specified in section 1.4.

1.6 Thesis structure

This chapter established the background for this research by providing an introduction to the issues surrounding cycling participation and cyclist safety in Australia. This chapter also outlined the objectives of the research and the research questions that were developed to guide the research program. The structure of the remainder of this thesis follows a relatively linear movement through the chapters that correspond with the progression through the research stages. The remaining components of this research are presented in the following chapters:

Chapter 2: Theoretical framework – introduces the theoretical frameworks that were adopted to guide the research undertaken in this thesis. The research was guided by the “Safe System” approach to road safety and the Kinetic Energy Management Model (KEMM). There are strong synergies between the two frameworks and they have both been utilised to guide the examination of cyclist collision factors and the selection of safer cycling infrastructure concepts that were evaluated as part of this research.

Chapter 3: Principles of cycling infrastructure design – presents a review of Australian and International cycling infrastructure design principles. This chapter builds on the theoretical frameworks presented in Chapter 2, with a more specific look at cyclist infrastructure requirements. The chapter also includes a discussion of evaluation techniques for road designs, with a focus on the use of road safety simulators as a preliminary evaluation technique at the concept design phase of infrastructure development.

Chapter 4: Road safety simulator review – this chapter builds on the discussion in Chapter 3 regarding the use of road safety simulators and presents a review of the use of driving and cycling simulators for road safety research. The chapter includes a discussion of simulator applications, limitations, the various types of simulators and a review of bicycle simulators that have previously been developed for research and education purposes.
Chapter 5: Bicycle simulator development – this chapter presents the process that was undertaken to develop the bicycle simulator. Included in this chapter is a discussion of the performance measures selected for the simulator and a description of the simulator architecture, including the hardware and software components that are incorporated into the simulator. The chapter also details some preliminary testing using the simulator which investigated the fidelity of the steering and braking controls and provided a preliminary assessment of simulator sickness induced by the bicycle simulator.

Chapter 6: Bicycle simulator validation – this chapter presents the findings of a validation study that was undertaken to establish the behavioural validity of the bicycle simulator. The study compared selected performance measures of participants collected while using the simulator with naturalistic cycling data collected while riding an instrumented bicycle on-road.

Chapter 7: Examination of cyclist collision factors – this chapter examines fatal and serious injury cyclist collisions throughout Australia and in the state of Victoria. The aim of this study was to identify key collision types for cyclists that result in high levels of trauma and identify factors associated with these collisions that could be addressed through safer infrastructure designs. The findings from this chapter form the evidence base for the selection of infrastructure concepts that are examined in the remaining chapters of the thesis.

Chapter 8: Infrastructure for safer cycling – this chapter details the process undertaken to select infrastructure concepts to address the cyclist collision types identified in Chapter 7. The infrastructure concepts selected align with the theoretical frameworks identified in Chapter 2 and the design principles identified in Chapter 3. The chapter considered both infrastructure designs and the use of perceptual countermeasures as methods to improve cyclist safety.

Chapter 9: Examination of bicycle lane design characteristics – presents the findings of three complementary simulator-based studies undertaken to gain a better understanding of how cyclists position themselves when riding in bicycle lanes. The first study was designed to assess how cyclists position themselves in bicycle lanes of different widths. The second and third study investigated how perceptual countermeasures can be utilised to encourage cyclists to adopt different and potentially safer rider positions and behaviours when riding on-road in bicycle lanes.

Chapter 10: Evaluation of safer cycling infrastructure - presents the findings of simulator-based studies that were undertaken to evaluate the bicycle infrastructure designs identified in Chapter 8. Two studies were undertaken to assess cycling infrastructure designs to address rear-end, side-swipe and car-door collisions, which were identified as key collision types resulting in serious casualty and fatal injuries in Chapter 7.

Chapter 11: Discussion and Conclusions – summarises the key findings of the research program. An overview of the research is presented, followed by a discussion of the key findings, the implications of these findings for road safety and road design, the limitations of this research, recommendations for translating this research into practice as well as identifying avenues for future cycling road safety research.
Chapter 2: Theoretical frameworks

As noted in Chapter 1, the objectives of this research were to develop a bicycle simulator to measure cyclist behaviours and evaluate the effectiveness of on-road cycling infrastructure designs that have the potential to reduce the risk of on-road urban fatal and serious injury collisions involving cyclists. By investigating cycling infrastructure there is the potential to better understand cyclist behaviour, especially how to encourage cyclist to adopt safer cycling behaviours. Furthermore through the ultimate installation of infrastructure that improves cyclist safety when riding on-road, there is the potential to encourage increased cycling participation, both as a recreational activity and a mode of transportation, particularly for the trips of less than ten kilometres in length, which has been shown to have the potential to generate significant personal and societal benefits.

In order to meet these objectives, a number of theoretical approaches and models from the fields of road safety and injury prevention were considered as the guiding framework for this research, particularly to address the issues surrounding cycling safety and to guide the selection and evaluation of safer on-road cycling infrastructure. The theoretical approaches and models considered included the Haddon Matrix (Haddon Jr 1968), Swiss Cheese model of accident causation (Reason 2000), Accimap, developed by Rasmussen (Rasmussen 1997) Vision Zero (Elvebakk 2007) and Sustainable Safety (Wegman & Mulder 1998). While all models and approaches were relevant for the research and each had specific strengths and limitations, ultimately the “Safe System” framework for road safety was adopted as the primary theoretical framework to guide this research.

The “Safe System” framework was selected as essentially its principles were progressively developed with consideration of the previously mentioned theoretical approaches. The “Safe System” framework uses a holistic systems-based approach that considers not just individual road users, but also the interactions between different road user groups, the road and roadside environment, and the differing physical properties of vehicles and road users (e.g. speed, mass, rigidity etc.), in order to address road safety issues. The principles of the “Safe System” framework are complemented by the principles of the Kinetic Energy Management Model (KEMM). Similar to the “Safe System” approach, the KEMM applies a systems-based approach that considers methods to avoid, reduce or mitigate the kinetic energy involved in a collision and reduce the transfer of energy to the road user if a collision occurs. In particular the design process that is conceptualised in the KEMM has been utilised when considering the selection of evidence-based road designs to address key crash types identified in this research.

This chapter presents an overview of the “Safe System” framework and the KEMM. Included are introductions of each of the frameworks, a discussion of how the components of the frameworks are applicable to cyclist safety and infrastructure design, and how the frameworks align with the research questions and the work that was undertaken throughout the course of this research program.
2.1 The “Safe System” framework for road safety

The “Safe System” road safety philosophy represents a fundamental change to traditional approaches in road safety thinking and the insight into society’s efforts to minimise road trauma (Chen & Meuleners, 2011). The Australian formulation of the “Safe System” combines elements of Sweden’s “Vision Zero” and the Netherlands “Sustainable Safety” road safety philosophies (Chen & Meuleners 2011). Both Sweden and the Netherlands are world leaders in road safety performance and the development of the philosophies behind strategic road safety thinking. Their respective philosophies were developed based on a platform that emphasise that a road system that tolerates high levels of serious injury is unethical (Wegman & Mulder 1998, Elvik & Amundsen 2000, Elvebakk 2007), while acknowledging the limitations of humans while using the road system, in terms of both vulnerability to high impact forces and the propensity to make errors.

The “Safe System” approach advocates for a road environment that is designed to be forgiving of these human limitations. That is to say that, while crashes will occur, no crash should result in serious casualty or fatal injury outcomes, provided that road users behave in accordance with the road system. More importantly, the approach advocates a shared responsibility: road users should behave in accordance with the road system and the designers of the system should provide a safe and crashworthy transport environment. The key methods of providing a safe and crashworthy environment are through providing safer roads and roadsides, safer vehicles and encouraging safe road user behaviours and travel speeds. In sum, the “Safe System” approach is structured around a framework that recognises the interaction between different components of the road system. A conceptual representation of the framework is shown in Figure 2.

In short, the framework comprises four key principles:

1. Recognising the limits of human performance and acknowledging that humans will make mistakes and that the system should be designed so that these errors can be accommodated;
2. The limits of human tolerance to violent forces;
3. Shared responsibility between road users, designers, operators and governments; and
4. Creating a forgiving road transport system.

These principles are targeted towards the development and implementation of evidence-based interventions that consider the four key elements of the road system being the road users and their behaviours, their vehicles, road user speeds and the interactions made between road users and the road and roadside environment. These elements are considered in greater detail in the following section.
Since its formulation, the “Safe System” approach has been widely adopted within the road safety community both in Australia and Internationally (Chen & Meuleners 2011). The “Safe System” was first adopted in Australia in 2003 as part of the National Road Safety Strategy 2001-2010 (ATC & ATSB 2000). The “Safe System” also forms the framework for the current Australia National Road Safety Strategy 2011-2020 (ATC 2011). The “Safe System” approach has also been incorporated into the majority of state road safety strategies around Australia including the current Victorian road safety strategy “Towards Zero” 2016-2022, which aims to reduce the annual road toll in Victoria to fewer than 200 people while reducing the serious injury toll by at least fifteen percent over the five year period compared to baseline conditions in 2016 (State Government of Victoria 2016). The need for a safe road environment for cyclists is also identified in both the Australia and Victorian cycling strategies (Australian Bicycle Council 2010, Victorian Government 2012), however, neither document specifically identifies the “Safe System” framework. However at the time of writing this thesis, both strategies were being redeveloped, by the respective road agencies.
2.2 The Kinetic Energy Management Model (KEMM)

The KEMM, as the name suggests, provides a framework for addressing the kinetic energy associated with vehicle collisions and defines aspects to address in order to prevent fatal or serious injuries to road users (Corben et al. 2010).

Energy has a range of forms including kinetic, potential, thermal, chemical, electrical, electromagnetic and nuclear. The principle of Conservation of Energy, can be taken that the total energy in an isolated system remains constant. Energy can be neither created nor destroyed, rather it is transferred from one form of energy to another. Of the various forms of energy, injury is most often associated with the transfer of kinetic energy (WHO 2008). Kinetic energy is energy which a body possesses by being in motion and is commonly expressed as a function of half the mass of the object and the square of the object’s velocity (WHO 2008).

Injuries to road users, including cyclists, occur when there is a transfer of kinetic energy that is beyond the levels of human biomechanical tolerance (Corben 2004). This transfer of energy causes the road user to experience a sudden change in velocity (acceleration or deceleration), which in turn causes resultant forces to act upon their body (Glaister 1978). The injury potential of a vehicle collision or the level of damage that occurs is related to the amount of mechanical work applied to, or the energy absorbed by the body (Glaister 1978). The energy absorbed will depend of the shape and rigidity of the colliding surface or object (WHO 2008) and the human tolerance is determined by the biomechanical strength of the body tissue to absorb the energy (Glaister 1978).

Eiband (1959) summarised that human tolerance to sudden acceleration depends upon:

- the direction in which the accelerating force is applied to the body;
- the magnitude of the accelerating force;
- the duration of the accelerating force;
- how rapidly the accelerating force is applied; and
- how the body is supported during the acceleration.

A fundamental requirement of a safe road environment is the condition that the kinetic energy and the resultant forces to which road-users are exposed must be below the levels that are capable of causing death or serious injury (Corben 2004).

The KEMM identifies two methods for managing the transfer of kinetic energy in the event of a collision. These are by either preventing the occurrence of a collision in the first place, or by managing the transfer of energy if an impact does occur (Corben et al. 2010). In order to prevent the transfer of energy in a collision the KEMM presents a five layer model, where each layer represents a level of protection around the centrally placed road user. The five layers of the model from the inner most layer represent:

- increasing the biomechanical tolerance of the human to violent forces (or kinetic energy);
- attenuate the transfer of kinetic energy to the human;
• reducing the level of kinetic (or other) energy to be managed in a crash;
• reducing crash risk for a given level of exposure; and
• reducing exposure

The KEMM is structured around the Haddon matrix which considers the three phases of a crash:

• the pre-crash phase;
• the crash phase; and
• the post-crash phase.

The KEMM identifies human, vehicle and environmental factors that can be influenced in the pre-crash and crash phases of an incident and the model focuses on ways to manage and control dangerous levels of kinetic energy that have the potential to cause serious casualty or fatal injuries to road users. When considering the KEMM there are few ways of increasing the biomechanical tolerance of cyclists to violent forces, as such in order to reduce cyclist injuries the a greater focus is placed on the four outer layers of the model, that is to either attenuate the transfer of energy in a collision or reduce the level of energy, risk or exposure to crashes.

2.3 Cycling within the frameworks of the “Safe System” and KEMM

The four key elements of the “Safe System” have been considered to investigate what is required to create a safe environment for cyclists within the principles of both the “Safe System” and KEMM frameworks.

2.3.1 Safe vehicles

Bicycles are characterised as being small, agile, light weight vehicles and it is these characteristics that make bicycles appropriate for human powered transportation. However, it is also due to these characteristics that they offer very limited protection to the road user in the event of a collision (OECD/ITF 2013). When considering a bicycle as a vehicle, it is unlikely that significant changes can be made to the vehicle design that could mitigate or transfer the kinetic energy in a crash with a motor vehicle away from the bicycle rider, while still maintaining the fundamental characteristics of the bicycle. However, that is not to say that there are no measures that can be put in place to enhance the safety of bicycles as a vehicle.

Research suggests that, for example, appropriate vehicle maintenance can reduce the risk of being involved in a collision. In their cohort study of injured cyclists, Shaw et al. (2012), identified that mechanical issues including gears jamming, chains falling off and brake failure were all noted as contributing factors in falls from bicycles. Furthermore there are aspects of the bicycle that can lead to an increased risk of a collision. For example Patel (2004) reported on three case studies where cyclists were hospitalised due to them being unable to release their feet from clipless pedals when they had lost control of their bicycle. These situations are examples of mechanical failures of the bicycle componentry in the pre-crash phase that have resulted in injury.

When considering the KEMM, the factors of a motor vehicle that result in significant injuries to cyclists are the speed, mass, geometry, and the rigidity or stiffness of the vehicle (Corben 2004). Other vehicle design features
such as bull bars and the vehicle bonnets (including the height, shape, area and slope) have been shown to influence injury risk in pedestrian collisions (Crandall et al. 2002, Corben 2004). When considering cyclist injuries, similar design features emerge as sources of injury, however cyclists have been found to have their own unique set of accident kinematics (Van Schijndel et al. 2012). In particular cyclists are generally found to impact higher on the motor vehicle and in more rearward areas of the windscreen and bonnet compared to pedestrians. This is due to the high seated nature of cyclists and associated higher centre of gravity, compared to pedestrians (Maki et al. 2003, Peng et al. 2012, Van Schijndel et al. 2012). Crash tests and simulations have also identified that cyclists tend to hit the bonnet or windscreen of a vehicle with higher head impact speeds, compared to pedestrians, providing further justification for the use of helmets (Van Schijndel et al. 2012).

Wegman et al. (2012) suggests that improved design of the front and sides of motor vehicles, such as increased protection to avoid under-run collisions, could significantly reduce the risk of cyclist injury. These types of collisions are particularly hazardous to cyclists. For example, research from Japan indicates that cyclists risk of fatal injury is reduced when colliding with vehicles with a sedan style bonnet-type, compared to vehicles with flat frontal structures such as mini-vans etc. (Maki et al. 2003), due to the reduced risk of underrun collisions.

The stiffness of the vehicle body is also a significant determinant in the level of energy transfer and absorption in a collision. Reducing the stiffness of vehicles allows for more energy to be dissipated through deformation of the motor vehicle (Corben 2004). Furthermore this can extend the duration of the collision, which allows the energy in the collision to be transferred at lower levels of force and over a longer period (Corben 2004).

The mass of a vehicle is a major contributing factor to the severity of injury sustained in a collision, due to its influence on the total kinetic energy available within the system. However, it does not seem likely that there will be significant reductions in mass across the full motor vehicle fleet in the near future. Significant reductions in the mass of private vehicles could increase the risk of injury for motor vehicle occupants in the event of a collision, particular in collisions involving larger freight vehicles (Elvik 2010). While the scale of freight vehicles is largely dictated by societies demand for consumer goods and the economies of scale that are offered by the use of larger vehicles (Elvik 2010), which is unlikely to see any meaningful decline.

Intelligent transport systems (ITS) and in-vehicle technologies have the potential to significantly improve the safety of cyclists (Silla et al. 2016). In-vehicles systems are currently available that can alert drivers of the presence of cyclists adjacent to the vehicle or in the drivers blind-spot (Silla et al. 2016) While the growing uptake in autonomous vehicles will reduce the probability of conflict between cyclists and motor vehicles (Rosén et al. 2010, Silla et al. 2016), these technologies are still in their infancy and have only begun to penetrate the high-end and mid-range vehicle market. As such these technologies are unlikely to have a significant impact on vulnerable road user safety in the short term. Furthermore to date it appears that limited research has been undertaken investigating how autonomous vehicles and cyclists will interact, however this is foreseen as a field of research that will grow rapidly in the near future.
2.3.2 Safe speeds

Speeding (driving above the speed limit) and inappropriate speed (driving too fast for the conditions, which relates to the driver, vehicle, road and the traffic mix rather than the speed limit) are recognised as major contributory factors in traffic crashes (WHO 2008). Speed contributes to unsafe road conditions in two ways.

- At higher speeds road users have less time to process information and to react to changes in the road environment (WHO 2008) and the braking distance required to stop is longer. Therefore the possibility of avoiding a collision is reduced and the probability of a collision is increased (WHO 2008).
- Speed is also a direct contributor to the kinetic energy within a collision. As speeds increase there is an increasing amount of kinetic energy that needs to be dissipated in a collision. Therefore collisions at higher speeds also result in increased injury severity and damage as the forces and accelerations in the collision exceed those that the human body can tolerate (WHO 2008).

In essence there are two main types of collisions that result in serious casualty or fatal injuries to cyclists (Boufous et al. 2013).

- Single vehicle collisions; which do not involve any other road users and occur due to the cyclist either hitting a fixed or stationary object, or falling from their bicycle due to a loss of control, and;
- Multiple vehicle collisions; where a cyclist and one or more other road users, typically a motorised vehicle, collide.

For single vehicle collisions, the source of damaging energy can be through the speed of the cyclist generating kinetic energy. Potential energy can also be the source of injury causing energy when cyclists fall from their bicycles. For multiple vehicle collisions it is the speed of the motor vehicle that will generally generate the majority of the energy during a collision.

Furthermore, at a minimum, a motor vehicle has approximately ten times greater mass than a person riding a bicycle. This results in the kinetic energy generated by the motor vehicle being at least an order of magnitude higher than the energy generated by a bicycle when travelling at the same speed. Furthermore motor vehicles are capable of travelling at higher speeds than bicycles, resulting in a greater amount of kinetic energy that would be dissipated and transferred in the event of a collision. The principles of conservation of momentum dictate that in a collision the forces imposed on a cyclist by a motor vehicle will result in rapid acceleration due to the constant mass within the system.

Research has shown that for unprotected road users, such as pedestrians and cyclists, the human tolerance to injury is exceeded if they are struck by a vehicle that is travelling at more than 30km/h (Rosén et al. 2011) (Figure 3). Despite this, the default urban speed limit, which is speed limit typically seen on local roads in Victoria, is set at 50km/h, while many arterials roads in Metropolitan Melbourne have speed limits of up to 80km/h. Furthermore many 80km/h roads throughout Melbourne offer no infrastructure provisions for cycling.
Various researchers including, Garrard et al. (2008), Tingvall & Haworth (2000) and Wegman et al. (2012), suggest that reduced motor vehicle speeds would improve cyclist safety. This in turn could lead to an increase in the number of people who are willing to ride bicycles on-road.

The concept that serious casualty and fatal injuries can be prevented by reducing speeds to below the threshold of vulnerable road users, underpins the “Safe System” concept of a “safe speed”. A speed of 30km/h is considered a safe speed for vulnerable road users to interact with motorised vehicles (Tingvall & Haworth 2000). This threshold is also identified in the Sustainable Safety principle of “Homogeneity” (Wegman & Mulder 1998).

The principle of “Homogeneity” states that where road users or vehicles with large mass differences interact within the same space, the speed should be set so that the most vulnerable road users, in this case cyclists, could survive a crash without sustaining any serious injuries (Wegman et al. 2012). This speed threshold is in-line with the research regarding the probability of serious and fatal injuries for pedestrians when colliding with motor vehicles (Kim et al. 2007, Rosén et al. 2011). However generally speeds in Australia are still beyond the survivable threshold for vulnerable road users when interacting with heavy vehicles (Schoon 2006), due to the greater mass differential and associated increase in forces involved in a collision.

When considering the KEMM and “Safe System” for developing safe cycling infrastructure, if it is not feasible to reduce the speed of motorised vehicles below the threshold of injury, then infrastructure designs need to consider separating various modes of transport either in space or time to reduce their interactions and risk of collision and serious injury.
2.3.3 Safe road users

One of the key principles of the “Safe System” is the recognition that there are limitations to human performance and acknowledging that humans will make mistakes. In recognition of this, a road environment needs to be designed to be forgiving of these mistakes so that road user errors do not result in serious or fatal consequences (OECD 2008). Furthermore while many mistakes are unintentional, some road users are less willing to comply with road rules, which can result in injury to themselves or other road users (OECD 2008).

Road users need to be well informed and trained to interact with the road environment. They need to be aware of the potential risks and develop safe behaviours to help mitigate the chance of a crash occurring. Previous research has identified that one of the key reasons for why people choose not to cycle for transport is the risk of being involved and seriously injured in a collision (Cycling Promotion Fund 2011, Fishman et al. 2012) and there is a particular fear associated with cycling on roads in mixed vehicular traffic, due to the risk of being hit by a motor vehicle and hostile behaviours from other road users (Garrard et al. 2010, Cycling Promotion Fund 2011, Fishman et al. 2012). Therefore in order to create a safe system for cycling there is a need for both cyclists and motor vehicle drivers to behave in accordance with the rules and guidance provided by the road environment.

Motor vehicle drivers also have a responsibility to be aware of the presence of cyclists. In their study looking at the application of the “Safe System” to cycling, Shaw et al. (2012) found that cyclists identify motor vehicle drivers as a key contributing factor in collisions. In particular, driver inattention was identified including, not looking out for cyclists before performing a manoeuvre and, failing to look properly before changing lanes (Shaw et al. 2012).

The issue of car dooring is also associated with drivers failing to look or see cyclists. These collisions can be particularly hazardous to cyclists due to the limited time to react and the chance of falling into the path of moving traffic, following the initial collision. In the Netherlands drivers are taught to open car doors with their outside hand in order to encourage drivers to perform a head check over their shoulder and look for passing cyclists (Pucher & Dijkstra 2003). Furthermore several European countries have addressed cyclist safety by placing a greater responsibility on the driver for avoiding harm associated with collisions with vulnerable road users (Pucher & Dijkstra 2003). This is complemented by extensive driver education and training programs. However, while the issue of car dooring can be addressed through education programs, this still relies on road users adopting appropriate behaviours. Alternate measures to address car-dooring include the use of physical infrastructure, alternate car-door designs or the use technology to sense the presence of cyclists and alter drivers or prevent doors from opening (Munro 2012).

Cyclists must also practice safe road user behaviours. There is little that can be done to a bicycle to reduce the vulnerability of cyclists to the transfer of forces in a collision. As such, cyclists need to consider the use of protective equipment and devices to increase their visibility to other road users (Shaw et al. 2012). Helmets are mandatory for almost all cyclists in Australia. Exemptions are available on the basis of extreme difficulty to
comply and helmets are only required on public streets in Tasmania and the Northern Territory (Cameron et al. 1994). Helmets reduce the risk of head injuries by creating a more energy efficient exchange between the cyclists head and the impacting object (Thompson et al. 1996, Thompson et al. 2000, Curnow 2003). Helmets essentially absorb some of the deformation energy and slow the rate of impact, therefore exposing the cyclist to lower levels of force albeit over a longer duration (Curnow 2003). High visibility clothing, lighting and reflective devices also have the potential to increase the visibility of cyclists for other road users. While this does not have any direct influence of the energy involved in a collision, wearing such clothing has the potential to reduce their exposure to collisions by alerting other road users of their presence (Raftery & Grigo 2012).

Previous research has identified age and gender as key factors in cyclist crashes (Heesch et al. 2011, Heesch et al. 2012, Boufous et al. 2013). Older persons are generally involved in a higher number of single vehicle bicycle crashes, compared to multiple vehicle collisions (Boufous et al. 2013). While exposure to different road environments has been suggested as a possible reason for the increased risk. Physical and cognitive decline may also increase the risk of an older rider losing control of a bicycle. Physical frailty may also result in older cyclists to sustaining more serious injuries than younger counterparts (Boufous et al. 2013).

Males are also typically over-represented in cyclist crashes compared with females (Heesch et al. 2011, Heesch et al. 2012). This is partly due to the fact that more males typically participate in cycling compared to females, particularly in Australia, however males also have a greater propensity for risk taking behaviours compared to female cyclists (Cobey et al. 2013). In their study of risk taking amongst Dutch cyclists, Cobey et al. (2013) found that male cyclists were more likely to cycle without the use of lights on their bicycles and were more likely to illegally cross railway tracks, both of these behaviours have the propensity to increase the probability of being involved in a collision. Male cyclists have also been found to have higher rates of red-light running compared to females (Pai & Jou 2014). Cyclist inattention (their own or another’s) and cyclist error have also been reported as contributing factors in cyclist collisions and falls (Schramm & Rakotonirainy 2009, Shaw et al. 2012).

The previous research suggests that there is a need for all road users to exhibit safer road user behaviours, including obeying road users, travelling at appropriate speeds and positions on the roadway, taking measures to improve their visibility and utilising appropriate safety equipment. These behaviours have the potential to reduce the prevalence and severity of collisions.

2.3.4 Safe roads and roadsides

The primary focus of this research is to identify cycling infrastructure solutions to address key crash types and the principles of safe road design are addressed in the following chapter. However the following section provides a brief overview of “Safe System” principles and how they relate to cycling.

When speeds cannot be lowered to appropriate levels for cyclists and motor vehicles to interact safely then there is a need to provide safer roads and roadside environments for cyclists. Essentially as speed environments increase, the principles of “safe speeds” can no longer be adhered to for all road user groups and it is not
possible for all road users to interact within the same space. In this situation vulnerable road users need to be separated from larger, faster moving vehicles (Wegman et al. 2012). This translates to cyclists requiring a separate right of way that provides space and priority in medium to high speed road environments. Within the Dutch principles of “Sustainable Safety” the concepts of “Functionality” and “Homogeneity”, suggest that roads should serve a single function and that there should be equality of direction of travel, and vehicle mass at medium and high speeds. When conflicts occur that contravene these principles road users need to be separated using physical infrastructure (Wegman et al. 2012).

Bicycle specific facilities have been consistently shown to provide improved safety for cyclists compared to cycling on-road in mixed traffic (Reynolds et al. 2009, Pucher et al. 2010, Lusk et al. 2011). Previous research also suggests that cyclists prefer routes with cycling specific infrastructure (Garrard et al. 2008, Winters et al. 2011). Reynolds et al. (2009) suggest that infrastructure modifications are advantageous over behaviour change approaches as they do not require action by the road users in order to achieve widespread benefits. Changes in infrastructure can also positively influence cycling participation rates, by reducing the fear associated with cycling (Garrard et al. 2008, Fishman et al. 2012).

At mid-block locations cyclists require spatial separation through the provision of lateral clearance from adjacent motor vehicles to avoid side-swipe and car door collisions and also to minimise the impact of wind forces associated with passing motor vehicles, which can cause cyclists to lose control of their bicycle without physical contact occurring between the road users (Levasseur 2014). Painted bicycle lanes and off-road bicycle paths have been found to be associated with lower injury risks for cyclists (Harris et al. 2013). Conversely, footpaths (sidewalks) and shared paths, where cyclists and pedestrians share the same facility, have been found to increase the risk of injury, mainly to pedestrians (Harris et al. 2013).

The issues of speed and the need for road users, both cyclists and motor vehicle drivers, to adopt appropriate speeds for the road environment, was addressed in a previous section. The speed and spatial separation of passing motor vehicles can have a significant influence on cyclist safety and comfort when riding on road (Levasseur 2014). In the consolidated report on cycling from the Austroads guidelines it is recommended that, due to the side wind forces from heavy vehicles, roads should be designed for adequate clearance between the bicycle and the vehicle, with the ability to provide a minimum clearance of 1.0 metres between motorised vehicles and cyclists recommended on roads with speed limits of 60km/h (Levasseur 2014). This also suggests that when inadequate space has been provided for cyclists, passing road users need to deviate from their path in order to provide a minimum of 1.0 metres clearance to minimise the sideways forces imparted on the cyclist (Levasseur 2014). This guidance is in line with minimum passing distance laws that have recently been trialled and introduced in several Australian jurisdictions, including Queensland, New South Wales and South Australia. Minimum passing distance laws recognise the prevalence of side-swipecollisions between cyclists and motor vehicles and identify the need for motor vehicles to provide clearance from cyclists when overtaking. A recent evaluation of minimum passing distance road rules conduct in Queensland identified that there where
practical difficulties with enforcing such laws. This was found to be due both to the difficulty of assessing distances for drivers and police officers and also difficulties with certain road environments (Schramm et al. 2016). In fact the study found that only about half of drivers were confident that they could accurately judge 1.5 metres in high speed zones. The study noted that, while it was too early to assess the road safety benefits of the new law, generally the laws were seen as a positive improvement for cyclist safety (Schramm et al. 2016).

Intersection locations are also associated with cyclist injuries. Research suggests that higher speed intersections, locations where cyclists approach motor vehicle traffic from the opposite direction and, roundabouts are all associated with increased risk for cyclists (Harris et al. 2013).

There is also a need to ensure that infrastructure is maintained and installed in an appropriate manner without impact from other services. Cyclist facilities are often installed adjacent to the kerb of the road, the kerb also forms a drainage function for the carriageway and drainage infrastructure has the potential to be a hazard to cyclists. Furthermore glass and debris collect on the edge of the road which has been found to be a contributing factor in cyclist falls (Shaw et al. 2012). Other infrastructure features have also been shown to influence cyclist safety, for example tram tracks have been found to increase the risk of serious cyclist collisions, with cyclists slipping on the polished metal tram tracks or falling due to their wheels becoming wedged in the track (Deunk et al. 2014).

Cyclists are not only at risk of colliding with other vehicles and road users. There are also risks associated with collisions with the road and roadside environment that must be considered. Many road side objects are designed from non-frangible materials, or are designed to absorb impacts associated with motor vehicle collisions. However these road-side objects can be hazardous to cyclists. For example (Pang et al. 2008) conducted crash reconstruction modelling looking at cyclist collisions with guardrail, which is often placed on the shoulder of higher speed roads. The modelling found that at a collision speed of 35km/h a cyclist could potentially sustain serious injuries including fractures to the skull and ribs. This example illustrates how a more forgiving roadside environment needs to be considered for all road users.

A safe road environment also needs to be a consistent road environment. Previously throughout Australia, cycling infrastructure has been developed in an ad-hoc manner with little consistency and an approach of anything is better than nothing (Pucher et al. 2011). There is a need for a more consistent approach to infrastructure in line with the Dutch road design principles of Functionality and Homogeneity and “Safe System” principles.

2.4 Summary

In summary, cyclist injuries typically result from a transfer of kinetic energy between a motor vehicle and the cyclist or the cyclist and the road or roadside environment that is beyond the tolerance of humans. Fundamentally there are two methods for managing the transfer of energy by either preventing the occurrence of a collision in the first place, or by managing the transfer of energy if an impact does occur (Corben et al. 2010).
When collisions do occur the severity of the collision can be reduced by lowering the kinetic energy within the system. Kinetic energy is a function of the mass of the vehicle and the square of the velocity. It is difficult to influence the mass of the vehicles in the system, however by controlling motor vehicle and cyclist speeds to appropriate levels for the road conditions and the range/mix of road users, the risk and severity of injuries can be reduced.

Spatial and temporal separation reduce the exposure to collisions by providing cyclists space within the road reserve. In higher speed environments increasing levels of separation are required between road users. Furthermore non-frangible and rigid objects needs to be removed from the roadside environment to reduce the risk of serious injury associated with loss of control of vehicles by road users.

Within the “Safe System” framework road users must also exhibit appropriate behaviours such as compliance with road rules and use of appropriate safety equipment. Road user behaviours must also be assessed when considering new infrastructure to ensure that new design illicit appropriate response from road users and that designs result in the intended outcomes.

The following chapter provides a review of cycling infrastructure design principles and infrastructure evaluation techniques and comparisons are drawn between the “Safe System” and KEMM principles and the principles of cycling infrastructure design.

The “Safe System” principles and the KEMM are further utilised in the investigation of cyclist serious casualty and fatal injury collisions in Victoria and Australia (Chapter 7). The underlying theories and principles of the “Safe System” and KEMM approaches were utilised to guide the investigation of key crash and identification of potential countermeasures.

The concepts were also applied to the development of simulator studies in Chapter 8 that aimed to develop a greater understanding of the influence of selected road designs on cyclist behaviours. These principles have also been applied in Chapter 10 to select of safer cycling infrastructure designs that address key cycling crash types that have then been evaluated in Chapter 11.
Chapter 3: Principles of cycling infrastructure design

It was established in the previous chapter, guided by the “Safe System” framework and the KEMM, that cyclists are vulnerable road users who require increasing levels of separation from motorised modes of transport as the speed environment increases beyond the tolerance of humans to forces associated with the transfer of kinetic energy in a collision. It was also noted that the “Safe System” framework highlights the need to create a forgiving road and roadside environment that is conducive of encouraging safe behaviours amongst road users. At the same time the “Safe System” establishes that cyclists and other road users have a responsibility to behave in accordance with the road environment and the road rules.

One limitation of these road safety frameworks is that while the principles address the risk of cyclist injury, they do not consider the specific requirements of cyclists as road users, nor do they explicitly consider how to develop infrastructure designs that are conducive to improving the safety of road users, which in turn may encourage increased participation.

To address this limitation, this chapter investigates design principles of cycling infrastructure and how these relate to improved road user behaviour and therefore the safety of cyclists. The focus of this chapter is not the geometric design of cycling infrastructure, but instead the principles that have been developed to guide the development and implementation of cycling infrastructure. The chapter begins with a review of Australian road design guidelines from Austroads, the peak organisation for Australasian road transport and traffic agencies, and VicRoads, the Victorian State road authority. Following the review of Australian cycling design principles, a number of international guidelines, considered from ‘best-practice’ cycling cities in the United States of America, the United Kingdom and Europe are reviewed in order to understand the design principles adopted by these jurisdictions that currently have high or increasing levels of cycling participation. This chapter concludes with a brief discussion of techniques utilised for the evaluation of road infrastructure design.

3.1 Australian cycling design principles

The focus of this thesis is the evaluation of infrastructure designs to address the most commonly occurring cyclist collision types that result in serious casualty and fatal injuries. A first step in identifying infrastructure designs that could be evaluated for their potential to address common cyclist crash types in Australia, was to consider cycling design principles at National and State levels. The Austroads guides provide a set of uniform guidelines for all Australia road authorities, while the VicRoads documentation provides amendments to align with legislation that is specific to Victoria. Both guides were reviewed and are discussed below.

3.1.1 Austroads cycling design principles

As part of the Government mandate, Austroads develop a range of guidelines for the development and management of road infrastructure for use in Australia and New Zealand. The most recent document addressing cycling facilities, “Cycling Aspects of Austroads Guides” consolidates information for all Austroads guidelines
specific to cycling and the development of bicycle facilities (Levasseur 2014). Within the document, sections two and three consider planning and traffic management for cyclists and bicycle rider requirements. The later chapters of the document deal with the specifics of infrastructure design, these chapters were considered when selecting infrastructure concept designs to address serious casualty and fatal injuries crash types of cyclists (Chapter 8).

3.1.1.1 The “Safe System” within Austroads guidelines

“Safe System” principles are acknowledged within the Austroads guidelines, with the overarching principles of the “Safe System” highlighted in the introductory chapter of the “Cycling Aspects of Austroads Guides” document. However, beyond the initial introduction to the “Safe System” there is no further mention of the approach throughout the documentation and it is therefore difficult to determine how ingrained the “Safe System” principles are within the guidance provided by Austroads.

3.1.1.2 Bicycle rider requirements

The Austroads guides identify six key requirements for infrastructure in order to create convenient, efficient and safe travel conditions for cyclists (Levasseur 2014). The requirements are: space to ride; a smooth surface; speed maintenance; sight lines; connectivity and; information. Furthermore the guidelines identify that cyclists require separation from motor vehicles in order to enhance their safety and comfort when riding on-road (Levasseur 2014).

In order to illustrate the spatial requirements of cyclists, the guidelines identify a basic design envelope that is required for a cyclist (Figure 4), and suggest that a typical cyclist is 0.8 metres wide and that they require an additional 0.1 metres clearance on each side of the bicycle for essential manoeuvring (Levasseur 2014). The envelope is considered relevant to the design of on-road, off-road and bicycle parking facilities. However Austroads caution that cyclists may also need additional clearance, beyond the 0.1 metre design envelope, to avoid fixed roadside objects and to pass vehicles (Levasseur 2014). However the rationale of this additional requirement for manoeuvring has not been quantified in the guidelines, and as such it is unclear if this recommended clearance is sufficient.

The remaining five rider requirements identified in the guideline could be considered common for all road users, in that they typically require: a relatively smooth road surface that is free of debris; speed maintenance to minimise the amount of acceleration and deceleration required; adequate sightlines to identify and avoid hazards; a connected network for continuous travel; and, information about their route.
3.1.1.3 Planning for cycling

When planning for bicycle facilities and networks, Austroads identified the need to ensure that facilities are suitable for a range of abilities and experience, that they provide links to key destinations and that they allow cyclists to travel safely and conveniently (Levasseur 2014). In order to meet these needs, Austroads identified five principles that are important for the development of cycling facilities and networks (Table 1). It is noted that these principles are adopted from international design guidelines as discussed in the following section.

The Austroads guidelines recognise the need to provide safe cycling facilities that have low perceived and actual risk and minimise conflict with other road users. Infrastructure should also be coherent, provide direct links, be attractive to use and be comfortable for cyclists. Austroads also identify the need for end-trip-facilities however this is not related to on-road infrastructure and instead covers the need for bicycle parking and change room facilities for cyclists. To complement the principles identified in Table 1 the Austroads guide makes reference to Figure 5 which has been adapted from the Dutch design manual for cycle-friendly infrastructure (CROW 1993).
Table 1: Bicycle network principles (Levasseur 2014)

<table>
<thead>
<tr>
<th>Principle</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Safety</strong></td>
<td>Minimal risk of traffic-related injury, low perceived danger, space to ride, minimum conflict with vehicles.</td>
</tr>
<tr>
<td><strong>Coherence</strong></td>
<td>Infrastructure should form a coherent entity, link major trip origins and destinations, have connectivity, be continuous, signed, consistent in quality, easy to follow, and have route options.</td>
</tr>
<tr>
<td><strong>Directness</strong></td>
<td>Route should be direct, based on desire lines, have low delay through routes for commuting, avoid detours and have efficient operating speeds.</td>
</tr>
<tr>
<td><strong>Attractiveness</strong></td>
<td>Lighting, personal safety, aesthetics, integration with surrounding area, access to different activities.</td>
</tr>
<tr>
<td><strong>Comfort</strong></td>
<td>Smooth skid-resistant riding surface, gentle gradients, avoid complicated manoeuvres, reduced need to stop, minimum obstruction from vehicles.</td>
</tr>
</tbody>
</table>

Figure 5: Cycling facility separation by motor vehicle speed and volume (adapted from CROW (1993))
Figure 5 highlights the need for increased separation between cyclists and motor vehicles as the volume and speed of motor vehicle traffic increase. For speed environments less than 60km/h, provided the traffic volume is low, the guideline recommends that cyclists can operate in mixed traffic. Between speeds of 40km/h and 60km/h cyclists require bicycle lanes or off-road bicycle paths as the traffic volume increases. In low traffic volume environments and speeds between 60km/h and 80km/h it is suggested that cyclists can utilise sealed shoulders or shoulder lanes, while at higher speeds and volumes fully separated facilities are required. Austroads recommends that road authorities should aim to comply with this guidance; however they also recognise that this may not be possible when retrofitting sites.

The principles expressed in Figure 5 align with the basic “Safe System” and KEMM principles of increasing cyclist separation as the speed environment increases. However, there is a disregard for the tolerance of cyclists to the kinetic energy associated with collisions, with recommendations that cyclists can interact with mixed traffic at speeds up to 60km/h. Furthermore the recommendation that cyclists can utilise sealed shoulders in higher speed environments disregards the requirements for spatial separation from passing motor vehicles, particularly large trucks, to minimise the impact of sideways wind forces and the risk of rear-end or side-swipe collisions. These issues highlight that the information provided by Australia may not entirely represent best-practice cycling infrastructure guidance.

### 3.1.2 VicRoads cycling design principles

VicRoads previously developed their own Traffic Engineering Manual which provided guidance to road design practitioners regarding the development and management of road infrastructure (VicRoads 2006). These guides have since been superseded with VicRoads now deferring guidance in accordance with the Austroads guidelines and Australian Standard AS1742 which covers the usage of uniform traffic control devices. VicRoads has developed supplementary material to provide further guidance regarding the use of bicycle infrastructure when Victorian guidance differs from Austroads or the Australian Standards. These supplements take precedence over the Austroads guides in Victoria, however the material presented in these supplements has little to do with bicycle facility design principles. Furthermore the infrastructure guidance presented in the supplements is not relevant to the infrastructure designs that are considered for evaluation throughout the remainder of this thesis and therefore are not discussed here.

### 3.2 International cycling design principles

For this review of international city cycling principles and design guides, city locations were selected based on a comparison of cycling mode share in cities throughout the world (see Figure 1 in Section 1.3). Two differing types of cities were selected for the review based on current cycling participation trends, as follows:

1. ‘Best-practice’ cities for cycling. These cities were identified as international locations that currently have high levels of cycling mode share. The assumption being that a country or city with a high level of cycling mode share must be providing conditions that are conducive to (safe) cycling.
2. Cities with similar characteristics to major Australian cities in terms of cycling mode share. For these
cities there was a particular focus on locations that have seen a recent increase in cycling mode share.
The intention was to understand the principles that have guided the recent increase in participation and
determine if these concepts could be applied in an Australian context.

Based on the cycling participation information presented in Figure 1 cycling infrastructure guidelines from the
Netherlands and Denmark were considered to represent ‘best practice’ cycling countries. From Figure 1 it can
also be seen that in the United Kingdom and the USA cycling mode shares are relatively similar to Australia.
Further analysis of cycling mode share identified that in inner London between 2001 and 2011 the mode share
for cycling has increased from 3.8 percent to 7.2 percent, which is well above the average of 3.0 percent for
England and Wales (Aldred et al. 2016). In the USA, the City of Portland, Oregon has a cycling mode share of
approximately 7.4 percent which is the highest cyclist mode share of any of the 100 largest cities in the USA
(McLeod et al. 2013). New York City has also been considered as it has the highest absolute number of
commuter cyclists of any city in the USA (McLeod et al. 2013). Furthermore, the City of New York has
undertaken a program of reallocating space for cycling within a particularly constrained, and car dominated road
network.

3.2.1 The Netherlands

In the Netherlands infrastructure design is guided by the five principles of Sustainable Safety (Table 2).
Sustainable Safety highlights that roads should serve a single function, that there should be equality of speed,
mass and direction between road users, that roads should be predictable for road users, be forgiving if an
incident occurs and that road users should be self-aware of their ability when it comes to interacting with the road
network (Wegman & Mulder 1998).

<table>
<thead>
<tr>
<th>Sustainable Safety Principle</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality (of roads)</td>
<td>Mono-functionality of roads as either through roads, distributor roads, or access roads in a hierarchically structured road network</td>
</tr>
<tr>
<td>Homogeneity (of mass, speed and direction of road users)</td>
<td>Equality of speed, direction, and mass at moderate and high speeds</td>
</tr>
<tr>
<td>Predictability (of road course and road user behaviour by a recognisable road design)</td>
<td>Road environment and road user behaviour that support road user expectations through consistency and continuity of road design</td>
</tr>
<tr>
<td>Forgivingness (of both the road/street environment and the road users)</td>
<td>Injury limitation through a forgiving road environment and anticipation of road user behaviour</td>
</tr>
<tr>
<td>State awareness (by the road user)</td>
<td>Ability to assess one’s capability to handle the driving task</td>
</tr>
</tbody>
</table>
The principles of Sustainable Safety were referenced in developing the “Safe System” approach to road safety and the KEMM (see Chapter 2). Sustainable Safety highlights the concept of increased separation as the speed of road environments increase, through the principles of “Functionality” and “Homogeneity”. The concept of “Predictability” also highlights the need for uniform road design to create consistent road user behaviours. Through combining these principles a safe and forgiving transport network can be created for all road users.

The development of cycling infrastructure is guided by the “Cycling in the Netherlands” guidelines (en Waterstaat 2009). The guideline provides an overview of the Dutch approach to cycling and the need to build cycling facilities to accommodate a full range of different cycling trips i.e. shopping, commuting, recreation etc. When developing infrastructure solutions the guidelines identify the principles of Safety, Directness, Comfort, Attractiveness and Cohesion as key infrastructure requires (as adopted by Austroads in Australia) while the guidelines emphasis the need to integrate cycling into the road network and not simply provide a network that is fully separated from motor vehicle network.

3.2.2 Denmark

Denmark, like the Netherlands, has one of the lowest road tolls in the world and is often considered to be at the forefront of road safety research and implementation (Danish Road Safety Commission 2012). Despite its impressive roads safety statistics, vulnerable road users including pedestrians and cyclists are disproportionally represented in the road toll, representing two out of every five killed or injured road users (Danish Road Safety Commission 2012). In order to further improve road safety in Denmark, The Danish Road Safety Commission developed a National Action Plan for road safety (Danish Road Safety Commission 2012). The plan addresses 10 key areas of road safety covering speeding, alcohol and drugs, inattention, seat-belt and helmet usage, pedestrians, cyclists, young drivers, head on collisions, single vehicle collisions and crashes on rural roads (Danish Road Safety Commission 2012).

The City of Copenhagen, is often considered one of the key best-practice cycling cities in the world, with over 36 percent of all Copenhageners commuting to work or study by bicycle (Heien et al. 2011). The City of Copenhagen released their latest guidelines for the design of on-road bicycle facilities in December 2013 (City of Copenhagen 2013).The primary goal of the guidelines is to continue to encourage increased participation in cycling while creating a safe cycling environment that is comfortable for everyone to ride while maintaining cycling as a competitive mode of transport (City of Copenhagen 2013). A unique aim of the guide is to deal with the increasing cycling congestion that is occurring on Copenhagen’s existing cycling network. This includes widening existing bicycle facilities to up to four metres, capable of accommodating flow of 5,000 cyclists per hour (City of Copenhagen 2013).

The Copenhagen design guide emphasises the need for uniform cycling infrastructure and proposes a hierarchy of cycling facilities suited to various road environments, with appropriate facilities selected based on the required capacity of the lane, adjacent traffic speed and degree of separation required. A summary of best practice
cycling facilities in Copenhagen is presented in Figure 6 (Copenhagenize Design Co 2013). This clearly illustrates that increased separation is required between bicycles and motorised traffic as the speed environment increases (as noted previously). Specifically, at low speeds, 30km/h and below, no separation is required and cyclists and motor vehicles can interact within the same space, in 40km/h zones it is recommended to install kerbside bicycle lanes, between 50 and 60km/h kerb separated lanes are recommended and at higher speeds full separation of bicycles from motorised modes of transport is recommended. The graphic also highlights that bicycle lanes should be placed kerbside of parked cars to provide additional protection to cyclists and reduce the risk of driver-side car door collisions.

![Figure 6: Copenhagen bicycle facilities (Copenhagenize Design Co 2013).](image)

These principles identified in the Copenhagen design guidelines strongly align with the “Safe System” and KEMM. There are also strong synergies between the design concept proposed in Copenhagen and the Sustainable Safety principles from the Netherlands where if the tenets of “Homogeneity” and “Functionality” can no longer be adhered to due to increases in the volume of traffic and traffic speeds, there is a need to provide increasing levels of separation between different modes and dedicated space for cyclists.

### 3.2.3 The United Kingdom

Road safety in the United Kingdom is guided by the Department for Transport Strategic Framework for Road Safety (DfT 2013). The guidelines outline a more tradition approach to road safety focusing on the principles of
Education, Enforcement, Engineering and also the role of various stakeholders such as Government, Industry and the broader community. Within the framework, the need to target vulnerable road users and particularly cyclists is highlighted, with recognition that the reduction in the road toll has been largely focused on motorised modes of transport and that more needs to be done for vulnerable road users. To address cyclists needs Transport for London developed the London Cycling Design Standards (Transport for London 2014), which covers specifics regarding bicycle facility planning and design. The standard was developed in response to the Mayor’s vision for cycling in London, which identified four key outcomes (Greater London Authority 2013):

- Developing a ‘tube style’ network – direct, high capacity cycle routes, many of which will run parallel to the London Underground.
- Safer streets for bicycles – focusing on improving the most dangerous intersections in the city.
- More people travelling by bicycle – ‘normalising’ cycling making it something that everyone feels comfortable doing.
- Better places for everyone – through creation of linear parks and reducing traffic through increasing cycling mode share.

To complement the Mayor’s vision, a series of cycling principles were identified including safety, directness, comfort, coherence, attractiveness and adaptability (which refers to the facilities ability to accommodate growing demand over time) (Transport for London 2014). These are the same set of principles adopted by Austroads to guide cycling infrastructure development in Australia.

The London Cycling Design Standard proposes creating a paradigm shift for cycling in London with the mode being considered as a form of mass transit, with bicycles treated as vehicles and not as pedestrians, while still maintaining an emphasis on separation of modes, particularly in higher speed road environments.

The London Cycling Design Standards place a strong emphasis on transportation planning in order to develop cycling networks as opposed to isolated infrastructure solutions. These networks are intended to provide cyclists with a high level of service and priority over other modes of transport that improve both the safety of cycling and reduce travel times. Apart from the increased emphasis on transportation planning and network design the guidelines cover typical cycling infrastructure solutions regarding mid-block and intersection treatments, signage, line marking, construction and maintenance. An additional topic considered in the guideline is the development of cycling friendly street design. This topic addresses Local Area Traffic Management issues specifically traffic calming and speed reductions in residential areas to create cycle friendly neighbourhoods.

### 3.2.4 USA

In the USA the Federal Highway Administration recommends that transportation engineers consult the American Association of State Highway and Transportation Officials (AASHTO) Guide for the development of bicycle facilities (AASHTO 2012) and, the National Association of City Transportation Officials (NATCO) Urban bikeway design guide (NACTO 2014) when developing cycling infrastructure in USA cities.
The AASHTO guidelines were reissued in 2012 and present a significantly different view of cycling compared to the previous version published in 1999. The 2012 guides cover both on-road facilities and off-road paths, bicycle facility design, and innovations in cycling. The AASHTO guidelines have a particular focus on providing space for cyclists, through a process called ‘lane diets’, which is essentially narrowing existing traffic lanes to provide dedicated cycling facilities, as opposed to previous USA practice of installing wide kerbside lanes, which is now largely discouraged.

To complement the AASHTO guide the NACTO design guide presents innovative cycling solutions, which have largely been adopted from European best practice and adapted to the USA road environment. The NACTO guide acts as a review of international best practice and provides recommendations for designers in the USA when considering installation of bicycle infrastructure features. Designs presented in the NACTO include a series of required, recommended and optional elements for each design, which are to be considered when adopting any of the recommended treatments.

3.2.4.1 Portland, Oregon

Apart from these two major guidelines there are various cycling designs and strategies that have been developed in various states, cities and regions across the USA. One such example, the city of Portland Oregon, has one of the highest cycling mode shares in the USA with approximately 5.8 percent of trips undertaken by bicycle. This is well above the USA average of less than one percent (Infrastructure Australia 2009).

In developing their most recent bicycle plan the City of Portland conducted a review of best practice bicycle facility design. The review includes a comprehensive examination of various cycling facilities including the application of the design, advantages and disadvantages of the design, maintenance considerations, relevant national and international design guidelines and examples of cities and countries that have adopted the design (City of Portland Bureau of Transportation 2010). The Portland cycling strategy also aims to better understand the issues surrounding cycling participation and recognises that there is a need to understand the types of people who participate in cycling.

To this end, the City of Portland developed a typology that classifies cyclists by their attitudes towards participation (Geller 2009). The typology classifies cyclists into four groups (Figure 7):

- **Strong and fearless (<1%)**
- **Enthused and confident (7%)**
- **Interested but concerned (60%)**
- **No way no how (33%)**

![Figure 7: Four types of transportation cyclists in Portland (Geller 2009)](image)

- “The Strong and the Fearless” - Cyclists who ride regardless of road conditions, who typically cycle as their primary mode of transport and will ride in the worst conditions.
- “The Enthused and the Confident” – Cyclists who are comfortable sharing the roadway with automotive traffic, but prefer to do so in dedicated bicycle facilities. These people have been attracted to cycling in recent times due to improvements in infrastructure and changes in cycling culture.

- “The Interested but Concerned” – These people are curious about cycling; they may be occasional or recreational cyclists. They would like to ride more. But, they are afraid to ride. They would ride if they felt safer on the roadways—if cars were slower and less frequent, and if there were more quiet streets with few cars and paths without any cars at all.

- “No way no how” – this group represents people who are not currently interested in cycling and includes people who are unable, have never ridden a bicycle or have no interest in riding. (Geller 2009)

The typology provides an indication of the proportion of the population represented by these four groups. While there is some variation in the exact percentages that the four groups represent, generally the typology has been accepted as a good illustration of the range of people engaging and not engaging in cycling as a mode of transportation in highly motorised countries.

Many cycling transportation plans, including the City of Melbourne Bicycle Plan (CoM 2012), are targeted towards encouraging increased participation amongst the “Interested but Concerned” group. These cyclists are recognised as representing the market group necessary to reach in order to achieve significant modal shifts and to normalise cycling (Dill & McNeil 2013). In their review of the Four Types of Cyclists, Dill & McNeil (2013) found that the “Interested but Concerned” group are curious about cycling, like to ride, but are also afraid to do so and therefore do not regularly ride and generally will try to avoid arterial roads.

The “Interested but Concerned” cyclists are those who are likely to benefit the most from improved cycling infrastructure, by reducing the perceived and actual risks associated with cycling and hence their barriers to participation. It is also important to consider the “Strong and Fearless” and “Enthused and Confident” cyclists as these cyclists are currently riding on road and currently are at the greatest risk of being involved in serious injury crashes. So, while facilities must be designed to encourage people to take up cycling in a safe environment, they must also be designed to be inclusive of more confident and experienced cyclists.

3.2.4.2 New York City, New York

Between 2007 and 2011 the number of people commuting by bicycle doubled in New York City, New York. In New York City, 10 percent of trips made by private vehicle are less than one-half mile (800 metres) and 56 percent of trips are less than 3 miles (4.8km): these are distances which can be served by bicycle. In recognition of this the New York City Department of Transportation set an ambitious goal to deliver over 200 miles (320km) of bicycle facilities in a three year period, roughly doubling the size of the on-road bicycle network.

Since 2009 development of the road environment in New York City has been guided by the New York street design manual. The manual was developed by the New York City Department of Transportation (DOT 2009) and
it establishes the guiding principles for transportation infrastructure development in New York. The guideline stipulates six key principles:

- Design for Safety;
- Design to Balance Local Access and Mobility;
- Design for Context;
- Design Streets as Public Spaces;
- Design for Sustainability and Resiliency; and
- Design for Cost-Effectiveness

Accordingly, it is the policy of the Department of Transport that practitioners follow the principles when designing city streets, all with an eye to achieving maximum inclusivity and the highest possible aesthetic standards. Within the principles there is a strong focus on the designing for safety. The principles state that safety should be prioritised for all road users, particularly vulnerable groups (children, elderly etc.) and vulnerable modes of transport (walking and cycling). In order to achieve this goal, there is a focus on designing for slower speeds to reduce the number and severity of crashes and also to discourage road users from using local areas to cut-through traffic. The safety principles also place an emphasis on research, testing and evaluation of innovative safety treatments, particularly those that have been successfully adopted in other cities (DOT 2009).

3.3 Best practice design principles

From the review of Australian and International design guidelines for cycling infrastructure it is clear that there are many common themes that have been adopted by various jurisdictions when developing cycling infrastructure. In all cases the design principles place a strong emphasis on designing and developing networks where safety is an intrinsic principle.

The principles of the “Safe System” are referenced in the Australian guidelines and there are synergies with the concepts of increasing separation as the speed environment increases, which is a strong tenet of the KEMM. One of the major limitations of these guidelines is that the recommendations can place cyclists in mixed traffic conditions well beyond the tolerance of humans to kinetic energy forces, and often without cycling facilities. Furthermore there are several caveats that recognise the limitations in applying these principles to existing on-road locations where there are competing demands for the available road space. These disclaimers essentially place the needs of cyclists behind the mobility needs of motor vehicle traffic. This has the potential to discourage normalisation of cycling as a mode of transport and, more importantly, place cyclists at increased risk.

European guidelines recommend design that focuses on the most vulnerable road users. These elements are also highlighted in Australian and American design recommendations, however there is still a more dominant focus on private motorised vehicles and traffic throughout Australia and America, compared to many Northern European countries. In best-practice European cities the needs of cyclists are placed above private motor vehicle occupants. This has seen the development of road networks where travel is faster by bicycle compared to motor
vehicles. Furthermore the investment in cycling in European nations has resulted in some of the highest cycling mode shares throughout the world (Infrastructure Australia 2009). The European design guides also recognise the vulnerability of cyclists and their need for increasing space and priority as both the traffic volume and speed increase.

Throughout the Australian and UK design guidelines the principles of safety, coherence, directness, attractiveness and comfort are recognised as key principles for developing cycling infrastructure. These principles have been adopted from the Dutch, not for profit organisation CROW who work with government and private industry developing transport, infrastructure and public space solutions (CROW 1993). These principles all grow from a desire to meet the needs of cyclists when using cycling infrastructure. These principles form a key approach in the evaluation of cycling infrastructure designs in Chapter 8 of this thesis.

The guidelines and principles reviewed in this section represent best-practice in terms of cycling infrastructure design principles. However these principles are often difficult to fully adhere to, particularly when implementing cycling infrastructure within an existing road network which is already constrained for space. Furthermore the application of “Safe System” principles can often require the implementation of more expensive design solutions, which can be difficult to implement due to budgetary constraints within road authority organisations. These constraints often see less than optimal infrastructure solutions developed and implemented, particularly when addressing cycling infrastructure.

In the following section, the concept of evaluation of infrastructure designs is presented. Throughout the reviewed guidelines it was noted that there was limited reference given to the evaluation of infrastructure either before it was implemented or following installation. In Australia there has tended to be a pragmatic approach to cycling infrastructure in that any infrastructure is better than no infrastructure. While this approach has been useful in seeing an initial wave of cycling infrastructure being implemented, this has been incremental and ‘piece-meal’. A more systematic and fundamental approach to infrastructure design and evaluation is required in order to ensure that the most suitable and effective design options are implemented.

### 3.4 Evaluation of cycling infrastructure

Evaluation is an important component of all infrastructure projects. Transport infrastructure has traditionally been evaluated with a focus on impacts such as changes in mode choice, vehicle kilometres travelled, travel times and to a less extent the health, economic and environmental benefits of the project (Handy 1996, Rissel et al. 2013). While these techniques have been extensively applied to projects involving motorised vehicles, Rissel et al. (2013) suggest that there are few evaluations of cycling infrastructure and there are limitations with these measures for cycling infrastructure in Australia, particularly when trying to quantify benefits in economic terms ((Rissel et al. 2013).

The Australian National Cycling Strategy specifies monitoring and evaluation as key priority objectives for the development of cycling infrastructure in Australia (Australian Bicycle Council 2010). However, while the cycling
guides discussed in the previous section highlight best-practice design principles and standards, they offer a very limited discussion regarding how to evaluate proposed designs or newly constructed cycling facilities.

Separate from the Cycling Aspects of Austroads Guides, Austroads have developed the “Guide for project evaluations”. Within the guidelines there is an emphasis on justification of projects through the use of economic evaluation, where the benefits generated from the operation of a new facility are compared to the costs associated with construction, operation and maintenance (Austroads 2009). Economic evaluation requires monitoring of the benefits and costs associated with projects and can be substantially influenced by which variables are included in the modelling and the costs allocated to benefits, which can often be quite subjective.

For cycling projects, economic evaluations typically require some assessment of the number of new cycling trips that the facility will generate and existing trips that will be diverted to the facility. Based on these trips, economic benefits are calculated for the direct benefits to the user (typically health benefits from exercise, travel time savings and saving associated with reduced vehicle operating costs compared to private vehicles and dis-benefits from increased risk of injury,) and societal benefits (reduced congestion, pollution, noise etc.) (Austroads 2009). Benefit Cost Ratios (BCRs) compare the net benefits to the construction and operation costs of the projects, with BCRs over one considered favourable projects. While this technique allows allocation of financial resources to the projects that are expected to generate the highest net benefits, the process does little to assess the suitability of the cycling facility, particularly in regards to safety and attractiveness for cyclists. Furthermore there are issues associated with the monetarisation of some benefits and costs associated with transportation infrastructure. For instance very small travel time savings taken for a very large number of road users can be used to justify projects that in reality offer minimum benefits (Austroads 2011). These types of economic evaluations do not align with the principles of the “Safe System” approach.

Another method that has been utilised to evaluate infrastructure design concepts is the use of trial construction at test facility and on-road sites. Both techniques result in construction of the proposed infrastructure with evaluation conducted in either a controlled or real life road environment. These methods offer various benefits, most importantly construction allows for a comprehensive and real-world evaluation of the infrastructure design where road users can interact with the physical infrastructure. However both techniques are costly. One such example is the trial construction of a bicycle friendly roundabout undertaken in the UK by Transport Research London (TRL) which cost over £2 million to construct and evaluate (Figure 8). Furthermore, there is a risk with this style of evaluation that road users may interact with the design in an unforeseen manner that could expose them to potential hazards.
In Victoria, VicRoads have developed a policy document regarding conducting on-road trials of new or innovative treatments (VicRoads 2014). The guidelines outline a six step process for conducting and evaluating new treatments: Accepting a treatment for trial; Planning the on-road trial; Designing the trial and evaluation methodology; Conducting the trial; Evaluating the trial; and Post – trial phase.

Prior to accepting a treatment for trial there is also a process of identifying the problem or opportunity, identification of options, analysis of options and identifying preferred options. The guidelines are not overly prescriptive in how the trials need to be evaluated and suggest that a range of qualitative and quantitative measures can be applied depending on the proposed treatment (VicRoads 2014). The guidelines identify the benefits in collecting baseline data prior to the implementation of changes to the road environment (VicRoads 2014). This allows for before and after evaluations to be undertaken to compare the relative benefits of the treatments. When before data cannot be collected an alternate approach is to identify control sites that have not received the treatment and compare the operation of the two sites. While both these methods offer an opportunity to assess the relative merits of the treatment, they can be susceptible to threats to validity, due to changes in the road environment, beyond the control of the study.

### 3.4.1 Simulator based evaluations

An alternative technique that is gaining increasing popularity for the evaluation of infrastructure designs, particularly related to road design, safety, comfort and road user understanding, is the use of driving simulators (Caird et al. 2011, Chrysler & Nelson 2011, Granda et al. 2011).

The increasing growth in the use of simulation techniques stems from the fact that they offer many benefits over and above those associated with field trials. These benefits include: provision of an inherently safe environment for research, which can be easily and economically reconfigured to allow for repeatable, non-destructive testing (Blana 1996); provision of an environment for testing human behaviour under rare or extreme events (such as
perception of hazards and potential collisions) that can be replicated and repeated in a safe environment which may be inappropriate to practice in real world environments due to the inherent risks associated with the task; reduced risk when testing intrinsic factors such as fatigue and driver impairment on driving behaviour, which raise ethical issues when tested in real world environments due to the associated risks (Fisher et al. 2011); and, increased control - simulators make it possible to control experiments for a wide range of variables, while the link to computer systems can help facilitate data processing, formatting, analysis and storage (Blana 1996).

Additionally, simulators can be used to gather a range of detailed performance data that is not feasible in the real world (Fisher et al. 2011). For example the collection of lateral position data can be challenging to collect in real world environments with weather conditions, reflection and shadows affecting the quality of the measurement (de Winter et al. 2012). Previous research has shown that the quality of lateral position data can be significantly improved when collected in simulator-based experiments compared to measurements collected from real-world instrumented vehicles (Santos et al. 2005).

Driving simulators have been used to evaluate a range of road infrastructure factors including the design of intersections (Lenné et al. 2011, Stephens et al. 2017), of traffic signals (Noyce et al. 2011), and road signs and pavement markings (Godley et al. 2004, Ben-Bassat & Shinar 2011, Chrysler & Nelson 2011).

Due to the benefits offered by the use of driving simulators, it was considered a necessary first step to develop a cycling simulator for the evaluation of cycling infrastructure considered in this research. The following chapter presents a detailed discussion of the benefits and limitations of using driving and cycling simulators for evaluation research, while Chapters 5 and 6 discuss the development and validation of the cycling simulator that forms a major component of this thesis.

3.5 Summary

In summary, this chapter has established best-practice principles for the development of cycling infrastructure. The principles of the “Safe System” have been adopted within the Austroads guidelines for the development of cycling infrastructure and these principles align with aspects of the KEMM. In particular the guidelines identify the need to provide increased separation between cyclists and motor vehicle traffic in higher speed environments. International best practice cities also identify the need to promote separation in higher speed environments. Furthermore the need to create consistent uniform road design is identified that accommodates a range of road users of different experience and confidence. In Australia and internationally, evidence shows that cycling infrastructure can be integrated into existing road networks. In particular this has been shown in New York City and London, which are some of the busiest cities in the world with the most congested road space.

When done well, introduction of best-practice infrastructure can increase cycling mode share and participation as shown in Portland, New York and London and once cycling infrastructure is implemented at a network wide level it can lead to substantial cycling mode share such as in the Netherlands and Denmark.
The review identified that there are a range of methods for evaluating infrastructure. The use of simulators offers a flexible, cost effective method to conduct initial evaluation of designs and there is good evidence that simulation provides a more robust technique compared with on-road and test track evaluation for preliminary evaluation, while also being less subjective compared to the economic evaluation process. That being said the evaluation process for on-road trials identified by VicRoads offers a useful framework for the process of evaluating infrastructure and can be equally applied to simulator evaluations of infrastructure designs.

The principles of best-practice design were further utilised in this research during the evaluation of infrastructure presented in Chapters 9 and 10. The principles helped guide the selection of infrastructure and were also applied by simulator study participants when assessing the proposed infrastructure solutions.
Chapter 4: Road safety simulator review

This chapter builds on the initial brief discussion of simulator-based evaluation methods presented in Chapter 3. In this chapter a more detailed overview of the literature regarding the use of driving simulator and their application to road design and road safety research is presented. Following the review of the literature, the requirements for developing a simulator are detailed including a discussion of the performance measures identified as crucial for the establishment of simulator functionality, simulator architectures and details of typical simulator hardware and software componentry.

This chapter aligns with the secondary research questions regarding the development and validation of a cycling simulator. Following this, Chapter 5 details the development of the simulator that forms a major component of this PhD research. The validation process for the bicycle simulator is then documented in Chapter 6.

4.1 Introduction

Driving simulators have been used as research tools to study the behaviours of drivers and their interactions with vehicles and the road environment since the early 1960’s (Allen & Jex 1980, Blana 1996). Simulators were initially developed to avoid the costs associated with field research and training (Allen et al. 2011) and have been utilised in various fields of study including psychology, engineering, transportation, ergonomics and medicine (Blana 1996). Driving simulators are used as a tool to study a range of research topics including: driver behaviour; education and training; design and evaluation of transportation infrastructure; medicine and therapy applications; ergonomics; cognitive testing; evaluation of intelligent transportation systems; and, evaluation of administrative methods (Wang et al. 2007).

Simulators provide a tool to re-create the experience of performing a desired task or operating a vehicle within a virtual and safe environment (Arioui & Nehaoua 2013). The ultimate aim of the simulator is to reproduce elements of the environment that the user will face in a real world situation (Arioui & Nehaoua 2013). Advances in sensors, electronics, processing, storage capability and visual display systems have led to significant progression in the capabilities and performance of simulators (Rudin-Brown et al. 2009). These trends have also led to simulators becoming increasingly cost effective to develop and operate, which in turn increases their availability for conducting research (Allen 2000, Rudin-Brown et al. 2009).

The increasing use of simulation techniques stems from the fact that they offer many benefits compared to field trials. Simulators offer a repeatable, non-destructive, safe testing environment and it is for these reasons that the use of simulators for infrastructure evaluation has continued to increase (Blana 1996). Simulator studies are considered to have the following advantages over field-based studies:

- **Cost effectiveness**: Simulators offer a cost effective alternative to on-road based studies, and, as such, a simulator can save both time and money while still effectively achieving the desired output (Moroney & Lilienthal 2008, Rudin-Brown et al. 2009). Simulators allows researchers to investigate the effects of new road design elements. These new design elements may be costly to construct and there may be
various iterations of the design that need to be tested to elicit the desired road user behaviours (Kaptein et al. 1996). These types of applications are ideally tested in a simulator which can be rapidly reconfigured at minimal cost and allow scenarios to be consistently repeated for each participant (Blana 1996).

- **Safety:** Simulators provide an inherently safe and non-threatening environment for conducting road safety research (Blana 1996, Moroney & Lilienthal 2008). While it is a safe environment for participants, the simulator does allow for testing of human behaviour under rare or extreme events which may be inappropriate to undertake in a real world environment due to the inherent risks associated with the task, for example testing road user behaviours under the influence of drugs and alcohol (Lenné et al. 2003, Lenné et al. 2010). Simulators are also particularly useful when testing intrinsic factors such as fatigue or driver impairment on driving behaviour, which raise ethical issues when tested in real world environments due to the associated risks to the participants and other road users (Caird & Horrey 2011).

- **Experimental control:** The simulator environment allows the experimenter to have considerably more control over the scenarios being investigated compared to field studies (Caird & Horrey 2011). Environmental control also allows presentation of scenarios in a standardised environment. Having control of the environment allows experiments to be replicated precisely for each participant. This allows consistency to be maintained between the test subjects. This is particularly advantageous when testing rare events, which may not be possible to recreate in an on-road or test-track environment. Furthermore, the simulator environment allows manipulation of independent variables related to the experiment such as light conditions, weather, atmospheric conditions, the speed environment or traffic volumes (Rudin-Brown et al. 2009).

- **Data collection:** Simulators provide an opportunity to collect data that may not be feasible in the real world (Moroney & Lilienthal 2008), again this can relate to dangerous driving activities, particularly when the vehicle operator is suffering from an impairment either substance induced of physiological. Simulator experiments are typically run in a controlled environment which allows for precise and reliable measurement to be performed. The simulator can also be integrated with data collection equipment such as cameras, microphones and data logging systems to further enhance the data collection capabilities of the simulator.

Despite the many benefits of simulators there are also various limitations including:

- **Simulator sickness:** One of the most common disadvantages noted in simulator studies is the issue of simulator discomfort and sickness associated with the use of simulators (Rudin-Brown et al. 2009, Stoner et al. 2011).

- **Fidelity:** Another significant issue for simulators is the issue of fidelity, which refers to the physical, perceptual and psychological realism of the simulator (Greenberg & Blommer 2011).
• **Unknown generalisability:** This refers to the ability of the simulator-based results to be compared with behaviour in real world environments. The issue of unknown generalisability can be addressed through behavioural validation studies that compare the performance of participants using the simulator with data collected performing the same task in the real world (Mullen et al. 2011). A similar issue is the Hawthorne effect, which involves modification or improvements in aspects of behaviour in response to awareness of being observed. This has been reported in various laboratory-based experiments. The Hawthorne effect can be minimised by comparing simulator data with naturalistic real world data (Harrell et al. 2013, Knapper et al. 2015).

• **Limited realism:** The realism of the simulator is often compromised by the artificial setting of the simulator laboratory and the artificial representation of the task being undertaken. The differences between the simulator environment and the real world can result in participants behaving differently in the simulator. For example simulator crashes do not have the same consequences as real world crashes and as such may affect user behaviours, with participants driving more aggressively in the simulator environment compared with the real world environment due to the lack of consequences (Caird & Horrey 2011).

These limitations are discussed in greater detail in the following sections. The following sections also include a broader discussion on the development and validation of simulators for road safety research.

### 4.2 Simulator applications

As noted previously, simulators have been used to investigate aspects of the road environment since the 1960s (Allen & Jex 1980, Roberts 1980, Blana 1996). In recent times the increasing advancement in computer power and visual display systems has resulted in increased availability and effectiveness of simulators for research applications (Allen 2000, Rudin-Brown et al. 2009).

Within the field of road safety research, driving simulators have been used for a vast array of applications including behavioural, functional and psychological assessments of different road user groups including young drivers (Ouimet et al. 2011) and older drivers (Pradhan et al. 2005, Ball & Ackerman 2011). Assessments of the influence of mobile phones (Strayer et al. 2011), driving in various road and environmental conditions, such as driving at night time (Wood & Chaparro 2011) are some examples of behavioural assessments. Driver behaviours have been assessed including the influence of fatigue, stress (Matthews et al. 2011), and anger (Stephens & Groeger 2011) on driver performance.

Driving simulators have also been utilised to assess how various medical conditions can influence driving performance including epilepsy, sleep disorders (Tippin 2011), Alzheimer's disease (Uc & Rizzo 2011) and traumatic brain injuries (Brouwer et al. 2011). While driving simulators have also been utilised to provide a safe environment to conduct research investigating the influence of impairing substances such as alcohol, illicit and licit drugs (Lenné et al. 2003, Lenné et al. 2010).
Engineers have used simulators extensively to assess various aspects of road and geometric design on road user behaviour including the design of traffic signals (Noyce et al. 2011), road signs and pavement markings (Godley et al. 2004, Ben-Bassat & Shinar 2011, Chrysler & Nelson 2011). More complex aspects of the road environment have also been assessed and evaluated such as new intersection designs (Stephens et al. 2017) and railway level crossings (Lenné et al. 2011).

4.3 Types of simulators

Depending on the needs of the research topic and the available resources, the performance and the realism of the simulator can vary substantially. Essentially all simulators are a compromise between the faithful perceptual representation of the task and the cost of the proposed simulator architecture (Arioui & Nehaoua 2013). The ultimate objectives of any simulator-based study are that users can experience the majority of the perceived sensations of real interaction with the environment, or at least experience the environment sufficiently to test the proposed hypothesis, while measuring the participants performance (Arioui & Nehaoua 2013).

Within the realms of transportation safety research, simulators have been developed for a range of transportation modes including flight simulators, driving simulators for commercial vehicles, heavy vehicles, public transport vehicles and private vehicles. Simulators are also used to study vulnerable road users including motorcyclists, pedestrians and cyclists (Allen et al. 2011).

Kaptein et al. (1996) classified simulators into three groups based on the structure and complexity of the simulator and the corresponding level of fidelity experienced by participants:

- **Low-level simulators**: Low-level simulators are usually characterised by their low cost. The simulators typically operate using a standard computer and screen and may also integrate basic control devices such as steering wheels or accelerators and brake pedals into the architecture.

- **Mid-level simulators**: Mid-level simulators encompass a broad range of simulators, they are more advanced and more expensive than low-level simulators. They usually incorporate multiple screens and provide some degree of dynamic feedback to participants.

- **High-level simulators**: High-level simulators represent the most advanced and most expensive simulators. High-level simulators can cost millions of dollars to develop and maintain and provide the participant with a high-quality, high resolution, virtual experience.

The structure provides a functional classification for road safety simulators, however the classification structure can be misleading and in fact is quite arbitrary. In reality, a lower fidelity simulator may not necessarily be less valid than a high-level simulator and in some situations may actually be more appropriate for investigating the designated research questions. Furthermore, the high costs associated with increased fidelity may overly complicate the research task when a suitably designed lower fidelity simulator would have been appropriate (Allen et al. 2011). As such when selecting a simulator for research it is more important to consider the structure of the simulator, the functions that the simulator can perform and data that the simulator can accurately capture.
in order to answer the research question as opposed to simply selecting a simulator with the highest level of fidelity.

4.4 Simulator considerations

In addition to the selection of simulators, when developing a simulator it is important to consider some of the issues associated with simulation based research. These include the fidelity of the simulator, the validity of simulators as research tools and the issue of simulator sickness, all of which have the potential to influence the results obtained from simulator based experiments.

4.4.1 Fidelity

Physical fidelity of a simulator refers to the degree to which the physical components of the simulator correspond with the real world in regards to the visual displays, sensory feedback, and vehicle control mechanisms (Godley et al. 2002). The closer a simulator can replicate operating the vehicle in the real world environment, the higher physical fidelity the simulator is considered to have (Godley et al. 2002).

Fidelity is a multi-dimensional variable that refers to the cues that are given to the users through the control system, the vehicle and the simulator scenarios or roadway. High fidelity simulators provide cues to the operator that replicate those experienced in a real environment, while low fidelity simulators have the potential to evoke unrealistic behaviours with the operator and hence produce invalid research outcomes (de Winter et al. 2012).

Typically when assessing a simulator’s physical fidelity considerations are made regarding the simulator layout, visual display and the dynamics of the simulated vehicle including speed profiles, steering and braking (Blana 1996). Simulators with high levels of physical fidelity have been found to increase the face validity of the experiment in the eyes of the participants (Orlady et al. 1988), that is, participants perceive high fidelity simulators to be a more valid research tool than lower fidelity simulators. Furthermore, it has been reported that simulators with higher levels of physical fidelity are associated with lower levels of simulator sickness and discomfort (McLane & Wierwille 1975, Harms 1996), compared with lower fidelity simulators. In contrast, this claim is disputed by others (Godley et al. 2002) and can vary for different tasks.

When developing a simulator, it is the fidelity of performance by the participants or behaviour validity that is under investigation, not the fidelity of the simulator itself. The simulator does not have to be identical to the real experience but must be able to sufficiently replicate the specific task or behaviour that is under investigation (Rudin-Brown et al. 2009). While the physical fidelity of a simulator is considered to be an important variable to ensure that the simulator provides an environment that is reasonably representative of the real demands of the activity, previous simulator research has suggested that behaviour validity can be more important with regards to ensuring that the results obtained from the simulator are applicable to the real world task (Godley et al. 2002). It is also suggested that increasing the physical fidelity of a simulator may not necessarily improve the behavioural
validity of participants’ actions and that it is possible to generate more behaviourally valid results from less sophisticated simulators (Godley et al. 2002).

4.4.2 Simulator sickness

Simulator discomfort or sickness is a condition where participants using a simulator experience symptoms similar to motion sickness. Simulator sickness has been documented by various research reports, most notably by Kolasinski (1995) in her report for the USA Army Research Institute regarding simulator sickness induced through the use of flight simulators. Simulator sickness is not limited to any one type of simulator and has been reported in simulators developed for various vehicle types (Kennedy et al. 1993, Brooks et al. 2010, Stoner et al. 2011). It has also been reported in both head-mounted and screen based simulators as well as simulators that utilise fixed bases or motion platforms (Draper et al. 2001).

Simulator sickness can undermine the validity of the experiment by affecting the operator’s performance and behaviour including, execution of inappropriate behaviours, inability to concentrate and avoidance of tasks that induce symptoms (Uliano et al. 1986). In addition to the issues of reduced validity created by simulator sickness, there is also the potential risk of inducing severe symptoms amongst participants such as nausea and vertigo if they suffer from high levels of simulator sickness while conducting the experiment (Kennedy et al. 1993).

The most significant effects of simulator sickness are generally experienced in flight simulators, particularly those used to simulate high gravitational force manoeuvres, such as those experienced when simulating combat manoeuvres in military aircraft. Additionally simulators and simulator scenarios that expose participants to long periods of rotation and rapid changes in acceleration have been reported to increase the likelihood of participants experiencing simulator sickness symptoms (Kolasinski 1995).

There are various theories regarding why some participants experience simulator sickness. One of the most common theories is that the symptoms of simulator sickness arise due to the mismatch that occurs between what sensory systems expect and what is actually occurring. In particular the mismatch between visual, auditory and vestibular system cues (Stoner et al. 2011) appears to affect the onset of simulator sickness. This is the primary theme behind cue conflict theory, but is also a component of other simulator sickness theories including, postural stability theory, poison theory and rest frame hypothesis (Stoner et al. 2011).

There is some evidence of increased rates of simulator sickness as a function of age and gender of participants, with older participants increasingly susceptible to simulator sickness (Klüver et al. 2015). Female participants also typically exhibit higher rates of simulator sickness compared to males (Allen et al. 2006). Brooks et al. (2010) also suggested pre-screening participants for motion sickness as there is a strong correlation between participants who experience motion sickness and simulator sickness.

Research has shown that, for driving simulators especially, avoiding sharp turns or rapid braking, and the use of short sessions can significantly reduce the effects of simulator sickness. In addition, latency (the time interval
between participant inputs and the reaction from the simulator) should be such that it is equal or less than that of the visual system (Stoner et al. 2011).

A commonly utilised tool for measuring simulator sickness is the Simulator Sickness Questionnaire (SSQ). The SSQ was developed based on the findings from over 1,000 participants in USA Navy flight simulators (Kennedy et al. 1993). The SSQ is a self-reported symptom checklist of sixteen symptoms that are associated with simulator sickness. Participants rate their symptoms on a four-point scale from no sickness to severe sickness for the sixteen symptoms. Simulator sickness is measured as both a total severity score and on three subscales:

- **Nausea subscale**: made up of symptoms including increased salivation, sweating, nausea, stomach awareness, and burping.
- **Oculomotor subscale**: includes symptoms such as fatigue, headache, eyestrain, and difficulty focusing.
- **Disorientation subscale**: is composed of symptoms such as vertigo, dizziness with eyes open, dizziness with eyes closed, and blurred vision.

It is recommended that the SSQ is administered to participants prior to simulator studies to gain baseline readings. The SSQ can then be administered throughout the study to monitor any changes in participant’s symptoms. However it has been noted that this approach can result in higher reported levels of simulator sickness, following the simulator experiment. For example, Young et al. (2007) conducted a study looking at two groups of simulator participants. One group were administered the SSQ before and after the study and their results were compared to a group who were only administer the test post study. Participants reported significantly higher results when administered the test twice. Young et al. (2007) hypothesised that the SSQ may have primed participants and resulted in them providing higher readings, however it was not clear if participants actually experienced higher levels of sickness and in the absence of randomisation inherent biases between the two groups may explain the differences.

### 4.4.3 Validity

Validity refers to how well a study or procedure measures what it is intended to measure (Rudin-Brown et al. 2009). The review of previous research using simulators identified various forms of validity including, physical validity, behavioural validity, internal and external validity, face validity, ecological validity, and statistically conclusive validity (Mullen et al. 2011).

However within the realms of driving simulation, there is often a particular focus on establishing behavioural validity of the simulator. Behavioural validity is a measure of the extent to which participants exhibit the same behaviours using the simulator as they do when operating the vehicle in the real world (Blaauw 1982, Godley et al. 2002). While the validity of the simulator is important, it is not necessary for all elements of the simulator to be identical to those associated with the real world task (Rudin-Brown et al. 2009). Instead, the simulator is only required to be sufficiently valid for the specific task or behaviour that is being investigated (Rudin-Brown et al. 2009).
Within the construct of behavioural validity, Blaauw (1982) detailed two different levels, absolute validity and relative validity. Absolute validity refers to the situation where simulated and on-road data provide the same or equivalent numerical results and relative validity refers to the situation where the numerical results differ between the two tasks but exhibit similar patterns in terms of their magnitude or direction (Godley et al. 2002).

Simulators are not capable of completely recreating the driving experience and these differences between the simulator and the real world can result in differences in the subjects’ behaviours and performance. It is because of these differences that there is a need to validate driving simulators. This allows the results of the simulator to be transferable, reliable and valid when comparing results from the simulator and the real world (Blana 1996).

4.4.3.1 Validation studies

In order for the results of the simulator to be meaningful it is essential that the correspondence between the real world and simulated environment is the same or at least sufficient to produce valid results (Törnros 1998). It is particularly important that the road-user behaviours elicited in response to events in the simulator are comparable to the real world situations (Törnros 1998). A review of the literature surrounding simulator validation studies reveals that a variety of different methods have been utilised to validate simulators. However a common factor in many studies is comparison between the simulator and some aspect of operation of the vehicle or road user behaviour in a real world setting.

Common methods have included utilising instrumented vehicles to collect naturalistic data from participant’s on-road driving tasks and comparing this data to data collected from the simulator when completing similar tasks (Blana 1996, Godley et al. 2002). Validation of driving simulators using naturalistic data has been performed both on public roads and using test-track scenarios (Blana 1996).

For example in their driving simulator validation study, Fildes et al. (1997) compared driving in the simulator with on-road data collected through the use of an instrumented vehicle. The study assessed driver’s reaction to a range of perceptual countermeasures in terms of their speed, braking, deceleration and lateral placement. Fildes et al. (1997) established correlations in speed and braking performance across a range of scenarios, however they did not establish absolute validity for deceleration and lateral position.

Similarly, Blana & Golias (2002) compared real drivers’ speed and lateral displacement to simulator data in their validation of the University of Leeds driving simulator, which was considered a high-fidelity simulator at the time the research was conducted. Data for the on-road component was collected from the vehicle stream using vehicle detectors, however the authors noted various limitations regarding the on-road data collection methods due to the limited available technology. The results found significant differences between the on-road and simulator data, particularly when considering lateral position, where there were significant differences in lateral displacement on curves and variance in displacement on curves and on straight sections of road.

Recently Meuleners & Fraser (2015) assessed the validity of the Curtin University high fidelity driving simulator, compared to on-road driving behaviour. Driving performance and driving errors including observation tasks,
speed control, vehicle positioning and compliance with road rules were compared between on-road and simulated environments and the authors did not find any significant differences between driving in the simulator and on-road when considering obeying traffic lights and stop signs, maintaining speed and performing mirror checks, concluding that the simulator is valid for the measures assessed in their study.

Most of the validation studies identified have focused on motor vehicles, however recently several studies have been conducted to validate aspects of high fidelity motorcycle simulators. One such study conducted by Savino et al. (2016) aimed to validate a motorcycle simulator that implemented a counter steering input. Savino et al. (2016) considered both objective and subjective data collected from participant’s and established relative validity for a range of objective measures including steering torque, slalom manoeuvres and lane change manoeuvres, where by the results in the simulator and from real world data were not identical but did express similar trends in terms of magnitude and variation. Subjective feedback from participants also showed that the simulator was realistic and comparable to simulators with significantly more expensive architectures.

Simulators are often validated against a set of key performance measures to assess the correlation between results. Traditionally simulator validations studies have relied on measures such as speed, speed adaptation and lane keeping (Törnros 1998, Blana & Golias 2002, Godley et al. 2002, Underwood et al. 2011). While the findings of many validation studies often show good correlation between these variables, it is argued that these variables measure relatively low-level vehicle control and there is an additional need for higher-level cognitive measures to be included as performance measures (Underwood et al. 2011). These higher level measures include behaviours that measure the drivers’ performance such as visual tracking, hazard detection, gap acceptance, driver error, and reaction time as well as measuring driver’s situational awareness and behavioural change in specific situations (Shechtman et al. 2009, Wetton et al. 2010).

While there is agreement that validation of a simulator is essential (Törnros 1998), validation is highly task dependent and the validation of the simulator for certain tasks does not guarantee the simulator’s suitability for application to broader research questions. Notwithstanding, the validation process does provide added confidence in the reliability and transferability of the simulator results.

As previously mentioned, Blaauw (1982) detailed two measures of behavioural validity, absolute validity and relative validity. Both measures of validity require a degree of statistical correlation between data collected in the simulator and the real world data. In order to established absolute validity there is a need to assess if the measures collected in the simulator and in the real world are equivalent. This is the same as setting a null hypothesis that there is no statistically significant difference in the results. As such the alternative hypothesis is that there is a statistically significant difference. These analyses require statistical hypothesis testing through measures such as analysis of variance (ANOVA) or paired-sample t-tests.

When a statistical significant difference is observed, absolute validity cannot be established. However if the magnitude and direction of data are equivalent it is possible to established relative validity. Relative validity has
been assess through visual comparison of the two data sets (Blana 1996). A more robust method for establishing relative validity is through regression analysis to assess the correlation between variables. Using this method high levels of correlation can be taken as a measure of relative validity (Godley et al. 2002).

4.5 Simulator structures

The structure of every simulator is different, however all simulators are designed to serve a common objective of recreating aspects of a real world task within a controlled environment. The structure of the simulator is often described by a systems architecture. The architecture is informed by the performance measures that the simulator is designed to monitor and collect. A simulator can display various qualities including the range of motion of the simulator, the display capabilities, the delay or latency of the simulator, scene animation, the physical models used for vehicle dynamics, the vehicle interface, and the programming languages and software incorporated into the simulator environment to control the simulator processes (Carsten & Jamson 2011).

As there is no standard structure of a simulator, a key stage in developing a simulator is developing a systems architecture. The architecture forms the conceptual model and defines the structure of the simulator, the interactions between various sub-systems and also include various specifications for the software and hardware componentry. An example of a simulator system architecture is shown in Figure 9.

![Figure 9: Example simulator architecture (Allen et al. 2011)](image)

The example architecture consists of four sub-systems responsible for the simulation and computing processes, sensory feedback generation, sensory display and cueing systems. The architecture also includes a feedback
loop between the human operator and the computer processing system, where the operator's actions and
reactions influence the underlying computer system and hence influence the sensor feedback and display
subsystems. The feedback loop also incorporates the performance measurement component of the simulator,
where the participant's actions and the simulator environment directly influence the measurement of key
performance data from the simulator. Figure 9 provides just one example of a simulator architecture. All
simulators will have different architectures based on the design specifications of the simulator, the data that the
simulator is proposed to collect, the feedback devices incorporated into the simulator and the cost of the
simulator as well as a range of other variables.

Accurate measurement of performance is crucial to any simulator, as are the performance measures that form
the key data for analysis and evaluation of the research questions being investigated in the simulator. As all
simulators are different, not all simulators are designed to record the same information. However, typically driving
simulators are developed to capture a range of measures including, speed, speed variability, lane position and
variability, braking and reaction times, braking pressure, brake force, throttle position, vehicle headways, steering
wheel angle. Simulators have also been developed to monitor functional measures including driver workload,
speed estimation, risk perception, behavioural adaptation, task-sharing, situational awareness, attention,
decision making, eye glance behaviours and hazard perception (Rudin-Brown et al. 2009).

The performance measures and the simulator architecture that guided the development of the bicycle simulator
which was developed as part of this PhD project are discussed in Chapter 5. The architecture was developed
based on a review of the key functions of a bicycle and cyclists behaviour when riding in the urban road
environment. To complement the development of the architecture a review is presented below which was
undertaken to identify existing bicycle simulators that have been developed for rider education and research
purposes. The purpose of this review was to gain an understanding of existing bicycle simulators and the
performance measures they are capable of collecting and their respective architectures.

4.6 Bicycle simulators

While the development and application of driving simulators has been a highly active field of research for many
years, comparatively much less research has been undertaken in the field of two-wheeled vehicle simulators
(Nehaoua et al. 2011). There are various reasons for the disproportionate research efforts, and these primarily
centre around the complex dynamics associated with vehicle stability and control. This makes the issue of
immersion much more complex and has been seen as a major restricting factor in the development of high

Despite these issues, in recent times the increase in popularity of two-wheeled vehicles combined with the
relative growth in the proportion of collisions involving these vehicles has seen interest in this field grow and
there is a growing number of motorcycle and a select few bicycle simulators being developed for various
research, training and education purposes throughout the world. Many two-wheeled vehicle simulators are
developed as fixed base systems with a bicycle or motorcycle placed in front of a screen which displayed the visual environment. Early simulators were primarily used as education tools, particularly in Japanese driving schools (Nehaoua et al. 2011).

Simulators built for the purposes of research have also incorporated various systems to provide motion cuing, particularly to simulate the pitch and yaw of motorcycles, which provide important haptic cues to the participant (Cossalter et al. 2010, Savino et al. 2016). Motion simulation range from moving platforms, through to hexapods that provide six degrees of freedom for the simulator and are capable of accurately simulating the range of motion and forces experienced by the rider, albeit under a limited number of situations or for only short durations of time.

Visual displays typically consist of projector screens, however some systems have incorporated Head Mounted Displays (HMDs). HMDs are a relatively new inclusion into simulator architectures. This is largely due to the recent advancements in HMD technology, in particular improvements in display quality and latency.

Worldwide there are only a few bicycle simulators that have been developed for research purposes. A summary of several documented bicycle simulators that have been formulated for education and research applications is presented below. When possible the discussion has included information of the simulators architecture, performance measures and research applications.

4.6.1 Honda bicycle simulator

The Honda bicycle simulator is a commercially available bicycle simulator developed by the Honda Motor Company that was designed for traffic safety education purposes. In Japan, approximately two thirds of traffic collisions involving cyclists are caused by a violation by the bicycle rider (Honda Motor Co 2016). Honda developed the system to educate young riders on how to ride a bicycle safely, while also helping to improve their ability to predict risks and increase their safety awareness. The simulator was designed to include several preloaded training courses such as “riding to school” and “riding to the shops”. The Honda bicycle simulator was designed to monitor a range of cyclist performance measures including monitoring their head checks, speed and position. A unique feature of the simulator is a set of sensors on the ground that can monitor when cyclists take their feet off the pedals and place their feet on the ground. The simulator is a medium fidelity simulator with a screen-based display and auxiliary screens that participants can use when performing head checks. The simulator operates using a designated computer and a custom bicycle with pedalling, steering and braking capabilities.

4.6.2 KAIST interactive bicycle simulator

The KAIST interactive bicycle simulator was developed by the Korea Advanced Institute of Science and Technology (KAIST) (Dong-Soo et al. 2002). The architecture for this simulator was developed around three computers controlling a motion platform, simulator displays and an instrumented bicycle. The instrumented bicycle was designed to measure steering, braking and rear wheel movement. The motion platform is
incorporated into the design to simulate the dynamics of the bicycle. The display system is capable of operating using either a screen based display or a head mounted display system. Communication protocols were developed between the three computers operating the various sub-system to minimise latency.

Unfortunately the review only found two papers regarding the KAIST simulator, one describing the initial simulator and one documenting an updated version of the simulator with advanced features, which have been listed in the above description. As such there is limited information available regarding research that has been undertaken using the simulator.

![Figure 10: KAIST bicycle simulator (Dong-Soo et al. 2002)](image)

### 4.6.3 University of Iowa: Hank Virtual Environment Lab

The University of Iowa, through their Hank Virtual Environment Lab, developed a high-fidelity bicycle simulator. The simulator operates using a complex PC-based architecture that utilises seven computers. The computers control the simulator engine, monitor the bicycle dynamics, three projection screens, a dedicated sound system and the final computer is used for video recording of experiments (Babu et al. 2011). A motion platform has not been incorporated into the simulator architecture (Plumert et al. 2004).

The instrumented bicycle is surrounded by three screens, which form a three-walled room. The instrumented bicycle monitors the steering angle and pedalling torque applied by the rider when using the simulator. The values are input into the bicycle dynamics model to compute bicycle speed and direction within the simulator.
environment. The bicycle dynamic model can also account for the mass of the rider and bicycle, inertia, terrain slope, ground friction and wind resistance (Babu et al. 2011).

The University of Iowa bicycle simulator has been utilised for a variety of research purposes, including investigating differences between adult and child cyclist behaviours when cycling across roads and accepting gaps in traffic streams (Babu et al. 2011, Grechkin et al. 2013, Chihak et al. 2014) and studying behaviour conditions such as risk taking behaviours of children with attention-deficit hyperactivity disorder (ADHD) (Nikolas et al. 2016).

4.6.4 Oregon State University: Bicycle simulator

The Oregon State University bicycle simulator is an integrated simulator capable of operating in conjunction with their motor vehicle driving simulator (Oregon State University 2014). The simulator operates using an instrumented bicycle on a motion platform with a large projection screen displaying the simulated environment to the cyclists. The simulator was developed to suit a range of different bicycle sizes and types. Integration with the Oregon State driving simulator is a key advantage of the simulator as it allows for drivers and cyclists to operate within the same simulated environment. Unfortunately the literature search did not uncover any published research undertaken using the simulator as such details regarding the architecture, performance measures and research uses are limited.

![Oregon State University bicycle simulator](image)

Figure 11: Oregon State University bicycle simulator (Oregon State University 2014).

4.6.5 FIVIS: Bicycle simulator

The FIVIS bicycle simulator was developed by the Institute of Visual Computing at the Bonn-Rhein-Sieg University of Applied Sciences in Germany. The objective of the FIVIS project was to develop a bicycle simulator
capable of simulating real life bicycle riding situations within an immersive virtual environment for the purpose of traffic safety education and training (Schulzyk et al. 2007).

The simulator operates using an instrumented bicycle that controls steering, pedalling and braking. The bicycle is mounted on a motion platform providing six degrees of freedom in order to simulate forces experienced while undertaking turns, balancing, braking and accelerating. Visual feedback is provided to the cyclist via three projection screens through a system developed at Bonn-Rhein-Sieg University known as the “Immersion Square”. Tracking systems are installed within the simulator architecture to detect participating cyclists gaze for hazard perception studies. The simulated environment has been developed to operate using a three dimensional video game engine (Schulzyk et al. 2007).

The key limitations of the FIVIS installation are the somewhat unrealistic heads-up display due to the three offset screens and the fact the visual environment is entirely forward facing limiting the fidelity of the cycling experience. The simulator has been used for various applications including cyclist education, performance measurement in response to visual and auditory cues and as an evaluation environment of physical and cognitive stress factors.

![Figure 12: Cyclist using FIVIS simulator (Schulzyk et al. 2007).](image)

4.6.6 **Viktoria Swedish ICT**

Viktoria Swedish ICT has demonstrated their BikeSIM project (Swedish ICT 2014). The simulator utilises a virtual HMD using the Oculus Rift Development Kit One, connected to an instrumented bicycle, mounted on a bicycle trainer. The ICT simulator was proposed for use in traffic research, with the simulator used to analyse difficult or
dangerous cycling situations and for behavioural research. The simulator represents a significant shift from
traditional simulators that utilise projectors and screens to display the virtual environment to cyclists and instead
creates an immersive environment through the use of the HMD system. Unfortunately the literature search did
not identify any publications presenting any research, education or training activities using this simulator.

4.6.7 Bicycle simulator summary

There were a limited number of bicycle simulators identified worldwide that are utilised to conduct cycling
research. Of those that were identified, they range from using simple stand-alone computer-based architectures,
to very complex systems utilising networked computer systems, motion platforms and highly sophisticated
bicycle dynamics models. A common element was the inclusion of an instrumented bicycle which acted as the
main human machine interface for participants to interact with the simulated environment.

Unfortunately, no validation studies were found comparing the performance of participants when riding on road to
when using the simulators. However, that is not to say that the simulators have not been validated, as generally
there were very few research papers that were available for the identified bicycle simulators. One exception was
the Oregon State University simulator which has been used for a variety of research projects, which have been
published in various psychology journals.

Of the simulators identified in the review, the Viktoria Swedish ICT simulator demonstrates a shift in simulator
design from projection-based simulators to utilising HMD technology providing a virtual reality environment. This
is likely a result of the Viktoria Swedish ICT simulator being the most recently developed bicycle research
simulator identified in this review. The virtual reality technology appears to offer a promising way forward for
simulator-based research as it allows participants to be placed in an immersive environment and requires
significantly lower computational demands compared to simulators that project environments onto multiple
screens. The use of HMD technology may also help to increase the face validity of the simulator by placing
participants in a more immersive environment and blocking out the stimuli associated with the laboratory setting,
therefore creating a more controlled environment.

It seems that the majority of identified bicycle simulators did not opt to utilise motion platforms. This is likely a
reflection of the complexity of and difficulty in simulating bicycle dynamics compared to four wheel motor
vehicles. It is unclear if the motion platforms incorporated into the KAIST and FIVAS simulators have resulted in
an increase in fidelity or more valid research results. Furthermore it is assumed that the inclusion of a motion
platform into the bicycle simulator architecture could significantly increase the cost and complexity of the
simulator and could result in a considerable increase in the time and research required to validate the simulator
prior to conducting research using the simulator to ensure that the motion generated by the platforms gave a
realistic representation of bicycle dynamics.
4.7 Summary

This chapter has presented an overview of driving and cycling simulators and their application within the field of road safety research. It established that the use of simulators is increasingly growing within road safety research and that simulators have been utilised to study a diverse range of road safety problems.

Driving simulators have previously been utilised to study a range of aspects of infrastructure, road and geometric design including the design of traffic signals (Noyce et al. 2011), road signs and pavement markings (Godley et al. 2004, Ben-Bassat & Shinar 2011, Chrysler & Nelson 2011), intersection designs (Stephens et al. 2017) and railway level crossings (Lenné et al. 2011). However, the field of bicycle simulators is much less active and, of the simulators that have been developed for cycling, the focus has been more on behavioural research than on the design and evaluation of infrastructure concept designs. Further, no validation studies of bicycle simulators were identified in the published literature at the time of this review.

This creates a unique opportunity for the current research to develop and validate a bicycle simulator that is capable of being utilised to evaluated infrastructure designs. The development of such a bicycle simulator has considerable scope to contribute to the field of road safety research. The process of developing the bicycle simulator is detailed in the following chapter of this thesis.

In reviewing the previously developed driving and cycling simulators, this chapter established several considerations that need to be taken into account when developing and conducting research with simulators. One of the key considerations is the issue of simulator validity. To address this concern, a validation study was undertaken using the simulator following its development and on-road instrumented bicycle (see Chapter 6). Furthermore the issues of simulator fidelity and simulator sickness were examined and these study components are presented in Chapter 5. Each of these three issues were identified in this chapter as key considerations for a simulator in order to have confidence in the research outputs generated by the simulator studies and to ensure face validity and safety for participants when using the simulator.
Chapter 5: Bicycle simulator development

This chapter presents the process undertaken to develop the bicycle simulator. The bicycle simulator was developed for the purpose of road safety research and more specifically the evaluation of infrastructure concepts to address common cyclist safety issues. The chapter begins with a description of the performance measures that were deemed essential for the evaluation of on-road cycling infrastructure designs. This is followed by a description of the development of the simulator architecture and specification of the simulator components that were selected to meet the requirements of the architecture.

Following the development and assembly of the simulator, calibration of the steering and braking controls was undertaken to enhance the physical fidelity of the simulator. The key procedures and findings from this process are outlined, including a discussion of the preliminary evaluation and potential limitations of the simulator such as extent of simulator sickness.

The findings and discussion within this chapter align with the secondary research question which was identified in Chapter 1, that is: what is required to develop and validate a cycling simulator for road safety research.

5.1 Performance measures

The first stage in the development of the bicycle simulator was to determine the most appropriate and feasible performance measures to be collected during simulator rides in order to evaluate cyclist interaction with road infrastructure designs. A key requirement for performance measures analysis was an ability to identify if the infrastructure designs that were being evaluated in the simulator were resulting in changes in participants’ riding behaviours. In order to identify suitable performance measures, as a starting point, consideration was made regarding what was required of a vehicle operator in order to engage in the task of operating a vehicle. It was decided to consider the driving task from an engineering point of view as the research conducted in this thesis is focused on the design and evaluation of physical infrastructure as opposed to psychological behaviours such as cognitive, attentional perceptual and physical functions of the road user. These vehicle operation requirements were then translated to the task of operating a bicycle. In their guidelines regarding the geometric design of highways and streets, The AASHTO outline that the driving task can be considered to comprise three essential tasks (AASHTO 2001). These were taken as the reference for what performance measures would need to be captured by the simulator. The three essential tasks comprised:

- Navigation: which includes trip planning and route following;
- Guidance: which consists of following the road and maintaining a safe path in response to traffic conditions; and
- Control: which involves steering and speed control of the vehicle.

When considering the operation of a vehicle in a simulator environment, the need for navigation is limited as generally the scenarios and routes that participants follow are predetermined as part of the experimental design.
Furthermore when participants are required to follow a set route, visual or auditory instructions can be given to the participant through the simulator or by the researcher conducting the experiment.

While navigation is not always an essential task, for most simulator experiments, the participant is required to guide and control the vehicle which they are operating within the simulated environment. The AASHTO state that the tasks of guidance and control require the road user to control the steering and speed of the vehicle while also following and maintaining a safe path in response to traffic conditions.

In essence these requirements represent the fundamentals of operating a vehicle within the road environment and are also relevant to the operation of a simulated vehicle within a virtual environment, where participants must control the motion of the simulator vehicle while reacting to the simulated road environment. The two tasks are discussed below regarding the operation of a bicycle.

5.1.1 Bicycle motion and control

The motion of a bicycle can be described using classical mechanics, where the motion of bicycle and the rider are described based on the forces acting upon them (Wilson 2004). Within classical mechanics the position of an object can be defined using three-dimensional Euclidean space and time. As such the location of the bicycle in the real world and in a simulated environment can be described based on three coordinate points in the x, y and z axis at any given moment in time. The change in location of an object is defined as its displacement, the first derivative of displacement or the change in displacement relative to the change in time gives the velocity of an object, while the second derivative of displacement describes the acceleration of an object.

These are all fundamental concepts of motion and, at a basic level, the simulator must be able to monitor and record the position of the cyclist in space and time. This in turn allows the simulator to determine the velocity and acceleration of the simulated bicycle. Furthermore the measurement of these variables must occur at a frequency that allows for meaningful analysis of the data, while the simulated environment must also be able to update at sufficient frequency to avoid issues associated with excessive latency, as discussed in the previous chapter.

Newton’s second law of motion postulates that changes in acceleration are a result of the application of force to an object. For a bicycle there are essentially two types of forces that can result in motion;

- External forces, which include gravitational forces (slope resistance), friction forces (or rolling resistance forces) and aerodynamic forces (air resistance), and
- Internal forces which are resultant to the rider pedalling, balancing and steering the bicycle.

The external forces that a cyclists must overcome were described by Di Prampero et al. (1979) and are shown in Equation 1.
Equation 1: Mechanical power output (Di Prampero et al. (1979):

\[ P_{TOT} = k_r M s + k_a A s v^2 + g M s i \]

Where PTOT is power,

- \( k_r \) is the coefficient of rolling resistance
- \( M \) is the combined mass of the bicycle and the cyclist
- \( s \) is the speed of the bicycle on the road
- \( k_a \) is the wind resistance coefficient
- \( A \) is the combined frontal area of the bicycle and cyclist
- \( v \) is the bicycle speed through the air
- \( g \) is the gravitational acceleration constant (9.81ms\(^{-2}\))
- \( i \) is the gradient of the road

Equation 1 consists of three key terms. The first term refers to rolling resistance of the bicycle, however for most modern bicycles this results in negligible resistance. The second term refers to aerodynamic drag, which is proportional to the velocity of the bicycle squared, as such as the speed of the cyclist increases the power required to overcome drag increases exponentially. The final term refers to forces due to gravity. For uphill slopes gravity increases the forces that the cyclist must overcome, while during descents the negative slope of the hills results in the addition of gravitational potential energy to the power equation. In essence in order to recreate the motion of a cyclist, the simulator must be able to replicate and monitor the external forces acting upon the cyclists and which they must overcome to propel the bicycle and maintain an upright position. Bicycle mechanical power equations, such as Equation 1 have been further developed, for example, Martin et al. (1998) also consider the power required to overcome the drag in wheel bearings and the efficiency of the chain drive system as other variables that influence the total power required to propel a bicycle. However, these additional forces are accounted for by the bicycle trainer that is incorporated into the simulator architecture (see Section 5.2.1) and for the purpose of developing the bicycle simulator, the simplified equation was utilised.

In order to overcome the external forces in Equation 1 the cyclist must generate power and apply internal forces that are greater than the external forces (Martin et al. 1998). These actions will cause the bicycle to accelerate, while conversely if external forces are greater than the internal forces generated by the cyclist the bicycle will decelerate or remain stationary (Martin et al. 1998). The primary source of power generated by a cyclist is through the pedals and gear train which results in rotational forces acting on the rear wheel of the bicycle. These rotational forces propel the bicycle forward. Cyclist can control the rotational force through changing the power applied to the pedals, changing the pedalling speed (cadence) or by applying the brakes.
Cyclists can also apply internal forces by steering the bicycle. In order for the bicycle to turn, the front wheel must be directed approximately in the desired direction of travel (Wilson 2004). A cyclists can steer the bicycle through two mechanisms. Riders can use the handlebar, which is connected to the front fork and wheel, to position the front wheel. Riders can also use their own body weight to change the centre of mass of the bicycle which can influence the lean of the bicycle (Wilson 2004). As such the simulator must also be able to monitor the internal forces applied by the participant to steer the bicycle.

In summary, in order to monitor the participants’ actions while riding and recreate these inputs in the simulated environment, the simulator must be able to monitor the pedalling inputs of the participant including their power and cadence, the application of braking (timing and pressure) and the steering forces applied by the participant. Additionally, the simulator must be able to recreate external forces that the cyclist must overcome in order to propel the bicycle. Finally, the simulator must be able to monitor the position of the bicycle within the simulated environment at regular intervals, as well as measure the changes in displacement, velocity and acceleration as a result of the internal and external forces acting on the bicycle.

5.1.2 Bicycle guidance

In addition to monitoring the control and motion of the bicycle, as stated by Underwood et al. (2011), simulators can often measure higher-level cognitive performance of participants as they engage with the simulator environment. These higher level measures include measurements of a participant’s performance such as visual tracking, hazard detection, gap acceptance, driver error, and reaction time as well as measuring driver’s situational awareness and behavioural change in specific situations (Shechtman et al. 2009, Wetton et al. 2010). Monitoring these behaviours align with the task of guidance as specified by the AASHTO (AASHTO 2001).

Reaction responses to environmental changes can be monitored by identification of changes in braking, pedalling and steering in response to stimuli in the simulated environment. This requires a simulator environment that can recreate a range of road environments including physical infrastructure and simulate behaviours of other road users and a simulator that records input data at a frequency that is sufficient to observe rapid changes in participant inputs. Some advanced simulators also incorporate eye tracking systems to monitor hazard detection and looking behaviours.

5.1.3 Summary of performance measures

Based on the requirements identified in the previous sections a set of key performance measures were selected that provide a platform to assess cyclist performance when trialling prototype infrastructure designs, while also creating a high fidelity environment for participants. It is noted that it would be an exhaustive task to develop a simulator to measure all functional performance and behavioural measures and this would be a much greater task than what was achievable within the scope of this thesis where the focus has been on developing a research tool suitable for understanding cyclist responses to various infrastructure designs. Therefore the key performance measures deemed necessary for the evaluation of infrastructure concepts consisted of:
• The position of bicycle measured in three dimensions, particularly regarding their location within the carriageway, and also relative to objects within the simulated environment such as parked or passing cars;
• Mean speed and speed profile of bicycle including the velocity, acceleration, braking and cadence, with a particular focus on monitor changes in speed profile on approach to critical events (i.e. intersections);
• Reaction time to critical events (such as car doors opening or sudden vehicle movements);
• Gap acceptance at intersections; and
• Cyclists head movements.

The simulator is also required to accurately reproduce the internal and external forces that act upon the bicycle and are imparted by the rider. The simulator must also monitor the behaviours and inputs of participants at a frequency that is sufficient to accurately recreate the simulated bicycles position in space and time and also collect and record meaningful data on how participants are interacting with the simulator.

5.2 Bicycle simulator architecture

Following the identification of the required performance measures to be recorded by the bicycle simulator, the architecture of the bicycle simulator was developed (see Figure 13). The simulator architecture consists of four key sub-systems: an instrumented bicycle, computer systems, a virtual simulator environment and feedback devices. The simulator was developed to incorporate a personal computer based architecture and due to cost constraints and the desire to maintain a relatively simple architecture it was decided that the simulator would not incorporate a motion platform. This restriction limits the ability of the simulator to recreate all internal and external forces. However this was deemed an acceptable limitation considering that the focus of this research was on trialling infrastructure design concepts. The intention of each of the subsystems are discussed in the following section.
5.2.1 Instrumented bicycle

An instrumented bicycle forms the primary interface for participants using the simulator. The bicycle acts as the main input device. Instrumentation of the steering, pedals and brakes allows participants to interact with the simulator environment and allows the simulator to capture key participant input data.

Steering controls are required to monitor the steering angle of the handlebar, front wheel and front fork of the bicycle. Braking controls monitor when participants apply either the front or rear brake, and pedalling controls monitor the power, cadence and speed inputs applied by the participant. The data collected from the instrumented sensors are sent to the computer system for data recording and input into the simulator environment.

5.2.2 Computer systems

The computer system functions as the link between the instrumented bicycle, the simulator environment and the feedback devices. The computer system is required to capture and transfer data between the simulator sub-systems and capture and record key performance measure data.

The computer system must have significant processing power to ensure that the simulator environment and the feedback devices produce a low latency experience for participants. If the system cannot operate at sufficient speed this will negatively impact the fidelity of the simulator, participant’s performance may also be influenced which could in turn increase the chance of participants experiencing simulator sickness.
5.2.3 Simulator environment

The simulator environment is required to take the inputs from the instrumented bicycle and recreate the equations of motion of the bicycle within the simulated environment. The simulator environment is also required to accurately recreate the road environment, simulate other road users and road infrastructure such as traffic signals. In order to meet these requirements the simulator environment needs to be programmable, flexible and capable of rapid scenario development. The environment must also be able to receive the data from the computer system which will come in a variety of different sources, including the HMD display, microprocessor and the bicycle. As such, the environment will likely be required to be compatible with a range of different programming languages and software packages.

5.2.4 Feedback devices

The final sub-system of the simulator are the feedback devices. The feedback devices are required to provide information to the participant to allow them to interact with the simulator environment. Furthermore the feedback devices play an important role in increasing the fidelity and the face validity of the simulator (Orlady et al., 1988). At the most fundamental level the simulator must provide relatively realistic visual feedback to the participants so that they can see and interact with the simulated road environment. To enhance the fidelity of the simulator, a sound system to provide auditory cues to participants was incorporated into the architecture. The ability to influence the resistance of the bicycle allows for haptic feedback to be incorporated into the simulator architecture and should enhance the fidelity for participants.

5.3 Simulator components

Following the development of the simulator architecture and specification of the requirements for each of the simulator sub-systems, the next stage in the development process was to specify the components of the simulator. The components were selected to meet the requirements of the simulator architecture. Components of the bicycle simulator are discussed below in terms of the physical components of the simulator (hardware) and the computer software that were incorporated into the design.

5.3.1 Hardware

In an effort to simplify the simulator componentry and cost, at the outset, a fixed based simulator was developed. As this simulator is intended for road safety research, in particular assessing how cyclists interact with infrastructure designs, it seemed overly ambitious to integrate a motion platform to simulate the range of motion experienced by a cyclist and it was assumed that a motion platform would require substantial programming and validation in order to accurately recreate the dynamics of riding a bicycle. Without extensive validation it is possible that a motion platform could reduce the face validity of the simulator if the range of motion or latency did not accurately represent riding a bicycle in the real world.
Additionally, it was expected that the range of infrastructure prototypes that were likely to be evaluated, at least in the short term, would not require the simulation of the acceleration forces associated with changes in grade. Further, the urban environment in which the infrastructure will be simulated is unlikely to see cyclists generate sufficient speeds that would require simulation of forces associated with rapid acceleration or deceleration. Furthermore, it was considered out of scope for this research to assess cyclist balance or stability when riding through infrastructure designs. Notwithstanding, while a motion platform was not incorporated into the initial design, the simulator was developed in a way that a motion platform could be incorporated into the architecture if it was required in future experiments, albeit this would require substantial validation of the motion platform as mentioned previously. The key hardware components for the simulator were selected to align with sub-systems of the simulator architecture and are presented below.

5.3.1.1 Instrumented bicycle

A standard flat-bar road bicycle was selected for the simulator to act as the main human machine interface for participants when interacting with the simulator (Figure 14). The bicycle is a medium sized Giant City Cross bicycle. The intention was to select a bicycle that the majority of participants would be comfortable riding. The choice of bicycle was also an important consideration as it was intended to use a similar bicycle for the on-road component of the simulator validation study (Chapter 6), as such it was imperative that a bicycle that could be comfortably ridden on-road by the majority of participants was selected for the simulator.

Figure 14: Simulator bicycle and trainer

Previous research by Mortimer et al. (1976) and Godthelp & Buist (1975) established that flat-bar bicycles are the most stable style of bicycle, particularly when riding at lower speeds. Furthermore the selection of flat handlebars was expected to minimise any issues associated with riders having to use handlebars which are less familiar, such as drop bar handlebars. Flat-bar road bicycles are also characterised as typically being less expensive than
other bicycle types, requiring less maintenance, travelling at lower speeds and cyclists typically adopt a more upright seating position, which has also been associated with increased stability.

Consideration of the required seat heights for participants was also made. Considering the geometry of the Giant City Cross bicycle, a medium sized frame could theoretically accommodate participants ranging in height from a 5th percentile female if the seat was raised 96mm from the top of the seat tube and could accommodate a 95th percentile male if the seat was raised 212mm from the top of the seat tube (Fryar et al. 2012), based on required saddle height calculations using the method proposed by LeMond & Gordis (1987) which suggests that saddle height should be set at 88.3 percent of inseam length and measured from centre of the bottom bracket to top of the seat height. While this range of saddle heights may not be practical for all participants when riding on road, considering the simulator is on a fixed base and the participants are not required to balance the bicycle, the dimensions were deemed suitable.

The simulator was designed to integrate a bicycle trainer into the architecture to provide a stable platform and to provide the equipment to collect data. The trainer selected is a Wahoo Kickr bicycle trainer (Figure 14). The trainer is an electromagnetic, direct drive bicycle trainer with an inbuilt power meter and can measure speed, cadence, distance and power. One specific requirement of the trainer is that the bicycle is required to have a 10 speed rear cassette for compatibility. The Giant City-Cross bicycle met this requirement while also providing a suitable range of seating heights for participants and providing a flat handlebars which were expected to be familiar to the majority of participants.

The bicycle is equipped with sensors that measure steering and braking inputs from the participant. Magnetic proximity switches (Hall-effect sensors) were installed in the handlebar to record when the front and rear brakes are applied, while a rotation sensor (potentiometer) is installed in the head tube of the bicycle to measure the steering angle of the handlebar, front fork and front wheel.

The bicycle trainer captures performance data from the participants including speed, acceleration, power, resistance and cadence and provides these inputs into the simulation environment. The trainer also functions as a feedback device for the simulator. The trainer can be used to adjust the rear wheel resistance to simulate changes in grade and variations in surface material friction (i.e. changes in rolling resistance) as well as emulating the sensation of applying the rear brakes by increasing the resistance.

5.3.1.2 Computer systems

A desktop computer and microprocessor are the main computer hardware components incorporated into the simulator architecture. The microprocessor is programmed to receive data from the sensors that are installed on the instrumented bicycle that measure the steering and braking inputs. The microprocessor has a 16MHz CPU speed and is connected to the main computer via a USB serial link.
The desktop computer receives inputs from the microprocessor as well as from the bicycle trainer and the head mounted display (HMD) and transfers this information to the simulation environment. Custom software and scripts were developed for communication between the computer, the microprocessor and the bicycle trainer.

The desktop computer also functions as the data capture and video recording system, recording the participants’ view of the simulation environment and performance data from the simulator. The speaker system from the computer is utilised to provide auditory cues to participants and to simulate traffic and ambient noise. It can also be programmed to provide consistent auditory instructions to participants, such as directing participants which direction to turn at intersections.

5.3.1.3 Feedback devices

An Oculus Rift development kit 2 is the key display hardware component for the bicycle simulator. The Oculus Rift is a virtual reality HMD system. The Oculus Rift features a high resolution, low–persistence organic light-emitting diode (OLED) display, which produces a high definition display while reducing motion blur from turning the head (one of the major causes for simulator sickness in HMD devices). The system operates with high refresh rates of between 60Hz and 75Hz (i.e. the system refreshes the visual display 60 to 75 times per second) and provides a field of view of approximately 100 degrees.

The HMD immerses participants in the virtual reality environment. The virtual environment allows the participant to more actively interact with the simulator environment, compared with conventional screen-based simulators, providing a strong advantage of this technology. Head movements of the participants are recorded using positional tracking that is an in-built feature of the HMD and this allows the graphical display to change relative to the participants head movements, creating a more realistic cycling experience. The positional tracking also allows monitoring and recording of the participants’ fixation durations, which can be a proxy measure for the measurement of functional processes such as hazard perception. A typical view from the HMD taken from a bicycle simulator scenario is shown in Figure 15.

![Figure 15: Typical simulator view](image)
Apart from the visual feedback provided to participants through the HMD, the simulator provides auditory and tactile feedback to participants. Auditory feedback is provided through the simulator environment, with the software programmed with sound effects and verbal instructions based on the actions of the participants and the surrounding road environment.

Tactile feedback is provided through resistance that is applied by the bicycle trainer. The resistance applied by the trainer can be adjusted based on changes in the simulator environment and the participants' pedal speed. This can be used to simulate the changing power required by participants to overcome changes in grade or wind resistance. The bicycle trainer can also be programmed to increase the rolling resistance based on the weight of the participant. As well as pedalling faster, participants can also change gears on the bicycle. Like a normal bicycle, changing the gear ratio can influence the power inputs from the rider.

### 5.3.2 Software

In order to develop the infrastructure prototypes, run the simulator’s virtual environment, communicate with the instrumented bicycle and the bicycle trainer several specialised software packages and custom programs were utilised and developed.

#### 5.3.2.1 Bicycle trainer

Communication between the simulator environment and bicycle trainer is performed using predefined device protocols developed by Wahoo Fitness (see www.wahoofitness.com). Sample software developed by Wahoo Fitness was modified to input key variables directly into the simulator environment. The bicycle trainer can communicate via either Bluetooth or ANT+ wireless protocols with the simulator PC. The simulator was designed to use Bluetooth as it was found to be more reliable with fewer dropped packages of information between the trainer and the computer system, compared to the ANT+ communication protocol. The computer system is set up to sample data from the trainer at 10Hz. As well as sending information to the simulator, the bicycle trainer can also receive data from the simulator environment to change the resistance of the trainer. This can be used to simulate changes in the grade of the road, surface material friction or alter wind resistance. The trainer software can also be programmed to alter the power requirements of the cyclist for different wheel diameters and the rolling resistance of the bicycle. The software also includes inputs for the participant dimensions including weight and frontal area. These variables influence the power requirements of the cyclist as per Equation 1 in Section 5.1.1 of this chapter. The software is also capable of incorporating a heart-rate monitor, however this feature was not utilised in the studies conducted throughout the current research. The graphical user interface (GUI) of the modified software package is shown in Figure 16.
5.3.2.2 Microprocessor

A microprocessor is programmed with a custom script to monitor data from the steering and braking sensors that are installed on the instrumented bicycle. The microprocessor operates at a baud rate of 57600 (bits/second), and due to requirements of reading and sending signals it samples data at 100Hz (i.e. 100 readings from the sensors are made per second). While the microprocessor can operate at higher speeds, considering output data files from the simulator environment occur at a rate of 10Hz and the visual display in the simulator operates at a rate of 70Hz it was not considered necessary to sample sensor data at a higher rate.

5.3.2.3 Simulator environment

The simulation environment is generated using Unity3D professional game engine. Unity is a cross-platform environment that can be used to simulate real-time three dimensional (3D) content (see http://www.unity3d.com). The package contains a graphical user interface (GUI) consisting of integrated tools for design and development of 3D real-time simulation content. The software package is capable of simulating physics, graphics, lighting, terrain and auditory features as well as receiving input from a variety of different devices. The software package is robust and can incorporate custom scripts using a variety of programming languages, this allowed for a number of different models to be developed within the simulator environment that control the movement of the bicycle, operation of traffic control devices and simulation of other road users.

A key component of the simulation environment is the bicycle model. The model specifies the bicycle dynamics and consists of four sub-models controlling steering, braking, power inputs and the wheel dynamics, essentially modelling the internal and external forces acting upon the simulated bicycle.
The software package is compatible with 3D computer-aided design software, allowing for accurate modelling of the road network and associated infrastructure. Autodesk produce a range of commercial computer aided design (CAD) software packages. The software packages are used in the civil engineering industry for road design and visualisation and were used to develop concepts and detailed bicycle infrastructure prototypes to incorporate into the simulator environment. A combination of both AutoCAD for conventional drafting tasks and 3DS Max for three dimensional visualisation were utilised when developing simulator environments. The CAD packages allow for a very high level of precision when designing simulator environments, which is imperative for the simulator applications where road infrastructure designs are evaluated.

Both software packages are capable of exporting files that are compatible with the Unity3D profession game engine. These files can be imported into the virtual environment to ensure that the prototype designs are represented accurately within the virtual environment which will increase the validity of the designs tested in the simulator.

![Figure 17: Sample AutoCAD design](image1.png)  
![Figure 18: Sample 3dsMAX streetscape](image2.png)

### 5.4 Examination of simulator fidelity

Following the development of the simulator an experiment was undertaken to investigate aspects of physical fidelity, particularly those associated with the steering and braking controls and assess the level of simulator sickness that participants experienced as a result of using the simulator under various calibration manipulations.

When riding a bicycle in the real world, the geometry of the bicycle, the steering inputs and the mass distribution of the rider play a role in how the bicycle can be manoeuvred (Wilson 2004). This allows steering to be performed by the rider through the application of internal forces using a combination of moving the handlebars and from the rider shifting their body weight and position (Wilson 2004). The bicycle model in the simulator is designed to receive steering inputs from the participant moving the bicycle handlebar when riding the instrumented bicycle. However, as the simulator is not designed to incorporate a motion platform there is a need to artificially account for the transfer of weight of the rider, particularly when performing turning movements, such as cornering or circling a roundabout. As such the bicycle model makes assumptions regarding how much lean occurs when turning and also the degree of steering required by participants in order to perform the expected turning movements. The lean is calculated as a function of the bicycle speed and the steering angle of the
handlebar. Based on these calculations the bicycle model in the simulator and the display presented to the participant using the HMD rotated to emulate the lean experienced when cornering when using a real on-road bicycle.

Braking is another fundamental control mechanisms for bicycles. The braking calibration experiment was designed to find an optimal brake setting for the bicycle model in the simulator and to assess if the braking applied by participants resulted in the expected brake force for the simulated bicycle.

The testing did not consider aspects of fidelity associated with the HMD system or the bicycle trainer. The capabilities and limitations of these devices are well documented by their respective developers and were considered to be adequate when selecting components for the architecture of the simulator (see www.wahoofitness.com & www.oculus.com).

5.4.1 Methodology

Two scenarios were developed to test the steering and braking controls of the bicycle simulator. The intention was to assess how accurately users perceived that the simulator replicated a real-world cycling experience and to objectively measure if there were differences in participant’s ability to control the simulated bicycle under different settings. The process also provided an important opportunity to ensure hardware and software incorporated into the simulator architecture were functioning as intended and allowed for any issues with the simulator’s hardware and software to be detected prior to the validation study (Chapter 6).

5.4.1.1 Steering

The steering calibration component of the study was designed to assess if the steering model behaviour appeared realistic to participants. In order to assess the accuracy of the steering model, five steering sensitivity settings were tested. The first setting consisted of the steering in the model being set at a 1:1 ratio with the instrumented bicycle, the second and third settings caused the bicycle to oversteer by 10 percent and 20 percent respectively and the final two settings caused the bicycle to understeer by 10 percent and 20 percent respectively.

Participants were instructed to ride along a narrow route in between traffic cones. The width between the traffic cones was approximately 1.5 metres (delineated with cones placed at approximately 1.0 metre spacing). The route consisted of a section of chicanes followed by two left hand turns and two right hand turns. An overview of the course is shown in Figure 19 and Figure 20.

The left and right hand turns were designed to replicate the swept path of a cyclist when performing a turn at a typical cross intersection and at a single lane roundabout, while the chicanes were designed to test finer control of the simulated bicycle. The simulator was programmed to record each time a participant hit a traffic cone, the location of each traffic cone that was hit, and the total number of traffic cones hit along the route. Location of the bicycle along the route and the time it took participants to complete the course were also recorded.
Figure 19: Steering study course

Figure 20: Steering study example scene
Each participant’s performance during the steering scenarios was measured using four variables: pass/fail criteria (pass = no cones hit; fail = one or more cones hit), the number of traffic cones that participants hit during each run, average riding speed, and time to complete the course.

A randomised presentation of the steering scenarios was adopted to control for the effects of order. After each ride, participants were asked to rate their perception of how accurately the steering replicated a real bicycle. The participants rated the steering using a five-point Likert scale ranging from very poor (score = 1) to very good (score = 5). The main analysis of the subjective steering data consisted of ANOVA testing. Post-hoc testing was also undertaken to identify differences between scenarios using Tukey’s Honest Significant Difference (HSD) test for pairwise comparisons.

5.4.1.2 Braking

The braking scenarios required participants to ride along a straight section of road. At a random point on the ride a set of traffic cones would appear in a transverse line obstructing the path of the participant (Figure 21). Participants were instructed to brake and stop to avoid hitting the cones. The transverse cones would randomly appear so that participants would need to decelerate at a rate of 2.0m/s², which is considered a safe deceleration speed for cyclists (AASHTO 2012). The cone spacing allowed for a 0.5 second reaction time between the point at which the cones appeared and when braking needed to be applied. The location of the cones was determined as a function of participants’ travel speed in the scenario, participants were instructed to travel at a comfortable riding speed.

The braking component of the study tested five settings of brake sensitivity. The first setting was a baseline setting that used the standard braking sensitivity developed for the bicycle model. The second and third setting
increased the brake force applied by the brake force equations in the bicycle model by 10 percent and 20 percent respectively, making the brakes more responsive which required a lower braking force to activate the brakes. The fourth and fifth settings decreased the sensitivity of the brakes by 10 percent and 20 percent respectively making the brakes less responsive. This meant participants were required to apply a greater braking force to activate the brakes. Participants completed each of the five scenarios in a randomised order to control for any order effects.

For each brake setting, three objective measures were recorded: pass/fail (pass = avoiding hitting cones; fail = hitting cones); location of the bicycle once it had come to a complete stop (the distance of the bike relative to the traffic cones); and reaction time (the time between traffic cones appearing and application of brakes). ANOVA was applied to examine the effect of braking settings on stopping location relative to the traffic cones.

Participants provided subjective feedback by rating each braking scenario. After each ride participants were asked to rate their perception of how accurately the braking sensitivity replicated braking on a real bicycle. Responses were provided using a five point Likert scale ranging from very poor (score = 1) to very good (score = 5). Finally analysis was undertaken to identify if there was a correlation between participants passing the scenario and their subjective rating. Participants' subjective scores were analysed using an ANOVA and post-hoc testing.

5.4.1.3 Simulator discomfort

Simulator discomfort was assessed by administering the SSQ (Kennedy et al. 1993) (Appendix C). The SSQ was administered before the practice scenarios to record baseline result for comparison. The SSQ was then administered at the completion of the study to assess the overall level of simulator discomfort experienced by participants and to determine if participants required further monitoring before leaving the research centre.

SSQ results were weighted using the criteria outlined by Kennedy et al. (1993). Statistical analysis was undertaken using a paired t-test to identify if there were any statistically significant differences in simulator discomfort subscales for participants following the simulator study, compared to their baseline measurements.

5.4.1.4 Participants

A convenience sample of 15 volunteers participated in the calibration experiment (11 males and 4 females) and ranged in age from 18 to 45 (M = 28.5, SD = 7). Eligibility criteria included: over 18 years of age, and be comfortable riding a bicycle. Exclusion criteria included: presence of medical condition(s) that might be aggravated due to exercise or using the bicycle simulator including epilepsy, high blood pressure; prior heart attack; required glasses for normal vision (participants who required contact lenses to correct their visions were allowed to participate); a history of suffering from either motion sickness or simulator sickness.
5.4.2 Results

5.4.2.1 Steering controls

The pass or fail analysis considered if participants were able to successfully negotiate the course without hitting any of the traffic cones. Participants completed the scenario with five steering sensitivity settings; 1:1 ratio of steering, two oversteer settings and two understeer settings. Across the five steering sensitivity settings, the highest pass rate was recorded for the scenario where the steering was detuned and required participants to oversteer up 10 percent. The lowest pass rate was recorded for the scenario which required participants to understeer up 10 percent.

Analysis of the number of traffic cones hit by participants during each simulator run indicated that there was an overall significant effect of steering settings (\(F_{4, 70} = 2.73, p = 0.04\)). Post-hoc testing revealed that this difference was only significant between both understeering settings and the 10 percent oversteering settings. With participants performing significantly worse in the understeering setting compared to when they had to oversteer by 10 percent (\(p=0.036\)), with no other significant differences observed between other steering settings.

Ride variability measures assessed average riding speed and travel time across the five scenarios. Analysis found that there were no significant effects of steering settings on average riding speed (\(F_{4, 70} = 0.02, p = 0.99\)) or travel time (\(F_{4, 69} = 0.01, p = 0.99\)), suggesting that participants were able to ride the bicycle in a relatively similar manner despite differences in steering sensitivity.

Overall, user perspectives of the five steering settings were similar with an average user perspective score of 3.5 for each setting, indicating no clear preference of steering settings with all five settings scoring reasonably well (\(F_{4, 70} = 0.52, p = 0.72\)). The average user perspective score for each steering setting was between ‘average’ and ‘good’ and the variance in results was similar for all scenarios. Overall, these results gave confidence that the steering model was reasonably accurate, with no distinguishable differences between performance and a generally high level of acceptance amongst participants.

5.4.2.2 Braking controls

The pass or fail analysis assessed if participants were able to stop before hitting the transverse row of traffic cones in each of the braking scenarios. The pass rate was highest for the second setting, with all 15 participants able to stop when the brake setting was increased by 10 percent. Similar results were recorded for the baseline setting and the setting with a 20 percent increase in brake force, with one participant failing in each of those scenarios. On average participants performed worst on scenarios involving reduced braking sensitivity.

Further analysis considered the average distance from the traffic cones when participants came to a complete stop (Figure 22). The testing did not identify any effect of braking setting on stopping location of participants relative to the traffic cones (\(F_{4, 70}= 2.41, p = 0.06\)). However, a linear relationship was apparent between the average stopping location and brake sensitivity. It is likely that a larger sample size may have produced significant results for this component of the study and the small sample size is noted as a limitation of the study.
Participants provided subjective feedback for each braking setting. The results indicated that on average the preferred braking setting consisted of a 10 percent increase in brake sensitivity compared to the baseline scenario. This scenario scored an average user perspective rating of 3.9 and also had the smallest variance amongst user perspective scores. Scenarios with reduced brake sensitivity received the lowest average scores, suggesting that those scenarios did not accurately represent the braking sensitivity that participants would expect when riding a bicycle in real world conditions.

ANOVA of the five braking scenarios identified a significant effect of brake setting manipulations on ratings \((F_{4, 70} = 7.18, p = 0.01)\). Post-hoc testing identified a significant difference when comparing the increased sensitivity settings with the reduced sensitivity settings, however there were no significant difference between any of the settings and the baseline condition. These results indicate that users perceived that the braking sensitivity was reasonable in the base case scenario and that increasing the sensitivity was beneficial for braking setting fidelity.

The findings of the braking scenario suggest that the preferred braking setting was a 10 percent increase to the baseline setting. Furthermore, all 15 participants were successful in completing the braking task for this scenario. Based on these findings, the brake sensitivity settings were increased by 10 percent in the bicycle model to reflect the performance of participants and the preferred subjective feedback.

5.4.2.3 Simulator discomfort

Average SSQ scores for both pre- and post-experiment surveys are presented in Figure 23. Few symptoms were recorded at baseline (pre-experimental survey), with the highest average baseline scores recorded for fatigue and eyestrain (0.4 and 0.2, respectively). Following the simulator experiment, a wider range of symptoms were observed, and the most notable increases in SSQ symptoms were for general discomfort, headaches, eyestrain,
sweating, increased salivation and stomach awareness. However, generally participants reported low level symptoms.

Figure 23: Pre and post SSQ survey average results

Comparison of weighted aggregate SSQ scores across the three subscales of Nausea, Oculomotor and Disorientation, highlighted the increases in all three subscales following completion of the simulator study (Figure 24). Compared to the initial baseline results the bicycle simulator resulted in a statistically significant increase in Nausea ($t_{14} = -3.0, p = 0.01$), Oculomotor ($t_{14} = -2.6, p = 0.01$) and Total Simulator sickness ($t_{14} = -2.7, p = 0.01$). The comparison of before and after results did indicate an increase in Disorientation symptoms, however the results were not statistically significant ($t_{14} = -1.6, p = 0.07$).
This chapter presented the development of the bicycle simulator including the identification of the simulator requirements, specification of the simulator architecture and componentry and the calibration process undertaken to enhance the physical fidelity of the simulator key control mechanisms. Simulators are an important tool for road safety research (Rudin-Brown et al. 2009), that are becoming increasingly cost effective to develop and operate (Allen 2000, Rudin-Brown et al. 2009). This trend is being driven by rapid advances in the technological components used in simulators including, sensors, computers and visual display systems. Recent advances in virtual reality technology have enhanced the ability to immerse participants within the simulated environment and the incorporation of virtual reality technology into simulator architectures creates a new opportunity to enhance the fidelity and face validity of simulators (Bright et al. 2012, Shetty et al. 2012).

The development of the bicycle simulator that is detailed in this chapter is an example of how the latest technology can be utilised to create a high fidelity, yet relatively low cost, simulator. The bicycle simulator creates an opportunity to conduct unique research investigating vulnerable road users and their interactions within the road environment. The use of the Oculus Rift Development Kit 2 virtual reality headset and an instrumented bicycle have created a high fidelity simulator experience that replicates the control mechanisms of a bicycle, while also creating a highly realistic and immersive simulator environment. The simulator was developed to assess new infrastructure designs that are aimed at making cycling safer. Pilot infrastructure evaluation is ideally suited to simulator studies as it can be significantly less expensive than on-road or test track studies (Blana 1996). The simulator allows for multiple iterations of designs to be evaluated and can also help to identify
potential issues with the way that people interact with the new facility that may not have been obvious when conceptualising the design.

The simulator offers a range of benefits for pilot evaluation of infrastructure designs, however the decision to create a relatively low cost simulator that does not incorporate a motion platform has resulted in a number of limitations. In particular the simulator does not recreate the roll, pitch or yaw that is typically experienced when riding a conventional bicycle, however accurately recreating these rotation angles and resultant forces can be difficult to simulate a would require extensive validation. Furthermore the steering for the simulator can only be performed using the handlebars and participants cannot use their own body weight to assist in manoeuvring the bicycle (as they might in real-world cycling). There are also some limitations associated with the use of the HMD, in that it limits the field of view of participants. However it is believed placing participants in an immersive environment offer many benefits over screen-based simulators and, as such, this limitation was deemed acceptable when selecting the componentry for the simulator.

Following the development of the simulator an evaluation was undertaken to investigate aspects of the physical fidelity of the simulator associated with the steering and braking controls and to assess the level of simulator sickness that participants experienced as a result of using the simulator (when conducting a range of braking and steering tasks). The study did not consider aspects of fidelity associated with the HMD system or the bicycle trainer. The capabilities and limitations of these devices have been well documented by their respective companies and were considered when selecting appropriate components for the architecture of the simulator.

The braking evaluation focused on the objective and subjective performance of participants when responding to the need to brake suddenly while using the simulator. Overall the braking study found that participants preferred the baseline setting and settings where the sensitivity of the braking was increased. User perception of the braking was significantly lower when brake sensitivity was reduced. The results of the user perception analysis showed a strong correlation between brake settings and the pass rate of scenarios. Participants provided higher scores to brake setting scenarios when they were able to successfully complete the task. In contrast, participants generally gave low scores to brake setting scenarios when they failed to complete the task.

The performance measure results did not identify any effect of braking setting on stopping location of participants relative to the traffic cones, however, a linear relationship was apparent between the average stopping location and brake sensitivity. The sample size was noted as a limitation of the study and it is likely that a larger sample size may have produced significant results for this component of the study.

Most importantly, the findings of the braking scenario experiment suggest that the optimal braking setting was when the brake sensitivity was increased by 10 percent compared to the baseline setting scenario. This scenario scored an average user perspective rating of 3.9 and had the smallest variance amongst participants. Furthermore, all 15 participants were successful in completing the braking task for this scenario. This brake
sensitivity setting was subsequently incorporated in the bicycle model and will be used for future simulator studies.

Overall the evaluation of the bicycle simulator steering found very little difference between the user perspectives of the five steering settings. The user perspective scores for each steering setting was 3.5 (between ‘average’ and ‘good’) and the variance in results was similar for all scenarios. Not surprisingly, there were no significant differences observed between user perspectives for the five scenarios.

When comparing how successful participants were at negotiating the different scenarios, there were some slight variations observed. In particular participants performed significantly worse when they were required to understeer the bicycle by 10 percent, compared to the most successful scenario when participants were required to oversteer by 10 percent. However the differences between scenarios were generally fairly minor. Furthermore, comparison of ride variability measures found that average speed and travel time did not vary significantly between the scenarios, suggesting that participants were able to ride the bicycle in a relatively similar manner despite differences in steering sensitivity. Include a statement about which steering setting was chosen for subsequent studies.

Assessment of simulator sickness was a key component of the calibration study. The bicycle simulator utilises a relatively new HMD device and the potential for simulator sickness symptoms were somewhat unknown prior to commencing this study. The assessment of simulator sickness identified a statistically significant increase in Nausea, Oculomotor and Total simulator sickness symptoms for participants following the simulator study, compared to baseline measurements. However the overall simulator sickness symptoms were relatively minor with most participants stating that they experienced either no symptoms or only slight symptoms. Furthermore it is hypothesised that the reported increases in sweating following the simulator study may have partially been attributed to the physical activity associated with riding a bike. If this were the case the scores for nausea and total simulator sickness would be heightened.

The simulator sickness results suggest that the use of the HMD is an appropriate technology for the bicycle simulator. Simulator sickness will be monitored in future studies to assess if there are increases in simulator sickness symptoms with differing simulator scenarios. A limitation of this study omitting administration of the SSQ following the completion of the braking study and before the steering study. In future studies it is proposed that the SSQ will be administered to participants following each scenario to monitor the onset of symptoms throughout the study and gain an understanding of which tasks have the greatest impact on sickness symptoms when using the bicycle simulator.

In addition to evaluating the steering and braking controls and the level of simulator sickness experienced by participants when using the simulator, the study also offered valuable insight into the performance of key software and hardware components of the simulator.
Several minor issues were identified throughout the study. For example, during the course of the study there were two occasions when the head movement tracking on the HMD did not accurately track the position of the participants head. This resulted in the participant’s view becoming distorted in the simulator environment relative the simulated bicycle. Fortunately, both instances occurred during the practice scenarios before the main study had commenced. It was found that the motion tracking camera was placed offset from the participant and therefore unable to track the movement of the HMD when the participant performed rapid head movements. A solution to this problem was identified and the motion tracking camera was repositions directly in front of the participant.

Another issue identified during the study was occasional overloading of the bicycle trainer software, due to a high volume of braking signals. This resulted in the very high resistance being added to the bicycle trainer fly-wheel, which caused high brake forces being simulated. Due to the overload of braking signals the bicycle trainer software would require a few seconds to reset. This only occurred twice during the study, however it required the scenario to be reset as the braking was creating an unrealistic sensation for participations. The issue occurred due to defects in the hall-effect sensor that was installed in the rear brake. The sensor occasionally failed to register brake release and therefore continued to send a brake signal to the bicycle trainer. In order to fix this issue the defective sensor was replaced. In addition, the script that controls the communication with the bicycle trainer was amended to restrict the number of braking messages sent to the trainer.

The final issues identified during the experiment were related to the bicycle model in the simulator. First, several participants noted that the position of the handlebar depicted in the simulator did not perfectly align with the instrumented bicycle. Participants felt that they had to reach further for the handlebar than they actually did when wearing the HMD. While this was a minor issue, it was resolved by shifting the head position of the cyclist in the bicycle model. Second, one participant noted some dampening of the front suspension on the simulated bicycle. Dampening had been added to the bicycle model to simulate suspension on the front fork of the bicycle and was programmed prior to selecting the instrumented bicycle for the simulator architecture. However, this programming proved to be unrealistic as the bicycle model in the simulator and the instrumented bicycle had a rigid front fork with no suspension. In order to fix the issue minor changes were made to the bicycle model to disengage the front suspension and make the front fork rigid. This change was particularly important for the validation study (detailed in the following chapter) as the study compared riding on-road with riding in the simulator and it was important to minimise the differences between the two tasks.

Overall the study provided valuable insight regarding the physical fidelity of the simulator that will help to guide future simulator settings and scenario development. This process has resulted in production of a high fidelity testing environment for cycling research. This is large attributed to the immersive scenarios that can be displayed due to the virtual reality technology that has been integrated into the simulator architecture. While not imperative to good research high fidelity simulators have been linked to reduced levels of simulator sickness amongst participants (McLane & Wierwille 1975, Harms 1996). The findings of the physical fidelity study will be used to
optimise the bicycle model equations to provide participants with optimised steering and braking control settings. This will further enhance the fidelity experienced by participants in future studies.

The following chapter presents the establishment of behavioural validity of the simulator. This research phase was considered crucial to establish before evaluating cycling infrastructure designs which are presented in the later chapters of this thesis.
Chapter 6: Bicycle simulator validation

Simulators offer a range of benefits for road safety research as highlighted in Chapter 4. However, in order for the results of simulator-based studies to be meaningful it is essential that the correspondence between the real world and the simulated environment is the same, or at least sufficient, to produce valid results (Kaptein et al. 1996, Tömrös 1998). While the simulator does not have to be identical to the real world experience, it must be able to sufficiently replicate the specific task or behaviour that is under investigation (Rudin-Brown et al. 2009). Further, it is particularly important that the road-user behaviours elicited in response to events in the simulator are comparable to responses and behaviours in real world traffic situations (Tömrös 1998). In order to meet this requirement, simulators are often validated against a set of performance measures to assess the correlation between results. Traditionally simulator validations studies have relied on measures such as speed, speed adaptation, lane keeping and variation in lateral position (Tömrös 1998, Blana & Golias 2002, Godley et al. 2002, Underwood et al. 2011).

This chapter presents the behavioural validation study that was conducted using the bicycle simulator. In Chapter 4 the need and general methodology for simulator validation studies was discussed. For the purpose of this study the focus was on establishing the behavioural validity of the bicycle simulator. Behavioural validity is a measure of the extent to which participants exhibit the same behaviours using the simulator as they do when operating a vehicle in the real world (Blaauw 1982, Godley et al. 2002). For simulator validation studies the key outcome under investigation is the performance of the participants, not the fidelity of the simulator itself (as in the previous calibration study) (Rudin-Brown et al. 2009). The aim of this validation study was to collect and compare various performance measures collected while using the simulator with naturalistic cycling data collected when riding an instrumented bicycle within an urban road environment, with the intention of validating behaviours that are likely to be investigated in future studies using the simulator (Rudin-Brown et al. 2009).

The bicycle simulator was designed to collect data regarding the behaviours involved in control and guidance of the bicycle in the simulated environment, such as cyclist looking behaviour and steering, braking and pedalling inputs from participants. These tasks are described by the AASHTO as: following the road and maintaining a safe path in response to traffic conditions; and steering and speed control of the vehicle (AASHTO 2001). The aim of this study was to assess if participants elicited the same behaviours when using the simulator compared to when riding on road.

Behavioural validity was assessed using the two levels of classification as specified by Blaauw (1982): absolute validity which refers to the situation where simulated and on-road data provide the same numerical results; and, relative validity which refers to the situation where the results differ between the two tasks but exhibit similar patterns in terms of their magnitude or direction (Godley et al. 2002).
This study addressed the two secondary research questions:

- What is required to develop and validate a high fidelity bicycle simulator to evaluate road design for improved cyclist safety?; and
- What cyclist performance measures can be accurately assessed in a bicycle simulator?

The findings from this chapter are summarised in the journal article (see Appendix A):

- O’Hern, S., Oxley, J. & Stevenson, M. Validation of a bicycle simulator for road safety research. Accident Analysis & Prevention 100 (2017): 53-58

6.1 Methodology

6.1.1 Study design

The validation study employed a within-subjects study design comparing selected measures of naturalistic on-road data with data collected when riding using the simulator. A comparison between the simulator and on-road environments is illustrated in (Figure 25). A within-subjects study design was chosen to control for variance between the participants undertaking the study. The within-subject design controls for confounding variables as participants complete each stage of the study and participant’s results for each stage are compared against themselves. Furthermore within-subject designs can be advantageous as a smaller sample size is required compared to a between-subject design, in order to obtain the same statistical power. However there are limitations associated with this method. One of the most common issues with with-in subject designs is the issue of carryover effects, where the performance of participants in one condition may impact their performance in the remaining stages of the study (Cobb 1998). Two procedures were adopted to control for these potential effects. First, participants undertook the simulator and on-road stages of the study on different days. This was also intended to reduce the chance of the participants experiencing any fatigue from riding the bicycle for prolonged periods of time. Second, the order that participants performed the on-road and simulator component was counterbalanced. This was undertaken for most participants, however, in some instances, due to the influence of inclement weather on the study the order that participants completed each stage of the study was not randomised, with participants completing the simulator component first when there was inclement weather on their first day of testing and they were originally allocated to perform the on-road task first. This affected the counterbalancing order of two participants.
6.1.2 Participants

Power analysis was undertaken to identify the required number of participants for the study. Based on the proposed statistical techniques for analysis and within-group study design, the sample size required for the study was determined using Eq 2.

\[
n = \frac{2(z_\alpha + z_{1-\beta})^2\sigma^2}{(\mu_1 - \mu_2)^2} = \frac{2(z_\alpha + z_{1-\beta})^2}{[(\mu_1 - \mu_2)/\sigma]^2}
\]

Eq 2: Sample size calculation

Where:

- \( n \) = the number of participants required in the study
- \( \alpha \) = represents the significance level of the two tailed t-test (set at 0.05 – representing the probability that the test will lead to a Type 1 error)
- \( \beta \) = represents the probability of failing to reject a false null hypothesis (representing the probability that the test will lead to a Type 2 error)
- \( 1-\beta \) = represents the statistical power of the experiment (set at 0.8)
- \( z_\alpha \) = is the value of the standardized score for cutting off \( \alpha/2 \) proportion of each tail of a standard normal distribution (1.96 when \( \alpha=0.05 \))
- \( z_\beta \) = is the value of the standardized score for cutting off the upper \( \beta \) proportion
- \( (\mu_1 - \mu_2)/\sigma \) = is the effect size of the experiment (Cohen’s D value, set at 0.8 for a large effect size)

An attrition rate of 10 percent was applied to the required sample to account for participants who may drop out of the study due to simulator sickness, failing to complete stages of the study or other unforeseen reasons. Based on these assumptions a sample of 27 participants was sufficient for the validation study. As an added safety factor a total of 30 participants were recruited for the study.

Participants were required to meet a number of criteria to be eligible to complete the study. Participants were required to be over 18 years of age and be comfortable riding a bicycle on local roads. Participants were excluded if they had medical conditions that might be aggravated due to exercise or using the bicycle simulator.
including epilepsy, high blood pressure, having previously experienced a heart attack, or if they had a history of suffering from either motion sickness or simulator sickness. Participants who required glasses for normal vision were also excluded from the study (participants who required contact lenses to correct their visions were accepted into the study). This exclusion criteria was necessary as it can be difficult for some glasses to be worn at the same time as the head mounted display and there were concerns that some glasses may damage the HMD lens.

Recruitment was undertaken by placing flyers advertising the study the around the Monash University Clayton campus, including the bicycle arrival station. An advertisement was also placed in the Monash Memo, which was a weekly e-newsletter sent to Monash University staff at the time of the study. Prior to undertaking the study participants were provided with an explanatory statement that detailed the requirements of the study. Participants also signed a consent form to state that they were aware of the risks associated with riding the simulator and riding a bicycle on-road and that they were willing to participate in the study and confident riding a bicycle on-road.

The research protocol for the study was reviewed and approved by the Monash University Human Research Ethics Committee (MUHREC). Participants received a $50AUD gift voucher for participating in the study and to compensate them for their time and travel expenses.

6.1.3 Data collection

6.1.3.1 Survey Component
Participants completed a short demographic questionnaire on the first day of testing (Appendix D). The questionnaire addressed demographic characteristics and cycling experience information. The questionnaire asked participants their age, gender, self-reported confidence level regarding cycling on-road, how frequently they rode a bicycle in the past month, how many kilometres they cycle in a typical week, their most common cycling times, the purpose of the majority of their cycling trips and if they had been involved in a collision while riding a bicycle in the past three years.

6.1.3.2 On-Road Component

6.1.3.2.1 Instrumented bicycle
In order to collect the naturalistic on-road data, an instrumented Giant City-Cross bicycle capable of capturing the same performance measures as those recorded by the bicycle simulator was developed.

The bicycle is essentially the same as the bicycle that is incorporated into the simulator architecture, with the same frame geometry and componentry. The only difference between the bicycle used for the on-road study and the simulator bicycle is that the on-road bicycle was equipped with mudguards, a rear rack, kickstand and chain guard. The added features for the on-road bicycle made it easier to install sensors on the bicycle frame and the kickstand made it easy to turn on and off the instrumentation. The mud and chain guards also help to protect participants clothing. The same style bicycle was selected to help control for any differences between the on-
road and simulator components of the study, which may have resulted in variations in participant cycling behaviour.

The bicycle was instrumented with sensors to collect a range of data including: the Geographic Positioning System (GPS) coordinates of the cyclist; the speed profile of the cyclist; and, the lateral position from passing objects on the left hand side of the bicycle.

GPS data was monitored in real-time to verify that participants had ridden the correct route. The GPS data was also monitored during the ride as a safety precaution. If participants stopped moving for a period of time, or at an unexpected location, the GPS system could alert researchers. If the cyclist did not begin to move soon after the researchers were alerted, staff on-site could be sent out to find the participant and render assistance if required. However at no stage in the study did any participants require assistance.

In order to measure the distance perpendicular to the cyclist a system using sonar sensors was developed and installed on the bicycle. The sonar system operates by measuring the time from transmitting a sound wave to the reception of the echo of that wave. This time is then converted to a distance based on the speed that the sound waves travel through the air. The speed of sound is calculated using the Newton-Laplace equation where the speed of sound \( c \) is the square root of the elastic bulk modulus \( K_s \) divided by the density of the medium \( \rho \), which in this case is air (Eq 3).

\[
c = \sqrt{\frac{K_s}{\rho}}
\]

\text{Eq 3: Newton-Laplace equation}

Substitution into the Newton-Laplace equation results in the speed of sound in air \( c_{air} \) being represented by Eq 4, where \( \vartheta \) is the ambient temperature in degrees Celsius. As ambient air temperature was required to accurately calculate distance, the sonar system was also developed to include a temperature sensor to measure temperature throughout the ride.

\[
c_{air} = (331.3 + 0.606^\circ\mathrm{C}^{-1} \cdot \vartheta) \text{m/s}
\]

\text{Eq 4: Speed of sound in air}

The distance between the sonar device and any adjacent objects can then be calculated by substituting from Eq 4 into Eq 5 where \( t_{echo} \) and \( t_{signal} \) correspond with the time that the sonar signal was sent and when the echo was detected. Readings from the sonar device were recorded at a rate of 10 Hertz.

\[
Distance = \frac{1}{2}(t_{echo} - t_{signal}) \cdot c_{air}
\]

\text{Eq 5: Sonar distance measurement}

Two Contour+2 video cameras were also installed on the bicycle for use during the on-road component of the study. The first video camera was fitted to the handlebar of the bicycle which was used to record footage of the ride and to measure the bicycle position within the carriageway using custom computer vision software which was developed specifically for the validation study.
The computer vision software captured the width of a road, the width of individual lanes and the position of the cyclist within the carriageway. The theory for calculating the lane width was adapted from work by Grammatikopoulos et al. (2002). Grammatikopoulos et al. (2002) developed a method for estimating the width of a road lane using frontal images taken from a video camera mounted to the roof of a car. The method only requires the height of the camera as an initial input in order to calculate lane width. Rotation about the pitch axis is also accounted for by the method, which can be a major source of error in video lane-tracking software. The final equation derived by Grammatikopoulos et al. (2002) is presented in Eq 6.

\[
\Delta X = \frac{Y_0}{(y - yF)} \Delta x
\]

Eq 6: Lane width equation

Lane width estimates (\(\Delta X\)) are calculated using the height of the video camera as a reference (\(Y_0\)). Camera height is related to the vanishing point within the video footage (\(F\)). The vanishing point is calculated at the convergence point of the outside of the lane and the horizon. Using the ratio between the height of the camera and the pixels in the image, the width of the lane is estimated. The variables in Eq 6: are illustrated in Figure 26.

The camera position is taken as the centre of the image and the position of the front bicycle tyre is determined based on the offset to the mounting location of the video camera. Cyclist position within the bicycle lane is estimated using the cosine rule and the triangle made from the vanishing point lines and the lane width estimation. The second camera was placed on the cyclist’s helmet and was used to collect head movement information. The video footage was timestamped and was used to monitor directions and durations of head movements. Several practice rides were undertaken along the on-road study route to test device operation and verify the accuracy of the data that was being collected.
6.1.3.2 On-road study route

The on-road component of the study was conducted on a fixed route of approximately four kilometres within and around the vicinity of Monash University campus, as shown in Figure 27. All tests were conducted in clear weather conditions and on dry roads. All roads were either local or private roads with speed limits ranging from 20km/h to 50km/h. All roads had relatively low traffic volumes. Each participant completed the on-road cyclist route twice.

Figure 27: On-road study route

6.1.3.3 Bicycle Simulator Component

6.1.3.3.1 Scenario development

For the bicycle simulator component of the study, computer aided drawings (CAD) were sourced for the portion of the roads that formed the study route. The CAD drawings provided accurate dimensions for all road geometry as well as an indication of line marking and the location of on-campus buildings.

Aerial photography was incorporated into the CAD drawing to verify signage, line marking and road geometry. Where further verification was required, site visits were undertaken at locations where there were discrepancies between the aerial photography and the CAD file. The type and position of all road signs were recorded during site visits so that they could be accurately recreated in the simulator. Finally several rides throughout the route were undertaken so that video footage from the rides could be compared to the simulator scenario and pilot data could be collected to test the instrumented bicycle.

The topography of the site was verified against government topographical contour data, however as the site was essentially flat, no changes in gradient were included in the simulated road environment. Furthermore buildings,
landscaping and trees surrounding the site were included in the scenarios, however in a simplified form to reduce the time required to program scenarios and computational requirements to run scenarios. While inclusion of these features would have increased the fidelity of the simulator experiment from the participant’s point of view, it was deemed unnecessary for answering the research questions regarding the behavioural validity of the cycling performance measures.

The simulator scenarios were designed to recreate aspects of the on-road ride and test the ability of the bicycle simulator to elicit cyclist behaviours similar to those during the on-road ride for the selected performance measures.

The simulator scenarios were broken into sections to reduce the complexity of simulator programming required, in particular the number of motor vehicles in the simulator scenario and the scale of the road environment that needed to be rendered in any scenario. Scenarios were also relatively short to minimise the risk of simulator sickness. The order that participants were shown each scenario was randomised to control for learning effects.

Five scenarios were developed providing a range of road environments. A brief description of each scenario is provided below:

- **Scenario 1**: recreated riding in the on-street bicycle lane on Northern Ring Road. The bicycle lane is approximately 1.8m wide, with one adjacent lane of traffic in each direction and a central median separating opposing traffic.
- **Scenario 2**: recreated riding along Beddoe Avenue and was designed to assess the passing distance that cyclists left between themselves and cars parked parallel to the kerb. Several cars are typically parked on-street and the approximate location of the parked cars were recreated in the simulator.
- **Scenario 3**: recreated Marshall Avenue, a straight section of road on a quiet local street and designed to assess the speed profile of participants.
- **Scenario 4**: recreated the minor approach to a T-intersection at the intersection of Beddoe Avenue and Bayview Avenue and assessed braking and deceleration behaviour.
- **Scenario 5**: recreated the approach to the roundabout at the intersection of Marshall Avenue and Bayside Avenue and assessed looking behaviour on the approach to the intersection.

6.1.3.3.2 Simulator discomfort questionnaire

Simulator discomfort was assessed by administering the SSQ (Kennedy et al. 1993) (Appendix C). Each participant completed the SSQ prior to commencing the validation study to collect baseline readings. Following completion of the final simulator scenario participants completed the SSQ again. Participants who experienced high levels of simulator sickness were excluded from the analysis. Participants were also excluded from the study if at any stage they felt uncomfortable or began to show obvious signs of simulator sickness, such as increased swallowing, burping or profuse sweating.
6.1.3.3 Simulator study protocol

The simulator component took approximately one hour to complete. The simulator study required participants to complete three practice rides and ride the five scenarios that recreated sections of the on-road route.

The HMD represents relatively new technology and it was important to familiarise participants with the device prior to commencing the simulator study. As such, prior to riding the simulator, participants completed a demonstration scenario developed by Oculus (the company that developed the HMD) which was designed to introduce participants to the virtual reality software and also help calibrate the headset to the participants’ preferred settings.

The practice rides were designed to familiarise participants with riding the simulator and use of the HMD, to ensure participants were comfortable controlling the bicycle and to screen for symptoms of simulator sickness prior to commencing the study rides. In the first practice scenario the steering controls were disabled and the bicycle moved in a straight path in response to the participants pedalling so that participants could familiarise themselves with the HMD and moving in the simulated road environment. The second scenario was similar to the first scenario, however in this scenario the simulator steering controls were enabled and participants were required to control the path of the bicycle. The final practice scenario required participants to ride a fixed route delineated with traffic cones. Along the route participants were required to complete basic steering manoeuvres such as performing left and right hand turns at cross intersections and roundabouts. Practice scenarios were repeated until participants felt comfortable using the simulator. One participant withdrew due to lack of feeling comfortable.

A summary of the experimental protocol for the simulator study was as follows:

- Completion of the baseline simulator sickness questionnaire;
- Demonstration of the HMD device;
- Practice rides (10 minutes);
- Simulator scenario rides (30 minutes); and
- Completion of final simulator sickness questionnaire.

6.1.4 Data analysis

Descriptive statistics were employed to examine demographic characteristics and cyclist experiences from the survey data. Performance data from the on-road and simulator components of the study were compared to assess the relative and absolute validity of the simulator for specific performance measures. These included: average lane position and lane position variation when riding in a bicycle lane; average passing distance when passing parallel parked cars; speed profile; speed reduction on approach to a T-intersection; and, head movements on approach to an intersection. These performance measures were considered important for the future studies that are detailed in Chapter 9 and Chapter 10 that investigate cycling design concepts and evaluate bicycle lane designs.
Absolute validity for on-road and simulator data was assessed using paired sample t-tests with the null hypothesis that the mean difference between the two samples was zero. Analysis was undertaken at a level of significance (α) of 0.05. Effect size was assessed using Cohen’s d statistic.

Absolute validity is established through obtaining non-significant results, that is to say that there is insufficient evidence to reject the null hypothesis that the mean values are equivalent, however non-significant results can also result from inadequate statistical power (Godley et al. 2002). A larger effect size corresponding with a non-significant result therefore may be a result of insufficient statistical power, while small effect sizes are more likely to reflect absolute behavioural validity (Godley et al. 2002). Where absolute validity is not established, simple linear regression was performed to assess correlation between the two datasets to identify the relative validity. Prior to analysis, tests for normality were conducted for each variable considered in the validation study, using skewness and kurtosis. Results were found to be normally distributed, therefore no transformations were performed. All statistical analysis was conducted using STATA version 13.1.

6.2 Results

Of the thirty participants, four were excluded from analysis. Two participants were excluded because they experienced high levels of simulator sickness during the experiment and were unable to complete the full set of simulator scenarios. One participant did not feel like they could comfortably control the bicycle simulator during the practice scenarios. The forth participant became lost during the on-road component of the study and the collected data was therefore not usable. Data from the remaining 26 participants were analysed, this was above the required sample size calculated (see Section 6.1.2).

6.2.1 Participant characteristics

The 26 participants included in the analysis ranged in age from 18 to 35 years (M = 25.0, SD = 4.8) and included six female participants and 20 male participants. Participants were asked to rate their confidence level regarding cycling on-road on a 10-point Likert scale. On average, participants were highly confident riding on-road (M = 8.5, SD = 1.3).

When asked how frequently they rode a bicycle, 79 percent stated they rode more than twice a week, four participants stated they rode a bicycle at least once every two weeks and two participants stated that they had not ridden a bicycle in the past month (apart from participating in this study), however these participants still rated themselves as highly confident cyclists. Participants typically rode bicycles for less than 30 kilometres per week (77%), however two participants stated that they rode for over 100 kilometres per week. Commuting to work or school (50%) and recreational riding (46%) were the most common reason for riding a bicycle. One participant had been involved in a bicycle crash in the past three years, however the crash was minor and did not result in any injuries.
6.2.2  Comparison of performance measures

6.2.2.1  Scenario 1 – Lane Position

The first scenario was designed to assess the lane position adopted by cyclists when riding in the simulator compared to data collected when riding on-road. For both on-road and simulator scenarios, participants started the ride positioned against the kerb and entered the bicycle lane from the left hand side of the road to establish themselves in the lane.

Data was collected for approximately 150 metres of bicycle lane. Comparison of the results found that, on average, participants selected similar lane positions in the simulator compared to when they were riding on-road (taken as the distance from the left edge of the bicycle lane), with a mean difference of 3.6mm recorded (Table 3). Comparison of the two sets of results using a paired-t test found that there was insufficient evidence to suggest that there was a statistically significant difference between the lane position chosen by participants when riding on-road compared to using the simulator ($t_{25} = 0.17$, $p = 0.86$, $d = 0.03$).

Table 3: Validation study - Lane position

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean (mm)</th>
<th>Standard Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Road</td>
<td>727.9</td>
<td>117.3</td>
</tr>
<tr>
<td>Simulator</td>
<td>731.5</td>
<td>99.7</td>
</tr>
</tbody>
</table>

While the average lateral position was relatively similar between on-road and simulator rides, an increased variation in average lane position was observed for on-road riding compared to simulator rides, however this variance was negligible, with the difference in standard deviation of lane position of only 17.6mm observed between the two tasks. Comparison of the deviation in lane position also found that there were no statistically significant differences between performance during the on-road and simulator rides ($t_{25} = 0.49$, $p = 0.62$, $d = 0.13$) (Table 4). Similar to average lateral position, there was slightly more variation when riding on-road compared to in the simulator, however this difference was negligible. It is noted that lane position and deviation in lane position are interacting factors.

Table 4: Validation study - Deviation in lane position

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean (mm)</th>
<th>Standard Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Road</td>
<td>227.3</td>
<td>113.3</td>
</tr>
<tr>
<td>Simulator</td>
<td>241.2</td>
<td>87.3</td>
</tr>
</tbody>
</table>
6.2.2.2 Scenario 2 – Passing Distance

The aim of the second scenario was to assess passing distance when travelling past a parallel parked car on the left hand side of the road. Comparison of the results between the simulator and on-road trials found that, on average, participants selected similar passing distances in both conditions, with a mean difference of approximately 15mm recorded (Table 5). Furthermore, the variation observed between the two measurements was relatively small with an average difference in standard deviation of 59.3 mm observed.

Comparison of the results using a paired-t test found that there was insufficient evidence to suggest that there was a difference between the passing distance chosen by participants when riding on-road compared to using the simulator ($t_{25} = 0.49$, $p = 0.42$, $d = 0.07$).

Table 5: Validation study - Passing distance

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean (mm)</th>
<th>Standard Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Road</td>
<td>1196.7</td>
<td>177.4</td>
</tr>
<tr>
<td>Simulator</td>
<td>1211.7</td>
<td>237.9</td>
</tr>
</tbody>
</table>

The results from scenarios 1 and 2 show that absolute validity was established between riding on-road and using the simulator, regarding lateral position and lateral position variability. Furthermore, the small effect sizes provide auxiliary confidence in these results.

6.2.2.3 Scenario 3 - Speed

The third scenario was designed to assess if participants rode at a similar speed in the simulator as they did on-road when travelling along a straight section of local road. A comparison of speed profiles between the simulator and on-road trials showed that, on average, participants cycled at a slower speed when riding in the simulator ($M = 14.5$, $SD = 2.0$), compared to riding on road ($M = 18.9$, $SD = 2.3$) (Figure 28) and the difference was statistically significant ($t_{25} = 12.4$, $p = 0.00$, $d = 2.05$).

As there were statistically significant differences in average speeds between the two conditions, absolute validity could not be established. However, there was a significant linear relationship between the on-road and simulator results ($F_{1, 25} = 17.74$, $p = 0.00$ $r = 0.66$) suggesting a level of relative validity between speeds when riding on-road and when riding in the simulator.
6.2.2.4 Scenario 4 – Braking/Deceleration

The fourth scenario assessed the deceleration made by participants on the minor approach to an un-signalised T-intersection. As absolute validity was not established for cyclist speed in the third scenario, speed reduction on approach to the intersection was measured in terms of percentage speed reduction from approach speed (taken as the speed before deceleration/braking commenced to the speed that the turning movement was undertaken).

Due to the nature of this experiment two participant’s on-road runs were excluded from the analysis due to the presence of passing motor vehicles on the approach to the intersection which was associated with substantially different speed and deceleration behaviours than the simulator scenario.

For the remaining comparisons between the simulator and on-road runs, the analyses showed that, on average, participants reduced their speed by a similar magnitude on approach to the T-intersection with a speed reduction of 27 percent observed on road compared to 28 percent in the simulator. A paired-t test found that there was no statistically significant differences in the percentage speed reduction between the two conditions ($t_{25} = 0.18$, $p = 0.85$, $d = 0.03$). The results suggest that relative validity was established for deceleration on approach to a T-Intersection between on-road and simulator rides.

6.2.2.5 Scenario 5 – Head Movements

Comparison of cyclist head movements proved difficult due to the constantly changing traffic conditions during the on-road component of the study. Participants did not exhibit similar patterns of head movements, in terms of the order of head movements made on approach to the intersection during on-road and simulator rides. However no significant differences were observed between the number of head movements performed on approach to the
intersection (1.9 vs 2.1) ($t_{25} = 1.3$, $p = 0.2$, $d = 0.28$), or the average duration of head movements (1.3s vs 1.2s) ($t_{25} = 0.69$, $p = 0.49$, $d = 0.13$), suggesting a degree of validity for the head movements between simulator and on-road conditions, with small effect sizes suggesting a degree of confidence with the results.

6.2.3 Simulator sickness

The majority of participants experienced little or no simulator sickness symptoms. The most common symptom reported by participants was sweating, however this may also have been a result of the physical exertion required to use the bicycle simulator. Other simulator sickness-related symptoms reported by participants were only slight and included stomach awareness, general discomfort and nausea. The two participants who were excluded from the study due to simulator sickness experienced a broad range of symptoms that they reported were either mild or severe. Both participants stopped using the simulator soon after the study commenced. One participant stated that they had not eaten on the day of the experiment and that that may have contributed to.

6.2.4 Summary

A summary of the key results for the validation study are presented in Table 6. Overall, the study established absolute validity for three key measures of position being average lane position, deviation in lane position and average passing distance. The study also established relative validity for average speed and speed reduction on the approach to the intersection. Analysis of cyclist head movements proved difficult due to the consistently changing road environment, however the study established a degree of validity for the number of head movements made by cyclists on approach to intersections and the average duration of these head movements.

Table 6: Validation study - Results summary

<table>
<thead>
<tr>
<th>Performance measure</th>
<th>On-Road Mean (SD)</th>
<th>Simulator Mean (SD)</th>
<th>p-value</th>
<th>Effect size (Cohen’s d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average lane position (mm)</td>
<td>727.9 (117.3)</td>
<td>731.5 (99.7)</td>
<td>0.86</td>
<td>0.03</td>
</tr>
<tr>
<td>Deviation in lane position (mm)</td>
<td>227.3 (113.3)</td>
<td>241.2 (87.3)</td>
<td>0.62</td>
<td>0.13</td>
</tr>
<tr>
<td>Average passing distance (mm)</td>
<td>1196.7 (177.4)</td>
<td>1211.7 (237.9)</td>
<td>0.68</td>
<td>0.07</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>18.9 (2.3)</td>
<td>14.5 (2.0)</td>
<td>0.00</td>
<td>2.06</td>
</tr>
<tr>
<td>Speed reduction on approach to intersection (%)</td>
<td>27.1 (10.5)</td>
<td>28.1 (12.7)</td>
<td>0.85</td>
<td>0.03</td>
</tr>
<tr>
<td>Head movements on approach to intersection (n)</td>
<td>1.9 (0.2)</td>
<td>2.1 (0.1)</td>
<td>0.20</td>
<td>0.28</td>
</tr>
<tr>
<td>Average head movement duration on approach to intersection (sec)</td>
<td>1.3 (0.9)</td>
<td>1.2 (0.5)</td>
<td>0.49</td>
<td>0.13</td>
</tr>
</tbody>
</table>
6.3 Discussion

The aim of this study was to validate the newly developed bicycle simulator for a select range of cycling performance measures. The simulator was developed to assess new infrastructure designs that will enhance cyclist safety when riding on-road. Pilot infrastructure evaluation is ideally suited to simulator studies as it can be more cost effective than on-road or test track studies (Stevenson et al. 2015). Simulation allows for multiple iterations of designs to be evaluated and can also help to identify potential issues with the way that people interact with the new facility that may not have been obvious when conceptualising the design (Stevenson et al. 2015).

The bicycle simulator validated in this study provides an example of how new virtual reality technology can be utilised to create a high fidelity, yet relatively low cost simulator. The bicycle simulator creates an opportunity to conduct unique research investigating vulnerable road user behaviours and their interactions within various road environment and traffic conditions. However, prior to using the simulator for road safety research, it is important to first establish the validity of the simulator as a research tool and identify the benefits and limitations of the simulator, particularly in terms of elicited behaviours, so that future research is conducted within the capabilities of the simulator.

This study focused on establishing the behavioural validity of the bicycle simulator for a set of performance measures associated with cycling on-road. The results of the study suggest that the simulator was capable of eliciting similar behavioural responses compared to on-road cycling amongst the group of participants. However it is recognised that due to the recruitment techniques, participants who undertook this study do not represent the full age range of cyclists, furthermore limitations placed on participants due to recruitment criteria may have introduced sample bias.

The validation study established absolute validity for the three measures of cyclist spatial position within bicycle lanes and relative to passing vehicles. The position of cyclists within the roadway has important implications for cyclist safety. For example Harkey & Stewart (1997) identified that bicycle lanes influence the cyclist’s position relative to the kerb, with bicycle lanes encouraging cyclists to ride further away from the roads edge. Furthermore, the Australian Road Safety Strategy identifies improving cyclist spatial separation from other modes of transport as one of the key methods for improving cyclist safety (ATC 2011). By reducing cyclists’ interaction with other modes of transport there is a reduction in the risk of collision. The finding that participants have selected lane positions in the simulator that reflect on-road riding will allow the simulator to be used to examine how cyclist spatial position and lateral clearance can be influenced by changing the on-road environment. Furthermore the simulator can be used to examine additional aspects of riding including passing behaviour and lane positioning. It is important to note that the simulator was assessed for relatively straight sections of road and that results may be different when considering curved sections of roads.
Absolute validity was not established for the average speed of cyclists when using the simulator compared with on-road riding. However, relative validity was established with a strong linear relationship found between on-road and simulator speeds. Furthermore, relative validity was established for the speed reduction of cyclists on approach to a T-intersection. When using the simulator, participant speeds were consistently lower than on-road speeds. These findings align with previous driving simulator studies where simulator speeds have differed from on-road speeds, however relative validity has been demonstrated (Tömros 1998, Blana & Golias 2002, Godley et al. 2002).

Possible reasons for the differences in speed in simulators compared with on-road speeds are related to difficulties in judging speed in a simulated environment. Simulators do not provide the same cues to participants as they would experience in the real world and as such, it is much more difficult to judge speed (Tömros 1998). Similar to driving simulator validation studies, when participants are not shown a display of the speed they are travelling there are often differences between the on-road and simulator speeds (Tömros 1998).

Differences in the simulator and on-road vehicle may also result in different user behaviours. While every attempt was made to use the same bicycle set-up in both on-road and simulator, the use of a bicycle trainer in the simulator may create different feedback to participants than on-road cycling regarding travel speed. Variation in the vertical road alignment and atmospheric conditions could also influence cyclist speed for the on-road component of the study.

The slower speeds in the simulator will have implications on future research and it is important to acknowledge and take into account the limitations of the simulator in this respect in future studies. The intention of the simulator will be to assess relative differences in speed between existing condition or control scenarios and proposed infrastructure designs. As such, the studies will focus on identifying the relative changes in speed compared to the control or existing condition scenarios and will be less concerned with the absolute speed of participants. As relative validity has been established for the simulator, it was considered that the simulator will be suitable for this intended purpose. If studies require participants to travel at a set speed, there is also the potential to display instantaneous speed to participants to help them regulate their speed.

Validity was also established between the simulator and on-road conditions for the number of head movements participants made on approach to an intersection and the average duration of these head movements. These results are promising and suggest that participants are exhibiting similar looking behaviour on-road and in the simulator, however, it is noted that due to the constantly changing road environment there was considerable variation between the on-road and simulator studies. Future validation of cyclist head movements may need to be conducted in a more controlled environment, potentially using a test-track to create consistent and controlled environments for participants. Furthermore, this validation study did not attempt to validate the simulator for more complex behavioural performance measures such as gap acceptance and cyclist reaction times, and further research addressing validation of these measures may be required if the simulator is proposed to investigate these measures in future research.
When considering the results from this study, it is noted that the recruitment process has the potential to introduce a number of biases into the results. Notably the validation study has considered a relatively young group of healthy cyclists who are unlikely to represent the full spectrum of cyclists riding on-road. Furthermore there are limitations regarding the road environments selected for this validation study and the range of behaviours that have been assessed. As such, and as with all simulator studies, there are limitations regarding the generalisability of results and caution should be taken regarding the extrapolation of findings to different cohorts and tasks.

There is evidence that aspects of cyclist performance when interacting with the road environment can be investigated using the bicycle simulator, with absolute validity established across a range of cyclist spatial position measures. Absolute validity was not established for measures of speed. While this is a known limitation of the simulator, relative validity was established and as such the simulator is suitable for comparison studies assessing differences in speed between different scenarios.

In summary, the validation process presented in this chapter has provided sufficient evidence to suggest that the bicycle simulator is suitable for assessing aspects of cyclist performance when evaluating on-road cycling infrastructure designs. The following chapter presents an investigation of cycling crashes that have occurred in Australia and Victoria. The findings from this investigation will inform simulator studies examining aspects of bicycle lane characteristics and evaluating cycling infrastructure designs, presented in Chapters 9 and 10.
Chapter 7: Examination of cyclist crash factors

In order to develop effective countermeasures to improve the safety of cyclists when riding on-road there is a need to understand the key contributing factors of collisions through the examination of quality data (Biegler et al. 2012). Furthermore, the prioritisation of countermeasures requires information about the burden of injury associated with the mechanisms of collisions (Biegler et al. 2012). That is to say, there is a need to understand the most frequent but also the most serious collision types involving cyclists in order for effective countermeasures to be developed that result in the greatest benefits for cyclist safety. By reducing the prevalence and severity of cyclist crashes there is also the potential to reduce the perceived risk associated with cycling and hence encourage increased cycling participation.

In this chapter the factors associated with serious casualty and fatal on-road cyclist injuries in Victoria and Australia are identified and investigated. The findings from this investigation help form the evidence base for the development of simulator-based studies investigating bicycle lane characteristics and infrastructure designs and their effect on cyclist riding behaviour that are presented in the following chapters of this thesis.

As highlighted in Chapter 1, previous research conducted in Victoria established that, compared with motor vehicle occupants, cyclists have an approximately thirteen times greater risk of being involved in a collision resulting in serious injuries and four and a half times greater risk of fatal injury per kilometre travelled (Garrard et al. 2010). It has also been established through examination of Victorian police-reported data that cyclists are at increased risk of serious injury when riding at night, without a helmet, on roads with higher speed limits, in rural areas, and on curved sections of road (Boufous et al. 2013).

Police reported data provides a valuable insight into cyclist injuries, however a commonly noted limitation of the use of this data is the underreporting of single-vehicle collisions (collisions involving only a cyclist) (Sikic et al. 2009, Garrard et al. 2010, Boufous et al. 2013). In their analysis of police-reported and hospital based cyclist crashes, Boufous et al. (2013) identified nearly twice as many single vehicle crashes, compared to multiple vehicle collisions in hospital records. Furthermore they noted that single vehicle collisions represented roughly five percent of collisions in the police dataset, however they represented nearly 55 percent of cyclist collisions when considering injuries that resulted in hospital admission or presentation at an emergency department (Boufous et al. 2013). The authors concluded that while hospital data provided a better indication of prevalence, compared to police-reported data, there was a lack of detail regarding the crash mechanisms and circumstances contained in hospital based injury surveillance datasets in Victoria (Boufous et al. 2013), thus highlighting the benefits and limitations with using various datasets when investigating cyclist collisions.

Based on the identified need to further understand the issues surrounding cyclist crashes, Biegler and colleagues (2012) conducted an in-depth crash investigation involving 158 bike riders who had crashed and presented to either the Sandringham or Alfred hospitals in Melbourne, Australia. Their study found that the majority of injured bike riders were regular cyclists and most cyclists wore a helmet at the time of the collision
(93%), of whom 45 percent sustained helmet damage due to a head strike during the crash. This study identified similar patterns regarding the proportion of single vehicle crashes as observed by Boufous et al. (2013), with 60 percent of the 158 collisions involving only a cyclist i.e. a single vehicle, with loss of control being the main cause of single-vehicle collisions (Biegler et al. 2012).

A similar in-depth methodology was adopted to the one used by Biegler et al. (2012) in an earlier stage of the broader study “Safer Cycling in the Urban Road Environment” that aligns with this Ph.D. thesis. The study recruited 186 cyclists who were admitted to the Alfred Hospital and the Royal Melbourne Hospital following a collision, two of the major trauma hospitals in Victoria, Australia (Beck et al. 2016). The study found that injured cyclists were predominately male and middle-aged with the majority of collisions occurring in daylight hours. The majority of injured cyclists (68%) were injured while riding on-road, with roughly half of on-road collisions involving no other vehicle (48%). Key collision types identified in the analysis included right-through collisions (n=18), where the cyclist and vehicle approached from opposing directions with the cyclist travelling straight ahead and the vehicle turning right at an intersection or into a side road. Twenty-five collisions occurred where the cyclist was riding in a bicycle lane (22%), and almost all of these collisions (90%) included motor vehicles as a contributing factor. Only one case involved a cyclist coming into contact with a vehicle door (i.e. “dooring”). While these are important findings, there are some noted limitations with in-depth study designs. In particular, only patients who were able to consent to the study were recruited, this likely resulted in patients who suffered lower severity injuries being recruited. Furthermore the study did not considered fatally injured cyclists in the analysis. A focus on less severe injury collisions may bias the findings and implications drawn from the study. The study also relied on participant self-report which may introduce further bias and limit the ability to determine the mechanisms of the collision.

In order to gain a broader understanding of severe injury cyclist collisions, for the research undertaken in this thesis it was decided to consider a combination of police-reported cyclist collisions in Victoria (severe injury outcomes) as well as collisions that resulted in cyclist fatalities throughout Australia. It is anticipated that through investigating and addressing the most severe cyclist collision types there will also be flow-on benefits for lower severity collisions resulting in less serious casualties and minor injuries. Furthermore it is expected that fatal injuries are likely to receive the most attention by the media, as such these collisions are likely to be the most prominent deterrents associated with the perception of danger that is attributed to on-road cycling. An effort addressing these collision types has the potential to encourage increased cycling participation. To complement the findings from the analysis of crashes resulting in a fatal injury to a cyclist, police-reported data was also reviewed. It is noted that police-reported cyclist crashes have previously been analysed and the findings of previous research have been discussed briefly in this thesis. However, for the purpose of comparison (and provision of updated/current crash trends) it was considered valuable to examine data over a consistent time period, in case any changes had occurred over time in regards to crash factors which would not be captured through referencing aforementioned studies and to provide a more holistic view of the range of cyclist collisions.
7.1 Methodology

The investigation undertaken in this chapter was designed to enhance our understanding of serious cyclist crashes in Victoria and fatal cyclist crashes throughout Australia and to use this information to form an evidence base for the development of simulator studies investigating infrastructure countermeasures that address priority cyclist safety issues.

This analysis considered a range of cyclist injuries of various severities across two databases, the National Coronal Information System (NCIS) and the Victorian police-reported crash data. Analyses considered all cases involving on-road cyclists within each dataset for the ten year period from 2006 to 2015. This time period was selected as it represented the most up to date data that were available at the time of investigation.

The analysis focused on collisions that occurred within the urban environment. For the purpose of this analysis the urban environment was defined as major urban regions of Australia which were classified in accordance with the Australian Bureau of Statistics, Australian Statistical Geography Standard (ASGS) Remoteness structure (ABS 2011). The remoteness structure classifies areas based upon their accessibility and remoteness. Highly accessible areas were classified as major urban regions, which generally correspond with the major metropolitan cities of Australia (ABS 2011). For example, in Victoria, major urban areas consisted of Greater Metropolitan Melbourne and Geelong.

7.1.1 Ethics

Ethics approval for the investigative analysis was obtained from the Department of Justice and Regulation Human Research Ethics Committee (JHREC) and reciprocal ethics approval was granted by the Monash University Human Research Ethics Committee (MUHREC). An access agreement was established with VicRoads (the Victorian State road authority) to access all police-reported cyclist crashes in Victoria.

7.1.2 Datasets

7.1.2.1 Coronial Reported Crash Data

The NCIS is a remote data entry and retrieval system containing coronial information managed by the Department of Justice (NCIS 2014). All coroner-reported closed cases involving a cyclist fatality in Australia from 2006 to 2015 were extracted from the database. Additional data extracted from Police, Autopsy, Toxicology and Coroner reports were attached to cases within the dataset. A limitation of this dataset is that only closed cases are available, this resulted in limited availability of some more recent cases where coronial investigations were ongoing. Furthermore, Police, Autopsy, Toxicology and Coroner reports were not available for all cases and as such not all variables were available for analysis for each case. A select few cases within the dataset were also subject to a coronial inquest, however inquest information has not been considered in this analysis. The availability of additional reports for the extracted cases is summarised in Table 7.
Cases were initially identified if the object inducing injury was coded as a pedal cycle. The initial search identified 344 cases during the study period. Cases were included for further analysis if they involved an injury to a pedal cyclist, occurred within the road reserve, were a result of normal cycling (i.e. not attempting a trick or stunt), and did not involve an attempted suicide. These criteria resulted in exclusion of 56 cases, leaving 288 cases for analysis.

The NCIS data was supplemented with spatial information using the geographic coordinates of the crash. Geographic information was utilised to assess location characteristics such as speed limits and road geometry. This information was also utilised to code missing data, such as when the speed limit had not been recorded, but sufficient information was available to identify the section of road where the collision had occurred.

7.1.2.2 Police-reported Crash Data

Victorian police-reported crash data held within the VicRoads Crashstats database were accessed and analysed to assess the characteristics and circumstances of cyclist collisions resulting in serious injuries in urban areas in Victoria. All on-road bicycle-related serious and fatal injury collisions from 2006 to 2015 were extracted for analysis. It has previously been established that single-bicycle crashes are typically under-reported in police datasets (Isaksson-Hellman 2012, OECD/ITF 2013) and this findings has also been confirmed for Victorian data (Boufous et al. 2013). However, as this research has a focus towards reducing the conflict between cyclists and motor vehicles (likely to contribute to severe injury outcomes) this limitation was deemed acceptable. In total, 4,634 collisions involving an injured cyclist were reported to police in Victoria during the study period. These collisions resulted in 4,693 serious casualty or fatal injuries to cyclists. As with the NCIS data, the collision information was supplemented with spatial information based on the geographic coordinates of the collision.

7.1.3 Data analysis

Descriptive analysis techniques were performed to examine the serious casualty and fatal crash data. Additional analyses included cross tabulation and Person’s chi-squared tests ($\chi^2$) for comparison of variables collected within the two datasets. All analyses were undertaken at a level of significance ($\alpha$) of 0.05. Effect size was assessed using Cramer’s V statistic ($\phi_c$). Variables included in the analyses included: age, gender, mechanism of injury, medical cause of death, object or substance producing injury, time and date of incident, modes of transport involved, context of collision, police narratives of collision, atmospheric conditions, road surface conditions, Definition of Classification of Accident (DCA) code, light condition, toxicology reports (presence of drugs and or alcohol) and narratives of coronial findings and recommendations. Statistical analyses were

---

Table 7: NCIS attached case reports

<table>
<thead>
<tr>
<th>Report type</th>
<th>Police</th>
<th>Toxicology</th>
<th>Autopsy</th>
<th>Coroner</th>
<th>Inquest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available/</td>
<td>85.8%</td>
<td>65.3%</td>
<td>72.9%</td>
<td>67.7%</td>
<td>5.2%</td>
</tr>
<tr>
<td>reported</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
conducted using STATA version 13.1. Spatial analysis of crash locations was undertaken to identify collision clusters using ArcGIS 10.2.

Comparisons were made between the results from the two datasets to identify common cyclist crash types resulting in serious casualty and fatal injuries. Based on these comparisons, further investigation was conducted of the most commonly occurring crash types in urban areas for both severity types. The results of this investigation were utilised to design and conduct experimental studies examining the effects of selected infrastructure-based countermeasures addressing these priority crash types.

### 7.2 Results

Initial summaries of the results are presented separately for the two datasets, followed by comparisons of the findings from the two datasets. Discussion of some of the key crash types identified through the course of this analysis and implication for further research is also included. Each summary begins by presenting all identified crashes, followed by a detailed examination of crashes in urban areas.

#### 7.2.1 Coronial dataset

In total, 288 cases were identified in the NCIS database involving a cyclist that occurred within the road reserve throughout Australia. The temporal distribution of cases by year is presented in Figure 29. On average, 28.8 (SD = 9.5) fatal cyclist cases were recorded in the NCIS dataset per annum. However, there was a substantial reduction in number of cases available for analysis in more recent years. This does not necessarily reflect a reduction in fatal cyclist crashes, as there were fewer closed cases during this period. As such, there is likely some underreporting of the actual number of cyclist fatalities, particularly in more recent years.

![Figure 29: NCIS closed cases involving cyclists (2006 to 2015)](image-url)
The spatial distribution of cases is illustrated in Figure 30. The figure shows the location of each incident based on the geographic information contained in the police report. For cases where the police report was not available, the geographic centroid of the postcode where the incident occurred was used to illustrate the approximate location.

From Figure 30 it can be seen that the majority of cases occur along the east coast of Australia and cases are clustered around major capital cities. Using the classification given by the Australian Bureau of Statistics Remoteness Structure (ABS 2011), it was identified that the majority of cases were in fact located in major city areas (51%) or inner regional areas (27.1%). The majority of cases occurred in New South Wales (27.1%), Victoria (25.0%) and Queensland (24.0%). Not surprisingly there was a rough correlation between the number of crashes in each state and the population distribution of Australia. A summary of cases by jurisdiction and remoteness structure region is presented in Figure 31 and shows that the majority of cases occurred in major city regions in NSW, Victoria, Queensland and Western Australia. Surprisingly a high proportion of collision were also found to occur in regional Queensland.
Comparisons were made between cases that occurred in major cities and other remote regions to identify if there were any statistically significant differences between collisions in urban and rural areas. The analysis identified that cases in major cities were more likely to occur on lower speed roads (>60km/h) \( (\chi^2\ (1) = 40.1, p = 0.00, \varphi_c = 0.38) \) and at intersections compared to mid-block locations in other remote areas \( (\chi^2\ (1) = 8.6, p = 0.003, \varphi_c = 0.17) \). Cases in other remote areas were more likely to occur on higher speed roads and, involve cyclists participating in a group ride \( (\chi^2\ (1) = 4.5, p = 0.03, \varphi_c = 0.19) \). There were also significantly more cases involving older cyclists aged 65 years and older in rural areas \( (\chi^2\ (3) = 15.5, p = 0.001, \varphi_c = 0.134) \).

No differences were observed between the urban and rural cases when considering gender \( (\chi^2\ (1) = 1.0, p = 0.31) \), helmet use \( (\chi^2\ (1) = 0.9, p = 0.34) \), the proportion of cases involving only single or multiple vehicles \( (\chi^2\ (1) = 1.2, p = 0.27) \), or the presence of drugs \( (\chi^2\ (1) = 1.7, p = 0.20) \) and alcohol \( (\chi^2\ (1) = 2.2, p = 0.13) \) identified in fatally injured cyclist autopsy or toxicology reports. The remaining analyses focus on collisions that occurred within major city regions as cyclist safety in urban environments is the key focus of the research in this thesis.

### 7.2.1.1 Major city region cases

Within the major city regions throughout Australia, there were 147 fatal cyclist cases recorded in the NCIS dataset between 2006 and 2015. A summary of the case demographics and collision contributing factors is presented in Table 8. The majority of cases involved male cyclists (89.1%) aged between 35 and 64 years (51.0%). Cyclists aged between 18 and 34 years were the next most frequent group of fatally injured cyclists, representing 25.9 percent of collisions.
Helmets use was reported in 53.7 percent of cases. Where reported, helmets were not worn by 20.4 percent of cyclists at the time of the incident. The presence of alcohol was detected in 15.6 percent of post mortem examinations. However it is noted that there are various issues associated with the post-mortem analysis of alcohol, including the possibility of ethanol being produced in the body after death and alcohol being unabsorbed or metabolised between the time of collision and post-mortem examination (Kugelberg & Jones 2007). As such, making a judgement on the influence of alcohol on these collisions is beyond the scope of this analysis. Notwithstanding, the findings suggest that alcohol and intoxication is likely a contributing factor in a number of cyclist collisions.

The presence of drugs including tetrahydrocannabinol (THC), opioids, benzodiazepines, amphetamines and methamphetamine were identified in 23.1 percent of cases. It was noted that opioids, benzodiazepines and amphetamines have pharmaceutical uses and may have been prescribed medication, or administered to the patient following the incident. Furthermore no assessment was made regarding the concentration of these substances and if that concentration was considered above pharmaceutical levels or if the presence of the drug could have impaired the cyclist and/or contributed to the collision. As for the effect of alcohol and intoxication, the results suggest that both licit and illicit drug usage may be a contributing factor in a number of cyclist fatal collisions.

Table 8: Urban cyclist demographics and collision contributing factors

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>131</td>
<td>89.1</td>
</tr>
<tr>
<td>Female</td>
<td>16</td>
<td>10.9</td>
</tr>
<tr>
<td><strong>Age Group</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-17</td>
<td>12</td>
<td>8.2</td>
</tr>
<tr>
<td>18-34</td>
<td>38</td>
<td>25.9</td>
</tr>
<tr>
<td>35-64</td>
<td>75</td>
<td>51.0</td>
</tr>
<tr>
<td>65+</td>
<td>22</td>
<td>15.0</td>
</tr>
<tr>
<td><strong>Helmet Use</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helmet</td>
<td>49</td>
<td>33.3</td>
</tr>
<tr>
<td>No-Helmet</td>
<td>30</td>
<td>20.4</td>
</tr>
<tr>
<td>Unknown</td>
<td>68</td>
<td>46.3</td>
</tr>
<tr>
<td><strong>Alcohol Present</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>23</td>
<td>15.6</td>
</tr>
<tr>
<td>No</td>
<td>94</td>
<td>63.9</td>
</tr>
<tr>
<td>Unknown</td>
<td>30</td>
<td>20.4</td>
</tr>
<tr>
<td><strong>Drugs Presents</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>34</td>
<td>23.1</td>
</tr>
<tr>
<td>No</td>
<td>65</td>
<td>44.2</td>
</tr>
<tr>
<td>Unknown</td>
<td>46</td>
<td>31.3</td>
</tr>
</tbody>
</table>
Characteristics surrounding cyclist crashes are presented in Table 9. The analysis found that collisions more frequently occurred on weekends compared to weekdays, with 22.4 percent of cases reported on Saturdays and 17.0 percent reported on Sundays. Crashes were found to occur more frequently in lower speed zones with 68.7 percent of cases reported in 60km/h or slower speed zones, however the police reports rarely gave an indication of the cyclist or the other road user actual speed at the time of the incident. The majority of cases occurred at mid-block locations (61.2%), compared to intersections (38.8%), while light vehicles, such as cars (37.4%) and heavy vehicles (27.9%) were the most common counterpart in the collisions, 23.8 percent of cases did not involve another road user, that is to say it was a cyclist only crash resulting from the cyclist hitting a fixed object, or losing control of their bicycle.

Table 9: Urban cyclist cases characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day of the Week</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weekday</td>
<td>89</td>
<td>60.5</td>
</tr>
<tr>
<td>Weekend</td>
<td>58</td>
<td>39.5</td>
</tr>
<tr>
<td><strong>Speed Zone</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>≤40km/h</td>
<td>4</td>
<td>2.7</td>
</tr>
<tr>
<td>50km/h</td>
<td>42</td>
<td>28.6</td>
</tr>
<tr>
<td>60km/h</td>
<td>55</td>
<td>37.4</td>
</tr>
<tr>
<td>70km/h</td>
<td>14</td>
<td>9.5</td>
</tr>
<tr>
<td>80km/h</td>
<td>19</td>
<td>12.9</td>
</tr>
<tr>
<td>90km/h</td>
<td>4</td>
<td>2.7</td>
</tr>
<tr>
<td>≥100km/h</td>
<td>6</td>
<td>3.4</td>
</tr>
<tr>
<td>Unknown</td>
<td>3</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Road Geometry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intersection</td>
<td>57</td>
<td>38.8</td>
</tr>
<tr>
<td>Mid-block</td>
<td>90</td>
<td>61.2</td>
</tr>
<tr>
<td><strong>Road users</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Counterpart</td>
<td>15</td>
<td>10.2</td>
</tr>
<tr>
<td>Fixed or Stationary Object</td>
<td>20</td>
<td>13.6</td>
</tr>
<tr>
<td>Light Transport Vehicle</td>
<td>55</td>
<td>37.4</td>
</tr>
<tr>
<td>Special All-Terrain or Off-Road Vehicle</td>
<td>10</td>
<td>6.8</td>
</tr>
<tr>
<td>Heavy Transport Vehicle</td>
<td>41</td>
<td>27.9</td>
</tr>
<tr>
<td>Pedestrian</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>Pedal Cycle</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>Two-Wheeled Motor Vehicle</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>Rail Vehicle</td>
<td>3</td>
<td>2.0</td>
</tr>
</tbody>
</table>

A summary of time of incident is presented in Figure 32, highlighting that a high number of cases occurred in the early hours of the morning and again in the late afternoon and early evening. This is likely a reflection of
exposure with increased volumes of cyclists and motor vehicles on the road during these time periods and lighting conditions (dawn, dusk).

Figure 32: Urban cyclist cases by time of day

With regard to collision type, DCA codes were extracted from police reports or determined based on police report narratives and coroner findings of the incidents (Table 10). The most common collisions involved vehicles travelling in the same direction as the cyclist (26.5%), in particular, rear-end collisions (14.3%) and side-swipe collisions (5.4%).

Intersection collision comprised 37.9 percent of all fatal collisions. The most common type of collision at intersections were cross traffic collisions (9.5%) and collisions involving vehicles travelling in opposing directions (8.2%), in particular right through (4.1%) and head on (4.1%) collisions.

Incidents where the cyclist lost control of their bicycle represented 27.9 percent of cases. These cases typically occurred when cyclists were travelling at higher speeds or around bends. Several of these cases were also associated with the cyclist suffering from a medical condition prior to the incident such as a heart attack or stroke.

Analyses of injury information held within the autopsy reports identified that the primary injury mechanism in the majority of cases was blunt force trauma, either from being hit by a motor vehicle, from falling onto the road surface, hitting a roadside object or a combination of these injury mechanisms. For most cases, it was reported that the cyclist sustained multiple injuries (38.8%). Injuries to the head (31.3%), chest (4.8%), neck (3.4%) and brain (2.0%) were also commonly reported (Table 11).
Table 10: Urban cyclist cases DCA

<table>
<thead>
<tr>
<th>DCA (Grouped)</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100s – Pedestrian</td>
<td>7</td>
<td>4.8</td>
</tr>
<tr>
<td>110s – Vehicles from adjacent direction</td>
<td>16</td>
<td>10.9</td>
</tr>
<tr>
<td>120s – Vehicles from opposing direction</td>
<td>12</td>
<td>8.2</td>
</tr>
<tr>
<td>130s – Vehicles from same direction</td>
<td>39</td>
<td>26.5</td>
</tr>
<tr>
<td>140s – Manoeuvring</td>
<td>10</td>
<td>6.8</td>
</tr>
<tr>
<td>160s – On Path</td>
<td>3</td>
<td>2.0</td>
</tr>
<tr>
<td>170s – Off Path on Straight</td>
<td>31</td>
<td>21.1</td>
</tr>
<tr>
<td>180s – Off path on Curve</td>
<td>10</td>
<td>6.8</td>
</tr>
<tr>
<td>190s – Passenger or Miscellaneous</td>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>Unknown</td>
<td>17</td>
<td>11.6</td>
</tr>
</tbody>
</table>

Table 11: Urban cyclist cases by mechanism of injury and injury type

<table>
<thead>
<tr>
<th>Injury mechanism</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blunt Force</td>
<td>146</td>
<td>99.3</td>
</tr>
<tr>
<td>Threat To Breathing</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>Injuries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple injuries</td>
<td>57</td>
<td>38.8</td>
</tr>
<tr>
<td>Head injury</td>
<td>46</td>
<td>31.3</td>
</tr>
<tr>
<td>Chest injuries</td>
<td>7</td>
<td>4.8</td>
</tr>
<tr>
<td>Head and Chest Injuries</td>
<td>5</td>
<td>3.4</td>
</tr>
<tr>
<td>Neck injury</td>
<td>5</td>
<td>3.4</td>
</tr>
<tr>
<td>Injuries sustained in a motor vehicle collision (cyclist)</td>
<td>5</td>
<td>3.4</td>
</tr>
<tr>
<td>Chest and abdominal injuries</td>
<td>3</td>
<td>2.0</td>
</tr>
<tr>
<td>Brain injuries</td>
<td>3</td>
<td>2.0</td>
</tr>
<tr>
<td>Head and neck injuries</td>
<td>3</td>
<td>2.0</td>
</tr>
<tr>
<td>Other</td>
<td>13</td>
<td>8.8</td>
</tr>
</tbody>
</table>

7.2.2 Police-reported cyclist crashes

In total, 4,693 serious casualty and fatal injuries involving cyclists were reported to police in Victoria between 2006 and 2015. These injuries resulted from 4,624 collisions. The majority of cases involved a serious injury to a cyclists, with 84 cases involving a fatal injury. Fatal injury cases were excluded from this analysis as most of these cases were captured in the NCIS database, reported above. The temporal distribution of police-reported serious injury cyclist collisions by year is presented in Figure 33. On average, there were 437.8 seriously injured cyclists on Victorian roads per year over the past decade.
Figure 33: Police-reported cases involving cyclists (2006 to 2015)

The spatial distribution of cases is illustrated in Figure 34, showing the location of each incident based on the geographic information contained in police reports. The majority of serious injury collisions (82%) occurred within major city regions (i.e. Metropolitan Melbourne and Geelong) with 3,787 collisions recorded involving 3,882 cyclists.

Figure 34: Spatial distribution of Victorian police-reported cyclist crashes
Comparison of the cases that occurred in major cities and other regions identified some significant differences that followed a similar pattern to the fatally injured group. Compared with regional cases, cases in major city urban areas in Victoria were more likely to occur on roads with lower speed limits (>60km/h) ($\chi^2 (1) = 229, p = 0.00, \phi_c = 0.23$), at intersections ($\chi^2 (1) = 27.8, p = 0.00, \phi_c = 0.08$) and were more likely to involve adults aged 18 to 65 years, ($\chi^2 (3) = 203, p = 0.00, \phi_c = 0.12$). In comparison, cases in other regions were more likely to occur on roads with higher speed limits, and at mid-block locations. Cases in major cities were also more likely to involve multiple vehicles ($\chi^2 (1) = 58, p = 0.00, \phi_c = 0.11$) compared to collisions that occurred in regional areas. No differences were observed between cases in major cities compared to rural areas when considering gender ($\chi^2 (1) = 0.0, p = 0.98$) or helmet usage ($\chi^2 (1) = 0.28, p = 0.60$).

As per the NCIS data analysis, the focus of this analysis was on crashes that occurred in urban areas. The remainder of this section therefore only considers cyclist crashes within the urban road environment.

7.2.2.1 Major city collisions

A summary of the case demographics and contributing factors for police reported cyclist collisions in major urban regions of Victoria is presented in Table 12. Similar to the NCIS data, the majority of cases involved male cyclists (76.3%), between the age of 35 and 64 years (47.9%). Helmets were not worn by 8.0 percent of cyclists at the time of the collision and helmet use was unknown for 14.8 percent of cases. This implies that the majority of cyclists who sustained serious injuries in a collision wore a helmet (73.7%).

Table 12: Cyclist demographics and collision contributing factors in Victorian urban areas

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>2,879</td>
<td>76.3</td>
</tr>
<tr>
<td>Female</td>
<td>866</td>
<td>22.9</td>
</tr>
<tr>
<td>Unknown</td>
<td>29</td>
<td>0.8</td>
</tr>
<tr>
<td>Age Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-17</td>
<td>291</td>
<td>7.4</td>
</tr>
<tr>
<td>18-34</td>
<td>1,526</td>
<td>39.0</td>
</tr>
<tr>
<td>35-64</td>
<td>1,872</td>
<td>47.9</td>
</tr>
<tr>
<td>65+</td>
<td>189</td>
<td>4.8</td>
</tr>
<tr>
<td>Unknown</td>
<td>33</td>
<td>0.8</td>
</tr>
<tr>
<td>Helmet Use</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helmet</td>
<td>2,883</td>
<td>73.7</td>
</tr>
<tr>
<td>No-Helmet</td>
<td>314</td>
<td>8.0</td>
</tr>
<tr>
<td>Unknown</td>
<td>577</td>
<td>14.8</td>
</tr>
</tbody>
</table>
Factors surrounding the crash characteristics are presented in Table 13. Cyclist crashes most frequently occurred on weekdays (78.4%), with the highest proportion of crashes occurring on Tuesdays. A summary of incident time is presented in Figure 35. The graph highlights that a high frequency of collisions occurred in the early hours of the morning and in the late afternoon and early evening. This crash profile matches a typical commuter peak profile for on-road motor vehicle traffic. Figure 35 suggests that there is likely a causal relationship between cyclist collisions and the volume of motor vehicle traffic on the road network, due to the peak collisions occurring in what is considered the AM and PM peak periods. Crashes frequently occurred on roads with lower speed limits with 79.3 percent of cases reported in 60km/h or slower speed zones. The majority of cases occurred at intersections (59.6%), compared to mid-block locations (40.2%). Collisions with a motor vehicle were the most common injury mechanism, representing 85.2 percent of cases.

![Figure 35: Police-reported cases by time of day in Victorian urban areas](image-url)
Table 13: Cyclist crash characteristics in Victorian urban areas

<table>
<thead>
<tr>
<th>Day of the Week</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekday</td>
<td>2,929</td>
<td>78.4</td>
</tr>
<tr>
<td>Weekend</td>
<td>809</td>
<td>21.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Speed Zone</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤40km/h</td>
<td>367</td>
<td>9.5</td>
</tr>
<tr>
<td>50km/h</td>
<td>997</td>
<td>25.7</td>
</tr>
<tr>
<td>60km/h</td>
<td>1,707</td>
<td>44.1</td>
</tr>
<tr>
<td>70km/h</td>
<td>208</td>
<td>5.4</td>
</tr>
<tr>
<td>80km/h</td>
<td>188</td>
<td>4.9</td>
</tr>
<tr>
<td>90km/h</td>
<td>4</td>
<td>0.1</td>
</tr>
<tr>
<td>≥100km/h</td>
<td>21</td>
<td>0.5</td>
</tr>
<tr>
<td>Unknown</td>
<td>246</td>
<td>6.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Road Geometry</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersection</td>
<td>2,229</td>
<td>59.6</td>
</tr>
<tr>
<td>Mid-block</td>
<td>1,502</td>
<td>40.2</td>
</tr>
<tr>
<td>Unknown</td>
<td>7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Road users</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Counterpart</td>
<td>400</td>
<td>11.5</td>
</tr>
<tr>
<td>Fixed or Stationary Object</td>
<td>61</td>
<td>1.8</td>
</tr>
<tr>
<td>Motor vehicle</td>
<td>2,966</td>
<td>85.2</td>
</tr>
<tr>
<td>Pedestrian</td>
<td>22</td>
<td>0.6</td>
</tr>
<tr>
<td>Two-Wheeled Motor Vehicle</td>
<td>25</td>
<td>0.7</td>
</tr>
<tr>
<td>Animal</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>Other</td>
<td>7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The majority of cyclist collisions occurred in clear weather conditions (85.6%) and on dry road surfaces (84.7%), suggesting that atmospheric conditions were a contributing factor in only a small proportion of serious injury cyclist collisions Table 14.
### Table 14: Atmospheric and road surface conditions for cyclist crashes in Victorian urban areas

<table>
<thead>
<tr>
<th>Atmospheric Conditions</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear</td>
<td>3201</td>
<td>85.6</td>
</tr>
<tr>
<td>Not known</td>
<td>294</td>
<td>7.9</td>
</tr>
<tr>
<td>Raining</td>
<td>210</td>
<td>5.6</td>
</tr>
<tr>
<td>Fog</td>
<td>17</td>
<td>0.5</td>
</tr>
<tr>
<td>Strong winds</td>
<td>10</td>
<td>0.3</td>
</tr>
<tr>
<td>Dust</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>Smoke</td>
<td>3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Road Surface Conditions</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>3165</td>
<td>84.7</td>
</tr>
<tr>
<td>Wet</td>
<td>327</td>
<td>8.7</td>
</tr>
<tr>
<td>Muddy</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>Unknown</td>
<td>244</td>
<td>6.5</td>
</tr>
</tbody>
</table>

DCA analysis (Table 15) identified that the most common serious injury cases involved collisions between cyclists and other road users travelling in the same direction (20.6%). At intersections, right through (14.6%) and cross traffic (8.5%) collisions were the most common crash types. At mid-block locations, collisions with open car doors (9.2%), left turn side-swipe (5.2%) and rear-end collisions (5.2%) were the most common crash types. Cyclists were also involved in a substantial number of collisions when emerging from footpaths or driveways onto the roadway (13.1%).

### Table 15: Police-reported DCA

<table>
<thead>
<tr>
<th>DCA (Grouped)</th>
<th>Cases (n)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100s – Pedestrian</td>
<td>21</td>
<td>0.6</td>
</tr>
<tr>
<td>110s – Vehicles from adjacent direction</td>
<td>716</td>
<td>19.2</td>
</tr>
<tr>
<td>120s – Vehicles from opposing direction</td>
<td>605</td>
<td>16.2</td>
</tr>
<tr>
<td>130s – Vehicles from same direction</td>
<td>771</td>
<td>20.6</td>
</tr>
<tr>
<td>140s – Manoeuvring</td>
<td>610</td>
<td>16.3</td>
</tr>
<tr>
<td>150s – Overtaking</td>
<td>30</td>
<td>0.8</td>
</tr>
<tr>
<td>160s – On Path</td>
<td>537</td>
<td>14.4</td>
</tr>
<tr>
<td>170s – Off Path on Straight</td>
<td>401</td>
<td>10.7</td>
</tr>
<tr>
<td>180s – Off path on Curve</td>
<td>22</td>
<td>0.6</td>
</tr>
<tr>
<td>190s – Passenger or Miscellaneous</td>
<td>25</td>
<td>0.7</td>
</tr>
</tbody>
</table>
7.2.3 Case comparisons

Comparisons of collision characteristics were made between the coronial reported cases and the police report cases to identify if there are any significant differences between crashes resulting in serious or fatal injury outcomes.

Across the two data sets, males were involved in the majority of collisions in both data sets (89% vs 77%), however, they were found to be involved in significantly more cases resulting in a fatal outcome compared with female cyclists \( (\chi^2_{(1)} = 11.6, p = 0.00, \varphi_c = 0.05) \). Likewise, cyclists 65 years of age and older, were significantly over-represented in the coronial dataset compared with younger cyclists \( (\chi^2_{(3)} = 33.2, p = 0.00, \varphi_c = 0.05) \).

Helmet use was significantly lower for the fatal cases with 20 percent of fatally injured cyclists reported to not be wearing a helmet compared to only 8 percent in the police reported data \( (\chi^2_{(1)} = 65, p = 0.00, \varphi_c = 0.13) \). Not surprisingly, the primary injury type for cyclists not wearing helmets in the coronial database were head, neck or brain injuries, representing 77 percent of non-helmeted cyclist injuries.

Several temporal differences were observed between the two datasets. The coronial database recorded significantly more fatalities on weekends compared to weekdays \( (\chi^2_{(1)} = 25.5, p = 0.00, \varphi_c = 0.07) \). Analysis of the time of collisions also revealed that fatal cases were significantly more likely to occur between midnight and 6am compared to serious injury cases, while no significant differences were observed throughout the remainder of the day \( (\chi^2_{(3)} = 43.0, p = 0.00, \varphi_c = 0.06) \).

Comparison of the speed zones where collisions occurred revealed that fatal collisions more frequently occurred when the speed environment was greater than 60km/h compared with serious injuries \( (\chi^2_{(1)} = 43.0, p = 0.00, \varphi_c = 0.1) \). While it is noted that neither the coronial nor police-reported datasets contain a great deal of detail regarding actual vehicle speeds at the time of collisions, it was not surprising that fatal injury outcomes were more common in higher speed environments. This assumes that the higher rate of fatal collisions in higher speed zones is likely a result of the higher levels of kinetic energy involved in the collisions which result in more severe injury outcomes and this is coupled with the reduced likelihood of road users being able to take evasive action in the event of an imminent collision.

When considering the location of crashes, there were significantly more fatal collisions at mid-block locations, compared to intersections \( (\chi^2_{(1)} = 25.2, p = 0.00, \varphi_c = 0.08) \). Fatal collisions were also more likely to involve fixed or stationary objects \( (\chi^2_{(3)} = 85.7, p = 0.00, \varphi_c = 0.09) \) compared to non-fatal collisions. It is difficult to draw conclusions here, as this finding is likely to be a result of the under-reporting of single-vehicle collisions in police-reported datasets (Sikic et al. 2009, Garrard et al. 2010, Boufous et al. 2013).

Analysis of key crash types revealed that fatal collisions were more likely than serious injury collisions to involve vehicles travelling in the same direction (27% vs 21%) and cyclists losing control of their bicycle (28% vs 12%). In contrast, serious collisions were more common at intersections (35% vs 19%) (Figure 36).
In was interesting to note that few car-door collision cases were found in coronial database, however they were a common source of serious injury reported in Victoria. Overall the findings show that there are significant differences between fatal and serious injury outcome cyclist collision, however, there were many similar trends emerging from both datasets. Common issues included gender (male), age (older adults) and speed (higher speed environments).

When considering the main types of crashes, crashes involving vehicles travelling in the same direction were the most common. These collisions included rear-end, side-swipe and car-door collisions. For intersection collisions, left turn side-swipe, right through and cross traffic collisions were the most common crash types.

### 7.2.4 Prominent collision types

This section presents a discussion of the most prominent collision types that were identified in the coronial and police-reported datasets. These crashes represent frequently occurring collision types that result in serious and fatal injuries and it is intended that through identifying these types of collisions and contributing factors there is the potential to identify infrastructure treatments that can significantly reduce cyclist collisions while at the same time reduce the perceived and actual risk associated with cycling on-road, which in turn may help to increase cycling participation.

Five crash types have been discussed:

- Rear-end collisions;
- Side-swipe collisions;
- Car-dooring collisions;
• Cross traffic collisions; and
• Right through collisions.

The intention of this phase of the thesis is to identify the key factors associated with these crash types, link these features with the principles of the “Safe System” and KEMM approaches and best-practice design principles, and apply this to the investigation of road design concepts to address these crash types. Due to the similarities between rear-end and side swipe collisions these crash types were combined for the purpose of this discussion.

7.2.4.1 Rear-end and side-swipe collisions

Rear-end and side-swipe collisions featured prominently in both the coronial and police-reported datasets. Diagrammatic representations of the typical circumstances of these crashes are presented in Figure 37 and Figure 38 respectively. In total, 27 cyclists were fatally injured in urban areas of Australia while 366 cyclists were seriously injured in major urban regions of Victoria between 2006 and 2015, as a result of these collision types.

These collisions represent the issues of insufficient lateral clearance between cyclists and motor vehicles. They are also a particularly hazardous crash type for cyclists for two reasons. First, these collisions are likely to involve high levels of kinetic energy as they tend to occur when motor vehicles are passing cyclists at mid-block locations when they are likely to be travelling at speed. Second, cyclists have a very limited ability to foresee and anticipate these collisions as the motor vehicle approaches the cyclist from behind, therefore limiting the cyclists’ ability to take evasive actions to avoid the collision. Furthermore for side swipe collisions the lateral space that cyclists has to manoeuvre within is often constrained by the edge of the road, or by other roadside objects such as parked cars or street furniture.

Analysis of police reported crashes found that the majority of these collisions occurred between cyclists and light vehicles (cars, SUVs, utilities etc.), based on vehicle characteristics collected by police, the average mass of the motor vehicles involved in these collisions was found to be 1800kg. Furthermore the majority of these collisions occurred in 60km/h speed zones. Using these heuristic values, these collisions would result in a transfer of up to 246 kilojoules of kinetic energy in a rear-end collision. This level of energy is far beyond the average human’s tolerance to kinetic energy forces for a collision (Corben et al. 2010, Candappa et al. 2015), illustrating why these collisions are over-represented in datasets concerning more severe injury types.
When considering the collisions reported in the coronial database that occurred in urban environments several common themes emerged. The collisions tended to occur on two way roads with two traffic lanes in each direction and on roads with an approximate width of 14 metres. The cyclist was often riding towards the edge of the road either on a sealed shoulder of within the kerbside traffic lane and the majority of collisions occurred at locations with a speed limit of 60km/h or greater.

Based on the principles of the “Safe System”, KEMM and Sustainable Safety approaches, as the speed environment increases beyond the tolerance of road user groups there is a need for increasing separation between modes of transport, based on their travel speed, mass and direction of travel. Due to the high frequency of these collision types it would suggest that, in Australia, insufficient space is provided for cyclists within the carriageway and that cyclists are at risk of collision when sharing space with motor vehicles.

Austroads recommend that, in 60 km/h speed zones and above a minimum lateral clearance of 1.0m should ideally be provided for cyclists (Levasseur 2014). However in many of the crash locations identified in the coronial and police datasets there were limitations in the ability to widen the carriageway to provide additional space for cyclists. One possible method for creating additional space for a dedicated bicycle facility is through narrowing the traffic lanes. This concept is frequently utilised in the USA, often referred to as a “lane diet” (AASHTO 2012).

In addition to providing more space for cyclists, there is a large body of literature showing speed reduction benefits of narrower traffic lanes. As an example, Godley et al. (2004) established that narrower traffic lanes can be utilised as a perceptual countermeasure that can be beneficial in reducing vehicle speeds. As such re-
allocating space from the traffic lanes into dedicated bicycle lanes could fulfil multiple goals of: lowering motor vehicle speeds and reducing the kinetic energy levels in the event of a collision; affording greater separation between cyclists and motor vehicles; and, reducing the exposure of cyclists to collisions and resulting in increases time for reaction for motor vehicle drivers. Additionally the re-allocation of road space has the added benefit of minimal construction costs compared to road widening.

7.2.4.2 Car-door collisions

Car-door collisions were a prominent crash type within the police-reported dataset, with 346 car-door crashes reported in urban areas in Victoria over the study period (Figure 39). It is noted that this collision type did not feature greatly in the coronial dataset, nor did it feature prominently in the major trauma hospital reported cases that were analysed by Beck et al. (2016), suggesting that car-door collisions more commonly result in less severe injuries to the cyclist compared with other collision types. However, despite the relatively low number of fatal car-door collisions reported, car dooring collisions are frequent and have gained prominence following a number of high profile cases.

![Figure 39: DCA 163 Vehicle door collision](image)

Similar to rear-end and side-swipe collisions, car-door collisions represent an issue of provision of insufficient lateral clearance for cyclists both within the road reserve and by other road users. These collisions occur when parked motor vehicle occupants open their door into the on-coming path of cyclists. This can result in a range of hazardous situations for cyclists. Often the cyclist has insufficient time to brake to avoid hitting the door and will collide with the vehicle door, either with a direct collision with the door, or with part of the bicycle typically the
handlebar or pedal hitting the door. Alternatively the cyclist may swerve to avoid the collision with the vehicle door, this can result in the cyclists being hit by motor vehicles travelling in the adjacent traffic lane. These types of collisions are often recorded as rear-end or side-swipe collisions, as the cyclist did not hit the car-door, despite the opening car-door being a key contributing factor in the collision. A third mechanism of injury is when the cyclist loses control of their bicycle as a result of rapid deceleration or swerving, resulting in the cyclist falling from their bicycle. This is often reported as a single vehicle collision as there was no physical interaction between the cyclist and another road user. Each of these collision types can result in secondary injuries when the cyclist is hit by adjacent motor vehicle traffic following the initial collision with the vehicle door.

In Europe the issue of car dooring has been addressed, through a range of treatments and programs. Behaviour change programs have been implemented that teach motor vehicle drivers to look for cyclists when opening their door. This practice is enhanced by teaching vehicle occupants to open their door using their inside hand, which encourages the occupant to perform a head-check over their shoulder (Munro 2012). However, a review of the literature did not identify any evaluations of the effectiveness of these behaviour change campaigns.

In contrast, there are a number of infrastructure/road design treatments that have been shown to address the issues of car dooring collisions. For example, in best-practice European countries such as Denmark, when bicycle lanes and on-street parking occur on the same street, it is general practice to place the cyclist closest to the kerb (Munro 2012). Kerbside bicycle lanes, also referred to as ‘Copenhagen’ style lanes in Australia when physical separation is included in the design, effectively swap the position of the bicycle lane and on-street parking. This lane configuration is also referred to as a parking protected bicycle lane in the USA (NACTO 2014). This treatment has been shown to reduce the risk of car-door collisions due to the reduced frequency of passenger vehicle doors opening compared to driver side doors, furthermore if a car-door collision does occur the cyclist typically will not fall into the path of adjacent traffic, reducing the chance of secondary injuries to the cyclist (Munro 2012).

There are other benefits associated with re-allocating bicycle lane locations. By shifting the location of parked cars, cyclists are protected from adjacent traffic and the risk of rear-end and side-swipe collisions is largely removed. Placing bicycle lanes kerbside also removes the need for motor vehicles to cross the bicycle lane when parking parallel to the kerb, which in turn reduces the number of conflict points between cyclists and motor vehicles. Within the police-reported crash dataset 65 crashes were reported which resulted from a motor vehicle hitting a cyclist when entering or exiting a parking space parallel to the roadway. While this is only a small number of collisions and no fatal injuries were recorded, these collisions could largely be avoided when bicycle lanes are placed kerbside. Furthermore, by providing space for cyclists through bicycle lanes, there is the potential to reduce some exposure to hitting stationary parked cars, which was the injury mechanism for over eight percent of mid-block cyclist collisions.

Road cross-sections can also be designed to encourage avoidance of the car dooring zone by cyclists and result in a reduction of opening of doors into the path of cyclists by vehicle occupants. One such concept is the use of
buffered bicycle lanes. This style of bicycle lane is used in the USA, in particular in Portland Oregon and the concept has been incorporated into American best practice design standards (AASHTO 2012). When evaluating this style of bicycle lane Monsere et al. (2011) found that 95 percent of cyclists were concerned about being stuck by an open car-door in conventional bicycle lanes, compared to only 36 percent in buffered bicycle lanes.

7.2.4.3 Cross traffic collisions

Cross traffic collisions occur when a cyclists and a motor vehicle are both travelling along straight paths perpendicular to each other (Figure 40). Cross traffic collisions are classified as an intersection collision, however they are not exclusive to major intersections and can also occur at intersections between major and minor roads or at vehicle crossovers, such as at driveways or entrances into car parks.

![Figure 40: DCA 110 Cross traffic collision](image)

Cross traffic collisions were the leading intersection type collision identified in the coronial dataset resulting in 15 cyclist fatalities. They were also the second most common serious injury collision type to occur at intersections in the police-reported dataset with 320 serious injuries reported in urban areas throughout Victoria.

The prevalence of these collisions is high due, in part, to the fact that there are a wide range of circumstances that can lead to cross traffic collisions. For example at intersections these collisions can occur if the cyclist or the motor vehicle travels through a stop sign or a red light, with one road user failing to obey the priority at the intersection. This was the primary mechanism for many of the fatal injuries identified in the coronial dataset. Ten cases were identified that involved cyclists failing to stop or give way prior to entering an intersection, or entering the intersection against a red traffic signal.

In several of the coronial reported cases, cyclists were travelling downhill on approach to the intersection, were travelling at considerable speeds, and therefore not able to stop in time and continued to move into the intersection where they were struck by the through moving vehicle. It was also noted that, in a number of cases, the cyclist lost control of their bicycle on approach to the intersection, resulting in the bicycle tyres losing traction.
with the roadway and skidding or the bicycle rear wheel lifting from the ground due to heavy application of the front brake. There were also three reported instances where motor vehicles entered an intersection and collided with cyclist who had the right-of-way.

Other commonly reported mechanisms that result in cross traffic collisions include, cyclists becoming “trapped” if they do not clear the intersection before the traffic signal turns green for cross traffic, this situation can be further complicated if motorists sightlines are obstructed by adjacent traffic. At minor intersections or at driveways, cross traffic collisions can occur when the motorist or cyclist fail to stop and look before entering the roadway, or there are significant sight distance restrictions.

Cross traffic collisions contain a common element in that one of the road users failed to give priority to the vehicle currently in the intersection. In their in-depth analysis of intersections crashes on behalf of the USA National Highway Traffic Safety Administration (NHTSA), Chio (2010) identified that almost all (96%) intersection crashes involved driver error. In 55 percent of cases, recognition errors were identified, that is driver inattention, inadequate surveillance and distraction, while in 30 percent of cases driver error was due to aggressive driving, incorrect expectations of driver behaviour, speeding or misjudging gaps in traffic.

Inadequate surveillance is defined as a situation where a driver is required to look to safely complete a manoeuvre and either fails to look or looks but does not see (Dingus et al, 2006). This is particularly prevalent in collisions involving cyclists and motor vehicles. Collisions where one road user fails to obey priority at the intersection typically involve severe injuries due to the high speed involved in the collisions (Candappa et al. 2015).

There are a number of ways that infrastructure can be utilised to reduce this type of collision, particularly for cyclists. Designs that reduce cyclist and motor vehicle speed on approach to an intersection are likely to help to reduce the kinetic energy involved in a collision and also increase road user reaction times (Corben et al. 2010). Furthermore designs that bring vehicles to a stop on approach to an intersection are also likely to be beneficial. This could be achieved through either vertical or horizontal deflection, or through the use of perceptual countermeasures such as lane narrowing (Mountain et al. 2005, Corben et al. 2010). Measures to improve sight distance at intersections are also likely to be beneficial for all road users. Besides infrastructure measures there is clearly a need to address both cyclist and motor vehicle user behaviours in terms of compliance with road rules and intersection priority and encourage road users to adopt safer speeds, particularly on approach to intersections.

### 7.2.4.4 Right through collisions

Right through collisions are another example of common intersection collision resulting in high levels of trauma to cyclists. Collisions occur when either a motor vehicle or a cyclist are attempting to turn right and are hit by, or hit an oncoming road user (Figure 41).
A common situation for these crashes is when cyclists are travelling straight along a road, often on approach to an intersection where motor vehicle traffic are required to form a queue, however the cyclists is still able to continue forward towards the stop line by riding on the left side of the stationary queue of motor vehicles. In this situation a motor vehicle attempting to turn right between a gap in queued vehicle traffic to access a side street may fail to notice and give priority to the through moving cyclist, often as their line of sight is obstructed by other stationary motor vehicles and as such the turning motor vehicle collides with the through moving cyclists. This situation accounted for two-thirds of right through collisions in the coronial dataset.

![Figure 41: DCA 121 Right through collision](image)

The other common mechanism for these collisions was when the cyclists were turning right at intersections and failed to judge the gap in traffic, or a motor vehicle unexpectedly travelled through the intersection. This situation was also a common mechanism for fatal injured cyclists.

Right through crashes can be addressed by improving sightlines for road users at intersection locations. Measures to alert motor vehicle drivers to the potential for cyclists may also reduce the prevalence of these collisions. One such approach is by provision of continuous bicycle lanes through major intersections and also by increasing the conspicuity of bicycle lanes at minor intersections. This is often achieved by painting conspicuous bicycle lanes across the face of the minor street intersection. At major intersections, fully controlled right turn phases have the potential to separate conflicting through and right turning movements, reducing the exposure of cyclists to right turning vehicles.
7.3 Discussion

Analysis of fatal and serious injury cyclist collisions provided valuable insight into the common crash types resulting in serious and fatal cyclist injuries both in Victoria and throughout Australia.

The analysis highlighted some general trends in cyclist crashes. Specifically, while intersections are the most common serious injury crash type for multiple vehicle cyclist collisions, fatal collisions commonly occurred at mid-block locations. This is possibly due to the increased levels of kinetic energy involved in collisions at mid-block locations where motor vehicles and cyclists are travelling a higher speeds.

Helmet use was also found to be proportionally lower amongst the sub-set of fatally injured cyclists, indicating the safety benefits of cyclist wearing helmets. The low levels of helmet usage reported amongst this group was of some concern. It is possible that, had a helmet been worn in some of these collisions, the injury consequences may have been lessened, however this is purely speculative.

The presence of alcohol and drugs in post mortem examinations of a substantial number of fatally injured cyclists was also concerning and highlighted that impairing substances may be a contributing factor in a considerable proportion of cyclist collisions. However it is noted that there are various issues associated with post-mortem examination of impairing substances, particularly as it is unclear if substances were taken preceding the crash or were administered proceeding.

Based on the findings from analysis of 10 years of cyclist collision data, five prominent crash types were identified:

- Rear-end collisions;
- Side-swipe collisions;
- Car dooring collisions;
- Cross traffic collisions; and
- Right through collisions.

These five types of crashes represent 42.0 percent of serious injury and 32.7 percent of fatal injury collisions involving cyclists identified in the respective datasets. Rear-end, side-swipe and car dooring collisions are largely a result of insufficient lateral clearance being provided between the cyclist and the adjacent motor vehicle. Austroads identified space to ride as one of the six key requirements for cyclists (Levasseur 2014) and identify that cyclists require separation from motor vehicles in order to enhance their safety and comfort when riding on-road (Levasseur 2014). These three crash types highlight that cyclists are at risk when they are required to ride on-road in locations where inadequate space is provided and where vehicle speeds exceed human tolerance.

One of the most commonly utilised methods for providing space for cyclists, is through the installation of on-road bicycle lanes. Previous research suggests that the presence of on-road bicycle infrastructure is associated with a reduced crash risk (Reynolds et al. 2009, Teschke et al. 2014). However, the presence of on-road bicycle
infrastructure does not guarantee safety for cyclists, as noted by Beck et al. (2016) who identified that one fifth of on-road cycling crashes in Victoria occurred when a cyclist was travelling in a designated and marked bicycle lane. Furthermore the study identified that the presence of on-street parking was associated with an increased crash risk for cyclists, partially due to the increased chance of car door collisions. These findings suggest that cyclist continue to remain at risk when riding on-road in bicycle lanes and that bicycle lanes by themselves, or design features of bicycle lanes, are not sufficient measures to reduce cyclist crashes. Instead the design of bicycle lanes must be evidence-based and adopt best practice cyclist design principles in line with “Safe System” thinking. This may include encouraging enhanced spatial separation or reconsidering road cross-sections.

Both cross traffic and right through collisions appear to represent issues of poor gap selection and sight lines or inappropriate road user behaviour. Measures that improve sight lines, lower vehicle speeds and reduce conflict points between opposing vehicles may all be effective countermeasures to address these crash types.

The analysis undertaken in this chapter has provided valuable insight into the factors associated with serious and fatal cyclist crashes, however the study design is not without limitations. First, analyses of crashes resulting in the most serious injuries alone are likely to neglect some crash types that may be highly prominent, yet typically result in less serious injuries. Second, there are discrepancies amongst the two datasets. As previously mentioned the coronal dataset only includes closed cases, as such several cases that are still under investigation were not captured in the analysis. This resulted in fewer cases in more recent years being available for analysis.

The issues with the use of the Victorian police-reported dataset has also previously been identified by Boufous et al. (2013), Garrard et al. (2010) and Sikic et al. (2009), particularly that the dataset tends to focus on multiple vehicle collisions therefore under-reporting single vehicle (bicycle only) collisions. Both datasets are also subject to coding errors. For the coronal dataset, cases were selected if the object or substance inducing injury was coded as a pedal cycle. However there is the potential that this selection criterion missed some cases without this description. Similarly for police-report crashes, it is possible that mode of transport could have been incorrectly coded. In particular there are instances where cyclists may have been coded as a pedestrian and vice versa. Despite these limitations, the analyses highlighted several prominent crash types in both datasets that account for a significant level of trauma to on-road cyclists when riding in urban road environments.

In the previous chapter, the bicycle simulator was found to have absolute validity when measuring cyclist position within the roadway and when passing roadside objects. The issues of vehicle side-swipes, rear-end collisions and car dooring can all be addressed through the provision of additional separation of cyclists from motor vehicles and the effect of these treatments on cyclist behaviour can be reliability measured using the bicycle simulator. The crash analysis also identified that a high proportion of fatal cyclist collisions occurred on mid-block road locations. Furthermore it could be argued that while intersections collisions are a hazard to cyclists, it is more often the motorist who is at fault in these collisions and that treatments should be developed that improve driver performance and these treatments would require evaluation from a motorist’s perspective. Given these
factors, mid-block crashes were selected for further investigation in the remaining chapters of this thesis, with particular focus on rear-end, side-swipe and car-door based collisions. The following chapter investigates these three crash types and identifies a range of lane design and perceptual countermeasures aimed at reducing the risk of cyclist collisions.
Chapter 8: Infrastructure for safer cycling

This chapter presents the cycling infrastructure concepts that were selected to address the key crash types identified in Chapter 7. The infrastructure concepts were selected by referring to the principles of the “Safe System” and the KEMM (Chapter 2) and the principles of best practice cycling infrastructure design (Chapter 3).

The bicycle lane concepts in this chapter focus on addressing three of the collision types identified in the analysis conducted in Chapter 7, namely, rear-end (DCA 130), side-swipe (DCA 133) and car door collisions (DCA 163). In Chapter 7 it was established that these three crash types represent some of the most commonly occurring collision types both within the coronial dataset for Australia and the police reported dataset for Victoria, suggesting that these collisions represent a road safety issue for cyclists at various levels of injury severity.

These collision types were also selected for further analysis as there are strong synergies regarding the mechanisms of injury and the likely measures that can be implemented to reduce the frequency of occurrence. That is to say, these collision types typically occur at mid-block locations (not at intersections) and occur when the cyclist and sometimes adjacent motor vehicles are travelling at speed. As a result of this, there are high levels of kinetic energy involved, often beyond the biomechanical tolerance of unprotected road users. Another common characteristic is that insufficient lateral clearance or spatial separation between cyclists and adjacent motor vehicles is associated with the risk of collision.

The concepts identified in this chapter focus on mid-block treatments that would be applicable for implementation between intersections. Intersection treatments were not considered in this assessment as a different sub-set of collision types are relevant at intersection locations and assessing these infrastructure treatments is beyond the scope of this research. However, this is not to say that there may be benefits associated with continuing mid-block treatments through intersections to maintain an established right of way for cyclists.

In the previous chapter the issues surrounding commonly occurring mid-block crash types and their contributing factors were identified. This chapter begins with a brief review of the crash analysis findings from Chapter 7 and the design principles and theoretical frameworks guiding the research identified in Chapters 2 and 3. Following the overview a set of “Safe System” bicycle lane design principles have been identified. Using these principles a set of bicycle lane concepts (both physical infrastructure designs and perceptual measures) were selected for evaluation using the bicycle simulator. Both types of infrastructure concepts are hypothesised to increase the spatial separation and reduce the interactions between cyclists and motor vehicles and hence reduce the frequency and severity of cyclist mid-block collisions.
8.1 Collision analysis key findings

The previous chapter identified five of the most commonly occurring serious and fatal collision types for cyclists that occur within urban road environments in Australian metropolitan regions. The collision types identified were:

- Rear-end collisions (DCA 130);
- Side-swipe collisions (DCA 133);
- Car-dooring collisions (DCA 163);
- Cross traffic collisions (DCA 110); and
- Right through collisions (DCA 121).

Due to the similarities between rear-end and side-swipe collisions these two collision types were combined for the purpose of analysis. Furthermore it was established that there are a number of similarities between these collisions types and car-dooring collisions. As such it was decided to consider these three crash types (DCAs 130, 133 & 163) in greater detail for the infrastructure evaluation.

While the issues surrounding intersection collisions are important when considering on-road cyclist safety, there was not sufficient scope within this thesis to undertake an investigation of both mid-block and intersection collisions, particularly as intersection collisions involve a high level of complexity. Furthermore, as this was the first application of the simulator as a research tool for the evaluation of infrastructure, it was logical to address a somewhat less complex issue. It is proposed that the issues surrounding intersection collisions will be assessed and infrastructure solutions will be evaluated using the simulator as part of the broader research project and future research.

To briefly summarise the previous chapter’s findings, mid-block cyclist crashes were found to be the most prominent fatal crash type within urban environments in Australia, representing 61.2 percent of fatal cyclist collisions in metropolitan regions of Australia. The majority of these collisions, occurred in speed zones of 60km/h or lower (70.7%), and involved the cyclist being struck by either a heavy or light vehicle (65.3%). Furthermore 40.3 percent of serious injury collisions in metropolitan regions in Victoria occurred within mid-block locations. Car door collisions were the second most prominent collision type overall and the most common mid-block collision type representing 9.2 percent of all serious injuries collisions, while the combination of rear-end and side swipe collisions represented another 9.7 percent of serious injury collisions in metropolitan regions of Victoria. These findings highlighted the issues of insufficient lateral clearance between cyclists and motor vehicles and highlighted that certain mid-block road cross section infrastructure improvements have the potential to reduce interactions.
8.2 Principles of safe road systems

In order to select appropriate bicycle lane design concepts for evaluation using the bicycle simulator, reference was made to the theoretical frameworks and the bicycle design concepts identified in Chapter 2 and Chapter 3.

The key principles of the “Safe System”, KEMM and best practice bicycle facility design are briefly reiterated below. This is followed by the identification of the key design principles adopted for the cycling infrastructure selection.

8.2.1 “Safe System” and KEMM for cyclists

The “Safe System” approach is structured around a framework that recognises the interaction between different components of the road system. The framework comprises four key principles:

1. Recognising the limits of human performance and acknowledging that humans will make mistakes and that the system should be designed so that these errors can be accommodated;
2. The limits of human tolerance to violent forces;
3. Shared responsibility between road users, designers, operators and governments; and
4. Creating a forgiving road transport system.

These principles are targeted towards the development of evidence-based interventions that consider the four key elements of the road system being the road users, their vehicles, road user speeds and the interactions made between road users and the road and roadside environment.

When considering cyclists within the “Safe System” framework, the need to develop a forgiving road system and one that recognises the limits of human tolerance to violent forces seem to be particularly relevant to cyclists, due to their vulnerability and lack of protection from violent forces. This suggests that road infrastructure for cyclists requires increasing levels of separation based on the differing physical properties of road users. Accordingly, the “Safe System” would advocate for a dedicated right of way for cyclists when riding on-road in higher speed road environments such as adjacent to arterial roads. While fully segregated facilities would be appropriate, through the use of cycle paths etc., when cycling adjacent to highways and freeways where the volume of traffic and speed differential would pose an unacceptable risk to cyclists.

The principles of the “Safe System” have strong synergies with the KEMM. The KEMM highlights that injuries to road users, including cyclists, occur when there is a transfer of kinetic energy that is beyond the levels of human biomechanical tolerance (Corben 2004).

Considering both the KEMM and the “Safe System” in unison when addressing cycling infrastructure there is a need to create infrastructure that supports a forgiving road transport system where minor mistakes by cyclists or motor vehicles do not result in serious consequences. Infrastructure must be developed with recognition of the limits of human performance and should not result in increased task loads on road users in order to interpret or interact with the infrastructure. Furthermore the infrastructure must be developed in recognition of the human
tolerance to violent forces. For cyclists it is not practical to increase the biomechanical tolerance of the human to violent forces, furthermore there are limited methods to attenuate the transfer of kinetic energy to the human, with exceptions of the use of bicycle helmets and newer technologies such as vehicle hood airbags. As such the methods for reducing kinetic energy must focus on reducing the level of kinetic energy involved in the crash, reducing the risk of the crash for the given exposure or reducing exposure.

8.2.2 Cycling design principals

Throughout the review of cycling infrastructure a key set of design principles were identified in various Australian and International of cycling design guides. The principles highlight the need for bicycle facilities and networks to consider cyclist safety and comfort in design as well as ensuring that facilities are coherent, attractive and direct. The Australian formulation of these principles is summarised in Chapter 3: Table 1.

The key theme of this research is developing cycling infrastructure to address safety concerns. Within the cycling principles, the safety for cyclists is defined as minimal risk of traffic related injury, low perceived danger, space to ride and minimum conflict with vehicles. These concepts align with “Safe System” principles in that there is a need to minimise the risk of injury to cyclists and the principles identify that this can be achieved by creating space for cyclists to ride and minimising the conflict with motorised vehicles. Both of these requirements can be achieved for mid-block bicycle lanes by increasing the spatial separation between cyclists and adjacent motor vehicles. Interestingly, the principles also highlight the need for a low perception of danger. This aligns with research by Fishman et al. (2012) and Garrard et al. (2008) in Australia that highlights that the perception of danger associated with cycling is one of the key barriers to increased participation.

The principles of attractiveness and comfort also align with the need for safer cycling infrastructure. For example lighting, and personal safety are both components of attractiveness, while riding surface and the need to avoid complicated manoeuvres and interaction with motorised vehicles both enhance cyclist perception of safety and their comfort.

The principles of increased separation were further reiterated by Austroads in presenting their speed versus traffic flow diagram as shown in Figure 2 of Chapter 3. This highlights the need for increased separation between cyclists and motor vehicles as the volume and speed of motor vehicle traffic increases, a concept that strongly aligns with “Safe System” and KEMM philosophies. In Australia, for speed environments less than 60km/h, provided the traffic volume is low, the Austroads guideline recommend that cyclists can operate in mixed traffic. Between speeds of 40km/h and 60km/h cyclists require bicycle lanes or off-road bicycle paths as the traffic volume increases. In low traffic volume environments for speeds between 60km/h and 80km/h it is suggested that cyclists can utilise sealed shoulders or shoulder lanes. While at higher speeds and volumes fully separated facilities are required. Austroads recommends that road authorities should aim to comply with the guidance within the document; however they also recognise that this may not be possible when retrofitting sites.
The Copenhagen design guide propose a more dramatic hierarchy of cycling facilities that better align with the principles of the KEMM and the biomechanical tolerance of cyclists. The guides identify the increased separation required between bicycles and motorised traffic as speed environment increases. Specifically, at low speeds, 30km/h and below, no separation is required and cyclists and motor vehicles can interact within the same space. In 40km/h zones installation of kerbside bicycle lanes is recommended, between 50 and 60km/h kerb separated lanes are recommended and at higher speeds full separation of bicycles from motorised modes of transport is recommended. In the following section concepts for providing dedicated space and increased spatial separation for cyclists at mid-block locations are discussed. This is followed by a discussion of the bicycle lane concept designs that will be evaluated in the simulator studies presented in Chapter 9 and 10.

8.2.3 “Safe System” bicycle lane design

The most effective way to reduce on-road cyclist collisions is through provision of fully segregated cycling facilities that remove cyclists from any interaction with motor vehicle traffic and create a complete cycling network. Such networks are emerging in many best-practice cities around the world (including some Australian locations within inner city regions), where cyclists are provided with their own dedicated right of way and are given priority over or are separated from motor vehicle traffic at intersections. However these networks are very costly to develop and it is often not practical, at least in the short term, for fully segregated networks to be developed across an entire city. As such, for the time being, there will remain a need for cyclists to interact with motorised vehicles within the same road reserve.

The next most promising road design mechanism to reduce cyclist injury would be lowering speed limits and travel speeds for motorised vehicles. Lowering speed limits and motor vehicle speeds has the potential to reduce the frequency and severity of on-road cyclist injuries in two ways. Firstly reductions in motor vehicle speeds can result in a significant reductions in kinetic energy in the event of a collision (Corben 2004). Lowering vehicle speeds would also increase the time available for road users to react to situations and would reduce the time and distance required to brake in the event of an imminent collision (WHO 2008). Research has shown that, for unprotected road users such as pedestrians and cyclists, the human tolerance to injury is exceeded if they are struck by a motor vehicle that is travelling at more than 30km/h (Rosén et al. 2011). Internationally, 30km/h speed limits have been implemented particularly in city centres and in mixed use zones, such as strip shopping centres and pedestrian malls (Haworth & Symmons 2001, Archer et al. 2008). However within an urban road environment there are practicalities that need to be considered regarding speed limits. While there are benefits associated with lowering speed limits on already congested sections of road, such as on inner city streets in the CBD and high street shopping districts (Archer et al. 2008), it is not realistic to lower the speed limit to 30km/h across the entire road network as this would reduce the capacity of the network and limit the ability to provide a movement function (Archer et al. 2008). Furthermore due to the layout of the road network in many Australian cities, the arterial road network provides the most direct route to key destinations (and therefore popular with many cyclists), however these roads are typically characterised by higher speed limits and higher traffic volumes.
due to their movement function within the road hierarchy (Brindle 1996, Brindle 2003). During peak times it may be practical to lower the speed limits on these roads when actual travel speeds are closer to posted speed limits. However outside of congested periods low speed limits are likely to see low levels of compliance and would restrict movement (Archer et al. 2008).

When speeds cannot be lowered to appropriate levels for cyclists and motor vehicles to interact safely and fully segregated cycling facilities cannot be provided then there is a need to accommodate cyclists within the road reserve. As previously stated, the Functionality and Homogeneity, suggest that roads should serve a single function and that there should be equality of direction of travel, and vehicle mass at medium and high speeds. When conflicts occur that contravene these principles road users need to be separated using infrastructure (Wegman et al. 2012).

Essentially as speed environments increase, the principles of “safe speeds” can no longer be adhered to for all road user groups and it is not possible for all road users to interact within the same space. In this situation vulnerable road users need to be separated from larger, faster moving vehicles (Wegman et al. 2012). This translates to cyclists requiring a separate right of way that provides space and priority in medium to high speed road environments. In essence there are two methods for separating cyclists from motor vehicle traffic, either through separation in space (spatial separation), or in time (temporal separation).

Temporal separation is most commonly applied through the use of traffic signals at intersections. For example bicycle signals can be installed at intersections to provide cyclists with a dedicated phase to travel through the intersection (SKM 2010). This reduces the risk of conflict with motor vehicle traffic and allows cyclists to re-establish themselves within the bicycle lane on the far side of the intersection prior to vehicular traffic reaching that point (SKM 2010). However as the focus of this investigation is on mid-block locations rather than intersections, the application of temporal separation is unlikely to be a practical solution for mid-block collision types. Instead, spatial separation is likely to be a more appropriate measure to address rear-end, side swipe and car door collisions at mid-block locations.

There are a variety of methods to provide space for cyclists. The highest level of service would be provided by developing a dedicated bicycle network that fully segregates cyclists from other modes of transportation. When considering segregation, at select locations within the network elevated cycling facilities could be utilised to provide spatial and temporal separation from motor vehicles. However this is usually reserved for significant conflict points such as to bypass a major complex intersection.

Throughout mid-block locations, spatial separation can be achieved through the provision of on-road bicycle lanes. In their review of cycling infrastructure, Reynolds et al. (2009) identified that bicycle-specific facilities consistently provide improved safety for cyclists compared to cycling on-road in mixed traffic. Painted bicycle lanes and off-road bicycle paths have been found to be associated with lower injury risks for cyclists (Harris et al. 2013).
The lowest level of cycling facility is considered to be a wide-kerbside bicycle lane, which as the name suggests essentially provides a widened kerbside lane for cyclists and motor vehicles to share and which increases the space available for cyclists. In Australia, wide kerbside bicycle lanes typically include intermittent bicycle logos to signify the locations where cyclists should ride and to signify that the route is utilised by cyclists (Levasseur 2014). Austroads consider wide-kerbside lanes an appropriate treatment in speed zones of 70km/h or less and for major traffic routes (Levasseur 2014). They specify a minimum desirable width for the kerbside lane as 4.2 metres, however their acceptable range has a lower boundary of 3.7 metres (Levasseur 2014). While the treatment is still accepted in Australia, it is now largely discouraged in the USA (AASHTO 2012).

Formalised bicycle lanes provide a higher level cyclist facility compared to wide kerbside bicycle lanes. The width of these lanes is an important design element and there is a need to consider the design envelop of the cyclists when installing such lanes, as well as the volume of cyclists likely to utilise the facility and the potential need of cyclists to perform overtaking manoeuvres. Austroads recommend a minimum desirable width of 1.5 metres for 60km/h speed environments, with an acceptable range between 1.2 and 2.5 metres. Lane width requirements increase with increasing speed environment of the roadway (Levasseur 2014). However, as mentioned in the previous chapter the mere presence of on-road bicycle lanes do not guarantee safety for cyclists, with recent research conducted in Victoria identifying one-fifth of recruited cyclists admitted to major trauma centres being involved in a collision while they were travelling in a designated and marked bicycle lane (Beck et al. 2016).

Given the substantial number of collisions occurring within bicycle lanes there are clearly elements of lane design that can be enhanced to improve cyclist safety by reducing interaction and encouraging increased spatial separation between cyclists and motor vehicles.

One such concept is the use of buffered bicycle lanes. This style of bicycle lane has been used in the USA and the concept has been incorporated into American best-practice design standards (AASHTO 2012). When evaluating this style of bicycle lane, Monsere et al. (2011) found that 95 percent of cyclists were concerned about being struck by an open car door in convention bicycle lanes, compared to only 36 percent in buffered bicycle lanes. Buffered bicycle lanes represent a form of perceptual countermeasure that is utilised to encourage increased spatial separation between road users and encourage cyclists to adopt safer lane positions. Godley et al. (2004) defined perceptual countermeasures as “non-obtrusive, low cost visual and/or haptic road markings, usually involving only paint or gravel or both”. Perceptual countermeasures have been utilised to encourage drivers to adopt safer driving behaviours, for example, more appropriate speeds on approach to intersections (Fildes et al. 1997), more appropriate lane position and speed when negotiating curves (Fildes et al. 1997, Palamara et al. 2014), and have been shown to encourage more consistent lane positioning for motorists (Godley et al. 2004). While the use of perceptual countermeasures has been shown to have benefits in adapting motor vehicle driver behaviours, applications of perceptual countermeasures to cycling infrastructure have been limited beyond the use of buffered bicycle lanes. Furthermore the benefits of the use of this technique are yet to be quantified and this presents a unique opportunity for simulator-based research.
Moving beyond the use of perceptual countermeasures, physical infrastructure can be utilised to separate modes of transport within the road reserve. This can take the form of installing a physical barrier that prevents motorised vehicles from accessing the bicycle lane and provides delineation. An important consideration for physical infrastructure is to ensure that there is still a degree of permeability to allow for pedestrians to cross the road or for cyclists to exit the bicycle lane to avoid an obstruction or debris (Levasseur 2014). These breaks in the kerb may also be important to maintain the drainage function of the roadway.

Kerb separated bicycle lanes have been trialled at various locations throughout the City of Melbourne. Kerb separation provides a physical barrier between the cyclist and adjacent motor vehicle through the installation of a mountable kerb that separates the adjacent traffic streams (Levasseur 2014). Physical separation can also be created between cyclists and motor vehicles through the use of flexible bollards. Flexible bollards mainly act to visually delineate the lane and will typically bend if struck by vehicles. These style of devices have been utilised in the US and in Australia. The NACTO, Urban Bikeway Design Guide suggests that flexible bollards are an optional inclusion when developing one-way protected cycle tracks (NACTO 2014). The US FHWA also suggests that flexible bollards can be utilised as a channelization device to delineate bicycle lanes and provide physical separation (FHWA 2009).

The highest level of physical separation is provided through the use of vertical separation within the road reserve. This is a concept commonly adopted in European countries where the height of the bicycle lane is raised above the road, typically to the height of the kerb or footpath, and the bicycle lane is separated from both the road and the footpath, within its own dedicated right of way (City of Copenhagen 2013). In Copenhagen, this style of treatment is referred to as a ‘cycle track’ and the treatment is typically installed without a median between the ‘cycle track’ and the traffic lane to maximise the width of the cycle track, however a median is recommended in locations with high levels of crossing pedestrians (City of Copenhagen 2013). In Copenhagen ‘cycle tracks’ are considered a higher level of infrastructure compared to conventional bicycle lanes and they are the preferred treatment for mid-block locations. The style of treatment has also been applied in various locations throughout the US. The Urban Bikeway Design Guide (NACTO 2014) suggests that the use of this style of treatment where possible as it provides a dedicated right of way for cyclists that removes cyclists for interactions with motorised vehicles at mid-block locations (NACTO 2014). Surprisingly, the Austroads guidelines do not make reference to cycle tracks (Levasseur 2014). This presents an opportunity to trial this type of bicycle facility and gather information from participants regarding the perception, understanding and potential use of this style of treatment.

8.3 Bicycle lane designs for evaluation

Based on the bicycle lane concepts discussed above, a set of conceptual bicycle lane designs were selected for evaluation across a range of simulator studies. Four main studies were undertaken assessing: i) the influence of bicycle lane widths on rider performance, ii) the use of perceptual countermeasures to influence cyclist lane positioning, iii) treatments to address rear-end and side-swipe collisions, and iv) treatments for car-door
collisions. Each of the design concepts for these studies is discussed in the following section and the simulator studies are presented in Chapter 9 and 10 of the thesis.

### 8.3.1 Bicycle lane width

At the most fundamental level spatial separation between cyclists and adjacent motor vehicles can be increased by increasing the width of bicycle lanes. Various studies have shown the benefits of bicycle lanes and reduced crash risks associated with on-road cyclist facilities (Reynolds et al. 2009, Teschke et al. 2014).

Austroads identify space to ride as one of the key requirements for cyclists (Levasseur 2014). Space for bicycle lanes can be provided through road widening, where by the kerb is extended, through reallocation of road space, i.e. removing traffic or parking lanes, or by narrowing existing traffic lanes to utilise the space more efficiently (Levasseur 2014). The final concept for providing space for cyclists, through narrowing existing traffic lanes is typically referred to as a ‘lane diet’ and is commonly recommended practice in the US (NACTO 2014).

In their study assessing the influence of perceptual lane width of driver speed Godley et al. (2004) identified a significant reduction in motor vehicle speeds when perceptual lane widths were reduced from 3.0 metres to 2.5 metres, furthermore they also found that the deviation in lateral displacement reduced. However relatively little research has been conducted to understand how lane width can influence cyclist behaviour. To gain an understanding of this issue, the first simulator study assessed how a range of lane widths influence cyclists speed and position, with a particular focus on cyclist lateral position within the bicycle lane and variability in position. Two road cross section configurations were trialled in the study to assess if cyclist change their riding behaviour based on the road environment.

### 8.3.2 Perceptual countermeasures

Perceptual countermeasures have been trialled in various applications to encourage safer driver behaviour. The benefits of perceptual countermeasures are that they are non-intrusive, are relatively inexpensive to implement and can often be applied to existing roads without any major and expensive infrastructure modifications (Godley et al. 2004).

The second study assessed if perceptual countermeasures can be utilised to encourage cyclist to adopt different lane positions when riding on road. The study tested five different pavement marking configurations incorporating buffer bicycle lanes principles in line with the guidance given by the AASHTO and Transportation Officials: Guide for the Development of Bicycle Facilities (AASHTO 2012). The concepts were assessed see how perceptual countermeasures can influence cyclist speed, position and variability.

Following successful results from the initial study a second study was formulated to assess if the use of bicycle lane logos could be utilised as a perceptual countermeasure to generate similar benefits. The perceptual countermeasure and lane width studies are presented in Chapter 9.
8.3.3 Rear-end and side-swipe collisions

Rear-end and side-swipe collisions featured prominently in both the coronial and police-reported datasets. In total, 27 cyclists were fatally injured in urban areas of Australia as a result of these collisions, while 366 cyclists were seriously injured in major urban regions of Victoria between 2006 and 2015.

Both rear-end and side-swipe collisions are particularly hazardous crash types for cyclists, due to the high levels of kinetic energy involved in the collision and limited ability for cyclists to anticipate the collision and take evasion actions, and both crash types represent the issue of insufficient lateral clearance between cyclists and motor vehicles.

The analysis in Chapter 7 identified that in Australia these collisions tend to occur on two way roads, with two traffic lanes in each direction and road widths of roughly 14 metres. The majority of collisions within urban environments were also found to occur on roads with speed limits of 60km/h or greater.

In order to address these collision types, bicycle lane concepts that utilise the design mechanisms of spatial separation, physical separation and vertical separation were investigated. Designs were compared to typical road designs which act as a baseline reference in comparing the relative safety improvements associated with each design.

8.3.3.1 Baseline conditions

Three baseline conditions were included in the study, a scenario with no bicycle lane, a wide kerbside lane scenario and a conventional 1.5 metre bicycle lane. The baseline conditions provide valuable comparisons for how cyclists ride on conventional bicycle lane treatments and help to assess the alternate design treatments.

8.3.3.2 Separated bicycle lanes

Three separated bicycle lane concepts were trialled to address cyclist rear-end and side swipe collisions.

8.3.3.2.1 Bicycle lane with green zone

Concept 1 utilises a green zone within the 1.5 metre bicycle lane with green pavement marking on the 1.0 metre section of the lane that is on the kerbside of the lane. (Figure 42). This is a similar treatment to that trialled in the perceptual countermeasure study discussed previously in this chapter and investigated in Chapter 9. This treatment utilises perceptual countermeasures to provide a visual cue to cyclists as to where they should ride within the bicycle lane, however the lane still provides 1.5 metres width for cyclists.
The second concept provides a chevron buffered between the cyclist and the adjacent vehicular traffic (Figure 43). Rather than encouraging cyclists where to ride, as in the previous design, this treatment discourages cyclists from riding close to traffic through the use of a chevron buffer. The concept consists of a 1.5 metre bicycle lane with chevron marking painted on the 0.5 metres adjacent to the traffic lane. This treatment may also have an added benefit in that it discourages motor vehicle drivers from driving on the chevron buffer resulting in increased spatial separation between the cyclist and adjacent motor vehicle traffic, however this would require a separate study to assess motor vehicle drivers behaviours which is beyond the scope of this thesis.

The third separated bicycle lane concept is very similar to the previous buffered lane. The main difference is that an alternate marking scheme is utilised to provide the buffer between the bicycle lane and the traffic lane (Figure 44). The proposed marking scheme is intended to represent the location of an open car door and provide a visual cue both to the cyclist and car passengers where car doors are likely to open.
8.3.3.3 Physically separated bicycle lanes

Physical separation has an added benefit over spatial separation as it forms a physical barrier between cyclists and adjacent motor vehicles. When physical separation is utilised to delineate a bicycle lane, motorists would need to perform a gross error to enter the bicycle lane. However physical separation also restricts the lateral movement of cyclists and this can cause issues if cyclists wish to turn, or if they need to swerve or change positions to avoid another road user or objects on the roadway such as debris. Two concepts were identified that provide physical separation between the bicycle lane and motor vehicles. These are: traffic bollards and kerb-separated bicycle lanes.

8.3.3.3.1 Traffic bollards

This concept utilises flexible bollards to create physical separation between bicycle lanes and adjacent traffic lanes. As previously mentioned, similar concepts have been utilised in various location around the world, including in Metropolitan Melbourne. Typically the flexible bollards are around 1.0 to 1.5 metres in height and have either a narrow diameter to reduce surface area or are flat and approximately 100 mm wide.

Flexible bollards do not provide any physical protection for the cyclists, they would simply bend on contact with motor vehicle, instead they are intended to provide a strong visual indication to motorists not to enter the bicycle lane. The concept for utilising flexible traffic bollards is illustrated in Figure 45. The concept again consists of a 1.5 metre bicycle lane width flexible bollards placed on the bicycle lane line between the bicycle lane and traffic lane. Due to the bollard stand diameter, there is a slight reduction in the effective width of the bicycle lane from 1.5 metre to approximately 1.45m as can be seen in the left image of Figure 45.
8.3.3.3.2 Kerb separated bicycle lane

Kerb separated bicycle lanes utilise sections of raised median or kerb and channel to provide physical separation between cyclists and adjacent motor vehicles. The concept trialled in this research is referred to as a ‘Copenhagen Style’ bicycle lane and has been implemented in locations around Metropolitan Melbourne. For this concept, a raised median is placed on the edge line of the bicycle lane, the median is approximately 300mm wide and reduces the effective width of the bicycle lane to 1.2 metres (Figure 46). Intermittent gaps are placed in the median – this is a common feature of kerb separated bicycle lanes in real road environments as it increases the permeability of the lane and allows cyclists to exit the lane if a hazard is observed upstream, however this feature was be assessed in the simulator studies.

8.3.3.4 Vertically separated bicycle lanes

The final concept trialled for addressing rear-end and side swipe collisions is vertically separated bicycle lanes (Figure 47). This is a concept based on the Dutch ‘cycle tracks’, whereby the bicycle lane is raised above the road level by 0.1 metres and kerbs are placed to separate the cyclist from the road and the footpath. The kerbs are intended to stop vehicles from entering the bicycle lane, there is also an added benefit of raising the height of the cyclist, making them more obvious to motorists, particularly truck drivers. The improved sight lines from raising the cyclist also has benefits.
8.3.4 Car-door collisions

The issue of car dooring is mainly associated with parked motor vehicle occupants failing to look or see cyclists and opening the door into the oncoming path of cyclists. These collisions can be particularly hazardous to cyclists due to the limited time to react and the chance of falling into the path of moving traffic, following the initial collision. As noted in Chapter 7, in Victoria, these collisions represent the leading cause of collisions resulting in serious injury at mid-block locations.

To address these collision types, two road configurations are considered. The first is the baseline scenario where kerbside parking is located adjacent to the kerb and cyclists ride between parked cars and an adjacent traffic lane (Figure 48). This road configuration is common in Australia, particularly on arterial roads and locations commonly associated with car-door collisions. The second configuration is with the bicycle lane located adjacent to the kerb. This is the recommended configuration in Copenhagen and other best-practice cycling cities as it reduces the frequency of car doors opening into the path of cyclists by placing them on the passenger side of the vehicle. This design has the added benefit of providing cyclists with protection from rear-end and side-swipe collisions (Figure 49).
8.3.4.1 Kerbside Parking

When there is kerbside parking it is not practical to implement measures that physically or vertically separate cyclists from motor vehicles as there is the requirement for motor vehicles to cross the bicycle lane to enter and exit the parking space. Unfortunately this road configuration exposes cyclists to a number of hazards, including car door collisions, rear-end and side swipe collisions as well as additional risks associated with manoeuvring vehicles entering and exiting parking spaces. When assessing infrastructure designs for this scenario three separated bicycle lane concepts were considered. Two baseline scenarios were included in this study, a scenario with no bicycle lane and a scenario with a typical 1.5 metre bicycle lane adjacent to on-street parking. Details of each design are presented below.

8.3.4.1.1 Spatially separated bicycle lanes

8.3.4.1.1.1 Bicycle lane with green zone

This concept is similar to the separated bicycle lane design shown in Figure 42. However this concept differs as it is designed to move cyclists outside of the car-door zone instead of moving them away from adjacent traffic. Therefore the location of the green zone is moved to the 1.0 metre closest to the traffic lane to discourage cyclists from riding in the car-dooring zone (Figure 50).
8.3.4.1.1.2 Bicycle lane with parking side buffer

These concepts are similar to the design shown in section 8.3.3.2.2 and section 8.3.3.2.3. However, the intention is to create a buffer between the parked car and the cyclist to discourage cyclist from riding in the car door zone. The first concept utilises a chevron buffer (Figure 51) while the second concept utilises a narrow buffered line that is intended to signify where car doors are likely to be opened (Figure 52).

![Figure 51: Spatially separated bicycle lane with car door buffer (Chevron)](image1)

![Figure 52: Spatially separated bicycle lane with car door buffer (alternate design)](image2)

8.3.4.2 Kerbside bicycle lane

Kerbside bicycle lanes reduce the number of conflicts for cyclists, compared with bicycle lanes adjacent to kerbside parking. They are also the recommended lane configuration in many best-practice European countries. While dimensionally there are limited differences between the two designs, it is of interest to understand if cyclist behaviours differ within a bicycle lane when there is kerbside traffic compared to kerbside parking.

Comparisons between these designs and the kerbside traffic designs will give an indication of whether cyclists position themselves differently in bicycle lanes depending on the adjacent traffic lane function. There is also the opportunity to assess if cyclists’ perceptions differ between lane configurations.

8.3.4.2.1 Baseline condition

This scenario includes one baseline condition only as it was not feasible to assess wide-kerbside or no bicycle lane concepts within the constrained space between parked cars and the kerb. As such, the baseline condition consists of a conventional 1.5 metre wide bicycle lane.
8.3.4.2.2 Spatially separated bicycle lanes

The three concepts presented for the kerbside parking scenario were tested for the kerbside bicycle lane scenario, that is, bicycle lanes with green zones (Figure 53), and the two buffered lane concepts (Figure 54 and Figure 55). The main difference in the design was the location of the buffer/green zones through swapping of the location of the bicycle lane (located on the passenger side of the parked vehicle, adjacent to the kerb).

![Figure 53: Spatially separated bicycle lane (green buffer)](image)

![Figure 54: Spatially separated bicycle lane (chevron buffer)](image)

![Figure 55: Spatially separated bicycle lane (car-door pavement marking)](image)

8.3.4.2.3 Physical separation

The same two physical separation measures, traffic bollards (Figure 56) and kerb separated bicycle lanes (Figure 57), that were considered for rear-end and side-swipe collisions are also considered for car-dooring...
collisions. There were no physical differences in the bicycle lane designs for these treatments compared to the previous designs, however the simulator scenarios differs with the presence of parked cars adjacent to the bicycle lane instead of moving vehicles.

8.3.4.2.4 Vertical separation

Finally vertically separated lane treatments were considered to address the issue of car-dooring as per section 8.3.3.4. Again there were no differences in the bicycle lane design, however there were differences in the overall cross section and lane function of the road in the simulator scenario, with presence of parked cars adjacent to the bicycle lane as opposed to a traffic lane in the previous scenario (Figure 58).
8.4 Summary

This chapter has highlighted that in order to address common cyclist crash types that occur along the length of bicycle lanes there is a need to provide a dedicated right-of-way for cyclists that increases their spatial separation with adjacent motor vehicles. To meet this objective, the concepts identified in this chapter utilise spatial separation techniques through the use of lane widening, pavement markings, physical infrastructure and perceptual countermeasures to encourage cyclists to adopt safer cycling positions.

Concepts also utilise physical and vertical separation techniques which require additional construction cost but act to form a physical barrier between cyclists and adjacent motor vehicles. This creates greater protection for the cyclist from adjacent vehicles, however this added protection requires significantly greater construction costs and may place additional limitations of the ability of cyclists to move freely when riding on road.

In the following chapters the findings of evaluations of the proposed bicycle lane concepts identified in this chapter using the bicycle simulator are presented. Chapter 9 presents three studies that were designed to assess the use of bicycle lane widening and perceptual countermeasures to enhance cyclist safety. Chapter 10 presents the study assessing bicycle lane concept designs aimed at reducing the risk of rear-end, side-swipe and car-door collisions.

Each simulator study assesses the extent to which the different lane designs influence cyclist’s position and speed profiles when interacting with the different lane designs. The presentation and examination of these measures were previously validated in Chapter 6. For the bicycle lane concepts evaluated in Chapter 10 participants were also asked to provide subjective feedback regarding their perception of safety, attractiveness and comfort for each of the designs and if the design would have the potential to encourage them to cycle more often. These measures have previously been identified in Chapter 3 as principles of best-practice bicycle lane design.
Chapter 9: Examination of bicycle lane design characteristics

This chapter presents three complementary simulator-based studies investigating the influence of bicycle lane design characteristics on cyclist behaviour. In particular, the experiments conducted investigated how cyclists respond when riding in bicycle lanes of a range of widths and how the use of perceptual countermeasures can be incorporated into bicycle lane designs to encourage safer cycling. The studies in this chapter considered the extent to which the use of countermeasures and lane widths influence the speed profile, lateral position and spatial separation between cyclists and adjacent motor vehicles. The findings from the first two studies presented in this chapter were summarised into a peer-reviewed conference paper: “Examination of bicycle lane design characteristics”. The paper was presented at the Road Safety and Simulation International Conference 2017 (Appendix B).

As established in Chapter 2, the speed and spatial separation of passing motor vehicles can have a significant influence on cyclist safety and comfort when riding on road (Levasseur 2014). Austroads recommend that roads should be designed to provide a minimum clearance of 1.0 metres between motorised vehicles and cyclists in 60km/h speed environments (Levasseur 2014). This recommendation is generally in line with road safety efforts in Australia that are designed to increase cyclist safety when riding on road including the Amy Gillett Foundation “metre matters”, “it’s a two way street” and associated minimum passing distance legislation and campaigns that have been adopted in several Australian States and Territories including Queensland, New South Wales and South Australia. A common theme of these campaigns and legislation is a focus on providing cyclists with adequate space and lateral clearance when cycling on-road. While national and international cycling guidelines emphasise the need to provide adequate space for cyclists, many recommendations and guidelines are based around the design envelop of cyclists (Levasseur 2014). Unfortunately, only limited empirical research has been undertaken to provide the evidence-base regarding the safety benefits of these initiatives.

The primary objective of road design is to optimise the safety and operation of the road while accounting for the volume, type and distribution of traffic (Austroads 2015). The main geometric elements of the road (cross-section, horizontal curves, vertical curves, intersections etc.) should be designed to provide road users with consistent information regarding how to interact with the road environment (Austroads 2015). Fuller & Santos (2002) describe this approach as a “self-explaining road”, with the road providing cues to the road user regarding what design elements are to be expected as well as appropriate speeds, behaviours and interactions with other road users.

The effect of various road design features have been investigated from a driver’s perspective including changes in lane widths (Poe & Mason Jr 2000, Fitzpatrick et al. 2001, Godley et al. 2004, Lewis-Evans & Charlton 2006) lane marking (Charlton 2007), shoulder width (Ben-Bassat & Shinar 2011), roadside obstacles and intersection designs, using both on-road and simulator techniques (Godley et al. 2004). These features can influence a driver’s behaviours including their speed and position within the carriageway. However, while considerable research has been conducted from the perspective of motorised vehicles and their drivers, relatively little
research has been conducted examining the influence of variations in road design elements on cyclist behaviour. Of the research that has been conducted it has been established that the presence of bicycle lanes can result in cyclists more likely to demonstrate predictable behaviours, by maintaining a consistent travel path (Schramm & Rakotonirainy 2009). Furthermore, bicycle lanes have been found to influence the cyclist’s position relative to the kerb, particularly encouraging cyclists to ride further away from the road’s edge, conversely riding closer to adjacent traffic lanes (Harkey & Stewart 1997). In the absence of bicycle lanes, carriageway width has been found to influence the displacement between cyclists and motorists (Harkey & Stewart, 1997). This research provides valuable insight into the cyclist behaviour, however, the research to date has largely consisted of small scale studies that were conducted in real world situations with limited control over independent variables. Furthermore, while bicycle lanes are accepted as a preferred on-road facility for cyclists and are associated with lower crash risks (Reynolds et al. 2009, Teschke et al. 2014), recent research from Victoria has shown that a fifth of on-road cyclist crashes occur when cyclists are travelling in designated bicycle lanes (Beck et al. 2016). The substantial number of cyclist crashes occurring within bicycle lanes, suggests that there is a need to further investigate bicycle lane design principles to identify how cyclists behave when riding in bicycle lanes and also how their behaviour can be influenced to adopt safer lane positions by increasing their spatial separation from adjacent vehicles (thereby reducing the likelihood of a crash). In order to address these questions three simulator-based studies were undertaken to examine bicycle lane design characteristics and the extent to which perceptual countermeasures can influence cyclist behaviour. The methods and findings from each study are discussed separately and the broader implications of the three studies are discussed at the conclusion of the chapter.

9.1 Study 1: The influence of bicycle lane width on cyclist performance

The first study examined the influence of the width of a bicycle lane on a cyclist’s speed, lateral position and spatial separation from adjacent motor vehicles in the traffic lane and parked cars. As mentioned previously, Austroads identify that a 1.0m wide design envelop for cyclists allows for the width of a bicycle and cyclist and for variations in tracking. Furthermore, in 60km/h road environments they recommend a desirable bicycle lane width of 1.5 metres, with widths of 1.25 metre to 2.0 metre within the acceptable range of lane widths for cyclists in these speed zones (Levasseur 2014). This study aimed to assess how cyclists behaved in a range of bicycle lanes that comply with the Austroads design recommendations.

9.1.1 Materials and methods

9.1.1.1 Study design

Five bicycle lane width conditions were tested, ranging from 1.0 metres wide to 2.0 metres wide, at 0.25 metre increments within two lane design scenarios. The two lane configurations were selected as they represent common configurations for bicycle lanes in urban road environments with a 60km/h speed limit. The first scenario was a kerbside bicycle lane (Figure 59) and the second scenario was a bicycle lane adjacent to on-street kerbside parking (Figure 60).
To control for the potential bias associated with learning effects, two strategies were adopted: i) the counterbalanced order of each stage, and ii) randomised order of presentation of lane widths. This was achieved through a custom script developed for the bicycle simulator that automatically randomised the study order. A within-subject study design was utilised with every participant completing each scenario and lane width configuration.

9.1.1.2 Participants
A total of 30 participants (21 males and 9 females) were recruited. The same exclusion criteria was implemented as per the validation study (see Chapter 6). Inclusion criteria were: aged over 18 years of age and comfortable riding a bicycle on local roads. Exclusion criteria were: presence of medical conditions that might be aggravated due to exercise or using the bicycle simulator including epilepsy, high blood pressure, having previously experienced a heart attack, and the history of suffering from either motion sickness or simulator sickness. Participants who required glasses for normal vision were also excluded from the study (participants who wore contact lenses to correct their visions were accepted into the study). In addition to the previous exclusion criteria, participants were required to not suffer from any hearing impairment that would limit their ability to respond to verbal instructions. This was an added requirement as the simulator was programmed to provide participants with auditory instructions on approach to each intersection regarding which direction they needed to turn at each intersection.

Recruitment was undertaken using similar methods to the validation study, with flyers placed around Monash University Clayton campus, including the bicycle arrival station, and an advertisement was placed in the Monash Staff e-newsletter.

Of the thirty recruited participants, three did not complete the study. Two participants were excluded as they experienced high levels of simulator sickness and were unable to complete the full set of simulator scenarios, the third participant was excluded because they were unable to complete the practice scenarios to an acceptable standard and experienced difficulties using the simulator. The remaining 27 participants formed the sample and ranged in age from 18 to 39 years (M=24.2, SD=5.7). The total study took approximately one hour to complete per participant. Participants received a $25 AUD gift voucher for participating and to compensate them for their
time and travel expenses. The research protocol for the study was reviewed and approved by the Monash University Human Research Ethics Committee (MUHREC).

9.1.1.3 Questionnaires

Participants completed two questionnaires as part of the study design. The first questionnaire was a short demographic survey providing information on demographic characteristics and cycling experience (Appendix D). The second questionnaire was the SSQ (Kennedy et al. 1993) (Appendix C) which was administered to participants to assess the level of simulator discomfort experienced by completing the study. As per the previous simulator validation study, each participant completed the SSQ prior to commencing the simulator study and following completion of the final simulator scenario. Participants who experienced high levels of simulator sickness during the experiment were excluded from data collection and subsequent analysis.

9.1.1.4 Simulator scenarios

Five lane width conditions were tested across two road cross section configurations. Participants rode through cycling routes depicting a typical 60km/h road, presenting the various bicycle lane width conditions on a set road grid, shown in Figure 61. Different road grids were used for the kerbside parking and kerbside bicycle lane configurations to ensure that participants did not become familiar with the cycling route. During each ride, five straight sections of road along the grid presented a different lane width conditions, shown in Figure 61. Each mid-block section was 100 metres in length and was separated by a signalised intersection. At each intersection participants received an automated verbal instruction from the simulator to either “turn left” or “go straight”. The verbal instruction was automatically trigger as the participants approached the intersection and was given well in advance of the intersection so that participants had ample time make the correct turning movement. Furthermore as participants approached the intersection the traffic signals would change to show participants either a green through phase or a green left turn arrow for a dedicated left turning phase. All other turning movements at the intersections were controlled (showed red symbols). Using this system of verbal instruction and traffic signals, no participants made incorrect turns during any of the three studies.

Simulated motor vehicles were present during each ride, however they were programmed to give priority to the participant and to avoid any collisions, parked cars were also included in the scenario with the bicycle lane adjacent to kerbside parking. When parked cars were present, three cars were randomly placed along each test section.

Participants were presented with a different lane width condition each time they performed a left hand turn at an intersection, with participants having to make a turning movement and then have to re-establish themselves in the next section of bicycle lane.
For each ride, the first section of road was a practice section that was essentially the same for each participant and each simulator run. Following the practice section, participants rode the five sections of road incorporating each lane width condition.

The key variables of interest for this study were the average speed of participants, their variability in speed (measured as the standard deviation of speed), the position of the bicycle within the bicycle lane and relative to adjacent motor vehicle traffic and parked cars (for the scenarios with kerbside parking) as well as their variability in lateral position. Simulator-generated data for each variable were collected at a rate of 10 hertz (10 recordings per second). Results are presented as averages and standard deviations for each length of bicycle lane section.

9.1.1.5 Data Analysis
Participant demographic characteristics were assessed using descriptive statistics. For the simulator-generated variables, repeated measure ANOVA techniques were applied. Effect sizes were measured using $\eta^2$ (Eta squared). Post-hoc testing was performed using Tukey’s Honest Significant Difference (HSD) test for pairwise comparisons. Prior to analysis, tests for normality were conducted for each variable considered in the study, using skewness and kurtosis. Results were normally distributed as such no transformations were performed. All statistical analyses were conducted using STATA version 13.1. Each of the three studies utilised the same data analysis techniques and for brevity they have not been restated.
9.1.2 Results

9.1.2.1 Participant characteristics

Participants completed a short demographic and cycling experience questionnaire prior to undertaking the simulator study. Participants were asked to rate their confidence level regarding cycling on road on a 10-point Likert scale, and on average participants were highly confident riding on-road (M = 8.1 SD = 1.3). These results are very similar with the previous validation study. The majority of participants rode less than 50 kilometres per week (76.7%) and typically rode a bicycle for either recreational (50%) or commuting purposes (53.3%). Three participants had been involved in a crash while riding a bicycle within the past three years. All crashes were relatively minor and did not result in serious injury. Across the study there was a good distribution of age, gender and self-reported cycling experience, suggesting the results should be somewhat generalizable to a broader spectrum of adult cyclists.

9.1.2.2 Simulator performance results

9.1.2.2.1 Lateral position

For both lane design configurations strong linear trends were observed between the width of the bicycle lane and the position of the cyclist within the bicycle lane. Cyclists generally rode in the middle of the bicycle lane, however tended to ride slightly towards the right side of the lane (towards the adjacent lane of motor vehicle traffic). There was a noticeable shift in lane position observed when riding in the bicycle lanes with kerbside parking, compared to when riding in a lane adjacent to the kerb. In the kerbside parking configuration cyclists rode towards the middle of the bicycle lane, however there was a more pronounced shift towards the right hand side of the lane, compared to the kerbside bicycle lane configuration (Figure 62). This may have been a result of the cyclists riding closer to adjacent traffic lane to mitigate the risk associated with riding to close to the parked cars.

A two-way repeated measures ANOVA was conducted to compare the two lane design configuration and the five lane width conditions on cyclist position relative to the left side of the bicycle lane. No interaction effects were observed between the two lane design configurations and the five lane width conditions (F4, 234 = 0.83, p = 0.51, η²= 0.01). A statistically significant main effect was observed for bicycle lane width on cyclist lateral position (F4, 234 =165.2, p < 0.001, η²= 0.74). Post-hoc testing found that cyclist position was significantly different between each lane width iteration indicating that cyclist lateral position within the bicycle lane is influenced by the available width of the bicycle lane. A statistically significant main effect was also observed for the lane design configurations (F1, 234 = 49.9, p < 0.001, η²= 0.18), identifying that there was a significant difference between participants’ lateral position when riding in kerbside bicycle lanes, compared with bicycle lanes with an adjacent kerbside parking lane.
Variation in lateral position was also compared for each condition and was measured as the standard deviation in lateral position along each 100 metre section of bicycle lane. A linear relationship was observed between lateral position variation and lane width (Figure 63). ANOVA identified a statistically significant main effect for the influence of bicycle lane width on lateral position variability ($F_{(4, 234)} = 20.52$, $p < 0.001$, $\eta^2 = 0.26$). No differences in lateral position variation were observed between the configurations with kerbside bicycle lanes and kerbside parking ($F_{(1, 234)} = 0.04$, $p = 0.84$, $\eta^2 = 0.0$) and no significant interaction was observed ($F_{(4, 234)} = 0.78$, $p = 0.53$, $\eta^2 = 0.0$).

Post-hoc testing identified significant differences in lateral position variability when lane widths differed by 0.5 metres or greater. A significant difference in variability was also observed between 1.5 metre bicycle lanes and 1.25 metre bicycle lanes ($p=0.01$). The findings show that, as the bicycle lane increases in width, cyclists become less consistent with their lane tracking. The findings also show that, for all lane width conditions, cyclist deviated in position beyond the 0.1 metre manoeuvring clearance that is specified in the Austroads cycling design envelop. This suggests that the design envelop specified by Austroads may be a conservative estimate of the lateral variability of cyclists when riding in bicycle lanes.
9.1.2.2.2 Passing Distance

For the kerbside parking lane design scenario, analysis of position of the cyclists relative to the edge of the bicycle lane when passing parked cars and when parked cars were not present was undertaken (Figure 64). ANOVA identified a small but significant difference between the cyclists lateral position when passing parked cars, compared with when cars were not present ($F_{1,234} = 6.67, p = 0.01, \eta^2 = 0.03$), indicating that, while cyclists adopt a position further away from the left hand edge of the bicycle lane when kerbside on-street parking is available, they also shift further towards the right of the bicycle lane when passing a parked car, however the very small effect size suggests that the differences observed in this study were minor. A significant difference was also observed for lane position adopted depending on lane width, ($F_{4,234} = 375.5, p < 0.001, \eta^2 = 0.87$). This was expected based on the previous findings, which show that cyclist position relative to the edge left side of the bicycle lane increases as a function of bicycle lane width. No significant interactions between bicycle lane width and the presence of parked cars were observed ($F_{4,234} = 0.13, p = 0.97, \eta^2 = 0.00$). The finding regarding lane position when parked cars are present is interesting as it shows cyclists provide themselves with additional clearance when passing parked vehicles, possibly as a safety precaution to mitigate the risks associated with car doors opening. The findings also show that the presence of on-street parking has the potential to increase cyclist’s exposure to rear-end and side swipe collisions from adjacent motor vehicles as the parked cars encourage cyclists to ride further away from the left-hand edge of the roadway. The findings in this scenario were small, yet significant and may have greater implications in situations when narrow bicycle lanes are placed adjacent to kerbside parking, such as in strip shopping precincts. Furthermore the parked cars in this scenario
were static (they did not move, or open their doors). It would be of interest to examine if passing lane position deviated in a more dynamic situation, such as when car doors were opening ahead of the cyclist.

![Figure 64: Passing distance from parked cars by lane width condition](image)

9.1.2.2.3 Speed

Participant speeds were generally slower in the kerbside bicycle lane compared to the lane configurations where the bicycle lane was adjacent to kerbside parking (Figure 65). This was confirmed through ANOVA which showed that there was a significant difference in average speed between the two lane design scenarios ($F_{1,324} = 32.7$, $p < 0.001$, $\eta^2 = 0.12$). Further, across the two lane design scenarios there was an approximate linear relationship observed between cyclist speed and the available lane width. On average participants tended to ride faster when the available lane width increased ($F_{4,234} = 12.3$, $p < 0.001$, $\eta^2 = 0.17$).

Post-hoc testing revealed that the significant differences were between the 1.0 metre lane width and the four other lane width configurations. The only other significant difference observed was for speed in the 1.25 metre and 1.75 metre lane width conditions, however based on the general trend more significant differences may have been observed had a larger sample of participants completed the study. No interaction effects were observed for cyclist average speeds when considering the lane with conditions or scenario ($F_{4,234} = 0.85$, $p = 0.50$, $\eta^2 = 0.01$).
Variation in cycling speed for each lane width condition was also compared. No significant differences were observed for speed variability between the five lane width configurations ($F_{4, 234} = 1.02, p = 0.40, \eta^2 = 0.05$), while a slight difference was observed between the two lane design scenarios ($F_{1, 234} = 8.7, p = 0.004, \eta^2 = 0.04$), however the effect size suggests that there was only a small difference. Furthermore no interaction effects were observed ($F_{4, 234} = 0.46, p = 0.77, \eta^2 = 0.01$). It is expected that participant speeds were slower in the 1.0 metre bicycle lane due to the added workload required to keep the bicycle within the narrow bicycle lane. This may have resulted in some task load shedding with participants placing an increased focus on maintaining lane position and reduced importance on maintaining speed.

9.1.3 Summary

This study was designed to understand fundamental information about how cyclists choose to position themselves when riding in various on-road bicycle lane designs and to assess if the width of the bicycle lane influenced cyclist variability in speed and positioning. The findings illustrate that, regardless of the width of the bicycle lane, cyclists tend to ride towards the centre of the lane. Selected lane positioning may represent a form of risk mitigation with cyclists selecting a location that they deem to be safe and provide adequate spatial separation from adjacent traffic and parked cars.

An interesting finding of this study was that for the kerbside bicycle lane design, the provision of wider bicycle lanes did not result in participants increasing their separation from moving traffic by an equal amount and instead cyclists still positioned themselves in the centre of the lane. This has important implications for the design of on-road bicycle facilities as it shows that increasing the width of cycling facilities does not necessarily increase the...
spatial separation between cyclists and adjacent motor vehicles by the same amount and that alternate methods need to be investigated that encourage cyclists to adopt safer cycling positions that do not just rely on increasing bicycle lane width. Furthermore it highlights that cyclists may also perceive risks associated with riding too close to the edge of the roadway, where fixed objects and pedestrians may present a risk. This is particularly likely in real world cycling environments where the edge of the roadway often serves a drainage function and debris can collect in kerb and channel structures and street furniture may be placed near the kerb, such as pedestrian fencing or utility poles.

One important finding from this study was that for all lane design configurations and width conditions, cyclists variability in lane position was greater than the 0.1 metre space design envelop for cyclists recommended by Austroads. The current finding suggests that cyclist may in fact require greater space than suggested for manoeuvrability and this in turn could have important implications for bicycle lane design specifications. The study also found that as lane widths increase, so does the cyclists speed and lateral position variability. This again illustrates that increasing the lane width for cyclists does not necessary result in safer cycling, with cyclists more willing to adopt faster speeds, which in would result in increased kinetic energy and therefore higher risk of serious injury in the event of a collision or fall from the bicycle. Furthermore, at higher speeds cyclists will require longer times to react to hazards on the roadway and will require longer distances to come to a stop. Additionally, as bicycle lane width increases, cyclists may exhibit less predictable behaviours, which may increase anxiety for other road users attempting to overtake cyclists. These findings are similar to findings amongst drivers investigating speeds in varying lane width configurations. In their study assessing the influence of perceptual lane width of driver speed, Godley et al. (2004) identified significant reductions in motor vehicle speeds and deviation in lateral displacement when perceptual lane widths were reduced from 3.0 metres to 2.5 metres. Godley et al. (2004) offered two possible explanations for the results. First they suggested that drivers’ perceived crash risk was higher on narrower roads or lanes, in line with the theories of risk homeostasis and concept of safety margins (Wilde 1982, Summala 1996). Their second explanation which suggests that reduced speeds in narrow lanes are a result of mental workload limitations, with higher speed requiring higher mental effort, seems to better reflect the results of this study. The current findings may be associated with participants trading-off between travel speed and maintenance of steering within the confines of narrow bicycle lanes, which require increased mental workload. This finding has important implications for designing and constructing on-road bicycle facilities and suggests that if bicycle lanes are designed with insufficient width there is a risk for cyclists to increase their level of concentration on the lane keeping task. This may have the potential of reducing a rider’s situational awareness and hazard perception ability when cycling in urban environments and may increase the chance crash involvement. This is a direct risk of poorly designed bicycle lanes, beyond the obvious risk of increased exposure to rear-end and side-swipe collisions when cyclists are constrained within a narrow space that provides insufficient clearance from adjacent vehicles.
9.2 Study 2: Perceptual countermeasures for painted bicycle lanes

Pavement markings are a necessary component of all on-road facilities including bicycle lanes. The effectiveness and safety of a bicycle facility is dependent on appropriate delineation. Pavement marking can also be utilised as a perceptual countermeasure to provide visual cues to the road user regarding appropriate behaviours. Godley et al. (2004) defined perceptual countermeasures as “non-obtrusive, low cost visual and/or haptic road markings, usually involving only paint or gravel or both”.

The second simulator-based study assessed the effectiveness of pavement marking along the length of painted bicycle lanes to encourage adoption of different, and potentially safer, riding positions within a bicycle lane. By providing visual cues to cyclists regarding where they should position themselves within a bicycle lane there is the potential to increase their spatial separation between adjacent motor vehicle traffic and parked cars and to encourage cyclist to adopt safer cycling positions.

In line with the KEMM, these types of interventions target the outer three layers of the model. That is, where the given the exposure of a collision can be reduced by increasing the spatial separation between cyclists and adjacent vehicles and if a collision does occur the level of energy can potentially be reduced by increasing the space and time between the motor vehicle and the cyclist, potentially allowing the driver of a motor vehicle to reduce their speed prior to the collision.

9.2.1 Materials and methods

9.2.1.1 Study design

The intention of the study was to assess if visual cues provided by bicycle lane pavement marking designs can influence cyclist position and speed. Five bicycle lane pavement marking conditions were examined within a roadway that consisted of a 2.0 metre wide kerbside parking lane, a 1.5 metre wide bicycle lane and two 3.5 metre traffic lanes (one lane in each direction). A typical road cross section is shown in Figure 66.

Figure 66: Typical cross section for study two
The lane conditions depicted varying proportions and sections of the bicycle lane coloured green, as shown in Figure 67.

Figure 67: Bicycle lane conditions

9.2.1.2 Participants
This study was conducted in conjunction with Study 1. As such the same participants were recruited to complete both tasks and the results for the demographic questionnaire and SSQ are identical.

9.2.1.3 Simulator scenario
The simulator scenarios were presented to participants using a similar grid layout as per study 1, albeit with a different route to avoid familiarity with the course. The order that participants completed this experiment and Study 1 was counterbalanced, furthermore the order that participants saw each of the lane marking conditions was randomised and counterbalanced to control for any learning effects. The same simulator-based performance measures were collected as described for Study 1. Results are presented as averages and standard deviations along the length of each bicycle lane section.

9.2.1.4 Data analysis
The same data analysis techniques were utilised for each study presented in this chapter and are detailed in section 9.1.1.5.

9.2.2 Results

9.2.2.1 Simulator performance results

9.2.2.1.1 Lateral position
Lateral position across the five pavement conditions is shown in Figure 68. Across these conditions, cyclists adopted significantly different riding positions ($F_4, 134 = 17.44, p=0.00, \eta^2= 0.59$). Post-hoc testing identified that the traffic side buffer condition resulted in participants riding in a significantly different position compared to the other four conditions (0.76 m Vs 0.90 m from the left hand edge of the bicycle lane). A significant difference was also observed between the parking side buffer condition and the parking and traffic buffer condition (0.96m Vs 0.85m from the left hand edge of the bicycle lane). These results highlight that the use of pavement marking
schemes as a perceptual countermeasure can influence the position adopted by cyclists within a bicycle lane and may be a useful countermeasure to encourage cyclist to adopt safer lane positions that increase their spatial separation from either passing cars or opening car doors.

ANOVA identified a significant difference between participants variation in lateral position across the five conditions ($F_{4, 134} = 3.87$, $p=0.00$, $\eta^2=0.76$). Post-hoc testing identified that lateral position variation was significantly lower for the parking and traffic buffer scenarios compared to the other four scenarios. No other significant differences were observed. This perceptual countermeasure lane design encouraged participants to ride on the 0.5 metre green section in the middle of the bicycle lane. This resulted in less deviation in their path, however it also resulted in a significant reduction in speed, as discussed in the next section. This was likely a result of task load shedding, similar to the findings for the 1.0 metre bicycle lane condition in study 1, where participants felt the need to increasingly concentrate on positioning the bicycle and as such reduced their speed to account for the increased difficulty of the lane keeping task.

9.2.2.1.2 Speed

ANOVA identified a significant difference between participants’ speed across the five pavement marking condition ($F_{4, 134} = 5.0$, $p=0.00$, $\eta^2=0.89$). Post-hoc testing identified that speed was significantly less for the parking and traffic buffer scenarios, no other significant differences were observed. Furthermore, no significant differences were observed for the variation in speed for the different pavement marking condition ($F_{4, 134} = 0.43$, $p=0.79$, $\eta^2=0.80$). This finding further aligns with the load shedding theory associated with participants attempting to ride within the narrow green section of the lane.
9.2.3 Summary

The study was designed to understand if the use of perceptual countermeasures, in particular the use of pavement marking along the length of a bicycle lane, could provide visual cues to cyclists in order to influence behaviour (lateral position and speed) when riding within a simulated bicycle lane. The results of this study indicate that cyclists responded to the visual cues (alternate pavement marking schemes) and that the different lane designs were capable of influencing cyclists’ speed and lateral positioning.

The findings suggested that throughout each of the five conditions, cyclists were encouraged to ride on the sections of the bicycle lane that were coloured green. This is an important finding as it highlights that the cyclists in the study understood the basic meaning of the green pavement marking and were compelled to ride on the green sections of each bicycle lane, irrespective of the placement. The finding shows that when constructing bicycle lanes the use of green pavement marking can be utilised to encourage cyclists to select particular lane positions, which has the potential to encourage cyclists to adopt safer cycling positions.

The results also indicate that the use of alternate pavement marking designs can influence cyclist speed and lateral position variability. In particular, in the condition with a 0.5 metre green marking in the centre of the lane, cyclist speed and lateral position variability significantly reduced compared with other marking conditions. This has important implications for design as it shows that very narrow sections of green marking may in fact be associated with cyclists shedding some of their task load to maintain lane position. While this results in the safety benefit of reducing their speed, it may also potentially result in reduced situational awareness as the cyclist focuses more on lane positioning and less on the surrounding road environment. This warrants further investigation.

The treatments assessed in this study could be considered appropriate for implementation in a variety of locations, particularly narrow lane locations where there is insufficient lateral clearance between cyclists riding in bicycle lanes and motor vehicles, at locations with a high frequency of car-door collisions, or at intersections with minor roads to encourage cyclists to ride away from the minor approach. Essentially this style of perceptual countermeasure could be utilised to encourage cyclists to adopt safer lane positions, which may have the potential to reduce the risk of rear-end, side swipe and car door collisions.
9.3 Study 3: Perceptual countermeasures for bicycle lane logos

The third experiment was designed to test a range of bicycle lane logo designs and assess if cyclists position within the bicycle lane could be influenced by the visual cues provided by the style and position of the bicycle logo utilised when marking lanes. Two bicycle lane logo designs in three positions within the bicycle lane were examined. The study sought to assess if similar changes in lateral position could be achieved through the use of bicycle lane logos similar to those achieved by pavement markings in the second study. It is noted that, while the bicycle lane marking in Study 2 provided a continuous visual cue to participants along the length of the bicycle lane, bicycle logos are not continuous. Essentially, the use of this method may represent a more cost effective measure to encourage cyclists to adopt safer cycling positions, compared to the continuous lane markings trailed in the second study. However the risk with this design is that without a constant or frequent visual reminder of where to cycle there is the potential that the intended position may not be maintained and that cyclists will adopt their natural position, which may not necessarily be the safest lane position to minimise the risk of collision. The concept for this study was developed following the successful findings in Study 2, as such a different cohort of participants were recruited for Study 3.

9.3.1 Materials and methods

9.3.1.1 Study design

For this experiment the road cross-section was identical to the road alignment utilised in Study 2 (Figure 66). The two bicycle lane logos that were presented to participants are shown in Figure 69 and Figure 70. The first bicycle lane logo was a conventional marking recommended by Austroads (Levasseur 2014). The second logo incorporated a dashed line, to encourage cyclists to ride along the centre of the logo, this and similar designs are utilised in jurisdictions particularly in the USA when marking cycling facilities. For example the FHWA, Manual on Uniform Traffic Control Devices recommends a similar design when installing bicycle detectors at intersections as the line marking provides a visual cue for cyclists to position their wheels on the most sensitive region of inductive loop detectors (FHWA 2009).

Research commissioned by Bicycle Network, a cycling advocacy group in Victoria, also recommends the use of this style of pavement marking to encourage cyclist to positing themselves at intersections in order to activate bicycle detection sensors (SKM 2010). While the bicycle logo design has been utilised at intersections to encourage cyclist to adopt a certain lane position it does not appear to be utilised for a similar purpose at mid-block locations along the length of the bicycle lane.

Three positions of the bicycle logo within bicycle lanes were tested: i) logo painted near the left hand side of the lane; ii) logo painted near the right hand side of the lane; and; iii) logo painted at the centre of the lane. For the purpose of this experiment the size of the bicycle lane logo was reduced from what is conventionally recommended by Austroads. This was to ensure that the three lane positions could be distinguished in the
experiment. The intention of the study was to assess whether the visual cues provided by the bicycle logo position and markings encouraged cyclists to adopt different cycling positions within the on-road bicycle lanes.

9.3.1.2 Participants

The study was undertaken separately to Study 1 and 2 and recruited 30 participants (24 males and 6 females). The same exclusion criteria and recruitment methods were implemented as the previous studies detailed in this chapter. Of the thirty recruited participants, two participants were excluded as they experienced high levels of simulator sickness and were unable to complete the full set of simulator scenarios. The remaining 28 participants ranged in age from 19 to 57 years (M=24.2, SD=5.7).

9.3.1.3 Simulator scenarios

The simulator scenarios were presented to participants using a similar grid layout as per Study 1 and Study 2, however an additional section was included in this grid to accommodate presentation of the additional six design conditions. The order of scenario presentations was randomised and counterbalanced to control for any learning effects. The same performance measures were collected from the simulator as the previous studies and the same results were gathered from each simulator ride.

9.3.1.4 Questionnaires

Participants completed the same demographic questionnaire (Appendix D) and the SSQ (Appendix C) as per the previous studies.

9.3.1.5 Data analysis

The same data analysis techniques were utilised as per the previous two studies.
9.3.2 Results

9.3.2.1 Participant characteristics
Participants were asked to rate their confidence level regarding cycling on road, as per the previous studies, and on average participants were highly confident (M = 8.1 SD = 1.3). Three participants had been involved in a crash while riding a bicycle within the past three years. The participant demographic results were very similar with the previous two studies presented in this chapter suggesting that a similar cohort of cyclists were recruited for each experiment. Again giving some confidence in the generalisability of the results to a broader cohort of adult cyclists.

9.3.2.2 Simulator performance results

9.3.2.2.1 Lateral Position
Cyclist lateral position relative to the edge of the bicycle lane was measured for each participant while riding along the lengths of all bicycle lane designs and lane marking conditions. Average lateral position along the length of each condition is presented in Figure 71. The results show a similar lane position as per Study 1 for the baseline condition with a conventional bicycle logo placed in the middle of the lane. Moving the bicycle logo to the left and right side of the lane appears to have resulted in cyclists changing their lane position to match the logo location. The alternate design appears to have resulted in cyclists riding in almost the exact centre of the lane for the middle of the bicycle lane option, while the left and right side options also resulted in lane position shifts, similar to the conventional logo.

![Figure 71: Average lateral position for bicycle logo condition](image-url)
A two-way repeated measures ANOVA was conducted to compare the effect of the two bicycle logo designs and the three locations on cyclist position relative to the left side of the bicycle lane. No significant interaction was identified when considering the two bicycle lane logo designs and the three locations ($F_{2, 115} = 1.38, p = 0.25, \eta^2 = 0.02$). A small but significant main effect was observed between the two bicycle logo designs ($F_{1, 115} = 3.98, p = 0.048, \eta^2 = 0.03$), indicating that cyclist adopted different lane positions based on the different designs. However, the small effect size suggests this difference is negligible. A significant main effect was also observed for the three locations of the bicycle logo ($F_{2, 115} = 22.0, p = 0.00, \eta^2 = 0.27$) indicating that the position of the logo within the lane had an influence on the average lane position for cyclists. Post-hoc testing identified that cyclist position was significantly different when assessing a number of logo placement conditions. A significant difference was observed between placement of the conventional logo in the middle of the lane compared with placement on the left side of the lane ($p = 0.01$) and between placement on the left and right sides of the lane ($p = 0.00$). Similar significant differences were found when comparing the different locations for the alternate logo designs ($p = 0.01$ and $p = 0.00$). No significant differences were observed when comparing the respective logo positions across the two designs. However, the results for the centre position were approaching significance ($p = 0.14$).

Comparison of the variation in cyclist lateral position was undertaken to identify any differences in position variability resulting from the alternate designs. A summary of average lateral position variability is presented in Figure 72, and shows that the alternate bicycle logo design appears to have resulted in a small reduction in lateral position variability amongst cyclists.

Figure 72: Average lateral position variability for bicycle logo condition

ANOVA was also conducted to determine if this difference was statistically significant when considering the six scenarios and deviation in lateral position. A statistically significant difference was observed between the two
bicycle logo designs, with deviation in lateral position reducing for conditions involving the alternate bicycle logo design compared to the conventional to the first design ($F_{1, 115} = 7.74, \ p = 0.006, \ \eta^2 = 0.06$ ). No significant main effect was observed when considering the different lane positions ($F_{2, 115} = 1.47, \ p = 0.23, \ \eta^2 = 0.024$), or the interaction between lane position and bicycle logo design ($F_{2, 115} = 0.66, \ p = 0.52, \ \eta^2 = 0.01$).

9.3.2.2.2 Speed

No significant differences were observed amongst cyclists’ average speed for any of the three lane position scenarios ($F_{2, 115} = 0.1, \ p = 0.9, \ \eta^2 = 0.02$), or the logo designs ($F_{1, 115} = 2.97, \ p = 0.08, \ \eta^2 = 0.025$), furthermore no interaction was observed ($F_{2, 115} = 0.05, \ p = 0.95, \ \eta^2 = 0.00$). This was to be expected as the designs did not constrain the space for cyclists and were not expected to influence their travel speed. Similar results were observed for deviation in average speed, with no significant main effects or interactions observed.

9.3.3 Summary

The findings demonstrated that the position and style of the bicycle lane logo were capable of encouraging cyclists to adopt different lane positions and influence their variability in lane position. For the base case scenario with a conventional bicycle lane logo placed in the centre of the lane, cyclists rode in a similar location to findings in Study 1, which utilised a very similar road cross section. This location was also similar to where cyclist chose to ride when the logo was placed to the right of the lane, further illustrating the findings from Study 1 that cyclists chose a position that is right of the centre of the bicycle lane when cycling in kerbside bicycle lanes. However, a significant difference was observed for cyclist position when the logo was placed on the left side of the bicycle lane, resulting in a roughly 0.14 metre change in lane position and increasing the spatial separation between cyclists and adjacent motor vehicle traffic, to their right.

The alternate bicycle logo design incorporated a straight line into the design, which was intended to encourage cyclists to position themselves in the middle when riding over the logo (i.e. ride the bicycle over the straight line). The results from this study suggest that the logo did encourage cyclists to adopt the recommended lane position suggested by the design. Compared to the conventional design, there was a statistically significant shift in cycling position when comparing the position of cyclists when the two logos were placed in the middle of the lane.

When considering variation in lateral position, the findings showed that the alternate design resulted in cyclists reducing their variation in position. This finding may suggest that the alternate design provided visual reinforcement to the cyclists as to where they should ride within the lane, resulting in a more consistent positioning, when they passed the lane logo and as a result more consistent positioning along the length of the bicycle lane. Overall, the study found no significant differences in speed or speed variation amongst the different bicycle lane logos or positions. This was an important findings as it shows that while the logos are capable of encouraging cyclists to adopt different cycling positions they did not influence speed profile. This suggests that
cyclists did not perceived any additional task load complexity with the logo designs or positions that would require them to reduce their speed.

The results of this study show that the type and placement of bicycle logos within a bicycle lane can have an influence on cyclist riding behaviour. This has important implications similar to the previous studies in this chapter, with the findings further illustrating that, through the use of perceptual countermeasures, designers can encourage cyclist to adopt different lane positions which can potentially result in adoption of safer lane positions when riding on-road, resulting in increased spatial separation from adjacent motor vehicles.

The findings of this study are particularly interesting as, instead of a treatment such as in Study 2 which provided continual reinforcement to the cyclist of the desired lane position, these treatments only appeared periodically, but result in cyclist lane positioning changing along the length of the bicycle lane. Furthermore, these treatments produced similar benefits to continuous pavement markings in their ability to encourage safer lane positioning by cyclists. From a practical standpoint, the use of this type of bicycle lane marking would be more cost effective than designs investigated in Study 2 which would require continuous application of pavement marking treatments such as paint or thermoplastics. However green lane markings are also likely to provide stronger visual reinforcement and alert other road users of the potential presence of cyclists. Furthermore this study did not vary the frequency of the logo marking, however typically in Australia bicycle logos are recommended at 200 metre spacing’s for bicycle facilities and further research may be warranted to better understand the use of this type of perceptual measure and optimal spacing to maintain safer lane positioning.

9.4 Discussion

This chapter presented three simulator-based studies designed to better understand how bicycle lane width and the use of perceptual countermeasures can be utilised to encourage safer cycling. Study 1 was designed to understand fundamental information about where cyclists choose to position themselves when riding in bicycle lanes. The findings illustrate that, regardless of the width of the bicycle lane, cyclists tend to ride towards the centre of the lane. It is believed that the selected lane positioning may represent a form of risk mitigation with cyclists selecting a location that they deem to be safe and one that provides adequate spatial separation from both sides - adjacent traffic and parked cars. An interesting finding of this study was that, when riding in kerbside bicycle lanes, the provision of wider bicycle lanes did not result in participants further increasing their separation from moving traffic, instead cyclists still positioned themselves in the centre of the lane. This has important implications for the design of on-road bicycle facilities as it shows that increasing the width of cycling facilities does not necessarily increase the spatial separation between cyclists and adjacent motor vehicles by an equal amount and that there are potentially alternate methods to encourage cyclists to adopt safer cycling positions. Furthermore it highlights that cyclists may also perceive risks associated with riding too close to the edge of the roadway, where fixed objects and pedestrians may present a risk.
An important finding of this study was that increasing the lane width resulted in cyclists adopting faster speeds. This has potential safety implications: in the event of a collision (either multi- or single-vehicle), higher travel speeds are associated with higher kinetic energy and therefore increase the potential for serious injury outcomes. Furthermore, at higher speeds cyclists have less time to process information, to react to changes in the road environment, and require longer distances to come to a stop (WHO 2008). Additionally, as bicycle lane width increase, cyclists may exhibit less predictable behaviours, which may increase apprehension for other road users attempting to overtake cyclists. These findings are similar to previous research examining driver travel speeds in varying lane width configurations conducted by Godley et al. (2004) and their theory that travel speed is associated with mental effort may be applied to the findings of this study: cyclists make a trade-off between speed and steering in narrow (1.0 metre wide) bicycle lanes, and this may be due to increased mental workload required to remain within the narrow bicycle lane.

Another interesting finding from this study was that, for all scenarios, variability in lane position was greater than the 0.1 metre recommended by the design envelop for cyclists which is presented in the Austroads guidelines (Levasseur 2014). The finding suggests that cyclists may in fact require greater space than suggested for manoeuvrability and this in turn could have important implications for bicycle lane design specifications, however this finding requires further empirical research to confirm.

Study 2 was designed to understand the extent to which the use of perceptual countermeasures such as pavement marking could provide visual cues that may be effective in influencing cyclists' choice of lateral position and travel speed when riding within a bicycle lane. The results of the second study indicated that cyclists responded to the visual cues provided through the use of alternate pavement marking schemes and that the different lane designs were capable of influencing the speed and lateral positioning of the cyclists.

Within all scenarios, cyclists were encouraged to ride on the sections of the bicycle lane that were coloured green. This is a valuable finding as it shows that the cyclists in the study understood the basic meaning of the green pavement marking and were compelled to ride on the green sections of each bicycle lane. The finding confirms that pavement marking can be effective in encouraging cyclists to select particular lane positions, which has the potential to encourage cyclists to adopt safer cycling positions. Previous studies have shown that the presence of bicycle lanes can reduce the separation distance between cyclists and adjacent motor vehicles (Harkey & Stewart 1997), as such alternate pavement marking designs may help to improve the spatial separation between modes.

The results also indicated that the use of alternate pavement marking schemes can influence cyclist speed and lateral position variability. In particular, the scenario with a 0.5 metre green marking in the centre of the lane was found to significantly reduce cyclist speed and lateral position variability. This has important design implications, as it shows that very narrow sections of green marking may in fact cause cyclists to shed some of their task load to maintain lane position. While this has the benefit of speed reduction, it may also potentially result in reduced situational awareness as the cyclist focuses more on lane positioning and less on the surrounding road.
The treatments assessed in this study could be implemented in a variety of locations, particularly to address locations where road design provides insufficient lateral clearance between cyclists and motor vehicles. These style treatments could also be utilised to encourage cyclists to adopt safer lane positions, which may have the potential to reduce the risk of rear-end, side swipe and car door collisions, all of which are common mid-block crash types for cyclists in Australia.

Study 3 was similar to Study 2 and assessed how the use of bicycle logos, that are utilised to mark the bicycle lane, can be used as a perceptual countermeasure for cyclist safety. The findings showed that the location of logos was capable of encouraging cyclists to adopt different lane positions. Furthermore the alternate design trialled in the study was capable of resulting in cyclists shifting their position towards the centre when the logo was placed in the centre of the lane. This was a particularly interesting finding as in the previous two studies cyclists generally rode towards the right side of the bicycle lane, however this alternate logo resulted in a more centralised lane position, increasing the spatial separation between the cyclist and adjacent motor vehicle traffic.

The alternate design also showed a significant reduction in lane position variability. Again this is an important finding as it illustrates how design elements can be incorporated into bicycle lane design that encourage cyclists to adopt more consistent behaviours. This findings relates to the concept of Predictability, one of the key principles of Sustainable Safety (Wegman & Mulder 1998), where consistent road user behaviour is considered a desirable outcome of infrastructure design.

In Australia, Austroads recommend that bicycle logos are painted on bicycle lanes to help delineate the treatment and alert motorists of the potential presence of cyclists, as such, alternate bicycle logo designs that encourage safer protection represent a very cost effective measure to incorporate into bicycle lane design as they are enhancing an existing design element of the lane.

In Australia, Austroads recommend that bicycle logos are painted on bicycle lanes to help delineate the treatment and alert motorists of the potential presence of cyclists, as such, alternate bicycle logo designs that encourage safer protection represent a very cost effective measure to incorporate into bicycle lane design as they are enhancing an existing design element of the lane.

The studies presented in this chapter provide valuable insight into road design features that can be utilised to encourage safer cycling however there are various limitations to this research. Firstly and obviously this research was conducted using a bicycle simulator. While the results give an indication of the likely behaviours of cyclists in a real world environment due to the confidence instilled in this simulator through the validation process undertaken in Chapter 6, there are still limitations associated with simulator-based research as noted in Chapter 4. While the simulator environment gives considerable experimental control, it does not and cannot perfectly recreate the experience of riding a bicycle on-road in mixed traffic conditions and as such it can only be utilised to give an indication of the likely behaviours of cyclists when riding in a real urban environment. Real world environments have considerably more variables that would need to be considered in the assessment of prototype infrastructure, for example, the time of day, different road surfaces, debris on the road and atmospheric conditions and all of these variables may need to be considered in an evaluation of on-road infrastructure as they
have the potential to influence the way that cyclists behaviour and interact with the road environment. As such while the designs may be promising in the simulator environment there may be external factors that result in changes in cyclist behaviour and the findings from these studies need to be taken as a generalised finding for idealistic situations and may not be applicable to every specific location.

Another limitation of these studies was the relatively small sample size. While the sample was selected, based on power calculations to provide sufficient statically power for the experiment, the study recruited a small cohort of adult cyclists, as such there is the potential that the result of this study are not necessarily generalizable to the entire population of cyclists, particularly younger cyclists below the age of 18 or older adult cyclists.

Two other important limitations of simulator-based research are the safe environment that the research is being undertaken in and the Hawthorne effect. These two issues can influence the way that participants behave when using the simulator. Risks and mistakes made by the participants do not have the same consequences when riding in a safe environment as they would in the real world, and this can result in participants performing riskier or more dangerous behaviours, for example riding faster than they would in a real world situation. The Hawthorne effect has an opposite influence, whereby participants may attempt to perform the task in a manner which they believe the research wants the task done, not how they would perform the task in a real world environment when they were not under observation.

It is for these reasons that it is recommended that any real world trials of designs that are deemed to have potential road safety benefits are initially conducted within trial locations and are subject to a full on-road evaluation to ensure that the infrastructure is having the desired effect in real world environments, prior to the treatment options being installed throughout the road and cycling network.

The findings in this study provided unique insight into how cyclists position themselves within bicycle lanes and how their speed profile can be influenced by the width of cycling facility whether that is due to the actual available width or through application of perceptual countermeasures that imply lane narrowing. In the following chapter the concepts of bicycle lane design are further developed through an evaluation of a range of different lane design concepts that are aimed at addressing common mid-block crash types resulting in serious and fatal collisions.
Chapter 10: Evaluation of safer cycling infrastructure

This chapter presents two final simulator-based studies that were conducted to assess bicycle lane infrastructure concepts that were presented in Chapter 8. The evaluated bicycle lane designs are intended to reduce the risk of common mid-block cyclist crash types, identified in crash analyses (see Chapter 7) including rear-end, side-swipe and car door collisions.

Both of these collision types are particularly challenging for cyclists: they are often sudden events and are largely caused by actions of other road users and often difficult to avoid. Furthermore, due to the nature of the collisions, cyclists are afforded very limited time to anticipate the collision or to react to avoid the collision from occurring. The collisions also represent issues of insufficient lateral clearance between cyclists and adjacent traffic or parked cars.

The aim of the studies presented in this Chapter, therefore, were to build on the findings presented in the previous studies (Chapter 9), and evaluate a range of bicycle lane designs that offer various degrees of spatial, physical and vertical separation for cyclists from adjacent traffic and parked cars. The studies assessed bicycle lanes in terms of cyclist performance data collected from the bicycle simulator. The studies also collected subjective feedback from participants for each of the design concepts. The proposed concepts were selected with reference to Australian and International design standards, the principles of “Safe System” and KEMM and also commonly cited principles of cycling facility design in particular designing for safety, comfort and attractiveness. A post-study survey was undertaken to evaluate the infrastructure designs using these latent constructs. Another key component of this thesis is the concept that by developing and installing safer infrastructure designs there is the potential to increase cycling participation. As such, the post study survey asked participants to indicate if any of the concepts would encourage them to cycle on-road or cycle more often.

The research presented in this Chapter aligns with the primary research questions from Chapter 1 namely, what changes can be made to on-road cycling infrastructure to reduce the prevalence of serious and fatal cycling injury collisions and how do cyclists interact with alternate infrastructure treatments?

10.1 Methodology

The research presented in this Chapter consisted of two simulator studies. The first study was designed to evaluate a range of bicycle lane design concepts to address rear-end and side swipe collisions and the second study assessed a range of lane design concepts to address car-door collisions.

10.1.1 Apparatus

10.1.1.1 Bicycle simulator

The studies were conducted using the bicycle simulator that was detailed in Chapter 5 and validated in Chapter 6 of this thesis. No changes were made to the simulator architecture compared to the previous studies.
**10.1.1.2 Surveys**

In addition to the simulator component of the study, participants were required to complete a number of surveys. Details of each survey are provided in the following sections.

10.1.1.2.1 Subjective survey

Upon completion of the simulator component of the study, participants completed a questionnaire designed to evaluate the concept designs and measures their awareness of car-door, rear-end and side-swipe collisions.

Participants were asked to rate each design in terms of Safety, Comfort and Attractiveness. These latent constructs are associated with the principles of best-practice cycling facility design and are recommended principles by Austroads in Australia as well as being identified in several international cycling design guidelines (Table 16), (see Chapter 3 for details). The principles of Directness and Coherence, were not included in this study, as these variables are more commonly concerned with the larger cycling routes as opposed to design features of individual facilities. Prior to evaluating each design concept participants were shown each of the principles and the criteria as specified by Austroads (Levasseur 2014), to ensure that they understood what was measured by each of the constructs.

<table>
<thead>
<tr>
<th>Principle</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>Minimal risk of traffic-related injury, low perceived danger, space to ride, minimum conflict with vehicles.</td>
</tr>
<tr>
<td>Coherence</td>
<td>Infrastructure should form a coherent entity, link major trip origins and destinations, have connectivity, be continuous, signed, consistent in quality, easy to follow, and have route options.</td>
</tr>
<tr>
<td>Directness</td>
<td>Route should be direct, based on desire lines, have low delay through routes for commuting, avoid detours and have efficient operating speeds.</td>
</tr>
<tr>
<td>Attractiveness</td>
<td>Lighting, personal safety, aesthetics, integration with surrounding area, access to different activities.</td>
</tr>
<tr>
<td>Comfort</td>
<td>Smooth skid-resistant riding surface, gentle gradients, avoid complicated manoeuvres, reduced need to stop, minimum obstruction from vehicles.</td>
</tr>
</tbody>
</table>

Participants were first asked to identify what they believed were the most common crash types affecting cyclists when riding on the road. This question was included to gain a general understanding of what participants perceived to be the greatest risk to cyclists and to assess if their perceived risk aligned with crash types being investigated in this study.

Participants then evaluated the designs addressing car-door collisions. First they were asked if they were aware of car-door collisions as a collision mechanism. They were then shown a brief written description explaining the
crash type. Participants were then presented simulator scenarios depicting each infrastructure concept intended to address car-door collisions. The order of presentation was randomised to control for any order effects. Participants then completed a similar evaluation of rear-end and side swipe bicycle lane concept designs.

The survey was conducted using Qualtrics, an online survey software package, selected to reduce the risk of any data entry errors when transferring results from paper forms to a database for analysis. Participants completed the survey using a computer in the research laboratory.

10.1.1.2.2 Demographic survey

Participants completed the same demographic survey utilised for the validation study and the evaluation of lane width and perceptual countermeasures detailed in Chapter 6 and Chapter 9, respectively. The survey collects demographic information and information on participant's level of cycling participation and self-reported level of confidence riding a bicycle on road (Appendix D)

10.1.1.2.3 Simulator sickness questionnaire

Participants were administered the SSQ prior to commencing the study and again following completion of the simulator rides as per the protocol for studies presented in Chapters 6 and 9. Any participants who experienced high levels of simulator discomfort or sickness were excluded from the experiment and analysis as per the previous studies (Appendix C)

10.1.2 Simulator studies

As noted previously, two simulator studies were designed and undertaken to evaluate bicycle lane concepts addressing two common crash types, as follows:

- Study 1: assessment of bicycle lane designs to reduce the risk of rear-end or side swipe collisions.
- Study 2: assessment of bicycle lane designs to reduce car-door collisions.

10.1.2.1 Study 1: Rear-end and side-swipe collisions

Three bicycle lane concepts designed to reduce the risk for cyclists of being involved in rear-end or side swipe collisions were assessed:

- Bicycle lanes with spatial separation;
- Bicycle lanes with physical separation; and
- Vertically separated bicycle lanes.

Within these groups of bicycle lane concepts a number of sub-options were assessed. These bicycle lane design concepts are detailed in the previous Chapter and are summarised in Table 17. The study also includes three control scenarios which represent typical bicycle facilities currently in use on Australia roads:

- A road with no bicycle lane;
- Wide kerbside traffic lanes; and
A 1.5 metre wide convention bicycle lane

The inclusion of the control scenarios provided a baseline measurement which could be utilised to draw comparisons between subjective and objective data.

Table 17: Study 1: bicycle lane concepts

<table>
<thead>
<tr>
<th>No bicycle Lane</th>
<th>Wide kerbside traffic lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 metre wide convention bicycle lane</td>
<td>Green zone buffered bicycle lane</td>
</tr>
<tr>
<td>Chevron buffered bicycle lane</td>
<td>Car door buffered bicycle lane</td>
</tr>
<tr>
<td>Physically separated lane with traffic cones</td>
<td>Kerb separated bicycle lane</td>
</tr>
</tbody>
</table>
Performance was monitored during scenarios to assess how participants interacted with the infrastructure designs. The primary outcome measure was the lateral position of cyclists within the bicycle lane. The assumption being that bicycle lanes resulting in increased spatial separation between the cyclist and adjacent traffic are safer than lanes with limited spatial separation as cyclists have increased separation and hence reduced risk of being hit by passing motor vehicles or effected by side wind forces. Lateral position variation, speed and speed variation were also recorded to assess if the bicycle lane concepts influenced these other performance measures compared to the baseline scenarios.

The scenarios consisted of a 14.0 metre wide roadway resembling a typical arterial urban road environment. The carriageway consisted of two traffic lanes in each direction and kerbside cycling facilities. Simulated motor vehicle traffic was programmed to travel at a maximum speed of 60km/h and accelerate and decelerate in accordance with the signal phasing at intersections. These conditions reflected the most common geometry and speed environments where rear-end and side-swipe collisions were found to occur in the analysis of crash data undertaken in Chapter 7.

**10.1.2.2 Study 2: Car door collisions**

Study 2 was conducted in two stages. The first stage assessed design concepts when on-street parking was located adjacent to the kerb. The second stage assessed design concepts when the bicycle lane and parking lane positions were swapped and the bicycle lane was repositioned adjacent to the kerb (Figure 73).
10.1.2.2.1 Part 1 – Kerbside parking

The first stage assessed bicycle lane concepts that were designed to reduce the risk of cyclists being involved in a car-door collision when riding on roads with kerbside parking for motor vehicles. As parking is provided adjacent to the kerb in this stage it was not practical to provide physical or vertical separation options for cyclists as motor vehicles are required to cross the bicycle lane to access on-street parking spaces. The lane design concepts therefore focused on measures to increase spatial separation through pavement marking designs. For this study, the lane design concepts were compared to two base case scenarios, the first was typical 1.5 metre bicycle lane and the second base case scenario was a road with no bicycle lane. The three concepts and two baseline conditions were previously discussed in Chapter 8, and are summarised in Table 18.

Table 18: Study 2: Part 1 bicycle lane concepts

<table>
<thead>
<tr>
<th>No bicycle Lane</th>
<th>1.5m conventional bicycle lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevron buffered bicycle lane</td>
<td>Car door buffered bicycle lane</td>
</tr>
<tr>
<td>Green zone buffered bicycle lane</td>
<td></td>
</tr>
</tbody>
</table>

10.1.2.2.2 Part 2 – Kerbside bicycle lane

The second stage assessed bicycle lane concepts designed to reduce the risk of cyclists being involved in a car-door collision when riding adjacent to the kerb. This lane configuration is theoretically considered safer as cyclists are riding on the passenger side of parked cars, which should reduce their exposure to car doors.
opening in their path. Estimates of car occupancy in Victoria suggest that the average private vehicle carries 1.2 occupants (VicRoads 2014). Therefore, while there are always drivers in the vehicle and the driver side door has the potential to be opened, on average only 1 in 5 cars are carrying a passenger, as such passenger side doors are opened less frequently, lowering the risk of car door collisions for cyclists when the bicycle lane is placed on the passenger side of parked vehicles. The lane configuration has added benefits as interactions with moving traffic are reduced as the parked cars form a barrier between the bicycle and traffic lanes. Furthermore there is a reduced risk of collisions between cyclists and motor vehicles as they enter and exit parking spaces.

Three lane design concepts were assessed considering spatial, physical and vertically separated lane concepts. Concepts were compared to base case scenarios which will represent typical 1.5 metre wide bicycle lane.

Table 19: Study 2: Part 2 - bicycle lane concepts

<table>
<thead>
<tr>
<th>1.5m conventional bicycle lane</th>
<th>Chevron buffered bicycle lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green zone buffered bicycle lane</td>
<td>Car door buffered bicycle lane</td>
</tr>
<tr>
<td>Physically separated lane with traffic cones</td>
<td>Kerb separated bicycle lane</td>
</tr>
</tbody>
</table>
10.1.2.3 Study procedure

The general study procedure consisted of participants receiving a brief explanation of the research project and what tasks they would perform on the day of testing. This included reviewing the explanatory statement and collecting signed consent forms if participants had not previously returned a digital copy of the form.

Participants then completed the demographic survey and baseline SSQ. Following completion of the surveys participants who were unfamiliar with Virtual Reality headsets were given a demonstration of the HMD.

Participants then completed four practice rides using the bicycle simulator. These rides were designed to familiarise participants with the HMD and the simulator environment and were the same rides used in the previous study detailed in Chapter 8. Following the practice rides participants completed the simulator scenarios in a randomised order. While there were two distinct studies addressing different design concepts, rather than separate the designs based on the intended crash type being addressed, participants were shown designs from both studies in a randomised order at the same time. This was done to control for learning effects or any fatigue that might occur due to riding on the simulator bicycle throughout the experiment.

Following completion of all simulator scenarios, participants completed the SSQ again and then completed the subjective questionnaire where they evaluated each of the bicycle lane design concepts.

10.1.3 Data Analysis

For the simulator component of the study, ANOVA was the primary statistical technique employed. Effect sizes were measured using Eta squared ($\eta^2$). Post-hoc testing was performed using Tukey’s HSD test for pairwise comparisons. Prior to analysis, tests for normality were conducted using skewness and kurtosis. Results were normally distributed and no transformations of the data were necessary.

Results from the post evaluation survey were assessed using descriptive statistics. ANOVA was also performed to check for differences between the subjective feedback for the different design concepts in each study. Post-hoc testing was performed using Tukey’s HSD test for pairwise comparisons. It is noted that this is a limitation of the analysis in that parametric tests were performed on non-parametric survey data. All statistical analysis was conducted using STATA version 13.1.
10.1.4 Participants

A total of 30 participants (23 males and 7 females) were recruited. The same exclusion criteria were implemented as in previous studies in Chapter 9. Recruitment was also undertaken using similar methods to the previous studies.

Of the 30 recruited participants, two participants were excluded from analysis. One participant experienced high levels of simulator sickness and was unable to complete the full set of simulator scenarios. The other participant was unable to control the bicycle when performing the practice scenarios. The remaining 28 participants ranged in age from 19 to 57 years (M=24.8, SD=8.1). The research protocol for the study was reviewed and approved by the Monash University Human Research Ethics Committee (MUHREC). Participants received a $25 AUD gift voucher for volunteering to take part in the study and to compensate them for their time and travel expenses. The study required approximately one hour for each participant to complete.

10.2 Results

Results are presented separately for each of the studies, including the simulator and subjective evaluation survey findings. This is followed by a comparison of findings from between studies.

10.2.1 Participants

As per the previous studies, participants completed a short demographic and cycling experience questionnaire prior to undertaking the simulator study. Participants were asked to rate their level of confidence regarding cycling on road. As with the previous studies participants were relatively confident riding on road with a mean self-reported confidence rating of 8.2 out of 10 (SD = 1.8).

Similar to the previous studies, the majority of participants cycled less than 50 kilometres per week (67.8%), and participants typically rode for either recreational (57.1%) or commuting (25.0%). Five participants in this study had previously been involved in a crash while riding a bicycle within the past three years, however all the crashes were relatively minor. One participant had to delay their participation in the study as they were involved in a fall from their bicycle the day before their initial test session. Across the study there was a good distribution of age, gender and self-reported cycling experience, suggesting the results should be somewhat generalizable to a broader spectrum of adult cyclists.

Participants were asked to describe their knowledge and thoughts on the most commonly occurring crash types involving cyclists. The most common response was for cyclist collisions with car doors (42.8%), followed by drivers failing to see cyclists (23.3%) and cyclists having single vehicle collisions either as a result of reckless riding or riding too fast (17.9%). These findings aligned well with the crash analysis conducted in Chapter 7, suggesting that the participants were reasonably aware of the common risks associated with on-road cycling.
10.2.2 Study 1: Rear-end and side-swipe treatments

For the first study assessing rear-end and side-swipe treatments, nine concepts were assessed including three baseline conditions.

10.2.2.1 Simulator results

Simulator results are presented separately considering the average lateral position, deviation in lane position, and their speed profile throughout the experiment.

10.2.2.1.1 Lane position

Average lane position along each 100 metre section of road was assessed for each scenario. Figure 74 shows that average lane position from the left hand side of the bicycle lane varied across the nine lane configurations. The baseline condition, consisted of a standard four lane road with two 3.5 metre wide lanes of traffic in each direction and no dedicated bicycle lane. This scenario was found to result in participants riding the furthest distance from the edge of the road, with an average offset of 1.16m (SD = 0.41m).

![Figure 74: Study 1: Position relative to the left edge of the bicycle lane](image)

Two other baseline conditions were included in this study, a wide kerbside bicycle lane and a conventional 1.5 metre bicycle lane. These two design concepts resulted in the next furthest offset from the kerb, with cyclists riding an average of 0.79 metres (SD = 0.10m) from the kerb for the wide kerbside lane scenario and 0.83 metres (SD = 0.13) from the kerb for the 1.5 metre bicycle lane scenario.
In relation to the three bicycle lane design principles, spatial, physical and vertical separation, each design option resulted in a shift in cyclist lateral position towards the kerbside of the lane, compared with baseline conditions (Figure 74).

ANOVA confirmed that there were significant differences in lane position amongst the nine scenarios ($F_{8, 251} = 30.56, p = 0.00, \eta^2 = 0.53$). Post-hoc testing identified that there were significant differences in average lateral position between the lane design concepts. Significant differences in lane position were observed between the baseline condition with no bicycle lane and the remaining designs (including the other two baseline conditions). This finding suggests that even lower order bicycle facilities such as wide kerbside lanes are capable of encouraging cyclists to adopt lane positions closer to the left edge of the roadway and away from adjacent motor vehicle traffic.

Further comparisons between lane positioning in the wide kerbside traffic lane scenario and the bicycle lane concept scenarios revealed that cyclists rode in significantly different locations for the green zone buffered bicycle lane (0.79 m vs 0.64 m, $p = 0.015$) and the kerb separated lane scenarios (0.79 m vs 0.63 m, $p = 0.006$). In addition, results approached significance for the concept incorporating traffic cones to provide physical separation between the cyclists and adjacent traffic (0.79m vs 0.66 m, $p = 0.072$).

When considering comparisons of lane position in the 1.5 metre bicycle lane baseline scenario and design concept scenarios, the findings identified significantly different riding positions for each of the design concepts, with the exception of the car door buffered lane concept ($p=0.314$). This suggests that, compared with a conventional 1.5 metre bicycle lane, most of the concepts demonstrated the potential to encourage cyclists to adopt lane positions further away from adjacent traffic and closer to the left side (kerb side) of the carriageway. No significant differences in lane position were identified between any of the concepts that utilised spatial, physical or vertical separation principles.

10.2.2.1.2 Lane position variability
Variability in lane position, defined as the standard deviation in lane position along the length of the bicycle lane, was assessed for each of the scenarios. A summary of lane position variability across the nine scenarios is presented in Figure 75, and shows that the variability in lane position was relatively constant across scenarios, with the exception of the scenario with no bicycle lane, which resulted in a higher average increase in lane position variability. Somewhat interestingly, the physically separated bicycle lane concept that incorporated traffic cones to provide a physical barrier resulted in lower lane position variability compared to the other concept designs.
These differences were confirmed through ANOVA which identified that there were significant differences in lane position variability between the scenarios ($F_{8, 251} = 6.89, p = 0.00, \eta^2 = 0.20$). Post-hoc testing identified that significant differences in lane position variability existed between the baseline scenario with no bicycle lane and all the other design scenarios. A significant difference was also identified between the baseline scenario with wide kerbside lane and the concept that incorporated traffic cones to provide physical separation ($p=0.19$), however the lower lane position variability was not significantly different to the other lane design concepts. Amongst the remaining concepts, no significant differences in variability were observed, this was largely to be expected as the bicycle lane concepts maintained a 1.5 metre lane width for participants. This finding was similar to the findings in Chapter 9 where it was shown that variability in lateral position only significantly reduced for the very narrow 1.0 metre bicycle lane, or when perceptual countermeasures were utilised to create a visual perception of a very narrow lane, which is occurring to an extent with the physically separated traffic lane scenarios.

10.2.2.1.3 Speed profile

Instantaneous speed was measured along the length of the bicycle lane for each scenario. A summary of the average speed of participants for each scenario is presented in Figure 76. Across the nine scenarios, participants tended to ride slightly faster for the scenario with no bicycle lane, followed by the scenario with wide kerbside traffic lanes. However, ANOVA identified that there were no significant differences in average speed when considering the nine different lane configurations ($F_{8, 251} = 1.39, p = 0.21, \eta^2 = 0.05$). This finding suggests that, while there was some variation in average speed, the influence of the designs on cyclist speed were negligible. This is an important finding as it is ideal that the proposed design(s) do not adversely compromise the performance of cyclists which may distract the cyclists from their other navigation and guidance tasks.
Speed variability was assessed for each of the lane design options, and ANOVA identified a significant difference in participant speed variability when riding each of the nine scenarios \((F_{8, 251} = 2.20, \ p = 0.029, \eta^2 = 0.075)\), however post-hoc testing did not reveal any significant pairwise differences between the individual scenario results, highlighting that the variability while statistically significant was trivial. This is also highlighted by the very small effect size.

10.2.2.2 Survey results

Following completion of the simulator rides, participants were asked if they were aware of minimum passing distance laws. The majority of participants (53.6%) stated that they were aware of the laws. Participants were then shown a brief description of how minimum passing distance laws are intended to increase the spatial separation between cyclists and motor vehicles and how these laws can help to reduce the incidence of rear-end and side swipe collisions (DCA code 130 & 133). Participants were also shown a diagrammatic representation of the crash types to ensure they understood the crash mechanism.

Next, participants were asked to rate each of the nine bicycle lane design concepts based on the bicycle design principle latent constructs of Safety, Comfort and Attractiveness as shown in Table 16. Participants were also asked if the lane design concept would encourage them to ride on road further or more often. Survey results for the nine bicycle lane designs were compared to assess cyclist preference for the design concept. A summary of the survey results for the three latent constructs (Safety, Comfort and Attractiveness) are presented in Figure 77, results for the question that asked if the lane design would encourage increased participation are presented in Figure 78 and a summary of the average and standard deviation of results for each of the four question are presented in Table 20.
Figure 77 shows that overall participants preferred the vertically separated bicycle lane design, which received the overall highest average scores for Safety, Comfort and Attractiveness. The kerb separated bicycle lane received the next highest score for Safety (7.4), however it received a lower average rating for Comfort and Attractiveness (6.7 and 6.4 respectively) and was outscored when considering Attractiveness and Comfort by the green buffered bicycle lane concept, however this concept received an overall lower safety rating (7.0). These findings suggest that participants recognised the safety benefit of physically separated treatments but found the design less visually appealing and comfortable to ride in, possibly due to the fact that the kerb separated bicycle lane constrains cyclists within the bicycle lane and reduces the ability to enter and leave the lane freely. At the other end of the scale, the least preferred design was the buffered bicycle lane that incorporated pavement marking to illustrate car door locations. This design received the lowest scores for Safety (5.3), Comfort (4.8) and Attractiveness (4.7) of the concept designs. When considering the baseline conditions the scenario with no bicycle lane, followed by the wide kerbside lane received the overall lowest scores, while the conventional bicycle lane was relatively well received, outscoring several of the design concepts.

ANOVA confirmed that, amongst the nine design options, there was a significant difference in the subjective ratings of the designs when considering participants perspective of safety ($F_{8, 269} = 15.78$, $p = 0.00$, $\eta^2 = 0.32$). Post-hoc testing confirmed that the baseline lane conditions with no bicycle lane and wide kerbside lanes were considered significantly less safe compared to the other designs. Furthermore, the perceived safety of the car-door buffered design was significantly lower than the kerb separated lane and the vertically separated lane. No other significant differences in subjective feedback were identified.
Similarly, there were significant differences identified for the Comfort ($F_{8, 269} = 12.47, p = 0.00, \eta^2 = 0.27$) and Attractiveness ($F_{8, 269} = 10.91, p = 0.00, \eta^2 = 0.25$) subjective ratings. Post-hoc analysis identified similar trends when considering pairwise differences between the scenarios. The scenario that incorporated traffic cones to provide physical separation was considered significantly less attractive, compared to the vertically separated concept design.

When asked if the designs could encourage participants to cycle further or more often, participants gave the highest overall score to the vertically separated bicycle lane (Mean = 4.07, Standard Deviation = 1.08), followed by the kerb separated style lane (M = 3.77, SD = 1.07) and the green zone buffered bicycle lane (M =3.7, SD = 0.99). On average, participants stated that the conventional bicycle lane would be more likely to encourage them to cycle more often compared to two of the buffered bicycle lane concepts and the concept that utilised traffic cones to provide physical separation, although the safety benefits of the traffic cones were rated higher by participants compared to a conventional 1.5 metre bicycle lane (6.8 vs 6.2).

ANOVA revealed that there were significant differences amongst users perspectives regarding the effect of the bike lane designs to encourage increased participation ($F_{8, 269} = 9.25, p = 0.00, \eta^2 = 0.22$). These differences were found between the baseline conditions with no bicycle lane, the wide kerbside traffic lane and the car door buffered treatment, as expected from the graphical representation of results in Figure 78.
Table 20: Study 1: Subjective feedback results [mean (SD)]

<table>
<thead>
<tr>
<th></th>
<th>Safety</th>
<th>Comfort</th>
<th>Attractiveness</th>
<th>Encourage riding*</th>
</tr>
</thead>
<tbody>
<tr>
<td>No bicycle Lane</td>
<td>2.50 (1.53)</td>
<td>2.67 (1.79)</td>
<td>2.83 (2.04)</td>
<td>1.90 (0.88)</td>
</tr>
<tr>
<td>Wide kerbside traffic lane</td>
<td>4.73 (1.93)</td>
<td>4.73 (1.91)</td>
<td>4.50 (2.15)</td>
<td>2.60 (1.07)</td>
</tr>
<tr>
<td>1.5m conventional bicycle lane</td>
<td>6.20 (2.09)</td>
<td>6.10 (2.11)</td>
<td>6.20 (2.11)</td>
<td>3.53 (0.97)</td>
</tr>
<tr>
<td>Chevron buffered bicycle lane</td>
<td>6.27 (2.26)</td>
<td>5.93 (2.26)</td>
<td>5.03 (2.41)</td>
<td>3.20 (1.16)</td>
</tr>
<tr>
<td>Car door buffered bicycle lane</td>
<td>5.27 (2.27)</td>
<td>4.83 (2.1)</td>
<td>4.67 (2.29)</td>
<td>2.67 (0.99)</td>
</tr>
<tr>
<td>Green zone buffered bicycle lane</td>
<td>7.03 (2.17)</td>
<td>6.83 (2.32)</td>
<td>6.70 (2.42)</td>
<td>3.70 (0.99)</td>
</tr>
<tr>
<td>Physically separated lane with traffic cones</td>
<td>6.77 (2.54)</td>
<td>6.30 (2.55)</td>
<td>5.47 (2.62)</td>
<td>3.47 (1.2)</td>
</tr>
<tr>
<td>Kerb separated bicycle lane</td>
<td>7.37 (2.34)</td>
<td>6.73 (2.66)</td>
<td>6.40 (2.7)</td>
<td>3.77 (1.07)</td>
</tr>
<tr>
<td>Vertically separated bicycle lane</td>
<td>7.47 (2.21)</td>
<td>7.47 (2.22)</td>
<td>7.6 (2.28)</td>
<td>4.07 (1.08)</td>
</tr>
</tbody>
</table>

*Participation out of 5 (1 = extremely unlikely, 5 = extremely likely)

10.2.2.3 Study 1 Summary

When considering the subjective feedback from participants the preferred design was clearly the vertically separated bicycle lane. This style of bicycle lane is considered best-practice design in the Netherlands and received the highest average ratings for all three network design principles and received the highest positive feedback regarding the extent to which lane design would encourage participants to cycle more often. Compared to the scenario with no-bicycle lane, the vertically separated lane also resulted in a shift in lateral position away from the adjacent motor vehicle traffic lane. This is a positive finding as while the vertical separation would reduce the chance of a physical conflict between cyclists and adjacent traffic due to the kerb separation, cyclists are still subjected to side wind forces from passing vehicles, particularly trucks. As such, it is beneficial that the design resulted in a shift of lateral position as it reduced the risk of cyclists having a single vehicle collision due to loss of control of their bicycle. The simulator component of the study also revealed similar speed profiles and variability in lateral position for this design compared to a conventional 1.5 metre bicycle lane. These are also positive findings, suggesting that cyclist found the design no more complicated than conventional on-road bicycle lanes to negotiate. The benefits of vertically separated bicycle lanes were discussed in Chapter 8 and include the provision of a physical barrier between cyclists and motor vehicles and pedestrians and raising the cyclist’s height making them more obvious to other road users, particularly heavy vehicles. However, the provision of vertical separation does require additional construction costs and is only suitable in locations where motor
vehicles are not required to cross the bicycle lane, such as arterial roads that do not have vehicle crossovers for adjacent properties. At cross over locations, it may be necessary to transition the vertically separated lane to a conventional lane, alternatively mountable kerb could be installed to allow vehicles to access adjacent properties, however this should be discouraged if possible, as it would increase cyclist exposure and interaction with motor vehicles which is essentially what the design is attempting to minimise.

The next most desirable treatment when considering participants subjective feedback was the kerb separated bicycle lane. This is a treatment that has been installed along some of the busier cycling routes in metropolitan Melbourne and it was reassuring that the design was generally well received by participants in the study. Obviously the lane design provides a high degree of physical separation, however the restriction on lane width due to the kerb separator seemed to reduce participant’s views towards the comfort and attractiveness of the design. Furthermore due to the physical barrier this style of bicycle lane can be restrictive for cyclists if they need to deviate from their trajectory to avoid objects or debris on the bicycle lane, or even to overtake slower moving cyclists.

The third most positively reviewed lane concept was the bicycle lane incorporating the green buffer into the design. Participants generally gave high ratings for this design. The use of pavement marking is much more cost effective than lane designs that require physical infrastructure. However there is a clear limitation of these designs in that they do not provide any physical barrier to prevent motor vehicles from interacting with cyclists.

10.2.3 Study 2: Car-door collisions

The second study assessed treatments to reduce the risk of car-door collisions. This study included two stages. Five concepts were considered for stage 1 which considered bicycle lane designs with kerbside parking. Seven concepts were considered for the second stage which considered bicycle lanes adjacent to the kerb.

10.2.3.1 Stage 1: Kerbside parking

10.2.3.1.1 Simulator results

The second study considered the same variables from the simulator as Study 1.

10.2.3.1.1.1 Lane position

A summary of average lane position for each scenario is presented in Figure 79, and shows that the average lane position away from the left side of the bicycle lane varied across the five bicycle lane concepts when kerbside parking was present. For the baseline condition, the carriageway consisted of two 3.5 metre wide traffic lanes in each direction and no dedicated bicycle lane. Participants rode between the parked car in the kerbside lane and the adjacent traffic lane. For the baseline scenario, participants were found to ride the closest to the parked cars, compared to the other four scenarios, with an average offset of 0.76 metres from the left edge of the bicycle lane (SD = 0.23). For the other baseline condition (a conventional 1.5 metre bicycle lane), participants rode at an offset of 0.94 metres (SD = 0.17). This distance was slightly higher than the results for a similar scenarios tested in Chapter 9. However, in this study car-doors were programmed to open in front of participants...
as they rode along the length of the bicycle lane and it appears that this has resulted in participants shifting further away from the left side of the bicycle lane, compared to the scenarios in Chapter 9 where the parked cars and car-doors remained static.

ANOVA confirmed that there was a significant difference in lane position amongst the five scenarios aimed at addressing car-door collisions when on-street parking was kerbside ($F_{4, 139} = 27.69$, $p = 0.00$, $\eta^2 = 0.51$). When considering the results of post-hoc testing a significant difference in lane position was identified between the baseline condition with no bicycle lane and the four other conditions, with participants riding closer to the parked cars when no bicycle lane was present compared to any of the bicycle lane concepts. A significant difference was also identified between the conventional 1.5 metre bicycle lane and the chevron and car-door buffered bicycle lanes ($p=0.034$ & $0.001$), with participants riding significantly further away from parked cars in the two buffered scenarios. Results were also approaching significance for the green zone buffered option ($p = 0.162$). No significant differences in lane position were observed between the three buffered lane design concepts, suggesting that the three designs resulted in similar lane positioning behaviours.

10.2.3.1.1.2 Lane position variability

A summary of the average lane position variability for each scenario is presented in Figure 80. Figure 80 shows that participant variability in lane position was greatest for the baseline scenario with no bicycle lane (0.36m). For this scenario the kerbside lane was 3.5 metres wide and the parked cars were positioned so that they extended approximately 2.0 metres out from the kerb, leaving an effective width of 1.5 metres for the cyclist when cars were present. However, in locations where on-street parking was not present, cyclists were able to ride closer to the kerb, that is to say they could ride in the space allocated for on-street parking. It appears that when there was
no bicycle lane to provide a visual cue of where participants should be riding, participants were inclined to ride much closer to the kerb and then move out from the kerb when passing parked cars. This in itself is not necessarily a dangerous behaviour as cyclists appear to have ridden closer to the kerb, and further away from adjacent traffic when parked cars were not present. However this style of riding could potentially be more difficult for car drivers and vehicle occupants to detect cyclists when opening car-doors as they may be obstructed from view and may be harder to observe because they are not positioned in a consistent location. It may also make it difficult for passing motorists to judge when it is safe to pass cyclists when they are riding in a less consistent manner.

Lane position variability was considerably lower for the four bicycle lane scenarios, albeit slightly higher for the conventional 1.5 metre bicycle lane. This was an expected finding as the buffered bicycle lanes utilised pavement marking to reduce the effective width of the bicycle lane and as such it was anticipated that cyclists would be considerably less likely to deviate from their path.

![Figure 80: Study 2: Lane position variability when kerbside parking was present](image)

The differences in lane position variability were confirmed through ANOVA, where a significant difference was detected when comparing the five design concepts \( (F_{4, 139} = 30.76, p = 0.00, \eta^2 = 0.53) \). As expected based on the graphical representation of the data in Figure 80, post-hoc testing identified that the differences in variability were between the baseline condition with no bicycle lane and the other four conditions. This finding demonstrates that the use of any style of bicycle lane, for this road cross section, has positive benefits in that it increases the spatial separation between cyclists and parked motor vehicles, while also reducing the variability in cyclist lateral position.
### 10.2.3.1.1.3 Speed

Average participant speeds across the five scenarios were relatively consistent (Figure 81). This was confirmed through ANOVA which identified that there were no significant differences in the average speed of participants amongst the five scenarios ($F_{4, 139} = 1.5, p = 0.20, \eta^2 = 0.05$), furthermore no differences in speed variability were observed ($F_{4, 139} = 0.65, p = 0.62, \eta^2 = 0.02$). This suggests that the lane design concepts did not influence participant performance in regards to their speed control and that they were capable of maintaining their desired speed equally regardless of the design.

![Figure 81: Study 2: Participant average speed when kerbside parking was present](image)

### 10.2.3.1.2 Survey results

Following completion of the simulator rides, participants were asked if they were aware of car-door collisions. The majority of participants (93%) stated that they were aware of these collision types, and this was significantly higher than the self-reported knowledge of minimum passing distance laws, suggesting that there is much greater awareness regarding the issues of car-door collisions amongst participants. Participants were also shown a diagrammatic representation of the crash types to ensure they understood the crash mechanisms, prior to evaluating the infrastructure designs.

Similar to study 1, participants were asked to provide subjective feedback on each of the designs regarding the Safety, Comfort and Attractiveness. A summary of the responses for the three latent constructs are presented in Figure 82, while responses regarding if the designs would encourage increased participants are presented in Figure 83 and a summary of the average and standard deviation of responses for each of the four question are presented in Table 21.
From Figure 82 the preferred design amongst participants was the green buffered bicycle lane, which received the overall highest ratings for all three latent constructs. This was also the preferred style of spatially separated bicycle lane in study 1. Compared with the 1.5 metre bicycle lane the other two buffered lane designs received higher average scores for Safety and Comfort, however the car door buffer lane received a lower Attractiveness rating. This was different to the previous study where the conventional lane style had outscored the other buffered lanes when considering rear-end and side swipe collisions. The findings suggest that participants perceived the spatial separation provided by the buffered lane to be a more important safety countermeasure to reduce car-door collisions as opposed to rear-end and side swipe collisions, which was expected. The baseline condition with no bicycle lane received the overall lowest scores for all three latent constructs. This was also an expected finding as the concept provided no dedicated space for cyclists and offered no real measure to provide separation from parked cars, or adjacent vehicular traffic.

ANOVA confirmed that amongst the five design options there were significant differences in the subjective ratings of the designs when considering participants perspective of Safety ($F_{4, 149} = 10.74$, $p = 0.00$, $\eta^2 = 0.23$), Comfort ($F_{4, 149} = 9.23$, $p = 0.00$, $\eta^2 = 0.20$) and Attractiveness ($F_{4, 149} = 8.05$, $p = 0.00$, $\eta^2 = 0.18$) subjective ratings. Post-hoc testing highlighted that these differences were largely between the no bicycle lane concept and the other designs, with the exception that the green buffered bicycle lane was significantly more attractive to participants compared to the car door buffer option.
When asked if the designs could encourage increased cycling, participants gave the highest overall score to the green zone buffed bicycle lane concept (M = 3.47, SD = 1.31), chevron buffered bicycle lane (M = 2.97, SD = 1.3) and the conventional 1.5 metre wide lane (M = 2.93, SD = 1.14). ANOVA revealed that there were significant differences amongst participant ratings for the likelihood of design concepts to encourage increased cycling ($F_{4, 149} = 7.07, p = 0.00, \eta^2 = 0.16$). Post-hoc testing identified that the differences were only significant between the no bicycle lane concept and the other four designs.

Table 21: Study 2: Bicycle lane adjacent to kerbside parking subjective feedback [mean (SD)]

<table>
<thead>
<tr>
<th></th>
<th>Safety</th>
<th>Comfort</th>
<th>Attractiveness</th>
<th>Encourage riding*</th>
</tr>
</thead>
<tbody>
<tr>
<td>No bicycle Lane</td>
<td>2.50 (1.72)</td>
<td>2.80 (1.86)</td>
<td>2.93 (2.3)</td>
<td>1.73 (0.78)</td>
</tr>
<tr>
<td>1.5m bicycle lane</td>
<td>4.90 (2.14)</td>
<td>4.83 (2.2)</td>
<td>4.93 (2.23)</td>
<td>2.93 (1.14)</td>
</tr>
<tr>
<td>Chevron buffered</td>
<td>5.80 (2.67)</td>
<td>5.57 (2.45)</td>
<td>5.17 (2.52)</td>
<td>2.97 (1.3)</td>
</tr>
<tr>
<td>bicycle lane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car door buffered</td>
<td>5.30 (2.52)</td>
<td>5.30 (2.6)</td>
<td>4.77 (2.47)</td>
<td>2.87 (1.2)</td>
</tr>
<tr>
<td>bicycle lane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green zone</td>
<td>6.13 (2.65)</td>
<td>6.30 (2.55)</td>
<td>6.50 (2.69)</td>
<td>3.47 (1.31)</td>
</tr>
<tr>
<td>buffered bicycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Participation out of 5 (1 = extremely unlikely, 5 = extremely likely)
10.2.3.1.3 Summary
The green zone buffered bicycle lane was the preferred concept when considering user perspectives of safety, comfort, attractiveness and if the design would encourage increased participation. Compared to the baseline scenario with no bicycle lane the green zone buffered lane resulted in cyclist riding an average of 0.26 metres further towards the right side of the bicycle lane, that is a quarter of a meter further away from parked cars. This behaviour significantly increased the clearance between cyclists and parked cars, which would theoretically reduce the risk of a car door collision occurring. However the buffered lane concepts did not result in as substantial shifts in lateral position compared to the conventional 1.5 metre wide bicycle lane, albeit there was a shift up to 0.14 metres which is still likely to be beneficial. The reduced shift in lateral position may be a result of the opening car doors in these scenarios causing cyclists to adopt positions further from the parked cars regardless of the pavement marking. The buffered bicycle lane concepts also resulted in a significant reduction in cyclist lane position variability. Again this is a positive findings showing that the designs encourage more consistent cycling behaviours.

No significant differences were identified between the buffered lane concepts and the 1.5 metre wide bicycle lane. However, there was a small, but not statistically significant, reduction in variability. None of the designs were shown to significantly influence cyclist speed profiles. This is an important finding as it is similar to findings from Chapter 9 whereby, if designs had resulted in significant reductions in speed it may suggest cyclists are shedding load to focus on the guidance task and comply with the lane position suggested by the concept design. Overall the study found that the buffered bicycle lanes were effective at shifting cyclists’ lateral position and could be implemented as an effective measure to move cyclists further outside the car-door zone when kerbside on-street parking is present. However this is cautioned as shifting cyclists position away from kerbside cars could move them towards adjacent vehicular traffic and potentially increasing their exposure to other collision types. It is therefore cautioned that the design concept should only be implemented when there is sufficient width within the carriageway to provide cyclists with minimum bicycle lane widths in accordance with their required design envelope once the buffered treatment is incorporated.

10.2.3.2 Stage 2: Kerbside bicycle lane
10.2.3.2.1 Simulator results
10.2.3.2.1.1 Lane position
For the scenario with kerbside bicycle lanes, it was not practical to consider the baseline options with no bicycle lane or with wide kerbside lanes as for this concept the bicycle lane is placed between the parked car and the kerb. This creates a constrained space for the cyclists between parked cars and the kerb, so there are limitations in a participant’s ability to deviate in lane position. As such, all the lane concepts encouraged cyclists to ride within the same 1.5 metre space. From Figure 84 it can be seen that the baseline condition with a conventional 1.5 metre bicycle lane resulted in participants riding further from the kerb, compared to the six design concepts. Essentially this concept resulted in participants adopting the most dangerous lane position with the greatest risk,
that is, positioning themselves closest to the parked cars, and potentially increasing the risk of car door collisions.

Amongst the six lane design concepts there were only minor differences in lane position, with the greatest spatial separation between parked cars seen from the kerb separated bicycle lane concept. ANOVA confirmed that there were significant differences in lane positioning between the lane design concepts ($F_{6,195} = 12.82$, $p = 0.00$, $\eta^2 = 0.32$). Post-hoc testing confirmed that participants' lane position was significantly different for the baseline condition compared to the six design concepts. The only other significant difference in lane position was observed between the kerb separated lane and the vertically separated lane ($p=0.014$).

10.2.3.2.1.2 Lane Position variability

When considering lane position variability, deviation in lane position was relatively consistent across the seven scenarios as shown in Figure 85. The highest deviation was observed for the scenario with the car-door style buffer (0.13m). ANOVA identified that there was a small yet significant difference between average lane position variability across the seven scenarios ($F_{6,195} = 3.01$, $p = 0.01$, $\eta^2 = 0.1$). However post-hoc testing identified that the only significance pair-wise differences was between the car-door buffered lane and the green zone buffered lane and that no other significant differences in lane position variability existed. This finding highlights that generally the design concepts did not influence the riding style of participants.
10.2.3.2.1.3 Speed

Average speeds across the seven scenarios were also relatively consistent (Figure 86). This was confirmed through ANOVA which identified no significant differences in average speed across the seven bicycle lane concept designs ($F_{6, 195} = 2.03, p = 0.06, \eta^2 = 0.7$). A small significant difference was observed when considering variability in speed ($F_{6, 195} = 2.84, p = 0.01, \eta^2 = 0.09$). Post-hoc testing identified that there was increased variability in speed for the base case scenario compared to the kerb separated and vertically separated bicycle lane, where cyclists rode at a more consistent speed, however the differences were negligible.
10.2.3.2.2 Survey results

Again, participants were asked to provide subjective feedback on each of the designs regarding the Safety, Comfort and Attractiveness. A summary of the survey results for the latent constructs are presented in Figure 87, while results regarding the effect of designs on encouraging increased participation are presented in Figure 88. Last, a summary of the average and standard deviation of results for each of the four question are presented in Table 22.

Similar to study 1, Figure 87 shows that the preferred design concept was the vertically separated bicycle lane, which received the highest average scores for all three latent constructs. This was followed by the green zone buffered bicycle lane and the kerb separated bicycle lane.

ANOVA confirmed that amongst the seven design options there were significant differences in the subjective ratings of the designs when considering participants perspective of safety ($F_{6, 209} = 5.14, p = 0.00, \eta^2 = 0.13$), comfort ($F_{6, 209} = 4.16, p = 0.00, \eta^2 = 0.10$) and attractiveness ($F_{6, 209} = 5.33, p = 0.00, \eta^2 = 0.14$) subjective ratings. Post-hoc testing highlighted that these differences were mainly between the car-door buffered bicycle lane and the other concepts.
Participants were also asked to provide subjective feedback regarding if the designs would encourage increased cycling participation. Participants gave the highest overall score to the vertically separated concept (M = 4.03 SD = 1.16), followed by the green zone buffered lane (M = 3.47, SD = 1.2) and the kerb separated bicycle lane (M = 3.83, SD = 1.09). ANOVA revealed that there were significant differences amongst participants ratings for each concept and encouragement of increased cycling (F = 4.62, p = 0.00, η² = 0.12). Post-hoc testing
again identified that the differences were between the car door buffered bicycle lane and the other concepts designs.

Table 22: Study 2: Kerbside bicycle lane subjective feedback [mean (SD)]

<table>
<thead>
<tr>
<th></th>
<th>Safety</th>
<th>Comfort</th>
<th>Attractiveness</th>
<th>Encourage riding*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5m conventional bicycle lane</td>
<td>5.93 (2.35)</td>
<td>5.77 (2.18)</td>
<td>5.80 (2.22)</td>
<td>3.50 (1.04)</td>
</tr>
<tr>
<td>Green zone buffered bicycle lane</td>
<td>7.23 (2.14)</td>
<td>6.97 (2.3)</td>
<td>7.13 (2.57)</td>
<td>3.93 (1.11)</td>
</tr>
<tr>
<td>Car door buffered bicycle lane</td>
<td>4.80 (2.2)</td>
<td>4.63 (2.09)</td>
<td>4.20 (2.23)</td>
<td>2.47 (0.94)</td>
</tr>
<tr>
<td>Chevron buffered bicycle lane</td>
<td>6.43 (2.3)</td>
<td>6.30 (2.38)</td>
<td>5.73 (2.36)</td>
<td>3.47 (1.22)</td>
</tr>
<tr>
<td>Physically separated lane with traffic cones</td>
<td>7.00 (2.74)</td>
<td>6.33 (2.64)</td>
<td>5.47 (2.99)</td>
<td>3.63 (1.35)</td>
</tr>
<tr>
<td>Kerb separated bicycle lane</td>
<td>7.33 (2.41)</td>
<td>6.73 (2.63)</td>
<td>6.37 (2.53)</td>
<td>3.83 (1.09)</td>
</tr>
<tr>
<td>Vertically separated bicycle lane</td>
<td>7.47 (2.32)</td>
<td>7.20 (2.37)</td>
<td>7.23 (2.7)</td>
<td>4.03 (1.16)</td>
</tr>
</tbody>
</table>

*Participation out of 5 (1 = extremely unlikely, 5 = extremely likely)

10.2.3.2.3 Summary

Overall for stage 2 of this study, vertically separated bicycle lanes were the preferred concept amongst participants to address car-door collisions when bicycle lanes were placed adjacent to the kerb. This was followed by the kerb separated lane and the green zone buffered bicycle lane. Participants clearly saw the benefits of physical and vertical separation concepts, indicating that incorporating physical barriers between cyclists and adjacent parked cars is perceived as a desirable design feature for on-road cycling facilities. Participants also rated the green zone buffered bicycle lane favourably, showing that as a more cost effective solution buffered bicycle lanes can offer perceived benefits to cyclists in terms of Safety, Comfort, Attractiveness and this can encourage increased participation.

Compared to the conventional 1.5 metre kerbside bicycle lane the three most highly rated designs all resulted in shifts in lateral position by cyclists away from the car-door zone. For the vertically separated lane concept, participants rode 0.61 metres from the left edge of the bicycle lane. That is to say they were 0.89 metres away from the right edge of the bicycle lane, suggesting that cyclists were leaving almost a 1.0 metre gap between themselves and parked cars, which would be sufficient to avoid car door collisions in most circumstances. The kerb separated bicycle lane resulted in greater lateral clearance between cyclists and parked cars, however this increase in separation was gained by sacrificing the effective width of the bicycle lane. Furthermore the kerb separated bicycle lane can be restrictive for cyclists wishing to exit the lane to overtake other cyclists or avoid debris etc. These negative elements associated with the design appear to be reflected in participants’ subjective feedback with lower scores obtained when considering the comfort and attractiveness of the design. Based on the concepts assessed it would appear the preference for installation of bicycle lanes would be for vertically separated lanes, while when project costs are prohibitive of physical infrastructure, buffered lanes are a viable
alternative that still offer safety benefits and are capable of increasing spatial separation between cyclists and parked cars, with minimal additional costs.

10.2.3.3 Comparisons of simulator study results

When considering the two concepts for addressing car door collisions, there was a clear preference amongst participants for the kerbside bicycle lane concepts, compared to placing parked cars adjacent to the kerb. The benefits of the kerbside bicycle lane concept are apparent as it theoretically reduces the cyclist's exposure to car doors, due to fewer passengers being present in vehicles compared with drivers, based on estimates of vehicle occupancy. It also eliminates the need for cars to cross the bicycle lane when entering and exiting parking spaces.

The benefits of the kerbside bicycle lane designs were apparent with higher overall scores for Safety, Comfort and Attractiveness compared to the kerbside parking scenarios. In addition, participants increased their clearance between parked cars for the kerbside parking scenario. This is likely a result of participants not be constrained within the bicycle lane for the kerbside parking scenario, allowing them to exit the bicycle lane into the adjacent traffic lane to provide further clearance if required. This may be advantageous for cyclists avoiding open car doors, however this behaviour may also increase the risk of moving into the path of adjacent vehicles, and therefore may not be seen as a desirable practice: instead the preference would be to provide bike lanes of sufficient width that cyclists did not have to move into the adjacent traffic lanes. The kerbside parking lane may also help cyclists to avoid debris or objects on the road as the cyclist is less spatially constrained.

10.3 Discussion

The studies presented in this Chapter were designed to evaluate riding behaviour and perceived and actual risk while riding in a range of bicycle lane concepts that were intended to reduce the risk of cyclists being involved in rear-end, side-swipe and car door collisions when cycling in urban road environments. These collision types were identified in Chapter 7 as some of the most prevalent mid-block collision types resulting in serious and fatal injuries to cyclists in Australia.

As previously mentioned, rear-end and side-swipe collisions are particularly hazardous to cyclists as typically motor vehicles approach the cyclist from behind while travelling at speed. This results in the cyclist being exposed to high levels of kinetic energy in the event of a collision, furthermore as the cyclist often cannot see the motor vehicle approaching they have limited ability to take evasive actions to avoid the collision from occurring.

Car-door collisions are also particularly hazardous for cyclists. This collision type was also identified in Chapter 7 and can result in a range of different injury mechanisms for the cyclist depending on if they are hit directly by the door, or the opening door triggers another collision type such as falling from their bicycle and potentially being struck by adjacent moving traffic.
Car-door, and rear-end and side-swipe collisions are associated with insufficient provision of spatial separation for cyclists from either adjacent motor vehicle traffic or from parked cars. Space to ride is one of the primary requirements for on-road cyclists while at the same time the need for increasing spatial separation as speed and traffic volumes increases was also identified as an important bicycle facility design principle (see Chapter 3).

A large body of literature attests to the benefits of bicycle lanes. For example, Harkey & Stewart (1997) identified that bicycle lanes influence the cyclist’s position relative to the kerb, with bicycle lanes encouraging cyclists to ride further away from the edge of the road. Other studies, including Reynolds et al. (2009) and Teschke et al. (2014) have identified how the presence of on-road bicycle lanes can reduce crash risk for cyclists. Notwithstanding, there are still risks associated with riding in conventional bicycle lanes as highlighted by Beck et al. (2016), who identified that one fifth of on-road cycling crashes occurred when a cyclist was travelling in a designated and marked bicycle lane.

The results from this Chapter illustrated how various bicycle lane concepts can be incorporated within the same road reserve and how these designs can result in both positive changes in cyclist behaviours and increased perceptions of safety, comfort, attractiveness and an increase likelihood of cycling participation. These are very valuable findings and show how road designers can work within a constrained road reserve and still create positive road safety improvements with minimal physical alterations to the roadway.

When considering rear-end and side-swipe treatments, the findings showed that each of the six design concepts resulted in improvements in the lateral clearance between cyclists and adjacent motor vehicles. This would result in a reduction in the risk of rear-end or side-swipe collisions and would also subject cyclists to lower side wind forces, particularly when heavy vehicles pass the cyclists in the bicycle lane. The use of physical, vertical and spatial separation techniques all had similar influences of spatial separation on cyclist behaviour, however, when considering participants subjective feedback the option to provide vertically separated bicycle lanes was clearly the preferred option. These lane concepts provide a dedicated right of way for cyclists, while kerbs provide a physical barrier between cyclists and motor vehicles, furthermore the stepdown from the footpath separates the cycling facility from the footpath. This concept of bicycle lane is considered best-practice in Europe and would be appropriate when treating arterial roads, particularly in inner urban areas where roads provide a higher order movement function and there is a reduced need for vehicles to access adjacent properties. The kerb separated bicycle lane, which has been trialled in Melbourne was also well received by participants and perceived to offer safety benefits. However, the current findings demonstrated that the design can reduce the overall capacity of the bicycle lane and constrain the space for cyclist to ride, and this may have been recognised by participants as the design received lower subjective ratings regarding the comfort and attractiveness of the design compared with vertically separated lanes.

For the car door collisions, two alternate road cross sections were assessed albeit while utilising the same width road reserve. The first layout represented a conventional street design in Australia, with kerbside parking and bicycle lanes placed between parked cars and adjacent traffic. The second layout represented best-practice road
cross section design where the bicycle lane is placed adjacent to the kerb, with on-street parking providing a buffer between cyclists and vehicular traffic. For both road cross-sections the concept designs were capable of encouraging cyclists to adopt riding positions further away from parked cars and as such reducing the risk of a car door collision. However, when on-street parking is located kerbside, moving cyclists outside of the car door zone places them closer to adjacent motor vehicle traffic, increasing their exposure to rear-end or side-swipe collisions. While these design concepts had some desirable features, the bicycle lane designs still exposed cyclists to a degree of risk by placing them in a constrained space between parked cars and high speed motor vehicles.

The second road cross section aimed at addressing car-door collisions has benefits for cyclists when considering road safety. By placing the lane adjacent to the kerb, parked cars form a physical barrier between cyclists and motor vehicle traffic, the lane cross section removes the need for vehicles to cross the bicycle lane when parking and as mentioned previously there is theoretically reduced exposure to opening car doors as the lane is located on the passenger side of the vehicle. While these benefits were not specifically expressed by participants completing the study, it was observed that the safety benefits of this second road cross section configuration were apparent to participants as generally each of the concepts with kerbside bicycle lanes scored higher safety ratings compared to equivalent concepts when on-street parking was located adjacent to the kerb. This was also generally true when considering the comfort and attractiveness of the designs and if participants perceived that the designs would be likely to encourage them to cycle on road more often.

These studies provide examples of how infrastructure designs can be effectively evaluated through the use of a bicycle simulator. The simulator has allowed participants to experience a range of designs in a repeatable manner that would not be practical in real world settings. Furthermore the laboratory setting provided a safe environment to conduct the experiments which have yielded a range of both objective data regarding how participants ride on each of the design concepts and subjective feedback regarding their perceptions of each design. The simulator is also advantageous as it allows a diverse range of participants with various cyclist experiences to undertake the same experiment. This is particularly powerful as some participants may not have felt comfortable riding a bicycle in real world situations, particularly for some of the baseline scenarios such as when no bicycle lanes were present. This allows the collection of feedback from a much broader cohort of both current and perspective cyclists, which is particularly valuable when trying to ascertain if designs are likely to encourage increased participation in on-road cycling amongst various cycling groups.

However, it is noted that there are a number of limitations with the research conducted in this study. First, as it is a simulator-based study the issues of the generalisability and representativeness of these findings to real world cycling is raised. These issues have been partially addressed in Chapter 6 through the validation of the simulator study. However, the results should still be interpreted with a degree of caution and further on-road evaluation of design would be required prior to large scale adoption of any of the infrastructure concepts. Furthermore it is noted that in order to maintain the same bicycle lane dimensions throughout the designs, some concepts would
only comply with minimum design standards. While safety benefits were established for these cross-sections, caution is given regarding designing to minimum standards and wider bicycle lanes may be more appropriate to implement if there is sufficient space within the road reserve.

It is also noted that the measures utilised in this study to assess safety are surrogate measures of crash risk and do not actually translate into a reduction in the probability of a collision (Wierwille et al. 1996, Rudin-Brown et al. 2014). While it is logical to assume that lateral shifts away from the car door zone and adjacent motor vehicle traffic reduce the risk of cyclist collisions, the reduction in risk has not been quantified and as such the exact benefits of these treatments has not been assessed. Translating these simulator measures into real world crash reduction factors would represent an important future research task that would provide added validity to the results of simulator-based studies.

This chapter presented two studies evaluating infrastructure concepts that are intended to improve cyclists safety at mid-block locations by reducing the incidence and severity of rear-end, side-swipe and car-door collisions. The findings provide unique insight into the effectiveness of physical, vertical and spatial separation techniques for mid-block bicycle lanes to improve riding behaviour and enhance safety, while the subjective feedback elicited by participants provides added confidence that the lanes not only elicited the desired responses amongst participants but there was also general acceptance of the design amongst the participants. The broader discussion of the research is presented in the following Chapter including a discussion of the key findings and implications of the research.
Chapter 11: Discussion and Conclusions

The research in this thesis presented an innovative approach to investigating cycling infrastructure and thereby addressed some of the most frequent and high severity mid-block collision types that occur within urban road environments throughout Australia. The centrepiece of this thesis, that represented both a unique and significant contribution to the field of road safety research, was the development and validation of a purpose-built bicycle simulator, designed specifically for the task of evaluating on-road infrastructure design concepts. Subsequent to the development and validation of the bicycle simulator, the research presented in the later chapters of this thesis utilised simulator-based research methods to investigate the effectiveness of cycling infrastructure selected to address high priority and common mid-block cyclist crash types.

This final chapter summarises the key findings from the research. First an overview of the background issues are presented, followed by a discussion of the key findings, implications of the findings for road safety and road design and limitations of the research. Finally, recommendations for translating the research into practice as well as identifying avenues for future cycling road safety research are discussed.

11.1 Overview of background issues

The overarching premise of this thesis was identified in the opening chapters, where it was recognised that cyclists are physically vulnerable road users, particularly when they share the road with motorised vehicular traffic (Chong et al. 2010, OECD/ITF 2013, Stevenson et al. 2015).

This premise was established through the review of literature presented in Chapter 1, where it was identified that cyclists have a higher relative risk of serious and fatal injury per kilometre travelled, compared to motor vehicle occupants in Melbourne, Australia (Garrard et al. 2010) and that they are overrepresented in injury statistics both in Australia and internationally, compared to motorised vehicle occupants (Henley & Harrison 2009, WHO 2013).

It was also established that there is scope to increase the mode share of cycling in Australia, with both a large proportion of the population living within a serviceable riding distance from their place of work or education and a large proportion of private motor vehicle trips being made over relatively short distances of less than ten kilometres (Infrastructure Australia 2009). However it was also established that key barriers to increased cycling participation is the vulnerability of cyclists when riding on the road with many people perceiving cycling on road to be a dangerous activity (Fishman et al. 2012).

Throughout the world various best-practice cities have implemented measures to increase cycling mode share and participation. The common themes amongst these best-practice locations were high level government decisions to promote cycling as a mode of transport and committed investment in infrastructure that has been shown to reduce the risk of injury to cyclists, established dedicated space for cyclists to ride and thereby, reduce the perception of risk associated with riding a bicycle (Pucher & Dijkstra 2003). Countries with high cycling mode share were also found to prioritise cycling over motorised modes of transport.
In Australia, attempts are underway to increase cycling mode share through various avenues including infrastructure investment, however to date, the prioritisation of infrastructure treatment has tended to focus on locations that are considered relatively easy and inexpensive to treat and may not necessarily pose the greatest risk to cyclists (Pucher et al. 2011). It is also suggested that this ad-hoc manner of infrastructure implementation has started to reach its peak benefits and is now associated with a slowing in the growth in cycling mode share (Pucher et al. 2011, CoM 2012). This illustrates the need for a more formalised, evidence-based and systematic approach to implementation of cycling infrastructure to ensure continued normalisation of cycling as a mode of transport. In Chapter 3 it was identified that in many best-practice European cities the process of systematically developing cycling infrastructure was established as early as the 1970, when government decisions were made to create cities that did not have a car centric focus (Pucher & Dijkstra 2000, Stevenson et al. 2016). An example is the Netherlands where the philosophy of Sustainable Safety guides road design and the development of integrated cycling networks throughout the country.

The concepts of Sustainable Safety were also identified as guiding the development of Australia’s “Safe System” for road safety (Chen & Meuleners 2011), which was selected as the underlying theoretical framework guiding this research. The “Safe System” principles are further complemented by the KEMM, which was selected as a secondary framework due to the fact that fundamentally cyclist and other vulnerable road user injuries result from a transfer of kinetic energy between a motor vehicle and the cyclist or the cyclist and the road or roadside environment and that these injuries occur because the transfer of energy is beyond the tolerance of (unprotected) humans (Corben 2004).

11.2 Key findings

11.2.1 Cycling simulation

This thesis documented the development and validation of an innovative new bicycle simulator. As such the research undertaken in this thesis has important implications for cycling research and the development of future cycling simulators and lessons can be learnt from the process utilised in developing this simulator. Currently there are a limited number of bicycle simulators that have been developed to study cycling throughout the world. Furthermore, of those that have been developed, the focus has been on education, training or understanding cyclist behaviours. This presented a unique opportunity to develop a simulator with the specific objectives of undertaking research to evaluate infrastructure from a cyclist’s perspective. Simulator-based research is well-established, however, the majority of work to date has been from a motor vehicle driver’s perspective when evaluating road design elements. With the development of this bicycle simulator, we now have a research tool to grow the field of cycling-based simulator research. This will have major implications for road safety research in Australia and internationally, particularly as the desire to increase cycling mode share continues to grow in many car dominated urban environments (Australian Bicycle Council 2010, City of Portland Bureau of Transportation 2010, Victorian Government 2012, City of Copenhagen 2013, Greater London Authority 2013).
The research demonstrated that bicycle simulators can be developed that produce a behaviourally valid representation of on-road cycling. The simulator demonstrated that new technology can be leveraged to develop low cost, high fidelity simulation, particularly with regard to the use of VR technology to create a relatively inexpensive yet fully immersive experience for participants. While the research demonstrated the technical benefits of using new VR technology, it also highlighted that new technology can be a barrier to participation with some participants taking longer to adapt to using the virtual reality headset due to it being unfamiliar with the technology.

Simulator sickness was also a concern with the use of VR equipment and it was unclear how participants would respond to using the technology. Fortunately, through the course of the studies, simulator sickness was only identified amongst a handful of participants. The participants who were found to experience simulator sickness tended to be slightly older and may not have been as familiar with video game style technology that was utilised in the simulator architecture. That being said, the majority of participants in the research were below the age of 35. There is the potential that, had an older cohort of participants been recruited, there may have been higher rates of simulator sickness. However recent literature suggests that there is some conjecture as to whether age is a significantly associated with simulator sickness when using VR technology (Klüver et al. 2015).

Furthermore the HMD device is not recommendation for use by anyone below the age of 13. It is for these reasons that it may be prudent to have an auxiliary screen or projector incorporated into the simulator architecture that could be utilised for future studies that address populations with demographic characteristics more susceptible to simulator sickness, however this may require further validation of the simulator as it is unclear if the behaviours demonstrated while utilising the HMD would be the same for a screen based simulator. Overall the findings surrounding simulator sickness have important implications for future simulators that are developed to incorporate VR technology and demonstrate the VR is an appropriate technology that can be incorporated into road safety simulator architectures.

The research also highlighted the importance of establishing physical fidelity when developing simulators (McLane & Wierwille 1975, Harms 1996). While not imperative to good research, high fidelity simulators have been linked to reduced levels of simulator sickness amongst participants (McLane & Wierwille 1975, Harms 1996). The investigation of physical fidelity in the current research provided valuable insight into how participants used the simulator and perceived the correspondence of the simulator controls compared to a real bicycle. The findings were promising and showed that the simulator produced a high fidelity testing environment for participants. This was large attributed to the immersive scenarios that can be displayed using the VR technology and were integrated into the simulator architecture. The findings also allowed for additional improvements to be made to the bicycle model equations to provide participants with optimised steering and braking control settings. This further enhanced the fidelity experienced by participants and is believed to have contributed to the successful outcome of the behavioural validation study in Chapter 6.
A significant contribution of this research was highlighting the importance of conducting validation studies for newly developed simulators. This was an integral component of the research and established a degree of confidence in the research findings, which is a primary consideration for simulator based research (Kaptein et al. 1996, Törnros 1998). The validation study established absolute validity for the three measures of the cyclist’s spatial position within bicycle lanes and relative to passing vehicles. While absolute validity was not established for the average speed of cyclists when using the simulator compared with on-road riding, relative validity was established with a strong linear relationship between on-road and simulator speeds. Furthermore, relative validity was established for the reduced speed of cyclists on approach to a T-intersection. When using the simulator, participant speeds were consistently lower than on-road speeds. These findings align with previous driving simulator studies where simulator speeds have differed from on-road speeds, often attributed to the difficulty in judging speed in the simulated environments, however relative validity has often been demonstrated (Törnros 1998, Blana & Golias 2002, Godley et al. 2002). While this is a known limitation of the simulator, relative validity was established and as such, the simulator is suitable for comparison studies assessing differences in speed between scenarios. Results from the validation study were also encouraging when assessing measures of cyclist head movements. However, further research is required in order to more comprehensively validate looking behaviours, as well as validate other more complex performance measures and validate the simulator for a wider age range and diverse group of cyclists.

11.2.2 Crash analysis

A key component of the research conducted in this thesis was the analysis of Coronial and police-reported collisions to establish an evidence base that guided the selection of infrastructure design concepts in Chapter 8 and informed the simulator studies conducted in Chapter 9 and 10. The findings of the analysis confirmed what was previously known about cyclist collisions that occur on Australian roads (Boufous et al. 2013). However, a unique component of the current research was the assessment of cyclist collisions reported to the Coroner and the comparison of these collisions to police-reported collisions.

The concurrent analysis of the Coronial and police datasets provided both the most serious and most prevalent cyclist crash types in Victoria to justify selection of infrastructure concepts for evaluation. The analyses also provided opportunities to i) identify any correlations between the two datasets, ii) assess if recording of crash types differed between datasets, and, iii) identify if any sub-groups of cyclists were more prevalent in either dataset or level of injury severity. While it was not surprising to find that there were many similarities between fatal and serious injury cyclist collisions, there were some unexpected and significant differences between the two datasets. These included an over-representation of males and older cyclists in the Coronial dataset, and significant differences in helmet use and the speed zones and road environments where collisions occurred.

A key finding from the crash analysis was the substantially higher number of fatal collisions at mid-block locations, compared to intersections. It is hypothesized that this was a result of the higher levels of kinetic energy involved in mid-block collisions when cyclists are hit by motor vehicles, compared to at intersections, as at mid-
block locations motor vehicles are much more likely to be travelling at higher speeds. Another interesting finding was the identification of significantly lower helmet wearing rates amongst fatally injured cyclists compared with injured cyclists. This was also associated with non-helmeted fatally injured cyclists sustaining head, neck and brain injuries. The findings highlight the protective factors and safety benefits of bicycle helmets and how they are one of the few methods available to enhance the biomechanical tolerance of cyclists in line with the innermost layer of the KEMM (Corben et al. 2010).

The investigation of Coronial data highlighted some less commonly explored factors associated with cyclist collisions with fatal injury outcomes. Substantial proportions of fatally injured cyclists were identified to have alcohol (15.6%) and 23.1 percent had potentially impairing licit or illicit substances identified in their body based on post-mortem toxicology reports. Further, as toxicology reports were only available for 65.3 percent of cases at the time of analysis, the rates of drug and alcohol use may be under-reported in the analysis. The patterns of alcohol and illicit substances were similar to that self-reported by motor vehicle drivers in Victoria (Stephens et al. 2017) and aligned with previous international research which identified higher rates of cycling under the influence amongst younger cyclists (Chataway et al. 2014) and the lower tendency of intoxicated cyclists to wear helmets, while also noting an increased risk of head injury and higher severity injuries associated with intoxicated cycling (Andersson & Bunketorp 2002).

Overall the analysis of cyclist collisions identified trends that were common with previous analyses, males were over-represented in cyclist collisions in both data sets. While ideally no cyclists would be injured, the disproportionate over-representation of male cyclists is representative of the predominantly male mode share in Australia (Australian Bicycle Council 2017). Garrard et al. (2008) postulates that one of the key signs of cycling being normalised as a mode of transport is an even share of male and female cyclists as seen in many European countries with high cycling mode share. Normalisation of cycling as a mode of transport would be more likely to show a more even split of male and females involved in injuries, however the crash statistics found males were involved in almost 90 percent of fatal collisions and 76.3 percent of serious injuries.

Older persons were also over-represented in both datasets, this seems to conflict with mode share, with higher cycling participant rates typically seem amongst children (Australian Bicycle Council 2015) and adults between the age of 30 to 45 (Australian Bicycle Council 2015). The higher proportion of injured older cyclists may instead be a reflection of the increased frailty of persons as they age (O’Hern et al. 2015) and the lowered tolerance to kinetic energy forces (Corben et al. 2010). This finding was not surprising, particularly for the Coronial data, and the finding justifies the importance of a system like the KEMM as a tool for road safety research as it appreciates the threshold of humans to biomechanical forces and there limited ability to withstand the forces associated with motor vehicle collisions. Again, reflecting the need for separation of cyclists from other modes of transport as speeds and traffic volumes increase.

The most important finding from the crash analysis was the identification of mid-block cyclist collisions as the most common fatal injury mechanism in urban areas of Australia and the identification of rear-end, side swipe
and car door collisions as key mid-block crash types that can be addressed through safer infrastructure concepts. In line with “Safe System” thinking, the primary way to reduce the risk of injury for these collisions would be to lower vehicle speeds, this would reduce the kinetic energy in a collision and result in lower levels of injury if a collision did occur. Furthermore lowering vehicle speeds would reduce braking distances and provide greater time for reactions, further reducing the likelihood of collisions occurring in the first instance. This is again in line with the principles of the KEMM whereby lowering vehicle speeds reduces the overall kinetic energy in the system.

Beyond lowering vehicle speeds the crash analysis points to investigating the potential benefits of increased physical separation between modes, to reduce the likelihood and consequence of conflicts. The findings from the crash analysis formed the evidence base for cycling infrastructure selection and evaluation conducted in Chapter 8, 9 and 10. The broader findings and implications of these studies are discussed in the following section.

11.2.3 Cycling infrastructure

There is recognition of the need to shift the prioritization, selection and implementation of cycling infrastructure design from an afterthought to a primary consideration in Australia (Pucher et al. 2011). This will only occur if there is an overall strategic shift in the priority of modes, where the needs of the most vulnerable road users are considered first, rather than secondary, as appears to be the current approach. Prioritising the most vulnerable road users first, is a concept that is central with “Safe System” thinking. However, there is a disconnect between best-practice principles and what is prioritized and implemented. The review of cycling design principles in Chapter 3 highlight that Australian cycling infrastructure design guides fall behind what is considered best-practice in the USA and many European countries.

The Australian National Cycling Strategy specifies monitoring and evaluation as a key priority objective for the development of cycling infrastructure in Australia (Australian Bicycle Council 2010). This is an attempt to change the culture of an ad-hoc approach and a mentality that ‘anything is better than nothing’ that has often been applied to the implementation of cycling infrastructure in Australia. The need for evidence-led evaluation of infrastructure forms a central tenant of this research. The development of the bicycle simulator as part of this thesis creates a unique opportunity to systematically evaluate concept designs prior to construction. This in turn, enables engineers to move away from an ad-hoc approach to cycling infrastructure implementation and move towards a more informed and evidence-based decision making process.

Improved cycling infrastructure can encourage participation (Pucher & Buehler 2008), however as the findings in Chapter 10 show, not all infrastructure design concepts will encourage increased participation as cyclists desire higher quality infrastructure that is designed to enhance their separation from motor vehicles and provide a dedicated right-of-way for cycling. This confirms previous research showing positive correlations between bicycle lanes and the level of cycling commuting (Dill & Carr 2003, Pucher & Buehler 2006). The findings also support previous stated preference surveys that have identified that cyclists prefer bicycle lanes over no facilities and that
bicycle lanes would encourage increased cycling (Hunt & Abraham 2007, Tilahun et al. 2007, Akar & Clifton 2009). Conversely, the research in Chapter 10 identified that low level cycling facilities, such as wide kerbside lanes, offer minimum perceiving safety benefits, are less likely to encourage increased cycling, and are less attractive and comfortable to cyclists.

Using the findings from the crash analysis (Chapter 7), two main concepts were investigated to address the issue of mid-block collisions. The concepts included the use of perceptual countermeasures to encourage safer lane positioning and more traditional infrastructure designs which were selected with reference to international best-practice design guidelines and principles.

Due to the constrained urban environments in inner urban areas in metropolitan Melbourne, the principle of “lane diets”, highlighted in the AASHTO (AASHTO 2012), was explored as a means of creating space for cyclists within the existing carriageway through narrowing traffic lanes, as opposed to considering options to widen road reserves, which is often challenging, expensive and performed at the detriment of pedestrian facilities, by narrowing footpaths, verges or removing nature strips.

The first simulator-based study (Chapter 9) established that low cost treatments that utilised perceptual countermeasures, such as painted buffers that can be retrofitted to existing road infrastructure, have a significant impact on the position that cyclists choose to ride within a bicycle lane. These treatments would be inexpensive to implement, particularly when compared to physical infrastructure concepts that may require more extensive and expensive changes to the road cross section, which may include road widening and changes to drainage. The concepts were shown to have a meaningful impact on the spatial separation provided between cyclists and adjacent parked cars and passing motor vehicles and the research highlighted that the use of perceptual countermeasures that encourage cyclists to ride in different spatial positions within a bicycle lane may be an effective measure to create safer cycling. Further research examining the effectiveness of these concepts is warranted and ultimately these treatments could be incorporated into road design guidelines.

Design concepts addressing some of the most prevalent mid-block collision types in Australia were examined in two studies in Chapter 10 addressing rear end and side swipe collisions and car door collisions. The lane design concepts were selected with reference to the principles of the “Safe System” and the KEMM. Across the design concepts, the idea of increased spatial separation was the key concept explored. In that, in order to reduce the likelihood of a collision, cyclists require increasing levels of separation from motor vehicles, particularly as the speed of the road environment goes beyond the human tolerance to biomechanical forces.

Based on the subjective feedback provided following the simulator studies, it appears that safer infrastructure designs may have the potential to increase cycling participation. This has also been shown in European countries where cycling mode shares are significantly higher as a result of investment in infrastructure (Pucher & Buehler 2008).
11.2.4 Theoretical frameworks

The overarching theoretical framework for this research was the Australian formation of the “Safe System” for road safety and this was complemented by referring to the principles of the Kinetic Energy Management Model. In Australia, the “Safe System” approach to road safety is well accepted in principle. However, there appears to be a barrier between theoretical acceptance of the principles of the “Safe System” and application of the framework in practice. This was evident in the review of cycling guidelines in Chapter 3 of this thesis where “Safe System” principles were highlighted but rarely implemented. An important output of this research is the implications of the findings for the “Safe System” when considering cyclist safety.

It is acknowledged that lowering vehicle speeds is not necessarily a practical solution for all road environments. When vehicle speeds cannot be lowered to safe levels within the biomechanical tolerance of cyclists, there is a need to introduce separation between modes of transport based on their speed, volume, mass and direction of travel. These principles and practical implementation of effective treatments are already commonly adopted in best-practice European nations (Wegman et al. 2012). Infrastructure provides a tool to encourage safer road user behaviour and this thesis has focused on providing the evidence for the most promising and effective infrastructure concepts to increase spatial separation between cyclists and motor vehicles in an Australian context. It is noted that the focus of assessing the infrastructure concepts in the current research has been on the cyclist. It would also be desirable to develop infrastructure solutions that encourage traffic calming measures to lower motor vehicle speeds, however this may not be entirely appropriate for implementation on arterial roads, which serve a movement function within the road hierarchy. In some situations, traffic calming infrastructure could potentially see a transition from cyclists requiring separation to being integrated with other modes of transport within the same space, provided the speed environment was safe to do so.

11.3 Limitations

11.3.1 Simulator

The first phase of this research was the development, validation and use of a new research tool for investigating cycling infrastructure designs from a road safety perspective. As with the development of any new research tool there are limitations with the design, as such there are opportunities for further development with regard to the capability of the instrument and what research questions that it is suitable for investigating. The validation study only considered a select range of measures that were primarily concerned with the control and guidance functions of operating a bicycle. If the simulator is to be utilised for further research studies it will require further validation of any additional performance measures that will be captured in these studies. This was a primary consideration when designing and undertaking the simulator studies (Chapters 9 and 10) to ensure that the relevant performance measures assessed were validated and to ensure there was a correspondence between the simulator-based and on-road cycling results.
Many of the limitations associated with the design of the simulator are a result of the decisions surrounding the simulator architecture and the desire to build a simulator for examining road designs from a road user (cyclists) safety perspective. While the simulator provides a good example of how the latest technology can be leveraged to developed high fidelity yet relatively low cost simulator architectures, it is recognised that in developing a low cost simulator there are limitations compared to higher cost and commercially developed simulators and that the low cost of the simulator has resulted in some sacrifices being made when selecting the components that form the simulator architecture.

One of the key limitations of the bicycle simulator is the lack of a motion platform. As stated in Chapter 5, the lack of a motion platform restricts the forces and range of motion that can be simulated and influences the degree to which bicycle dynamics can accurately be recreated. During the development phase, efforts were made to synthetically recreate bicycle dynamics based on the restricted range of motion of the stationary bicycle, however it is noted that the simulator does not have the capacity to recreate many of these forces associated with riding a bicycle in the real world. Despite this, it is noted that some of the experiences were recreated through the use of the VR technology where the display can be altered to give the partial sensation of riding a bicycle, such as leaning into corners. It is important to remember, as stated in Chapter 4, that it is not the simulator itself that is under investigation when conducting a simulator study (Rudin-Brown et al. 2009), rather the simulator only needs to sufficiently recreate the experience of operating the vehicle to the point where participants perform the same behaviours as they would in a real environment, which was the actual intention of the experiment.

There are also various limitations associated with the HMD incorporated into the simulator architecture. At the time of developing the simulator, VR technology was a relatively new phenomenon and the VR headset incorporated into the simulator has limitations regarding the screen resolution, latency and the field of view. However the VR was considered ‘state-of-the-art’ at the time of developing the simulator, and these issues were considered minor at the time of selecting the HMD device. Moreover, as new and improved technologies appear on the market, these limitations could easily be reduced by upgrading the VR device to a newer model. In fact, since the development of the simulator there have been a vast number of commercial VR devices enter the market.

Beyond the limitations associated with the bicycle simulator architecture there are also a range of limitations that exist with simulator-based research generally and these are common to the current research. As with most simulator-based studies the current research utilised relatively small samples of participants, and it is recognised that the size of the sample is a major limitation of the research. Larger samples sizes would lead to greater insight being gained from the data and would create the ability to stratify findings by demographic variables such as age and gender, or other socioeconomic factors. It would also allow consideration of differences in infrastructure preferences based on variables such as cycling characteristics or self-reported confidence. This would allow the research to delve deeper into understanding cycling factors associated with particular sub-
groups of cyclists and non-cyclists. Notwithstanding, the sample sizes were selected using power calculations and they are entirely consisted with sample sizes recruited for many other simulator-based studies.

There are also a range of potential biases introduced through the recruitment strategies utilised in the studies. When advertising the research studies participants were informed that the research was focused on bicycle safety and that they would need to be comfortable riding a bicycle to participate in the research, particularly for the validation study which required participants to ride on-road as well as in the simulator. These recruitment criteria would automatically exclude a range of people from participating in the study and may have discouraged less confident bicycle riders from participation. The use of the VR technology may also have introduced a bias regarding the types of people interested in participating in the study, with the technology aspect of the research potentially attracting certain participants.

11.3.2 Crash analysis

One of the central components of this research was utilising large administrative collision and injury data gathered from the police and Coroner to form an evidence base to inform the simulator studies. There are a range of issues with utilising any dataset not designed for research purposes. Foremost there is the potential for case data to be entered incorrectly. This was observed in the preliminary search of cyclist collisions in the Coronial dataset where several pedestrian fatalities were identified, where a pedestrian had been struck and killed by a pedal cyclist.

As previously highlighted in Chapter 7 there are a range of issues associated with the use of police reported data, particularly when considering cyclist collisions. One of the major limitations, identified by numerous researchers (e.g. Boufous et al. (2013), is the under-reporting, particularly of single vehicle (cyclist only), of collisions when comparing police reported data to hospital admissions. Furthermore, not all deaths are investigated by the Coroner and as such it is possible that not all fatal cyclist collision cases were identified, however in Australia Coroners typically investigate all cases involving road fatalities (NCIS 2014).

Another issue with the use of the Coronial data was the issue of missing case file data. In several instances there were missing toxicology or autopsy reports, limiting the ability to analyse the dataset. Furthermore there limitations due to closed cases, and missing variables in the dataset. Despite these limitations the analyses yielded significant and important information that was utilised as part of the evidence base for selecting infrastructure options for evaluation in the bicycle simulator.

11.3.3 Cycling infrastructure

The final experiments dealt with the selection and evaluation of infrastructure concepts to address the issues identified in the crash analysis. At the outset, this was an overwhelming task as within any one infrastructure concept there are a plethora of variables that could be examined in unison or in combination with other design variables. The simulator creates an environment where minute variations in designs can be tested, however at the same time there was a desire to gather a wide range of generalizable data from the simulator studies rather
than focusing in detail on specific elements. This approach resulted in some unique findings and highlighted some important concepts for bicycle lane design, however at the same time it is noted that many of the promising designs would require further research across a range of differing road environments and configurations to provide robust evaluations of the benefits of the designs.

One particular limitation that was identified through the course of this research was the restriction in the number of scenarios that can be evaluated per participant. This is both due to the time required to run participants through the experiment, the costs associated with offering gift vouchers to incentivise participants to volunteer for the studies and the risk that during prolonged studies participants may become fatigued, or there may be cumulative effects of simulator sickness associated with longer data collection times. All of these factors combined led to a decision to design data collection to be no longer than one hour.

It is recognised that there is significant scope to expand the simulator-based studies conducted in this thesis. The findings from the research are not definitive regarding optimal infrastructure concepts for mid-block locations, however they have provided valuable insight that will assist in guiding policy and future research and give an indication of the general types of infrastructure concepts that cyclists consider safe when considering Austroads cyclist design principles, without necessarily answer the specific requirements for detailed design of such infrastructure.

11.4 Implications and future research

The current research has provided a preliminary evidence base which can contribute to policy decisions on potentially effective infrastructure to address high priority cyclist collisions. Furthermore there is the potential opportunity for extensive future research addressing a range of issues surrounding cyclist safety and participation rates using this newly created research tool.

As established in the early chapters of the thesis, preliminary infrastructure evaluation is ideally suited to simulator-based research where various design features can be easily manipulated and concept variations can be evaluated using consistent repeatable protocol. Simulators are advantageous for preliminary concept design evaluation and can help to identify unforeseen issues with designs and road users’ behaviours. The simulator evaluation allows for these issues to be identified and rectified prior to construction saving money and also resulting in implementation of more robust infrastructure designs. In summary, preliminary evaluation using simulators is a relatively inexpensive exercise, however it has the potential to save money and result in road infrastructure that is more beneficial than traditional methods of selecting and evaluating infrastructure.

The simulator environment also creates an important opportunity to gather behavioural information and perceptions from the users of the transport system and feedback on designs. In this thesis subjective feedback was gather from participants regarding the designs presented in Chapter 10. However more detailed user perspective surveys could be administered to participants. It is expected that having experienced the designs in the simulated environment, participants can provide far greater insight into their perspectives of the designs,
compared to simply looking at designs or renderings of the concepts. This is because the simulator gives participants the opportunity to experience what it may be like to actually interact with the infrastructure. It is for these reasons that it would seem logical to pilot new infrastructure concepts using simulator technology prior to detailed design and construction and, with the increasing affordability of developing simulators, there would appear to be far fewer barriers to undertaking this exercise than in the past.

As such it would seem prudent to conduct evaluation of future infrastructure concepts and prototype designs using simulators and there is the potential for the requirement to conduct pre-evaluation of design to be placed into policy. This will help to ensure that infrastructure that adhere to “Safe System” principles is evaluated and implemented and that there is a level of assurance with the effectiveness of the design in addressing road safety concerns. Furthermore there is potential for the designs and information garnered from this research to be incorporated into design guidelines. With the findings from this thesis disseminated to the project stakeholders including State road authorities, cycling advocacy groups and other government organisations and to the broader cycling community through publication of the research findings.

11.4.1 Future Research

There is significant scope for conducting further research addressing a range of issues surrounding bicycle infrastructure design and cyclist safety utilising the bicycle simulator. When considering mid-block bicycle lane design the research presented in this thesis has only scratched the surface of possible infrastructure design features that could be better understood through evaluating design concepts utilising the simulator. In reality there are a myriad of variables that can be altered when developing road infrastructure and therefore requires the evidence base to examine their effectiveness in providing a safe cycling environment and in increasing cycling participation. These could include the speed environment, the width of the carriageway and road reserve, the traffic composition, passing distances, horizontal and vertical alignments, sight distances, the road user mix, the surrounding land uses, street furniture within the road side environment and it would even be possible to evaluate how participants interact with other road users or cyclists within the concepts.

For example, Rudin-Brown et al. (2014) investigated how differing the density of parked cars influence driver lane positioning when driving on simulated arterial roads. Their research highlights how risk mitigation behaviours can be dependent on exposure to the risk for motor vehicle drivers. Presumably the behaviours observed amongst motor vehicle drivers would be similar to those of cyclists. However many of these well researched topics regarding driver behaviour, have not been considered from a cyclists perspective. It is possible that cyclist behaviours change in a similar manner to drivers, however there are other factors such as cycling specific infrastructure that may alter the way cyclists interact with the road environment compared to motorised vehicle users.

There is also the influence of environmental factors on safety that could be investigated such as, how changes in light and atmospheric conditions influence the way cyclists choose to ride and whether adverse conditions
encourage cyclists to adopt safer stopping distances and leave greater safety margins. Research suggests that cyclist risk of injury increases in adverse lighting conditions (Boufous et al. 2012) and there is the potential to further investigate some of these variables in the simulator environment where a diverse range of atmospheric conditions can be consistently reproduced for each participant. There is also significant scope to continue research to understand the influence of perceptual countermeasures and how they can be utilised to encourage safer cyclist and safer cyclist and driver interactions. From a drivers perspective perceptual countermeasures have been utilised to control drivers speed and lateral positioning on approach to intersections and on corners (Godley et al. 2004) and similar experiments and scenarios could be considered utilising the bicycle simulator. Essentially it is recognised that the concepts evaluated in the simulator were relatively generic and there is significant scope to continue the investigation of mid-block infrastructure design.

Beyond mid-block infrastructure design research, the current research highlighted the dangers faced by cyclists when riding through intersections. Investigating and evaluating infrastructure designs for intersections is likely to be increasingly complex as there are substantially more variables to control, or that can be altered, in each experiment. At a preliminary level there are a vast variety of different intersection configurations that could be evaluated including, the number of approaches, traffic control techniques and lane geometry. There are also other variables to consider such as signalisation and signal phases, as well as a range of cycling specific infrastructure concepts including head start boxes, specific cycling signal phases and lanterns and these could all be evaluated objectively to examine how participants interact with the designs and subjectively by gathering user perspectives of design concepts.

Roundabouts are commonly cited as a key concern for cyclists, particularly when there are multiple circulating lanes (Mulvaney et al. 2013) and the simulator would provide a safer method to evaluate a range of roundabout concept designs to address cyclist safety and the interactions between cyclists and other road users. In fact there are previous examples of evaluations of unique roundabout concepts in driving simulators (Stephens et al. 2017) and similar experimental protocols could be applied to concepts for cycling safety and be evaluated from both road users perspectives.

In Chapter 4 the review of simulator literature identified that driving simulator have been utilised for a range of psychology-based research assessing behaviour, functional and psychological aspects of different road user groups. While it is noted that the simulator was not developed or validated for assessing these measures, it would not be beyond the scope for future research to validate further measures that could be utilised conduct this type of research in the simulator.

The analysis of administrative data (Chapter 7) highlighted that the safety risks of cyclist intoxication and use of illicit substances may be more prevalent than initially anticipated. It is likely that some people who lose their drivers licences due to driving under the influence of alcohol or illicit substances choose to ride a bicycle but do not reform from their substance abuse habits. People may also see riding a bicycle as a less dangerous option than driving when they have been drinking. The bicycle simulator could provide an inherently safe environment to
conduct research addressing these issues. Indeed, the influence of alcohol and THC has previously been investigated using driving simulators (Lenné et al. 2004, Lenné et al. 2010).

The review of cycling simulators (Chapter 4) highlighted how bicycle simulators have previously been utilised as an education tool to teach children road safety skills. While research involving children this would not be practical for the current simulator due to the adult bicycle and restrictions on children using HMD devices, there is potential to utilise the simulator environment and adapted bicycle models to create a similar training simulator that would be appropriate for such an application.

In the near future the vehicle fleet will see rapid changes with the introduction of autonomous vehicles. As the vehicle fleet begins to change there will be a need to investigate how the vehicles interact with vulnerable and non-autonomous road users and vice versa. Cyclists tend rely on visual cues provided by motor vehicle drivers, however with the introduction of autonomous vehicles, the way cyclists interact with vehicles may change and this warrants further research to ensure that cyclists can safely interact with the new fleet of vehicles. Autonomous vehicles are also likely to bring a range of efficiencies to the road environment. It is hypothesised that they will reduce demand for parking and on-street space, while they will also be able to operate in smaller headways and have much more control over their lateral guidance. This could result in the potential to redistribute parts of the road reserve and there is the potential to increase the space allocations for cyclists and this could allow for considerable increase in the potential to provide cyclist infrastructure.

However, as with any new technology, there are likely to be difficulties that require research. One potential issue is the fact that autonomous vehicles will be designed to interact with other autonomous vehicles and motor vehicles which are far more predictable. Given that bicycles are a much more nimble vehicle that can change direction rapidly, there will be a need to investigate if autonomous vehicles can detect cyclist behaviours and predict their behaviours, particularly when cyclists are riding outside of the direct path of travel of the autonomous vehicle.

11.5 Conclusions

This doctoral research presents a unique undertaking that makes a significant contribution to the fields of cycling safety and road safety research. It has produced a very tangible output with the development and validation of a bicycle simulator. In addition, the research conducted using this tool has practical implications for cycling infrastructure design. The development of the bicycle simulator has created a new tool which will see continued application beyond the research conducted in this thesis that will make an ongoing and significant contribution to road safety research.

In order for cycling participation to continue to grow in Australia and other developed nations there is a need to provide high quality safe cycling infrastructure. This has been shown to help encourage cycling mode share throughout best-practice countries in Europe and could have similar impacts in Australia. It is hypothesized that through the development of safe, evidence-based infrastructure that cycling participation can continue to grow.
However, until sufficient, evidence-based and targeted investment is made in cycling infrastructure it is unlikely that mode share targets such as those identified in the Australian National Cycling Strategy (Australian Bicycle Council 2010), will be met and the normalisation of cycling as a mode of transport is unlikely to be achieved.

Cyclists will always remain a vulnerable road user group, particularly when interacting with motorised modes of transportation and there is a need to better understand how cyclists can interact more safely with the road environment and road infrastructure designs, this is in line with one of the key tenets of the “Safe System” approach to road safety. Cities are becoming increasingly constrained for space and the world is currently undergoing the most rapid period of urbanisation in our history. With this comes an increased risk of a rise in road trauma, particularly for vulnerable road users. There is international recognition of the need to increase cycling participation in major cities and to normalise cycling to make it a mode of transportation. This is reflective of the paradigm shift identified in various cycling design guidelines and cycling strategies, with cycling considered as a mode of transportation and bicycles being treated as vehicles rather than pedestrians.

The research presented in this thesis demonstrates the use of a bicycle simulator that has the potential to assist in the development and evaluation of bicycle infrastructure designs that will have the greatest chance of being utilised and encouraging increased participation. Pre-evaluation using a simulator has the potential to reduce the cost of infrastructure by piloting various design scenarios and reducing the need to retrofit designs when they result in unintended road user behaviours.

However, ultimately increased cycling participation rests on government decisions to invest in high quality cycling infrastructure that creates a safe environment for cycling by providing a dedicated right of way and minimises interaction with other road users.
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Appendix A: Validation of a bicycle simulator for road safety research
Validation of a bicycle simulator for road safety research

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A B S T R A C T
The study’s aim was to assess the behavioural validity of participants using a newly developed bicycle simulator with respect to a range of cycling performance measures collected both using the cycling simulator and on-road. The validation study consisted of a within-subjects study design comparing participants riding on-road with riding in the simulator.

The study recruited 26 participants ranging in age from 18 to 35 years (M = 25.0, SD = 4.8). Absolute validity was established for measures of spatial positioning including average lane position, deviation in lane position and average passing distance from kerbside parked cars. Relative validity was established for the average speed of cyclists and their speed reduction on approach to intersections and a degree of validity was established for aspects of the participants head movements on approach to intersections.

The study found evidence to suggest that aspects of cyclist behaviour can be investigated using the bicycle simulator, however further validation research may be required in order to more comprehensively validate looking behaviours, more complex performance measures and for a wider age range of cyclists.

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1. Introduction

Driving simulators offer a range of benefits compared to on-road studies by creating an inherently safe environment to consistently and systematically create traffic scenarios, in a cost effective manner, that would be difficult (due to the inherent risks for the participant) in a real world environment (Blana, 1996; Godley et al., 2002; Meuleners and Fraser, 2015; Moroney and Lilienthal, 2008). For these reasons, the use of simulators continues to grow within the field of road safety research (Meuleners and Fraser, 2015). While the use of automobile simulators has been an active field of road safety research (Blana, 1996; Godley et al., 2002), there is a paucity of simulator-based research investigating the vulnerable road users, especially users of two-wheeled vehicles (Nehaoua et al., 2011). There are various reasons for the disproportionate research efforts (Nehaoua and Nehaoua, 2013), however, in recent times the increase in the use and mode-share of two-wheeled vehicles combined with the relative growth in the proportion of collisions involving these vehicles has seen research in the field grow (Pucher et al., 2011; Stevenson et al., 2015).

Cyclists, along with motorcyclists, are physically vulnerable road users, especially when they share the road with motor vehicle traffic (Chong et al., 2010; OECD/ITF, 2013; Stevenson et al., 2015). Their vulnerability as road users stems from their limited protection in the event of a collision and their low tolerance to biomechanical forces (OECD/ITF, 2013). In Australia, the proportion of serious and fatal road traffic injuries involving cyclists is increasing (Garrard et al., 2010; Garratt et al., 2015) and it is recognised that there is a growing need to improve cyclist safety to encourage increased participation in this sustainable mode of transport (Stevenson et al., 2015). A recent in-depth investigation of cyclist crashes in Australia highlighted that when riding on-road there is a roughly even split between bicycle only (48%) and multiple vehicle collisions (52%), with multiple vehicle collisions most often associated with a collision involving a car (48%) (Beck et al., 2016).

The Australian Road Safety Strategy recommends the use of evidence-based road designs as one of the key measures to help create safer road environments for cyclists and provide effective measures to reduce cyclist trauma (ATC, 2011; Stevenson et al., 2015).

Simulators provide a cost effective method for preliminary evaluation of evidence-based road designs (Blana, 1996; Moroney and Lilienthal, 2008). The use of simulators allow the researcher to have considerable control over the experiment and simulators allow for scenarios to be repeated consistently (Godley et al., 2002;
Simulators also allow for multiple iterations of designs to be tested and evaluated without the need to construct road infrastructure. Through investigating how road users interact with new road design concepts, it is possible to examine the safety benefits of interventions and identify some relevant unexpected behaviours and issues with the concepts prior to construction. Furthermore, the inherently safe simulator environment allows for potentially dangerous traffic conditions and behaviours to be examined, while removing the physical risks to the participants and other road users (Godley et al., 2002; Rudin-Brown et al., 2009).

While simulators offer a range of benefits for research, in order for the results of simulator-based studies to be meaningful it is essential that the correspondence between the real world and the simulated environment is the same, or at least sufficient, to produce valid results (Kaptein et al., 1996; Törnros, 1998). For simulator studies it is the performance of the participants that is under investigation, not the fidelity of the simulator itself (Rudin-Brown et al., 2009). The simulator does not have to be identical to the real experience but it must be able to sufficiently replicate the specific task or behaviour that is under investigation (Rudin-Brown et al., 2009). Further, it is particularly important that the road-user behaviours elicted in response to events in the simulator are comparable to responses and behaviours in real world traffic situations (Törnros, 1998). In order to meet this requirement, simulators are often validated against a set of key performance measures to assess the correlation between results. Traditionally simulator validations studies have relied on measures such as speed, speed adaptation, lane keeping and variation in lateral position (Blana and Golias, 2002; Godley et al., 2002; Törnros, 1998; Underwood et al., 2011).

The aim of this study was to assess the validity of the performance of participants using a newly developed bicycle simulator, compared to riding on-road. The study sought to assess the behavioural validity of the simulator compared to a selected range of performance measures for cycling on-road including the average and standard deviation in lane position of the cyclist when riding in a bicycle lane, average passing distance when passing parallel parked cars, the speed profile of the cyclist, speed reduction on approach to a T-intersection and head movements on approach to an intersection. These measures were selected as they relate to basic control functions for a bicycle. The study monitored participants’ simulator sickness symptoms to ensure that simulator sickness was not experienced amongst large numbers of participants, which would have the potential to introduce biases into the findings.

Behavioural validity is a measure of the extent to which participants exhibit the same cycling behaviours using the simulator as they do with riding on-road (Blauuw, 1982; Godley et al., 2002). Behavioural validity was assessed on two levels; absolute validity and relative validity, where absolute validity refers to the situation where simulated and on-road data provide the same numerical results and relative validity refers to the situation where the results differ between the two tasks but exhibit similar patterns in terms of their magnitude or direction (Godley et al., 2002).

2. Materials and methods

2.1. Study design

The validation study consisted of a within-subjects study design comparing selected measures of performance of participants riding on-road with riding in the simulator (Fig. 1). A within-subjects study design was chosen to control for variance between the participants undertaking the study. To control for carryover effects, participants undertook each stage of the study on different days. The order that participants performed the on-road and simulator components was counterbalanced, however due to the influence of weather the order was not randomised, with two participants completing the simulator component first when there was adverse weather on their first day of testing when they were originally allocated to perform the on-road task first.

2.2. Participants

A convenience sample of 30 participants (22 males and 8 females) were recruited for the study. Power calculations were performed to identify the required number of participants for the study, based on the proposed statistical techniques and within group study design. Participants were required to be over 18 years of age and be comfortable riding a bicycle on local roads. Participants were excluded from the study if they had medical conditions that might be aggravated due to exercise or using the bicycle simulator including epilepsy, high blood pressure, having previously experienced a heart attack, or if they had a history of suffering from either motion sickness or simulator sickness. Participants who required glasses for normal vision were also excluded from the study (participants who required contact lenses to correct their visions were accepted into the study). This exclusion criteria was necessary as it can be difficult for some glasses to be worn at the same time as the head mounted display.

Recruitment was undertaken by placing flyers around Monash University Clayton campus. An advertisement was also placed in the Monash Memo, which is a weekly e-newsletter sent to Monash University staff.

The research protocol for the study was reviewed and approved by the Monash University Human Research Ethics Committee. Participants received a $50AUD gift voucher for participating in the study and to compensate them for their time and travel expenses.

2.3. Data collection

2.3.1. Survey component

Participants completed a short questionnaire addressing demographic characteristics and cycling experience information.
Simulator discomfort was assessed by administering the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). The SSQ is a self-reported symptom checklist that includes sixteen symptoms that are associated with simulator discomfort. Participants were asked to rate their symptoms on a four point scale from none to severe. Each participant completed the SSQ prior to commencing the simulator study and following completion of the final simulator scenario. Participants who experienced high levels of simulator sickness were excluded from the analysis.

2.3.2. On-road component

The on-road component of the study was conducted using an instrumented Giant City-Cross bicycle. The bicycle model was the same as the bicycle that is used in the simulator. The bicycle was instrumented with sensors to collect a range of variables including: the GPS coordinates of the cyclist; the speed profile of the cyclist; and, the lateral position from passing objects on the left hand side of the bicycle. Two Contour + 2 video cameras were also used during the on-road component of the study. The first video camera was fitted to the handlebar of the bicycle which was used to record footage of the ride and also to measure the bicycle position within the carriageway using custom computer vision software. The second camera was placed on the cyclist’s helmet and was used to collect information on head movements. The on-road component of the study was conducted on a fixed route of approximately four kilometres shown in Fig. 2. All tests were conducted in clear weather conditions on dry roads. All roads were either local or private roads with speed limits ranging from 20 km/h to 50 km/h, with low traffic volumes.

2.3.3. Bicycle simulator component

The bicycle simulator was developed with the specific objective of evaluating the effects of road infrastructure designs intended to improve cyclist safety. The simulator was developed to provide a cost effective, computer-based architecture while still providing a high level of fidelity (Fig. 3). Participants rode an instrumented road-bicycle that has its rear wheel mounted to a bicycle trainer. The simulator architecture does not include a motion platform nor is the simulator designed to assess the stability of instrumented bicycle.

A virtual reality (Oculus Rift DK2) head mounted display (HMD) was incorporated into the simulator architecture to function as both the HMD and also a positional tracking device to monitor par-
participant head movements. The HMD immersed the participant in the virtual reality environment. Head movements of the participants were recorded using positional tracking of the HMD and this allowed the graphical display to update relative to the participant’s head movements, creating a realistic cycling experience. The simulator captured the speed, steering and braking inputs from the instrumented bicycle, these inputs were recorded for analysis and input into the simulator environment.

The simulator component of the study took approximately one hour to complete. The simulator study required participants to complete three practice rides and five rides depicting specific riding scenarios. The practice rides were designed to familiarise participants with the simulator and the HMD. The simulator scenarios were designed to recreate aspects of the on-road ride and test the ability of the participant to display performance measures similar to those during the on-road ride.

The experimental protocol for the simulator study was as follows: Completion of the baseline simulator sickness questionnaire; demonstration of the HMD device; practice rides (10 min); simulator scenario rides (30 min); and the final simulator sickness questionnaire.

2.4. Performance measures

Performance data from the on-road and simulator components of the study were compared to assess the relative and absolute validity of the simulator for a selected range performance measures including the average and standard deviation in lane position of the cyclist when riding in a bicycle lane, average passing distance when passing parallel parked cars, the speed profile of the cyclist, speed reduction on approach to a T-intersection and head movements on approach to an intersection. These performance measures were considered essential for future studies that will investigate and evaluate conceptual infrastructure designs.

2.5. Data analysis

Descriptive statistics were assessed for the survey responses providing demographic characteristics and cyclist experience. Absolute validity for on-road and simulator data was assessed using paired sample t-tests with the null hypothesis that the mean difference between the two samples was zero. Analysis was undertaken at a level of significance (α) of 0.05. Effect size was assessed using Cohen’s d statistic.

Absolute validity was established through obtaining non-significant results, that is to say that there was insufficient evidence to reject the null hypothesis that the mean values are equivalent, however non-significant results can also result from inadequate statistical power (Godley et al., 2002). A larger effect size corresponding with a non-significant result therefore may be a result of insufficient statistical power, while small effect sizes are more likely to reflect absolute behavioural validity (Godley et al., 2002). Where absolute validity was not established, simple linear regression was performed to assess correlation between the two datasets to identify the relative validity of the simulator. Prior to analysis, tests for normality were conducted for each variable considered in the validation study, using skewness and kurtosis. Results were normally distributed as such no transformations were performed. All statistical analysis was conducted using STATA version 13.1.

3. Results

Of the thirty required participants, four did not complete the study. Two participants were excluded because they experienced high levels of simulator sickness and were unable to complete the full set of simulator scenarios. One participant did not feel like they could comfortably control the bicycle simulator and the forth participant became lost during the on-road component of the study and the collected data was not usable. Data from the remaining 26 participants were analysed.

3.1. Participant characteristics

Participants ranged in age from 18 to 35 years (M = 25.0, SD = 4.8). Participants were asked to rate their confidence level regarding cycling on-road on a 10 point Likert scale. On average, participants were highly confident riding on-road (M = 8.5, SD = 1.3). When asked how frequently they rode a bicycle, 79% stated they rode more than twice a week, four participants stated they ride a bicycle at least once every two weeks and two participants stated that they had not ridden a bicycle in the past month (apart from participating in the study). Participants rode less than 30 kilometres per week (77%). Commuting to work or school (50%) and recreational riding (46%) were the most common reason for people riding a bicycle. One participant had been involved in a bicycle crash in the past three years, however the crash was minor and did not result in any injuries.

3.2. Performance measures

Table 1 displays a summary of the performance measure resulting from the on-road and simulator components of the study. The findings showed no significant difference in terms of the average lane position of cyclists when riding on-road compared to in the simulator (t(25) = 0.17, p = 0.86, d = 0.03). Furthermore there were no statistically significant differences between a cyclists performance during on-road and simulator rides for the deviation in lane position (t(25) = 0.49, p = 0.62, d = 0.13). It is noted that lane position and deviation in lane position are interacting factors. When considering passing distance from kerbside parked cars, again there were no significant differences between the simulator rides and the on-road rides (t(25) = 0.49, p = 0.42, d = 0.07). These measures show that absolute validity was established between riding on-road and using the simulator, regarding lateral position and lateral position variability. Furthermore, the small effect sizes provide confidence in these results.

A statistically significant difference was identified for average cyclist speed when riding on-road compared to the simulator (t(25) = 12.4, p = 0.00, d = 2.05). The average cyclist speed was 18.9 km/h on-road compared to 14.5 km/h in the simulator. As there were statistically significant differences between the two measures of speed, absolute validity could not be established. However, there was a significant linear relationship between the on-road and simulator results relating to speed (F(1,25) = 17.74, p = 0.00 r = 0.66) suggesting a level of relative validity between speeds when riding on-road and when riding in the simulator.

As absolute validity was not established for cyclist speed, speed reduction on approach to an intersection was measured in terms of the percentage speed reduction from approach speed (taken as the speed before deceleration/braking commenced to the speed that the turning movement was undertaken). When considering this measure, there were no statistically significant difference in the percentage speed reduction when cycling on-road compared to riding in the simulator (t(25) = 0.18, p = 0.85, d = 0.03). However, due to the difference in absolute speeds, only relative validity could be established for this measure. The small effect size provided added confidence in this finding of relative validity.

Comparison of cyclist head movements proved difficult due to the constantly changing traffic conditions during the on-road component of the study. Participants did not exhibit similar patterns of head movements, in terms of the order of head movements made on approach to the intersection. However no significant differences
were observed between the number of head movements performed on approach to the intersection ($t_{25} = 1.3$, $p = 0.2$, $d = 0.28$), or the average duration of head movements ($t_{25} = 0.69$, $p = 0.49$, $d = 0.13$), suggesting a degree of validity for the head movements for participants using the simulator, compared to cycling on-road. Small effect sizes were observed for the two measures of head movements suggesting a degree of confidence with the results.

4. Discussions

The aim of the study was to validate a newly developed bicycle simulator at the Monash University Accident Research Centre (MUARC) for a select range of cycling performance measures. The simulator has been developed to assess new infrastructure designs that will enhance cyclist safety when riding on-road. Pilot infrastructure evaluation is ideally suited to simulator studies as it can be more cost effective than on-road or test track studies (Stevenson et al., 2015). Simulation allows for multiple iterations of designs to be evaluated and can also help to identify potential issues with the way that people interact with the new facility that may not have been obvious when conceptualising the design (Stevenson et al., 2015).

The bicycle simulator validated in this study provides an example of how new virtual reality technology can be utilised to create a high fidelity, yet relatively low cost simulator. The bicycle simulator creates an opportunity to conduct unique research investigating vulnerable road user behaviours and their interactions within various road environment and traffic conditions. However, prior to using the simulator for road safety research, it is important to first establish the validity of the simulator as a research tool and identify the benefits and limitations of the simulator, particularly in terms of elicited behaviours, so that future research is conducted within the capabilities of the simulator.

This study has focused on establishing the behavioural validity of the bicycle simulator for a set of performance measures associated with cycling on-road. The results of the study suggest that the simulator was capable in eliciting similar behavioural responses amongst the group of participants compared to on-road cycling. However it is recognised that due to the recruitment techniques, participants who undertook this study do not represent the full range of cyclists, furthermore limitations placed on participants due to recruitment criteria may have introduced sample bias.

The validation study established absolute validity for the three measures of cyclist spatial position within bicycle lanes and relative to passing vehicles. The position of cyclists within the roadway has important implications for cyclist safety. For example Harkey and Stewart (1997) identified that bicycle lanes influence the cyclist’s position relative to the kerb, with bicycle lanes encouraging cyclists to ride further away from the roads edge. Furthermore, the Australian Road Safety Strategy identifies improving cyclist spatial separation from other modes of transport as one of the key methods for improving cyclist safety (ATC, 2011). By reducing cyclists’ interaction with other modes of transport there is a reduction in the risk of collision. The finding that participants have selected lane positions in the simulator that reflect on-road riding will allow the simulator to be used to research how cyclist spatial position and lateral clearance can be influenced by changing the on-road environment. Furthermore the simulator can also be used to further study aspects of riding including passing behaviour and lane positioning. It is important to note that the simulator was assessed for relatively straight sections of road and that results may be different when considering curved sections of roads.

Absolute validity was not established for the average speed of cyclists when using the simulator compared with on-road riding. However, relative validity was established with a strong linear relationship found between on-road and simulator speeds. Furthermore, relative validity was established for the speed reduction of cyclists on approach to a T-intersection. When using the simulator, participant speeds were consistently lower than on-road speeds. These findings align with previous driving simulator studies where simulator speeds have differed from on-road speeds, however relative validity has been demonstrated (Blana and Gollas, 2002; Godley et al., 2002; Törnros, 1998).

Possible reason for the differences in speed in simulators include that the simulators do not provide the same cues to participants as they would experience in the real world and as such, it is much more difficult to judge speed (Törnros, 1998). Similar to driving simulator validation studies, when participants are not shown a display of the speed they are travelling there are often differences between the on-road and simulator speeds (Törnros, 1998).

Differences in the simulator and on-road vehicle may also result in different user behaviours. While every attempt was made to use the same bicycle set-up on-road and in the simulator the use of a bicycle trainer in the simulator may create different feedback regarding travel speed for participants compared to on-road cycling. Variation in the vertical road alignment and atmospheric conditions could also influence cyclist speed for the on-road component of the study.

The slower speeds in the simulator will have implications on future research and it is important to acknowledge and take into account the limitations of the simulator in future studies. The intention of the simulator will be to assess relative differences in speed between existing condition or control scenarios and proposed infrastructure designs. As such, the studies will focus on identifying the relative changes in speed compared to the control or existing condition scenarios and will be less concerned with the absolute speed of participants. As relative validity has been established for the simulator, the simulator will still be suitable for this intended purpose. If studies require participants to travel at a set speed, there is also the potential to display instantaneous speed to participants to help them regulate their speed.

Validity was also established for the number of head movements participants made on approach to an intersection and the average duration of these head movements between the simulator and on-road conditions. These results are promising and suggest that participants are exhibiting similar looking behaviour on-road and in the simulator, however due to the constantly changing road environment there was considerable variation between the on-road and

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**Table 1**

On-road and simulator performance measures.

<table>
<thead>
<tr>
<th>Performance measure</th>
<th>On-Road Mean (SD)</th>
<th>Simulator Mean (SD)</th>
<th>p-value</th>
<th>Effect size (Cohen’s d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average lane position (mm)</td>
<td>727.9 (177.3)</td>
<td>731.5 (99.7)</td>
<td>0.86</td>
<td>0.03</td>
</tr>
<tr>
<td>Deviation in lane position (mm)</td>
<td>227.3 (113.3)</td>
<td>241.2 (87.3)</td>
<td>0.62</td>
<td>0.13</td>
</tr>
<tr>
<td>Average passing distance (mm)</td>
<td>1196.7 (177.4)</td>
<td>1211.7 (237.9)</td>
<td>0.68</td>
<td>0.07</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>18.9 (2.3)</td>
<td>14.5 (2.0)</td>
<td>0.00</td>
<td>2.06</td>
</tr>
<tr>
<td>Speed reduction on approach to intersection (%)</td>
<td>27.1 (10.5)</td>
<td>28.1 (12.7)</td>
<td>0.85</td>
<td>0.03</td>
</tr>
<tr>
<td>Head movements on approach to intersection (n)</td>
<td>1.9 (0.2)</td>
<td>2.1 (0.1)</td>
<td>0.20</td>
<td>0.28</td>
</tr>
<tr>
<td>Average head movement duration on approach to intersection (sec)</td>
<td>1.3 (0.9)</td>
<td>1.2 (0.5)</td>
<td>0.49</td>
<td>0.13</td>
</tr>
</tbody>
</table>
simulator studies. Future validation of cyclist head movements may need to be conducted in a more controlled environment, potentially using a test-track to create consistent and controlled environments for participants. This represents a key limitation of the study, furthermore there may be a requirement to further validate the study for more complex behavioural performance measures such as gap acceptance and cyclist reaction times if these measures were to be investigated in future simulator-based research.

When considering the results from this study it is noted that the recruitment process has the potential to introduce a number of biases into the results. Notably the validation study has considered a relatively young group of healthy cyclists who are unlikely to represent the full spectrum of cyclists riding on-road. Furthermore there are limitations regarding the road environments selected for this validation study and the range of behaviours that have been assessed. As such, and as with all simulator studies, there are limitations regarding the transferability of results and there needs to be caution regarding the extrapolation of findings to different cohorts and tasks.

5. Conclusions

There is evidence that aspects of cyclist performance when interacting with the road environment can be investigated using the bicycle simulator, with absolute validity established across a range of cyclist spatial position measures. Absolute validity was not established for measures of speed. While this is a known limitation of the simulator, relative validity was established and as such the simulator is suitable for comparison studies assessing differences in speed between different scenarios. Results were encouraging when assessing measures of cyclist head movements, however further validation research may be required in order to more comprehensively validate looking behaviours, more complex performance measures and for a wider age range of cyclists.

Acknowledgements

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References


Appendix B: Examination of bicycle lane design characteristics
Examination of bicycle lane design characteristics

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Abstract

In Australia, the proportion of serious and fatal road traffic injuries involving cyclists is increasing and it is recognised that there is a growing need to improve cyclist safety to encourage increased participation in this sustainable mode of transport. Relatively little research has been conducted in Australia to understand how cyclist behaviour can be influenced through variations in road design aimed to improve safety.

This paper presents the findings from a study using a newly developed virtual reality bicycle simulator. The study examined how bicycle lane width and perceptual countermeasures can influence cyclist speed and position. Twenty seven participants ranging in age 18 to 39 years (M=24.2, SD=5.7) participated in the study.

A statistically significant main effect was observed for the influence of bicycle lane width on cyclist lateral position. Post-hoc testing found that cyclist position was significantly different between each lane width iteration indicating that cyclist lateral position within the bicycle lane is influenced by the available width of the bicycle lane. Statistically significant differences were also identified between participant’s position and variation in lateral position across five different perceptual countermeasure configurations.

The findings of this study provide fundamental information about how cyclists choose to position themselves when riding in bicycle lanes in a validated virtual reality environment. The findings illustrate that, regardless of the width of the bicycle lane, cyclists tend to ride towards the centre of the lane and the study illustrated that use of perceptual countermeasures can be an effective measure to encourage cyclists to adopt safer cycling positions. The implications of these findings for enhanced road design to improve cyclist safety are discussed.

Keywords: Bicycle simulator; bicycle lane design, perceptual countermeasures
1 Introduction

In Australia, the proportion of serious and fatal road traffic injuries involving cyclists is increasing [1, 2] and it is recognised that there is a growing need to improve cyclist safety to encourage increased participation in this sustainable mode of transport [3].

Throughout Australia road safety is guided by the principles of the “Safe System” [4]. The “Safe System” approach recognises that people will make mistakes when interacting with the road environment, and that there is the potential for those mistakes to result in a crash. However, the “Safe System” approach advocates for a road environment that is designed to be forgiving. That is to say that if a crash does occur it does not result in serious casualty or fatal injuries provided that road users behave in accordance with the road system. The principles of the Safe System are incorporated into the Australian Road Safety Strategy which recommends the use of evidence-based road designs as one of the key measures to help create safer road environments for cyclists and provide effective measures to reduce cyclist trauma [3, 4].

The primary objective of road design is to optimise the safety and operation of the road while accounting for the volume, type and distribution of traffic [5]. The main geometric elements of the road (cross-section, horizontal curves, vertical curves, intersections etc.) should be designed to provide road users with consistent information regarding how to interact with the road environment [5]. Fuller and Santos [6] describe this approach as a “self-explaining road”, with the road providing cues to the road user through design elements to determine choice of appropriate speeds, behaviours and interactions with other road users.

Various road design features have been investigated from a driver’s perspective including changes in lane widths [7-10] lane marking [11], shoulder width [12], roadside obstacles and intersection designs with investigations conducted using both on-road and simulator techniques [9]. These various features all have the propensity to influence a road user’s speed and position within the carriageway. However, while extensive research has been conducted considering motorised vehicles and their drivers, relatively little research has examined how cyclist behaviour can be influenced through variations in road design elements. Of the research that has been conducted it has been established that the presence of bicycle lanes can result in cyclists being more likely to demonstrate predictable behaviours, by maintaining a consistent travel path [13]. Furthermore, bicycle lanes have been found to influence the cyclist’s position relative to the kerb, with bicycle lanes encouraging cyclists to ride further away from the roads edge, conversely riding closer to adjacent traffic lanes [14]. In the absence of bicycle lanes, carriageway width has been found to influence the displacement between cyclists and motorists [14]. While this research provides valuable insight into the cyclist behaviour, the research to date has largely consisted of small scale studies that have been conducted in real world situations with limited control over the independent variables in the experiment.

While bicycle lanes are accepted as a preferred on-road facility for cyclists and have been associated with lower crash risks [15, 16], there is also evidence to suggest that substantial numbers of injury collisions when cyclists are travelling within bicycle lanes. For example, recent research from Victoria showed that a fifth of on-road cyclist crashes occur when cyclists are travelling in designated bicycle lanes [17]. These findings suggest that there is a need to further investigate bicycle lane design principles to address some of the gaps in knowledge. For instance, we need to identify how cyclist behave when riding in bicycle lanes and how their behaviour may be influenced to adopt safer cycling positions by increasing their spatial separation from adjacent vehicles, which in turn may reduce the likelihood of multiple vehicle (cyclist and a motor vehicle) crashes.

This paper presents the findings from a study undertaken using a newly developed and validated virtual reality bicycle simulator. This study examined how bicycle lane width and various perceptual countermeasures can influence cyclist speed and position. Stage 1 of the study assessed the influence of different bicycle lane widths on cyclist lane position and behaviour in two scenarios. The first scenario depicted a kerbside bicycle lane and the second scenario depicted a bicycle lane adjacent to on-street kerbside parking. The second stage of the study assessed the influence of a range of perceptual countermeasures on cyclist lane positioning.
2 Materials and methods

2.1 Bicycle Simulator

The Monash University Accident Research Centre bicycle simulator is a virtual reality simulator. This is a purpose-built facility designed to examine the impact of road design features on cyclist behaviour. A validation study was undertaken to assess the behavioural validity of the simulator by comparing a range of performance measures using on-road and simulator data and was successful in establishing absolute and relative validity for selected behaviours [18]. The simulator utilises a stationary instrumented bicycle and a head mounted display (HMD) that allows participants to cycle through an immersive virtual reality environment that simulates the experience of riding a bicycle on-road.

2.2 Participants

A convenience sample of 30 participants (21 males and 9 females) were recruited for the study. Power calculations were performed to identify the required number of participants for the study, based on the proposed statistical techniques and study design.

Participants were required to be over 18 years of age and be comfortable riding a bicycle on local roads. Participants were excluded from the study if they had medical conditions that might be aggravated due to exercise or using the bicycle simulator including epilepsy, high blood pressure, having previously experienced a heart attack, or if they had a history of suffering from either motion sickness or simulator sickness. Participants who required glasses for normal vision were also excluded from the study (participants who required contact lenses to correct their visions were accepted into the study). This exclusion criteria was necessary as it can be difficult for some glasses to be worn at the same time as the head mounted display. In addition, participants were required to be free of any hearing impairment that would limit their ability to respond to verbal instructions. This was a requirement as the simulator was programmed to provide participants with auditory instructions on approaches to intersections. The study took approximately 1 hour to complete.

Participants were recruitment through placement of flyers around Monash University Clayton campus. An advertisement was also placed in the Monash Memo, which is a weekly e-newsletter sent to Monash University staff.

The research protocol for the study was reviewed and approved by the Monash University Human Research Ethics Committee. Participants received a $25 AUD gift voucher for participating in the study and to compensate them for their time and travel expenses.

2.3 Study design

The study comprised two phases investigating the influence of selected design aspects of bicycle lane design characteristics on cycling behaviours. In particular the experiments investigated how cyclist respond to differing perceptual countermeasures, with a particular focus on the influence of the countermeasures on speed profile, lateral position and spatial separation between cyclists and adjacent motor vehicles.

The experimental protocol for the simulator study was as follows: Completion of the baseline simulator sickness questionnaire; demonstration of the HMD device; practice simulator rides (10 minutes); simulator study rides (30 minutes); and the final simulator sickness questionnaire.

2.3.1 Study 1: Bicycle lane width evaluation

Australian road design guidelines identify space to ride as one of the six key requirements for cyclists when developing on-road cycling facilities. Furthermore guidelines identify that cyclists require separation from motor vehicles in order to enhance their safety and comfort when riding on-road [19]. Austroads, the peak organisation of Australasian road transport and traffic agencies, identify that a 1.0 metre wide design envelop for cyclists allows for the width of a bicycle and cyclist and for variations in tracking. Furthermore in 60km/h road environments Austroads recommends a desirable bicycle lane width of 1.5 metres, with a minimum recommended width of 1.2 metres.

Five bicycle lane widths were tested in this study, ranging from 1.0 metres to 2.0 metres, at 0.25 metre increments. These widths were selected as 1.0 metre represents the design envelop recommended by Austroads for cyclists [19], while bicycle lanes between the width of 1.25 metres and 2.0 metres are within the acceptable range of lane widths for cyclists in 60km/h speed zones [19]. Two different scenarios were tested. The first scenario was a kerbside bicycle lane (Figure 1) and the second scenario tested a bicycle lane adjacent to on-street kerbside parking (Figure 2) these are two of the most common configurations for bicycle lanes in urban 60km/h speed environments in Australia. This study aimed to assess how cyclists behaved in a range of bicycle lanes that complied with the design recommendations as specified by the Austroads guidelines.
2.3.2 Study 2: Alternate pavement marking designs

The second experiment was designed to test a range of alternate pavement marking designs for bicycle lanes. The intention of the study was to assess if cyclist position and speed can be influenced by the visual cues provided by the bicycle lane. The experiment tested five bicycle lane pavement marking schemes. For this experiment the roadway consisted of a 2.0 metre wide kerbside parking lane, a 1.5 metre wide bicycle lane and the two 3.5 metre traffic lanes (one lane in each direction).

The proportion of the bicycle lane coloured green was designed to vary for each iteration of the experiment as shown in Figure 3. The intention of the study is to assess whether the visual cues provided by the pavement markings encouraged cyclists to adopt different cycling positions within the on-road bicycle lanes.

2.3.3 Simulator protocol

The simulator scenarios were designed to place participants in an environment where observations could be made to address the specific study objectives. Each lane design iteration was presented to participants on a road grid, shown in Figure 4. Different road grids were used for each study to prevent participants from becoming familiar with the cycling route.

The order of scenario presentation was randomised and counterbalanced to control for order and learning effects. Within each scenario, a different bicycle lane configuration was presented along five sections of the grid, shown in Figure 4.

Each mid-block section along the road grid was 100 metres in length and was separated by a signalised intersection. At each intersection participants received an automated verbal instruction from the simulator to either “turn left” or “go straight”. The verbal instruction was automatically triggered as the participants passed a designated point on the approach to the intersection. To provide further guidance, as participants approached the intersection the traffic signals would change to show participants either a green through phase or a dedicated left turning phase. All other turning movements at the intersection were controlled. Simulated motor vehicles were present during the scenario, however they were programmed to give priority to the participant and to avoid any...
collisions with the simulated bicycle. Parked cars were also included in the scenario when bicycle lanes were adjacent to kerbside parking. For these scenarios three parked cars were randomly placed along each test section.

Participants were presented with a different lane width configuration each time they turned left, with participants being required to make a turning movement and then re-establish themselves in the next section of bicycle lane.

For each ride, the first section of road was a practice section that was the same for each participant and each simulator run. Following the practice section, participants rode the five different sections of road, one for each iteration of the experiment.

2.3.4 Survey Component

Participants completed a short questionnaire addressing demographic characteristics and cycling experience information. Simulator discomfort was assessed by administering the Simulator Sickness Questionnaire (SSQ) [20]. The SSQ is a self-reported symptom checklist that includes sixteen symptoms that are associated with simulator discomfort. Participants were asked to rate their symptoms on a four point scale from none to severe. Each participant completed the SSQ prior to commencing the simulator study and following completion of the final simulator scenario. Participants who experienced high levels of simulator sickness were excluded from the study (n=2).

2.4 Data Analysis

Participant demographic variables were assessed using descriptive statistics. For the simulator component of the study analysis consisted of a repeated measure ANOVA. Analysis was undertaken at a level of significance (α) of 0.05. Effect size were measured using Eta-squared ($\eta^2$). Post-hoc testing was performed using Tukey’s honest significant difference (HSD) test for pairwise comparisons.

Prior to analysis, tests for normality were conducted for each variable considered in the study, using skewness and kurtosis. Results were normally distributed, and as such no transformations were performed. All statistical analysis was conducted using STATA version 13.1.

3 Results

Of the thirty participants recruited, three did not complete the study. Two participants were excluded as they experienced substantial levels of simulator discomfort and were unable to complete the full set of simulator
scenarios, and the third participant was excluded due to difficulties steering the simulated bicycle and non-completion of practice scenarios. Data from the remaining 27 participants were analysed.

3.1 Participant characteristics

Participants ranged in age from 18 to 39 years (M=24.2, SD=5.7). Participants were asked to rate their confidence level regarding cycling on-road on a 10 point Likert scale. On average, participants were highly confident riding on-road (M=8.1, SD=1.3). When asked how frequently they rode a bicycle, 80% stated they rode a bicycle at least once a week, although four participants stated that they had not ridden a bicycle in the past month. Participants generally rode less than 30 kilometres per week (73%). Commuting to work or school (76%) and recreational riding (43%) were the most common reason for riding. Three participant had been involved in a bicycle crash in the past three years, however the crashes were all relatively minor.

3.2 Study 1: Bicycle lane width evaluation

There were strong linear trends observed between the width of the bicycle lane and the position of the cyclist within the bicycle lane in both scenarios when bicycle lanes were located adjacent to the kerb and when kerbside parking was present. Cyclists tended to ride towards the middle of the bicycle lane, however slightly towards the right side. There was a noticeable difference observed for cyclists position when riding in the bicycle lanes with kerbside parking, compared to when riding in a lane adjacent to the kerb. In the kerbside parking scenario participants rode towards the middle of the bicycle, however there was a more pronounced shift towards the right hand side of the bicycle lane, compared to the kerbside bicycle lane scenario (Figure 5).

A two-way repeated measures ANOVA was conducted to examine the influence of the two scenarios and the five different lane width conditions on cyclist position relative to the left side of the bicycle lane. No interaction effect was observed between the scenarios and the five lane width conditions (F(4, 234) = 0.83, p = 0.51, η²= 0.01). A statistically significant main effect was observed for the influence of bicycle lane width on cyclist lateral position (F(4, 234) =165.2, p < .001, η²= 0.74). Post-hoc testing found that cyclist position was significantly different between each lane width iteration indicating that cyclist lateral position within the bicycle lane is influenced by the available width of the bicycle lane, with cyclists shifting further away from the left edge of the lane as the bicycle lane width increased.

A statistically significant main effect was also observed for scenarios (F(1, 234) = 49.9, p < .001, η²= 0.18). Post-hoc testing identified that there was a significant difference between lateral position for cyclists when riding in kerbside bicycle lanes, compared to bicycle lanes with an adjacent parking lane, with cyclists adopting a position further away from the left edge of the bicycle lane when kerbside parking was present.

![Figure 5: Lateral position results summary](image-url)
Variation in lateral position was also compared for each scenario. A linear relationship was observed between lateral position variation and lane width. ANOVA identified a statistically significant main effect for the influence of bicycle lane width on lateral position variability (F4, 234 = 20.52, p < .001, η² = 0.26). No differences in lateral position variation were observed between the scenario with kerbside bicycle lanes and the scenario with kerbside parking (F1, 234 = 0.04, p = 0.84, η² = 0.00) and no interaction effects were observed (F4, 234 = 0.78, p = 0.53, η² = 0.00). Post-hoc testing found that there were significant differences in lateral position variability when lane widths differed by 0.5 metres or greater. A significant difference in variability was also observed between 1.5 metre bicycle lanes and 1.25 metre bicycle lanes (p=0.01).

For the scenario where kerbside parking was present adjacent to the bicycle lane, analysis was undertaken of position of the cyclists relative to the edge of the bicycle lane when passing parked cars and when parked cars were not present. ANOVA identified a small but significant difference between the cyclists lateral position when passing cars were present, compared to when cars were not present (F1, 234 = 6.67, p = 0.01, η² = 0.03). The analysis indicated that cyclists adopt a position further away from parked cars and closer to traffic lanes when on-street parking is present.

A linear relationship was observed between cyclist speed and the available lane width. On average participants tended to ride faster when the available lane width increased. Interestingly, travel speeds were slower in the kerbside bicycle lane scenarios compared with the bicycle lane adjacent to kerbside parking scenarios (Figure 6). This was confirmed through ANOVA which showed that there was a significant difference in participants average speed between the two scenarios (F1, 234 = 32.7, p < .001, η² = 0.12).

The ANOVA identified that there were significant differences in cyclist speed depending on the width of the bicycle lane (F4, 234 = 12.3, p < .001, η² = 0.17). Post-hoc testing revealed that the significant differences were between the 1.0m lane width and the four other lane width configurations, with cyclist riding significantly slower in the 1.0 metre wide lane. The only other significant difference observed was between the 1.25m and 1.75m wide lanes, again with cyclist riding slower in the 1.25m lane compared to the 1.75m lane. No interaction effects were observed for average speeds when comparing the experiment and scenario (F4, 234 = 0.85, p=0.50, η² = 0.01).

Variation in travel speed was also compared for each scenario. No significant differences were observed for speed variability between the five lane width configurations (F4, 234 = 1.02, p = 0.40, η² = 0.05). A significant difference was observed between the two scenarios (F1, 234 = 8.7, p = 0.004, η² = 0.04) with cyclists riding significantly slower in the kerbside bicycle lane scenario, however the effect size suggests that there was only a small difference. Furthermore no interaction effects were observed (F4, 234 = 0.46, p = 0.77, η² = 0.01).
3.3 Study 2: Alternate pavement marking designs

Across the five pavement marking configurations, cyclists adopted significantly different riding positions based on the various bicycle lane marking configurations ($F_{4, 134} = 17.44, p=0.00$). Post-hoc testing identified that the traffic side buffer resulted in participants riding in a significantly closer to the left edge of the bicycle lane compared to the other four scenarios (0.76 m Vs 0.9 m). A significant difference was also observed between the parking side buffer and the parking and traffic buffer scenario (0.96m Vs 0.85m).

![Figure 7: Position relative to left edge of bicycle lane for pavement marking configurations](image)

The ANOVA identified a significant difference between participants variation in lateral position across the five configurations ($F_{4, 134} = 3.87, p=0.00$). Post-hoc testing identified that lateral position variation was significantly less for the parking and traffic buffer scenario. No other significant differences were observed.

The ANOVA identified a significant difference between travel speed across the five pavement marking configurations ($F_{4, 134} = 5.0, p=0.00$). Again, post-hoc testing identified that travel speed was significantly lower for the parking and traffic buffer scenario, no other significant differences were observed. Furthermore, no significant differences were observed for the variation in speed for the pavement marking configurations ($F_{4, 134} = 0.43, p=0.79$).

4 Discussion

This study was designed to understand fundamental information about where cyclists choose to position themselves when riding in bicycle lanes in a validated virtual reality environment. The findings illustrate that, regardless of the width of the bicycle lane, cyclists tend to ride towards the centre of the lane. It is believed that the selected lane positioning may represent a form of risk mitigation with cyclist selecting a location that they deem to be safe and provides adequate spatial separation from both sides - adjacent traffic and parked cars. An interesting finding of this study was that, for the scenario with kerbside bicycle lanes, the provision of wider bicycle lanes did not result in participants further increasing their separation from moving traffic and instead cyclists still positioned themselves in the centre of the lane. This has important implications for the design of on-road bicycle facilities as it shows that increasing the width of cycling facilities does not necessarily increase the spatial separation between cyclists and adjacent motor vehicles by an equal amount and that there are potentially alternate methods to encourage cyclists to adopt safer cycling positions. Furthermore it highlights that cyclists may also perceive risks associated with riding too close to the edge of the roadway, where fixed objects and pedestrians may present a risk.

An important finding of this study was that increasing the lane width resulted in cyclists adopting faster speeds. This has potential safety implications: in the event of a collision (either multi- or single-vehicle), higher travel speeds are associated with higher kinetic energy and therefore increase the potential for serious injury outcomes.
Furthermore, at higher speeds cyclists have less time to process information and to react to changes in the road environment, furthermore they require longer distances to come to a stop [21]. Additionally, as bicycle lane width increase, cyclists may exhibit less predictable behaviours, which may increase apprehension for other road users attempting to overtake cyclists. These findings are similar to previous research examining driver travel speeds in varying lane width configurations. In their study assessing the influence of perceptual lane width of driver travel speed, Godley et al. identified a significant reduction in travel speeds when perceptual lane widths were reduced from 3.0 metres to 2.5 metres, and found that the deviation in lateral displacement also reduced [9]. Godley et al. [9] offered two possible explanations for these results. First, they suggested that drivers perceived crash risk was higher on narrower roads or lanes compared with wider roads/lanes, which supports theories of risk homeostasis and concept of safety margins [22, 23]. Their second possible explanation was to suggest that travel speeds are associated with mental effort, and reduced travel speeds in narrow lanes are a result of mental workload limitations. This theory may be applied to the findings of this study: cyclists make a trade-off between speed and steering in narrow (1.0 metre wide) bicycle lanes, and this may be due to increased mental workload required to remain within the narrow bicycle lane.

Another interesting finding from this study was that, for all scenarios, variability in lane position was greater than the 0.1 metre space recommended by the design envelop for cyclists which is presented in the Austroads guidelines [19]. The finding suggests that cyclists may in fact require greater space than suggested for manoeuvrability and this in turn could have important implication for bicycle lane design specifications, however this finding requires further empirical research to confirm. The study also found that as lane widths increase so do the cyclists speed and lateral position variability.

The second study was designed to understand if the use of perceptual countermeasures such as pavement marking could provide visual cues to cyclists that may be effective in influencing their choice of lateral position and travel speed when riding within a bicycle lane. The results of the second study indicated that cyclists did respond to the visual cues provided through the use of alternate pavement marking schemes and that the different lane designs were capable of influencing the speed and lateral positioning of the cyclists.

Within all scenarios, cyclists were encouraged to ride on the sections of the bicycle lane that were coloured green. This in itself is a valuable finding as it shows that the cyclists in the study understood the basic meaning of the green pavement marking and were compelled to ride on the green sections of each bicycle lane. The finding confirms that green pavement marking, or presumably any colour, can be effective in encouraging cyclists to select particular lane positions, which has the potential to encourage cyclists to adopt safer cycling positions. It has previously been shown that the presence of bicycle lanes can actually reduce the separation distance between cyclists and adjacent motor vehicles [14], as such alternate pavement marking designs may help to improve the spatial separation between modes.

The results also indicated that the use of alternate pavement marking schemes can influence cyclist speed and lateral position variability. In particular, the scenario with a 0.5m green marking in the centre of the lane was found to significantly reduce cyclist speed and lateral position variability. This has important design implications, as it shows that very narrow sections of green marking may in fact cause cyclists to shed some of their task load to maintain lane position. While this does have the benefit of resulting in cyclists reducing their speed, it may also potentially result in reduced situational awareness as the cyclist focuses more on lane positioning and less on the surrounding road environment, similar to what Godley et al observed when assessing motor vehicle drivers [9].

The treatments assessed in this scenario could be implemented in a variety of locations, particularly to address locations where road design provides insufficient lateral clearance from motor vehicles to cyclists riding in bicycle lanes. These style treatments could also be utilised to encourage cyclists to adopt safer lane positions, which may have the potential to reduce the risk of rear-end, side swipe and car door collisions, all of which are common mid-block crash types for cyclists in Australia.

An important consideration of all simulator studies is the generalisability of results to the real world. To help address this issue, the bicycle simulator was validated for the performance measures utilised in this research including cyclists speed and position compared to on-road data [18]. This previous research gives a degree of confidence that the findings from the simulator would have a high degree of correlation with what would occur in a real on-road environment. However it is recognised that further research would be required to evaluate the concepts presented in this research and to assess if the changes observed in the simulator matched real world cycling.
5 Conclusions

The findings of this study provide fundamental information about how cyclists choose to position themselves and choose travel speeds when riding in bicycle lanes in a virtual environment. The findings illustrate that, regardless of the width of the bicycle lane, cyclists tend to ride towards the centre of the lane and the study illustrated the use of perceptual countermeasures can be an effective measure to encourage cyclists to adopt safer cycling positions and travel speeds.

6 Acknowledgements

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7 References


### Appendix C: Simulator Sickness Questionnaire (SSQ)

<table>
<thead>
<tr>
<th>Symptom</th>
<th>None</th>
<th>Slight</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>General discomfort</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fatigue</td>
<td></td>
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<tr>
<td>Headache</td>
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<tr>
<td>Eyestrain</td>
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<td></td>
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<tr>
<td>Difficulty focusing</td>
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<td></td>
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<tr>
<td>Increased salivation</td>
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<td></td>
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<tr>
<td>Sweating</td>
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<td></td>
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<tr>
<td>Nausea</td>
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<tr>
<td>Difficulty concentrating</td>
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<td></td>
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<tr>
<td>Fullness of head</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Blurred vision</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Dizzy (eyes open)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dizzy (eyes closed)</td>
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</tr>
<tr>
<td>Vertigo</td>
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<td></td>
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<td></td>
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<tr>
<td>Stomach awareness</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Burping</td>
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</tr>
</tbody>
</table>
Appendix D: Demographic questionnaire

Participant ID: Entered by researcher prior to survey

Date: Entered by researcher prior to survey

PLEASE READ THE FOLLOWING BEFORE COMPLETING THE SURVEY

The following demographic information will not be used to identify you as an individual, but to describe the sample used for this research project. This information is STRICTLY CONFIDENTIAL and will only be used by the research team.

Please enter you details, or tick/circle the item that applies to you.

What is your gender?
☐ Male ☐ Female

What is your age?
__________________________ Years

Do you have a valid Driver’s Licence?
☐ Yes ☐ No

How would you describe your level of confidence when riding a bicycle on-road?

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not very confident</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Very confident</td>
</tr>
</tbody>
</table>

Over the last month how frequently have you rode a bicycle?

☐ More than 3 times a week ☐ 2-3 times per week

☐ Once a week ☐ Once every two weeks

☐ Once ☐ I have not rode a bicycle in the last month
What time of the day do you most often ride?
☐ Midnight -3am☐ 3am-6am
☐ 6am -9am☐ 9am-12noon
☐ Noon -3pm☐ 3pm-6pm
☐ 6pm-9pm☐ 9pm-Midnight

How many kilometres do you ride in a typical week?
☐ Less than 10km☐ 10-30km
☐ 31-50km☐ 51-100km
☐ 101-200km☐ More than 200km
☐ Not applicable

What is the purpose of the majority of your cycling trips?
☐ Recreational riding☐ commuting to work or school
☐ Utilitarian☐ Fitness
☐ Work related travel☐ Social
☐ Club/ group cycling ☐ Not applicable
☐ Other_________________________

Have you been involved in a bicycle crash in the past 3 years?
☐ Yes☐ No