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Interactively visualising street design scenarios for communicating bike infrastructure options to communities and policymakers
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1. Introduction

Interactively visualising street design scenarios for communicating bike infrastructure options to communities and policymakers is a two-year three-phase research project with Transport for NSW (TfNSW) and iMOVE CRC. This research project investigated how to integrate bicycle facilities into urban environments in ways that address the concerns of the 48 percent of NSW residents who are 'interested' in riding, but 'concerned' about safety (Transport for NSW, 2013, 2020).

According to previous research undertaken by TfNSW, there should be an increased focus on meeting the needs of the 48 percent of potential riders who are 'interested but concerned' (Cycling Customer Value Proposition Research 2013). Targeting these potential riders means focusing cycleway design on the aspects that these customers value. Investigating what these aspects are is the key focus of this research project.

Transport for NSW's current evidence base in this area is as articulated in Transport for NSW's *Cycleway Design Toolbox: Designing for Cycling and Micromobility* (2020) which in turn draws on the Cycling Aspects of Austroads Guides (2017 Edition). The Toolbox illustrates good, better and best practice at the NSW government level. Importantly, it also shows how streets might be reconfigured to better achieve desired outcomes. These guidelines reflect that providing safe, attractive, and supporting environments is essential to encourage more people to choose the bicycle as a form of transport.

This research project is intended to strengthen this evidence base by complementing the use of stated preference surveys. Stated preference surveys have been extensively used to understand bicycle riders' preferences for routes and riding environments and to subsequently assist planning new or improved cycling infrastructure. However, there is a known discrepancy between what people state, and what their actual preference, is. In a stated preference survey, problems arise with participants' engagement, or responding based on participants' assumptions or other attributes not included in the study design.

Revealed preferences studies, where participants are studied for the 'actual' (i.e. behavioural) decisions, indicate that people's actual behaviour may be different – and sometimes completely opposite from – their stated preferences. This research project therefore seeks to better understand how potential riders make cycling related decisions in a more 'real' context and mitigate the problems that can arise through the sole use of stated preference surveys.

An important component of the research project is the use of virtual reality (VR) as a means of evaluating possible design elements (i.e. facilities) for their acceptance by the 'Interested but Concerned' cohort of potential bicycle riders. The Travel Choice Simulation Laboratory, (TRACSLab), located at UNSW, is a world-first in multi-modal, multi-user transportation visualisation. The simulator is capable of integrating bicycle riding and driving, with study participants able to ride or drive through urban transportation systems. By using the simulator and 'immersing' study participants in the VR environment, various design interventions can be evaluated by their impacts of participant behaviours while in the simulated environment. A range of possible design interventions can therefore be introduced, manipulated and tested for their impact on participant behaviours.

1.1. Interested but concerned

Over the last three decades, there has been a significant increase in the number of people riding bicycles in cities around the world, accompanied by a matching shift in government policy and urban planning (Buehler & Pucher, 2021). There is widespread agreement among policymakers and researchers that increased bicycle riding as a mode of transport can help address many of the persistent and difficult transport, economic, environmental and health issues facing cities today (De Hartog et al., 2010; Garrard et al., 2012; Kingham & Tranter, 2015; Krizek, 2007). Bicycle riding rates in Australia are moving up from a very low baseline in comparison with cities in Asia and northern Europe (Buehler & Pucher, 2021). As a result, this shift in public attitudes and policy includes a recognition that bicycle riding must appeal to a broader audience than the sport-oriented riders that have characterised the past fifty years of Australian ridership (Fitzpatrick, 2015).

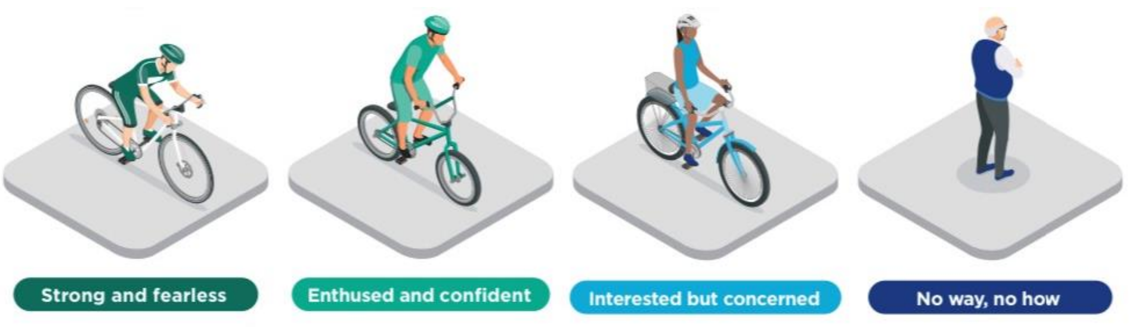
A framework for identifying and addressing this broader audience was theorised in 2006 by Roger Geller from the City of Portland, Oregon (Geller, 2009). Geller categorised people as falling into one of four categories based on their attitudes and practices around bicycle riding – the ‘Strong and Fearless,’ the ‘Enthused and Confident,’ the ‘Interested but Concerned,’ and the ‘No way, No how’ (Figure 1). The ‘Interested but Concerned’ cohort is typically about half of the adult population of a city.[1]

This study gathered new data on what design features influence or change this cohort’s perception of safe bikeability by utilising immersive virtual reality technology to test design improvements on study participants’ sense of safety. This approach aims to mitigate the known weaknesses of stated preference surveys, which has been the predominant approach for examining rider preferences for routes and riding environments. The findings will inform coordination and decision-making processes for the NSW Government’s cycling infrastructure planning and investment strategy.

Targeting these potential riders means focusing design techniques on the aspects that these customers value. Identifying and investigating these aspects is the key focus of the research project.

Figure 1. The four types of cyclists as illustrated by Transport for NSW (2020a)

[1] The ‘four types of cyclists’ is explored further in section 2.1 of this report.



2. Project structure

This research project consists of three phases. The first phase is a literature review on current global best practice facility design and alignment with the TfNSW Cycleway Design Toolbox. This review included emerging and ongoing development of the standard bidirectional cycleway treatment in Sydney as a context specific design solution and recent developments regarding the roll out of pop-up cycleways. The second phase is an interactive bicycle infrastructure design tool that provides a range of design options for particular streets suitable for attracting the interested but concerned and are physically achievable for the street conditions in question. The third phase is a virtual reality simulation experiment of six infrastructure scenarios across two streets, informed by best practice identified in phase 1, with participation from a cohort of people who fit the characteristics of the 'Interested but concerned'.

2.1. Designing for the 'Interested but Concerned': A literature review on cycling infrastructure design

This literature review aims to understand current and emerging cycling facility design practice within Australia and internationally, and to consider these trends alongside the TfNSW Cycleway Design Toolbox. Thirty-nine bicycle plans from twenty-two jurisdictions were reviewed (at city, state, and national levels). The goal was twofold – to compare the TfNSW Cycleway Design Toolbox to international best practice for cycleway design and policy, and to identify a range of best practice design solutions for 'Interested but Concerned' riders to be tested in the VR simulator.

The 'Interested but Concerned' cohort consists of potential riders who "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" (Geller, 2009). The number of potential riders in this cohort is substantial, estimated to be 48% of the adult population of NSW (Transport for NSW, 2013), and a similarly high proportion of the adult population in other cities and countries (Dill & McNeil, 2016). Research in the City of Sydney in 2021 found a similarly large group of people concerned about safety– a majority (61%) of potential riders reported being more likely to ride if there were separated bicycle paths, and a large majority (76%) of infrequent or potential riders were interested in riding more, but were fearful of riding with vehicle traffic (Taverner Research, 2021).

The importance of improved safety and comfort to this cohort has spurred a generation of bicycle plans that have gone beyond painted bicycle lanes toward networks of diverse facilities, ranging from quiet, traffic controlled local streets to off-street paths. These facilities all aim to provide greater separation between bicycles and other road users or otherwise reduce the 'level of traffic stress' (LTS) for riders (Furth et al., 2016).

Bicycle plans are often explicit in their aim to provide low LTS environments to appeal to the large percentage of the population that indicate they would cycle or cycle more if their concerns about danger from motor vehicle traffic were alleviated. For example, the TfNSW Cycleway Design Toolbox recommended an increased focus on meeting the needs of this population, with LTS used as a measure of infrastructure types (Transport for NSW, 2020).

This paper considers the use of Geller's 'four types of cyclists' framework in relation to research undertaken by Transport for NSW, the City of Sydney, and in other Australian and international cities and countries. A detailed analysis of the design process in NSW and the City of Sydney for separated infrastructure provides a spatial design and legislative context for Australian efforts to build safe cycling networks.

This is followed by an international design literature review that aims to understand the common practices and themes of current bicycle planning in thirty-nine bicycle plans from twenty-two jurisdictions at local, state and national levels. The focus of the review was on plans that include specific infrastructure types and designs, rather than purely strategic or network plans. The plans were reviewed for their general rationale and strategy; for the included (or excluded) mid-block and intersection infrastructure strategies; for general network strategies; and for other supporting programs or policies. The plans were also reviewed for their evolution over time – where feasible, current plans were compared with their previous versions.

A thematic content analysis was undertaken to determine the most common facility design themes in relation to the aim of growing cycling mode share. A conventional and summative approach was undertaken of subjective interpretation of content through systematic identification patterns in which themes were progressively grouped and reduced (Hsieh & Shannon, 2005). Based on this analysis three dominant themes emerged that were subsequently expanded and framed in reference to the literature related to each theme. These are:

1. A general global trend to establish protected cycleways as standard practice, rather than an exceptional condition;
2. The formalisation of quietways and low-traffic neighbourhoods as a core element of local bicycle networks; and
3. A growing emphasis on the need for protected intersection design.

The literature review concludes that Roger Geller's 'four types of cyclists' categorisation (Geller, 2009) has found broad appeal in bicycle planning globally and directly informed a number of government bicycle plans around the world. The general framework has been confirmed as a compelling model for a population-wide understanding of opportunities to increase cycling and provides clear direction on what would be required to enact a cycling mode share shift, primarily with increased safety through separation from traffic.

The review also confirms that the leading-edge designs and policies within the TfNSW Cycleway Design Toolbox are consistent with international best practice for safe infrastructure design and provide clear direction toward a statewide bicycle network that appears to address the concerns of the 'interested but concerned' cohort of potential bicycle riders.

2.2. Interactive Bicycle Infrastructure Design Tool

In this phase a tool was developed that provides a range of design options suitable for attracting the interested but concerned for particular streets and are physically achievable for the street conditions in question. The facility type options that are presented by the tool for a given street are based on the level of safety required by the interested but concerned as demonstrated by the TfNSW Cycleway Design Toolbox the findings from the literature review in Phase 1 of this research project and the findings from the VR scenario experiments in Phase 3 of this research project.

2.2.1. Tool Design and Functions

Tool overview

The "Interactive Bicycle Infrastructure Design Tool" is a tool that takes the current street layout and traffic conditions as input and provides users with recommendations for the design of new bicycle infrastructure, including the recommended type of infrastructure, and how the recommended infrastructure integrates into the existing road cross-section. These design recommendations are based on a comprehensive review, analysis, and synthesis of existing literature and global best practices, including a subsequent user testing to validate these design recommendations through VR simulation.

The tool informs users on "what to build" on a particular road section. The tool is constructed as an Excel VBA (Visual Basic for Applications) tool, which is a dynamic and user-friendly solution designed to enhance functionality and streamline tasks within Microsoft Excel. The tool operates through a custom-built macros and automation scripts, which provides an interactive experience in data entry and output.

User interface, data input

The tool functions by first asking the user to describe the current condition on a road segment. This information is then processed by the tool to provide contextual design recommendations for cycling infrastructure. The user interface is designed to facilitate the process of user input.

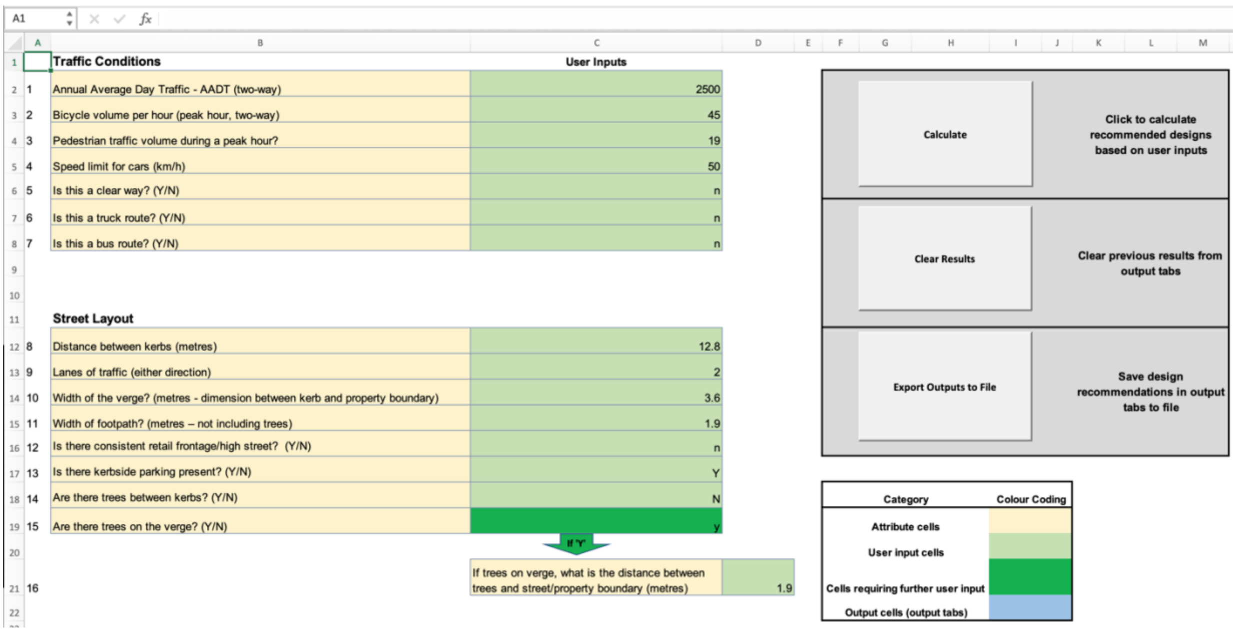
Data entry covers two topics which are necessary to describe the conditions of a street, namely the street layout, and traffic conditions. Table 1 lists the range of required data input to describe the road condition.

Table 1. Required user data entry describing the road condition

Street Layout	Traffic Conditions
Distance between kerbs	Daily traffic volume
Number of lanes	Cyclist volume
Width of the verge	Pedestrian volume
Width of footpath	Speed limit
Presence of retail frontage	Presence of clear way
Presence of kerbside parking	Presence of truck route
Presence of trees between kerbs/on verge	Presence of bus route

Users can enter data directly into designated cells in an excel spreadsheet (Figure 2). Cells are pre-populated with default values of either numeric numbers, or letters of Y/N; these pre-populated values provide visual guidance and reduce the cognitive load during data entry. Input cells are colour coded and arranged in groups to facilitate data entry. Explanatory texts are also provided to explain each data input.

Figure 2. Data entry tab for the Interactive Bicycle Infrastructure Design Tool



Data processing and output

Following the data entry stage, the tool includes an actionable button: “Calculate”. Clicking on the button will send the user-provided input to the processing script behind the tool, which generates design recommendations based on the user input. A wide range of factors are considered in generating the recommended design options. For instance, the location of street trees, the amount of pedestrian and bicycle traffic, whether the segment is bus or truck route, and the width of different parts of the road cross-section are important considerations behind the generated design recommendations.

The tool includes three excel sheets for displaying design outputs, namely the “Facility Type Feasibility”, “Between Kerbs Design Options’, and “On Verge Design Options”. Once the user clicked on the “calculate” button, the tool will automatically zoom to the “Facility Type Feasibility” sheet, which presents the feasibility of different cycling infrastructure for that particular cycling infrastructure.

Where certain facility types were not feasible, this output sheet also includes notes explaining reasons behind such recommendation. Feasible design recommendations are generated in separate sheets. Depending on the type of the recommended design options, outputs are displayed either in the “between kerbs”, or the “on verge” sheet. Design outputs specific the width for different parts of the road cross section (e.g. bike path, median, parking lane and traffic lanes, etc.). For each design recommendation, images are provided to enhance understanding of the recommended street layout.

In addition to generating design recommendations, the tool includes additional actionable buttons to facilitate the interactive user experience. A second actionable button, “Clear Results”, clears outputs generated from the previous scenario. This is useful when users try out different inputs. Under some circumstances users may wish to export and save design outputs. A third actionable button, “Export Outputs to File”, exports design recommendations to files; clicking this button saves design recommendations to excel files. This export function allows users to save design recommendations, and to rapidly test a wide range of scenarios and design options.

2.3. Virtual reality (VR) scenario experiments

The final phase of this research project is a virtual reality simulation of six scenarios across two streets. These scenarios were informed by the TfNSW Cycleway Design Toolbox and the literature review undertaken in phase 1 of this research project.

2.3.1. VR integration and testing briefing paper

This key research activity addresses Aim 2 in the iMOVE project brief:

> To rigorously and empirically test, validate and improve these best practice principles in location specific settings within Sydney through creating and testing a simulation / visualisation prototype to understand community (i.e. the ‘Interested but Concerned’ cohort) preferences for cycling environments and facilities in order to inform astute investment decisions.

The research questions that this activity addresses are:

1. What are the impacts of various design interventions of the proposed cycling facility design options on participant's **cycling behaviour**?
2. What are the impacts of various design interventions of the proposed cycling facility design options on participant's **sense of safety**?
3. What are the impacts of various design interventions of the proposed cycling facility design options on participant's **acceptability of cycling**?
4. Which of the proposed cycling facility design options is **preferred** by participants?

The use of human-in-the-loop bicycle simulators as research tools attracts the interests of researchers in this field because they can provide a bridge between traditional non-naturalistic data collection methods, such as stated preference survey which are commonly adopted to study riders' perceptions on safety and comfort (Caviedes et al., 2017), and naturalistic approaches, such as observation of rider behaviour through in-situ observations (Werneke et al., 2015). There are limitations associated with both approaches. Non-naturalistic methods are usually administered by presenting several pictures or short videos of bicycle facilities and subsequently ask respondents to rate the facilities based on their perceptions (Winters & Teschke, 2010; Che et al., 2021). With this approach, there is a concern regarding the extent in which those visualizations mediums can accurately convey the experience of cycling to the participants. Consequently, the validity of results collected by this method might be distorted (Nazemi et al., 2018). On the other hand, naturalistic methods have associated challenges relating to the replication of experimental conditions due to the significant difficulty to control for external factors, e.g. weather condition, pedestrian and vehicle traffic volume, other road users' behaviour, etc.

The bicycle simulator might address those limitations by providing first-hand cycling experience in a highly immersive environment that participants can interact with, while also providing a consistent, controlled, and repeatable experiment condition (O'Hern et al, 2017). However, developing a reliable bicycle simulator is a complex technical task and therefore there is only a limited number of bicycle simulator facilities in the world (Horne et al., 2018).

Early bicycle simulators (Carraro et al., 1998; Jeong et al., 2005), while useful for their objectives, possesses several technical limitations, particularly related to user immersion. More recent development of bicycle simulator utilise virtual reality (VR) head mounted display (HMD) which can immerse its user in the virtual environment (Nazemi et al., 2018; Bogacz et al., 2021) and provide the ability to freely move their vision space in all encompassing 360-degree direction and presents an opportunity to simulate the immersive experience of cycling to its users. Bicycle simulator has been utilised to study Autonomous Vehicle-Cyclist Interaction (Hou et al., 2020; Kas et al., 2020), infrastructure design (De Leeuw & de Kruijf, 2015; Nazemi et al., 2018), riders' behavior (Nazemi et al., 2018), perceived safety (Nazemi et al., 2021), rehabilitation training (Jeong et al., 2006), and crossing behaviour (Handa et al., 2017).

The simulator consisted of a standard bicycle with a step-through frame, mounted on a fixed cycling trainer stand with a roller to support the bicycle and simulate rolling resistance from a road surface. A set of sensors were attached to the bicycle, relaying information on rear tyre rotation and steering to a high-performance desktop computer to translate bicycle simulator movements into speed and turning data within the simulated environment.

The simulated environment was created within a custom-built simulator software platform by the rCITI research team, based on longstanding expertise in vehicle simulators and a body of literature on bicycle simulator development. The simulator captures a range of data as a participant moves through a simulated environment, including travel speed, lateral position relative to the centre of a simulated travel path, acceleration, steering rate, and distance from vehicles or pedestrians within the simulated environment.

The simulated environment was presented to participants using a VR headset, which allows for a naturalistic engagement with a simulated environment, and also allows for eye tracking of participants, which were used to evaluate participant focus and visual scanning of the simulated environment. A wrist-mounted sensor also recorded participant heart rate and electrodermal activity, which was used to analyse stress responses to various simulated environments.

2.3.2. Bicycle infrastructure scenario simulations

Based on project team discussions and the literature review of NSW and international best practice for bicycle infrastructure design, six infrastructure scenarios were modelled in the simulated environment.

These scenarios were based on two real streets in New South Wales: Derby Street in Penrith, from Woodriff Street to Evan Street, and Smith Street in Wollongong, from Keira Street to Harbour Street. A high degree of accuracy was achieved for the conditions on each street, including junctions, road sections, and lane markings. Video footage of the cycling routes, recorded by the UNSW project team with a 360-degree camera, was used as reference for the simulator environment modelling. Satellite images of the existing conditions, as well as technical drawings provided by council staff, were also referenced to replicate certain critical sections of the routes.

For Derby Street scenario, three bicycle facilities options were tested:

D1: One-way bicycle path: A 1.4m path for one-way bicycle traffic, separated from vehicle parking and travel lanes using concrete or landscaped barriers.

D2: Two-way bicycle path: A 2.4m path for two-way bicycle traffic, separated from vehicle parking and travel lanes using concrete or landscaped barriers.

D3: Shared path: A 2.5m path on one side of the roadway, separated from the roadway by a kerb and planted verge, where riders and pedestrians share the path.

On Smith Street, three facilities options were tested:

S1: Two-way pop-up bicycle path: A 2.4m wide, two-way bicycle path separated from vehicle parking and travel lanes using bolt-down plastic kerbs with high-visibility plastic vertical posts.

S2: Interim two-way bicycle path: A 2.4m wide, two-way bicycle path, demarcated by signage and line marking, but no physical barrier.

S3: Quietway: A street in which design elements and visual cues reduce motor vehicle speeds and volumes, and riders share the roadway space with motor vehicles.

A sample video of a virtual reality scenario was prepared by the project team and reviewed by Transport for NSW staff for approval of the modelling and rendering techniques and infrastructure design standards.

2.3.3. Guidelines for usability testing and acceptance using virtual reality simulators

A guideline document was prepared to provide a procedural overview for the VR simulator experiment, and as a training manual for experiment staff. A clear and consistent process for each participant, including a standardised script and forms for feedback, were developed to ensure reliable results.

2.3.4. Simulator evaluation report

The study was designed as a within-study experiment in which each participant rode on the three scenarios based on either Derby Street or Smith Street. A minimum sample of 30 participants per street was identified, and a set of criteria was established for participation, based on ethics considerations for human experiments, and on best practices for simulator experiments. These included a minimum and maximum age, an ability to ride a bicycle and normal vision (including colour vision) or vision corrected by contact lenses.

Volunteer participants were recruited via social media and Transport for NSW internal newsletters. Potential participants were directed to an online screening survey that provided information on the study and recorded responses about basic demographics, the inclusion and exclusion criteria, current cycling behaviours and attitudes, and comfort with different cycling infrastructure conditions. The infrastructure questions followed the methodology developed by Dill and McNeil (2016) to sort respondents into one of the 'four types of cyclists' framework. Respondents who met the inclusion and exclusion criteria and were identified as a potential 'Interested but Concerned' rider were then invited to participate.

Recruitment attempted to match previous findings of the gender and age balance of 'Interested but Concerned' riders in Greater Sydney. However, the inclusion and exclusion criteria limited the participation of older people, and the location of the experiment on the UNSW campus increased the number of younger people who were able to participate.

In total, 98 people participated in the experiment, but 16 people were unable to complete the study due to motion sickness or (in the case of two participants) technical problems with the simulator. The partial results for these participants were excluded from the study. Of the 82 people who completed the experiment, 50 were shown the Smith Street scenarios, and 32 were shown the Derby Street scenarios.

In terms of safety perceptions, the scenarios with dedicated bicycle paths scenario (e.g., 'One-way bicycle path', 'Two-way bicycle path', 'Two-way pop-up bicycle path' and 'Interim two-way bicycle path') were rated to be significantly safer than the scenarios with the mixed traffic paths (e.g., 'Quietway' and 'Shared path'). For instance, the 'Quietway' scenario raised concerns due to the lack of demarcated space for bikes and risk of potential conflict with cars, both driving straight and parking. Eye gaze behaviour and physiological responses also varied across intersection types, highlighting the need for more controlled and legible intersection design.

This finding is also consistent with participants' responses regarding their willingness to ride. The results revealed that the 'Interested but Concerned' cohort expressed a clear preference for dedicated bicycle paths separated from both vehicular traffic and pedestrians. At Derby Street the 'One-way bicycle path' was rated as the most comfortable and preferred, followed by the 'Two-way bicycle path'. At Smith Street the 'Two-way pop-up bicycle path' was rated as the most comfortable and preferred, followed by the 'Interim two-way bicycle path'. This underscores the importance of dedicated bicycle paths to attract the interested but concerned cohort.

3. Conclusion

Interactively visualising street design scenarios for communicating bike infrastructure options to communities and policymakers is a two-year three-phase research project with Transport for NSW and iMOVE CRC. This research project investigated how to integrate bicycle facilities into urban environments in ways that address the concerns of the 48 percent of NSW residents who are 'interested' in riding, but 'concerned' about safety (Transport for NSW, 2013, 2020).

The first phase; *Designing for the 'Interested but Concerned': A literature review on cycling infrastructure design* determined three key findings:

1) A global trend to establish protected cycleways as standard practice, rather than an exceptional condition;
2) The formalisation of quietways and low-traffic neighbourhoods as a core element of local bicycle networks; and
3) A growing emphasis on the need for protected intersection design.

The literature review also found the TfNSW Cycleway Design Toolbox aligns with global best practice in designing for the interested but concerned. The second phase; Interactive Bicycle Infrastructure Design Tool developed a tool that takes the current street layout and traffic conditions as provided by users and generates recommendations for the design of new bicycle infrastructure, including the recommended type of infrastructure, and how the recommended infrastructure integrates into the existing road cross-section. The facility type options that are presented by the tool for a given street are based on the level of safety required by the interested but concerned as demonstrated by the TfNSW Cycleway Design Toolbox, the findings from the literature review in Phase 1 of this research project and the findings from the VR scenario experiments in Phase 3 of this research project.

The final phase of this research project was a virtual reality simulation of six scenarios across two streets. These scenarios were informed by the TfNSW Cycleway Design Toolbox and the literature review undertaken in Phase 1 of this research project. Under physiological testing and post-ride surveys the scenarios with dedicated bicycle paths (e.g. 'One-way bicycle path' rated the highest and 'Two-way bicycle path' rated the second highest) were found to be significantly safer and more attractive than the scenarios with mixed traffic paths (e.g., 'Quietway' and 'Shared path'). For instance, the 'Quietway' scenario raised concerns due to the lack of demarcated space for bikes and risk of potential conflict with cars. Pop-up and interim facilities rated higher than these mixed environments yet lower than the formalised 'One-way bicycle path' and 'Two-way bicycle path'. Eye gaze behaviour and physiological responses also varied across intersection types, highlighting the need for more controlled and legible intersection design. These findings underscore the importance of dedicated bicycle paths and controlled interactions with traffic to attract the 48 percent of NSW residents who are 'interested' in riding, but 'concerned' about safety (Transport for NSW, 2013, 2020).

4. Recommendations

The following recommendations represent the key findings from the iMOVE research project *Interactively visualising street design scenarios for communicating bike infrastructure options to communities and policymakers*. These recommendations are derived from the results of the virtual reality scenario experiments. The scenarios were developed to represent guidance in the TfNSW Cycleway Design Toolbox and global best practice from the literature review on cycling infrastructure design.

It is important to note that a 'do nothing' scenario was not included alongside the six bicycle facility scenarios. As discussed in the Literature Review phase of this research project there is clear evidence that existing mixed traffic environments have failed to attract the Interested but Concerned. The question for the VR scenarios was thus focussed on how Interested but Concerned participants responded to different types of bicycle facilities. It should be acknowledged that had a 'do nothing' scenario been included it is highly likely all six scenarios would have rated higher in comparison.

4.1.1. A connected network of dedicated bicycle paths

This research has highlighted the importance of a connected network of dedicated bicycle paths to attract the Interested but Concerned to riding on a regular basis. Building a connected dedicated bicycle path network should be the priority if the goal is to increase bicycle mode share. A connected dedicated bicycle path network is embodied in five of the six TfNSW Cycleway Design Toolbox Design Principles: Safe, Connected, Direct, Attractive, and Comfortable.

The TfNSW Cycleway Design Toolbox states that "bicycle paths and quietways… are the required facility types on priority cycling routes" (Transport for NSW, 2020, p 14). However, this study highlights the critical importance of careful quietway design if they are intended to attract the Interested but Concerned. The quietway scenario presented to participants included a range of common traffic calming techniques. Despite these, the Interested but Concerned participants in this study had generally negative responses to riding in mixed traffic. In this experiment, the quietway scenario was not perceived as adequately safe compared with separated facilities. It is difficult to ascertain whether these negative perceptions were due to the particular configuration of this quietway scenario, lack of awareness of and experience with this type of infrastructure, or the simulated environment itself. However it is not possible to provide separated bicycle paths on all streets and low speed, low volume, mixed traffic environments will inevitably form parts of the network. This study suggests that designs for quietways must carefully manage rider-vehicle interactions in order to be attractive to new or less-confident bike riders.

Shared paths are increasingly being seen as supplementary in NSW. The findings from this study supports reducing the role shared paths play in the bicycle network in favour of separated facilities. The TfNSW Cycleway Design Toolbox states that shared paths (Transport for NSW, 2020, p 14).:

> …may be considered where the predicted demand or activity is low and where there are limited interactions along the cycleway (ie. driveways, side streets). Shared paths are not preferred in areas with high pedestrian activity, where there is significant cross cycleway movement, or where cycling speeds may be high. Mixing pedestrian and cycling movements in these locations could pose safety risks to users and offer a low Level of Service to bicycle riders.

Based on the negative responses exhibited by the Interested but Concerned participants in this study to mixing with pedestrians on shared paths, these facility types should be considered supplementary or interim solutions. In cases where shared paths and quietways exist or are implemented additional treatments are needed at intersections to come closer to the level of safety required to attract the Interested but Concerned.

4.1.2. Type of separation

The type of separation for bicycle paths has an impact on the degree of safety and facility attractiveness to the Interested but Concerned. Grade separation, in the form of a kerb to parked cars, provides the most comfort. This is followed by the bolt-down composite median commonly used for pop-up bicycle paths, and lastly the line marking only separation in which there is no physical barrier. This indicates that lightweight or line marked separation should only be considered for short term or interim measures.

This aligns with guidance in the TfNSW Cycleway Design Toolbox (Transport for NSW, 2020, p 13) that states:

> Incorporating a buffer between people cycling and parked cars is a key safety design feature for cycling facilities…. The buffer can take the form of a median, kerb, verge or planting.

All four of these buffer examples provide clear separation in the form of physical barriers between people riding bikes and motorised traffic. The findings from this study supports this approach.

4.1.3. One way bicycle paths

One way bicycle paths should be prioritised over two-way bicycle paths. One way bicycle paths were the most comfortable, safe, and attractive facility type for the Interested but Concerned in this study. This aligns with guidance in the TfNSW Cycleway Design Toolbox (Transport for NSW, 2020, p 8) which states:

> One-way (uni-directional) bicycle paths located on each side of a road and operating in the same direction as adjacent motor vehicle traffic are the preferred design for cycleway facilities. One-way bicycle paths reduce delay, improve road safety (both at intersections and along road sections) and improve operations at intersections when compared with two-way bicycle paths. One-way bicycle paths also offer improved coherence, legibility and local access, and should therefore be installed where adequate space allows.

In practice however one-way bicycle paths are rarely implemented in NSW, primarily due to space constraints within typical 20 metre road reserves. Adequate one-way bicycle paths require more overall space than two-way bicycle paths. The one-way bicycle path scenario in this study provides a 1.8 metre wide path with a 0.4 metre median, car parking on both sides and a 4.2 metre space for traffic in both directions under a yield street condition. This configuration fits into the typical 20 metre road reserve with 12.8 metres between kerbs. Harley Street in Alexandria is the only built example of these dimensions in NSW. In this built example the space between kerbs is 8.1 metres and complies with the Movement and Place yield street guidance in which “Carriageway width is approximately 7.6-8m, with parallel car parking on both (sides)” (NSW Government 2023). This study suggests this configuration is the most attractive to the Interested but Concerned as well as the most achievable one-way bicycle path variation and warrants further implementation. All variations of the one-way bicycle path in the TfNSW Cycleway Design Toolbox show the removal of one side of car parking to achieve one-way bicycle paths on both sides of the street. The removal of car parking is not required under this yield street condition and presents a more palatable option for local communities. The Harley Street example could be further enhanced by raising the bicycle path to be flush with the median and either flush or with a low kerb (below pedal height) to the footpath/verge. This would be a more expensive variation however would increase the operating width of the bicycle path to allow more comfortable overtaking and less chance of pedal strike on the kerbs. Accommodating easy overtaking is important to achieve the TfNSW Cycleway Design Toolbox principle *Comfortable: Ensure that riders of all ages and abilities can ride at a speed they are comfortable.* The one-way bicycle path / yield street combination should be included in the next iteration of the TfNSW Cycleway Design Toolbox.

4.1.4. Raised priority crossings

Raised priority crossings are the most comfortable and attractive intersection types to the Interested but Concerned and should be implemented where possible at all side streets for bicycle paths and shared paths. Based on participant's written feedback the preference for raised priority crossings is likely due to the integrated nature of the crossing within the road related area as well as with pedestrian crossings and the clear priority given to riders and pedestrians.

4.1.5. Protected intersections

Gentler bends in protected intersections should be investigated. For the Interested but Concerned in this study signalised intersections are more comfortable than protected signalised intersections and protected signalised intersections are more comfortable than protected roundabouts. Based on participant's written feedback this is likely due to the degree of deviations required for riders to navigate different types of protected intersections. The protected signalised intersections have less severe deviations than the protected roundabouts and received fewer negative comments from participants. The simpler signalised intersections in which riders travel straight were the most comfortable. These intersection variations were modelled from the examples in the TfNSW Cycleway Design Toolbox and for the protected roundabouts riders are required to make four consecutive 90-degree turns, for example left, right, right, and left again, to continue along the same street. Doncaster Avenue at Ascot Street in Randwick is a recently built example. The evidence in the literature indicates protected intersections significantly reduce the frequency and severity of crashes between motorists and bike riders and are thus important design techniques to pursue. Protected intersections have been developed and implemented most in The Netherlands. These examples tend to have much gentler deviations than NSW guidance. Preliminary investigations suggest a protected roundabout in the TfNSW Cycleway Design Toolbox for a two-way bicycle path with four 90-degree turns could be re-designed with two gentler bends. This should be investigated as potential updated guidance in the TfNSW Cycleway Design Toolbox.

4.1.6. Quietways

It is not possible to provide dedicated bicycle paths on all streets. Inevitably local streets without separated facilities will need to form part of the bicycle network. Quietways have been identified as an important complement to separated infrastructure for several reasons. They can be implemented in narrower street reserves or roadways that cannot accommodate a separated path without loss of a parking or traffic lane. They can provide important local links between corridors with separated paths, or as part of a Low Traffic Neighbourhood where traffic is calmed across an entire area. They can potentially be a lower-cost solution than a separated path, and so can assist in achieving a more expansive network within public budgets. Finally, quietway designs can also create street environments that are more peaceful and pleasant for all street users.

The results of this study highlight the need for careful quietway design. The quietway ranked the lowest overall in this study for the Interested but Concerned due to the necessity of sharing space with cars. It is important to note however when designing quietways there is a wide range of physical interventions and their combinations to choose from. The quietway scenario in this study was one combination. It may also be that a different configuration of quietway elements may have led to different responses from participants.

Nevertheless, this study reinforces the established understanding that real and perceived safety for riders increase with the reduction in interactions with cars and other large vehicles. The results of this study suggest that if a quietway has the aim of attracting new riders, reducing the volume and speed of cars along the quietway should be a fundamental principle. This is best achieved through three key interventions:

- Modal filters to reduce traffic volumes and speeds while still providing access for private vehicles. Each street needs to be considered in relation to its specific context. Modal filters can be located midblock or take the form of a closure to cars at one end of the block and in some cases at multiple blocks along a route. Lawrence Street and Belmont Street in Alexandria are examples in which modal filters are present on consecutive blocks. Modal filters arguably provide the greatest impact on reducing through traffic.
- Raised, coloured, and narrowed intersections with clear sight lines. Intersections on the quietway scenario, all of which had narrowed thresholds, elicited the greatest concern across all intersections tested for the Interested but Concerned. Additional techniques are required to increase perceived safety. Further consideration should be given to applying these techniques further from the intersection as approach treatments. Fear of car interactions at intersections can be reduced by street closures or partial closures to cars to reduce car turning movements and car-bicycle interactions.
- Reallocation of road space to provide improved facilities and safety for pedestrians and people riding bikes. Participants expressed concern at the potential for conflict with cars performing parking movements. When parking is provided within a quietway, parking design should be configured to reduce real and perceived risk. This includes increasing parking setbacks at intersections and crossings, and street tree planting in line with car parking. If angled or 90-degree parking is provided rear to kerb angled parking should be required to eliminate reversing movements out of parking spaces.

It is recommended that these three points are included as principles for quietways in the next iteration of the TfNSW Cycleway Design Toolbox.

4.1.7. Shared paths

Raised pedestrian and bicycle priority crossings should be provided at all shared path side streets. This study has found the most significant reduction in stress levels for the Interested but Concerned at intersections on existing infrastructure can be achieved by installing raised pedestrian and bicycle priority crossings at shared path side streets. While shared paths are not favoured by the Interested but Concerned there are many built examples on important routes, and it is highly likely more will be built where it is considered too difficult to provide separated facilities. Stop and give way crossings of side streets on shared paths are common in NSW. This study found the greatest difference in heart rate increases along any type of facility occurred between stop and give way crossings and raised crossings on shared path side streets. Stop and give way side street crossings are confusing for pedestrians, bike riders and motorists given the complicated nature of who gives way to who that changes depending on if motorists are entering or exiting the side street and if the person crossing the road is a pedestrian or a bike rider. The Queensland Government recognised this lack of clarity and resulting risk several years ago and made changes to the Queensland Road Rules that gives priority to pedestrians and bike riders crossing a side street over motorists entering or exiting the side street. It is recommended similar changes to the NSW Road Rules are investigated. This would result in significant road safety improvements for pedestrians and bike riders. Raised shared path priority crossings at side streets addresses this issue as a design intervention with or without changes to the NSW Road Rules.

4.1.8. VR simulations

To the authors' knowledge, this study is the first application project in New South Wales that utilises an interactive VR bicycle simulator as a visualisation platform to communicate and evaluate bicycle facility design options to users. The outcomes from this study demonstrate the feasibility of VR simulations as a data collection platform to collect participant cycling data for refining and validating alternative bicycle facility options.

Based on the experience from this study, the utilisation of a simulators offers several key advantages to other methods. It should be noted however that further refinement of the technology is required before being industry ready.

- **Firsthand experience**: bicycle riding simulators can provide an immersive and realistic virtual environment compared to traditional methods (such as images or videos), allowing participants to experience the proposed bicycle facilities firsthand. This can potentially enhance the understanding of the design elements and potential challenges associated with each bicycle facility option, fostering a more informed decision-making process.
- **Quality of collected data**: Obtaining valid naturalistic bike riding behaviour data on a real street is very difficult because there is no data acquisition equipment available in the market that can capture numerous variables that are present in the real-life bicycle riding experience, e.g. speed and location of each individual road user on the street. Moreover, it is almost impossible to keep a comparable testing condition across participants due to variation of external factors such as weather and traffic volume. A driving simulator can address these issues by offering a consistent testing condition because environmental parameters such as weather, traffic composition, volume, and behaviour can be defined during the scenario

development stage. Furthermore, the simulator software enables accurate logging of bicycle riding data with high frequency.

- **Cost-effective and rapid prototyping:** on-site trial of bicycle facility options can be time-consuming, cost prohibitive and highly disruptive to road users due to the need to physically construct the bicycle facility. Simulator environments, on the other hand, can be manipulated in the bicycle riding simulator with ease by a 3D designer. Therefore, bicycle riding simulators can offer a cost-effective alternative, allowing for rapid prototyping and iterative testing of various bicycle facility options. This iterative approach offers the possibility to refine the designs based on feedback collected from participants. Moreover, trialling proposed design options in a simulator will cause minimal disruption to road users because no physical construction on site is necessary until the design is finalised.
- **Data-Driven decision support:** The interactive and portable natures of simulations mean that the simulator can be easily relocated to different locations and could serve as a tool for engaging various stakeholders, including community members, interest groups, policymakers, and urban planners. Feedback from different stakeholder groups and quantitative data on user behaviour and safety metrics, collected from the simulator, can be used to facilitate evidence-based decision-making that lead to more targeted infrastructure design.
- **Assessing impact of traffic on riders**: Future research should explore how varying degree of vehicle and pedestrian traffic volumes might affect riders' experiences. This could include studying riders' sense of safety and comfort in various traffic conditions to better understand how to design effective bicycle facilities in both high and low traffic areas over different types of cycling facilities.

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