When Bike Lanes Are Not Enough:

AN EXPLORATION OF THE LEVEL OF TRAFFIC STRESS FRAMEWORK IN AOTEAROA NEW ZEALAND

A thesis

submitted in partial fulfilment

of the requirements of the degree of

Master of Environmental Planning in the Faculty of Arts and Social Sciences

at

the University of Waikato

by

MELISSA LOUISE SMITH

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2024

Abstract

The Level of Traffic Stress (LTS) Framework is a recently developed bicycle infrastructure classification scheme that is growing in popularity in the field of transportation planning due to its relatively simple data requirements, its intuitive description of cycling networks, and its potential to increase the uptake of cycling through application in policy and planning. However, there are a dearth of studies that aim to empirically validate the LTS Framework and its use. This thesis aims to empirically validate the LTS Framework in the context of Aotearoa New Zealand, asking: ***To what extent does the provision of low stress cycling infrastructure relate to cycling uptake in major cities in Aotearoa New Zealand?*** The Level of Traffic Stress framework is applied to seven cities across Aotearoa New Zealand that vary in population, topography, and commitment to cycling as an everyday traffic mode which results in roads being designated as either low stress or high stress. Measures of the networks formed when only considering low stress roads are tested against levels of cycling commuting across different neighbourhoods. It is found that for six of the seven studied cities, the majority of the roads are low stress, and in all seven cities, the low stress roads are poorly connected. However, there is a link between greater provision of low stress cycling infrastructure and the number of people cycling to work. The percentage of low stress infrastructure at both the city and the neighbourhood level is the only significant variable for increasing bicycle commuting levels. Further, this variable is expressed stronger at the city level than the neighbourhood level, indicating that new low stress infrastructure is likely to increase cycling uptake regardless of where it is located. Policy makers and planners can have confidence that the provision of low stress infrastructure is correlated to increased cycling uptake in Aotearoa New Zealand and beyond.

Acknowledgements

It has been an absolute whirlwind of a year working towards this thesis. I have learned a lot of valuable skills about research, project planning, and academic writing that I know I will take with me into any and all future prospects. I would like to first and foremost thank my thesis supervisor, ***Dr Xinyu Fu***. You encouraged me to take on this challenge and offered me so many opportunities throughout my time at the University of Waikato Te Whare Waananga o Waikato. Thank you for your support, your feedback, and, most of all, your time. I would also like to thank ***my friends and family*** for listening to me grumble while I'm working through a particularly challenging problem and bringing me motivation in the form of snacks when I'm spending another late night coding. In particular, I want to highlight my mother, ***Sandrine Smith***, for helping me with the Herculean task of grammar and spell checking this beast. Any remaining errors are my own! In addition, I must also acknowledge ***all the amazing cycling advocates*** based here in Kirikiriroa Hamilton. Your tireless work making an incredible case for cycling in our city inspires me every day. Thank you for bringing me into the fray and demonstrating to me why this topic is such an important one. Finally, I would like to acknowledge the ***local government staff*** who responded to my multitude of queries and emails about cycling data. This research would not have been possible without you.

Contents

List of Figures

List of Tables

1 Introduction and Motivation

1.1 The Case for Cycling

The need for sustainable transportation is paramount. City planning dominated by the motor vehicle has resulted in increased traffic congestion and traffic crashes, reduced economic development, and environmental degradation in the form of increased greenhouse gas emissions, air pollution, and noise pollution (Litman and Laube, 2002).

Cycling for the purpose of everyday transportation – commuting to work, going grocery shopping, running errands, visiting friends, and so forth – is one proposed solution. More than solely the domain of the classic road bicycle, cycling includes tricycles, recumbent bicycles, cargo bikes, hand cycles, and all electric variations thereof. For straightforwardness, we will refer to all these modes as bicycles.

People who cycle for transport often not only have improved health outcomes, exhibiting reduced rates of obesity and diabetes (Pucher et al., 2010), but also improved wellbeing (Wild and Woodward, 2019). The estimated health benefits are even estimated to be substantially higher than the risks associated with exposure to traffic and air pollutants (Johan de Hartog et al., 2010) and represent potential annual savings in the hundreds of millions due to reduced rates of injury and death (Lindsay et al., 2011). Interventions to promote cycling result in a measurable decrease in travel by motor vehicle and therefore a reduction in the emission of greenhouse gases (Keall et al., 2018). People who often ride bikes for transport tend to have more disposable income, spending more per month at businesses such as restaurants, bars, and convenience stores than those who drove (Volker and Handy, 2021). If taken in stride with the fact that bicycle infrastructure is significantly cheaper to build and maintain than infrastructure for cars, the relatively low cost of purchasing and maintaining a bicycle, and the abundance of social benefits discussed herein that translate to financial savings for the public, it is clear that urban cycling provides an excellent return on investment for urban centres. This is why cities and countries across the world are aspiring to move away from car-dominated planning and pivot towards urban cycling as a critical transport mode for investment.

1.2 The Situation in Aotearoa New Zealand

Following the international trend, Aotearoa New Zealand suffers from car dominated planning which, without intervention, is expected to reduce access to social and economic opportunities, increase congestion and greenhouse gas emissions, and worsen public health outcomes (Waka Kotahi New Zealand Transport Agency, 2019). For these reasons and more, many cities have committed to improving access to utilitarian cycling. For example, cycling is referenced as a key element in both the Kirikiriroa Hamilton transport strategy, with the Council committing to *"providing a range of transport options... [including] active transport such as walking and biking"* (Hamilton City Council Te Kaunihera o Kirikiriroa, 2022a), as well as the climate change strategy, recognising the need to *"shift from the car-dominant city we are today to a city that embraces low-emissions travel options such as walking, biking, and public transport"* (Hamilton City Council Te Kaunihera o Kirikiriroa, 2022b). Similar aspirations are touted by other cities (Tauranga City Council, 2021; Christchurch City Council, 2012) and the national transportation delivery agency (Waka Kotahi New Zealand Transportation Agency, 2019).

> *"[In a future state of transport system], access via public transport, walking and cycling will be easy, safe, and convenient which will ultimately reduce our reliance on cars and the current traffic congestion we face."*
>
> – The Western Bay of Plenty Transport System Plan, Tauranga City Council

> *"There are many reasons why Christchurch residents should be encouraged to cycle for short trips and for recreation. These include improved health and wellbeing through increased physical activity; reduced congestion and energy dependence; a reduced need to build new roads; reduced parking problems and costs; greater and more equitable transport choice; increased social interaction; and community resilience."*
>
> – Christchurch Transport Strategic Plan 2012 - 2042, Christchurch City Council

> *"Improved urban mobility [utilitarian cycling] means that people are able to more easily travel to the social and economic opportunities that make cities attractive places to live: productive jobs, educational opportunities, friends and relatives, recreational activities and more."*
>
> – Keeping Cities Moving, Waka Kotahi New Zealand Transport Agency

Despite such commitments, however, these cities and others have struggled to increase the number of people cycling for everyday purposes, with only 2% of people commuting to work by bicycle across the country, in stark contrast to the more than 80% making use of motor vehicles (Statistics New Zealand Tatauranga Aotearoa, 2018a). In reality, private vehicle use has increased in recent years and vehicle ownership remains high compared to peer nations (Waka Kotahi New Zealand Transport Agency, 2019). In Aotearoa New Zealand, surveys have consistently found that cycling is perceived as unsafe (Mandic et al., 2017; Hawley at al., 2019; Waka Kotahi New Zealand Transport Agency, 2018), with insufficient infrastructure, a lack of separation between people on bikes and motor vehicles, large distances between origins and destinations, weather conditions such as wind and rain, and a lack of end-of-trip facilities including bicycle parking and showers all cited as barriers. However, the same studies note that support for cycling is high, indicating that more people would cycle if barriers were addressed. There is evidently a disconnect between the way that people want to move around their cities and the ways that are available to them.

1.3 Low Stress Cycling

Roger Geller (2009), a transport planner based in Portland, Oregon, aptly notes:

> *"Riding a bicycle should not require bravery. Yet, all too often, that is the perception among cyclists and non-cyclists alike."*

Through his own experiences riding a bike in Portland, Geller made a pertinent observation: bicycle infrastructure, ostensibly provided to create a more comfortable riding environment for people on bikes, is unsuitable for the majority of people. Under North American infrastructure design practices which typically require riding in mixed traffic with little or no separation, only those few who are already accustomed to those conditions or are willing to take risks will ride. The traffic-intolerant majority will make use of other transport modes – almost certainly the motor vehicle – which is incorrectly interpreted as a lack of support for utilitarian cycling. This group, however, would be willing to cycle in a suitably safe environment.

(a) Te Awa River Ride (Kirikiriroa Hamilton) (b) Anglesea Street (Kirikiriroa Hamilton)

Figure 1: Which road environment would you prefer to cycle in?

Photos by the thesis author.

Following from his ideas, the Level of Traffic Stress (LTS) Framework emerged (Mekuria et al., 2012), which proposed a road classification scheme based on how suitable the road environment is for the majority of people, rather than only the prototypical ‘cyclist’. This Framework was developed to address the lack of mainstream cycling guidelines suitable to this group. Roads are classified as ‘low stress’ (i.e., suitable for the majority) or ‘high stress’. This recontextualises cycling networks into the streets that are suitable for cycling rather than the streets that feature dedicated bicycling infrastructure. Streets without dedicated bicycling infrastructure can still be friendly to people on bikes under certain conditions and, likewise, dedicated bicycling infrastructure may not be suitable if it requires proximity to high speed traffic, as is unfortunately the case in Geller’s home state of Oregon and indeed much of Aotearoa New Zealand. From this emerged the concept of the low stress network: if only the subset of streets and paths with a low stress classification are considered, it becomes clear that the majority of streets present a suitable level of stress for the everyday person, but these streets are poorly connected and fail to form a cohesive network. In effect, “islands of low stress connectivity” emerge (Mekuria et al., 2012). With current transportation planning practices that aim to prevent traffic on local streets, this is inevitable. Traffic is funneled to arterial roads which, much like the arteries of the human body, connect the bulk of origins and destinations. Therefore, in spite of the majority of streets being suitable for utilitarian cycling, the inability to reach practical destinations without using high stress streets severely limits the degree to which utilitarian cycling can occur.

Since the introduction of the LTS Framework, many studies have used it to evaluate existing networks (see: Cabral et al., 2019; Imani et al., 2019; Boisjoly et al., 2020; Cervero et al., 2019; Abad and Van der Meer, 2018) or to build prioritisation tools for proposed cycling projects (see: Lowry et al., 2016; Kent and Karner, 2019; Gehrke et al., 2020). There is an implication in these works that the increase in low stress streets is a significant result because it will enable more people to cycle for transportation purposes, however, there are a dearth of studies that empirically validate this relationship.

1.4 Research Question

Therefore, the research question that we seek to answer is:

> ***To what extent does the provision of low stress cycling infrastructure influence cycling uptake in major cities in Aotearoa New Zealand?***

In addressing the research question, we will construct bicycle networks in seven major cities based on available network data, identify low stress roads, and compare network measures against observed cycling levels in Aotearoa New Zealand. We expect that there will be some correlation between the LTS Framework and cycling ridership.

1.5 Thesis Structure

Following a brief statement on the use of language, this thesis is divided into five sections.

The literature review will explore existing work, particularly the key factors influencing existing cycling levels and previous frameworks that have attempted to address this issue. We will also cover aspects of graph theory, the mathematical framework that will be used for the analysis of the structure of cycling networks, and the history of transportation planning practices. The methodology section will outline the practical steps taken to answer this research question, including an overview of the modelling and the collection of dependent and independent variables. The results section will communicate the structure of Aotearoa New Zealand low stress network and the outcomes of modelling, including a discussion and comparison to literature which will put these results into context. Finally, we end by exploring the implications for planning and policy and a conclusion that will summarise key results and recommendations.

1.5.1 Use of Language

In Aotearoa New Zealand culture, English and Māori are both used in everyday conversations. The Māori language is called te reo and is recognised as an official language.

It is common for te reo words, such as kai (food or meal), mahi (work), or koha (donation) to be used in the place of English equivalents, more so in recent years. In particular, many cities with English names have starting using te reo names alongside the English names. This is also the case for the te reo name of New Zealand, which is Aotearoa. Many Government institutions have also adopted te reo names.

In acknowledgement of tangata whenua (the original inhabitants of Aotearoa), bilingual names for cities and institutions will be used throughout this work, with the te reo name preceding the English name. For example, the te reo name for Hamilton is Kirikiriroa, so the city will be referred to as Kirikiriroa Hamilton. The names of some cities, such as Tauranga[1], are already in te reo and thus will be referred to as is. For Government departments and ministries, where there are two names, the primary name is used first. For instance, the New Zealand Transport Agency is branded as Waka Kotahi[2], so it will be referred to as Waka Kotahi New Zealand Transport Agency, but Statistics New Zealand primarily uses its English name, so it will be called Statistics New Zealand Tatauranga Aotearoa.

The Waikato-Tainui dialect of te reo, spoken in the Waikato and therefore the University of Waikato Te Whare Waananga o Waikato, uses double vowels in the place of macrons. In this localisation, Māori is written as Maaori. This thesis acknowledges this difference in spelling but will use the standard spelling (with macrons) as this research involves cities across the country.

---

[1] The name Tauranga Moana is sometimes used to refer to the city of Tauranga, but it is also used to refer specifically to Tauranga harbour and the adjoining coastline. For simplicity, the name Tauranga will be used.

[2] All institutions except for those that directly relate to Māori affairs have been recently directed to primarily use an English name, but at the time of writing (November/December 2023), this has not yet come into effect.

2 Literature Review

2.1 Why Cycling?

Historical planning practices focused on the motor vehicle above other transport modes has ill-prepared cities in Aotearoa New Zealand to tackle issues of increasing urbanisation. In Kirikiriroa Hamilton, population growth is expected to contribute to a 50% increase in peak time congestion by 2040 (Hamilton City Council Te Kaunihera o Kirikiriroa, 2022a), meaning that a trip that takes twenty minutes at peak time today will take thirty minutes at peak time in 2040. Excessive congestion leads to less reliable travel times (Waka Kotahi New Zealand Transport Agency, 2019) and reduced labour productivity (Leung et al., 2017).

The consequences of car dependent planning, however, are not solely limited to congestion; a feature of car dependent planning is that alternative transport modes, particularly public transportation, are unavailable or unreliable, forcing households to spend a significant proportion of income on operating and maintaining a motor vehicle, which is not only inequitable, but from an economic perspective, reduces the disposable income that can be spent on other consumer goods (Litman and Laube, 2002; Waka Kotahi New Zealand Transport Agency, 2019). In Aotearoa New Zealand, approximately 16% of weekly household income is spent on transportation costs (Statistics New Zealand Tatauranga Aotearoa, 2020)[3]. Combined with the household necessities of food (17%) and housing (25%), this totals more than 50% of household income spent on non-discretionary costs. If household transportation costs were reduced even by half, this would free approximately $100 per week to spend elsewhere in the economy.

Car dependent planning also results in urban sprawl (Litman and Laube, 2002), which is characterised by large geographic extents of low density single family housing (Weiner, 2016). When the distances between origins and destinations are larger, public transportation is less efficient and cycling is less practical, and people come to rely on the motor vehicle. This reliance produces a feedback loop, wherein more space in the form of roads and parking is needed to accommodate the increase in motor vehicle use, which in turn pushes origins and destinations further apart.

---

[3] In the cited dataset, the ‘Transport’ group is used to calculate transportation costs, which includes private vehicle use as well as public transportation, bicycles, and domestic air travel, the ‘Food’ group is used for spending on food, and ‘Housing and Household Utilities’ is used for spending on the household. All data from 2018/19.

Utilitarian cycling is posited as a solution. In contrast to cycling undertaken for recreational purposes, utilitarian cycling refers to cycling taken for the primary purpose of transportation: going to work, grocery shopping, visiting friends, and so forth. Biking for transportation results in improved health outcomes, with people who bike often exhibiting reduced rates of obesity and diabetes (Pucher et al., 2010) and other chronic diseases associated with a sedentary lifestyle (Waka Kotahi New Zealand Transport Agency, 2019). While there are health risks associated with increased exposure to traffic and air pollutants, these risks are estimated to be more than outweighed by the benefits of regular exercise (Johan de Hartog et al., 2010), with the number of lives saved each year due to increased physical activity and reduced air pollution estimated to be worth $200 million NZD (Lindsay et al., 2011). Utilitarian cycling is particularly useful for improving public health because incorporating active transport into everyday lifestyles is more likely to be successful than exercise regimes (Hillsdon et al., 1995). Mental health and wellbeing is also improved. People who commute by bicycle report the highest level of satisfaction with their transport mode, citing feelings of independence, ‘arrival-time reliability’, and greater opportunities for social interaction as reasons (Wild and Woodward, 2019). In total, widespread adoption of utilitarian cycling can not only save lives but reduce public spending on health initiatives.

Turning to environmental effects, cycling results in a measurable decrease in greenhouse gas emissions (Keall et al., 2018), which is important for mitigating the effects of climate change. While there is some environmental degradation associated with lithium-ion battery production for electric bicycles, this is less than the operating environmental costs of a petrol car (Elliot et al., 2018). In contrast to the space required for moving and storing motor vehicles, bicycles take up significantly less space in the urban environment – up to 28 times less when moving and 10 times less when parked (Waka Kotahi New Zealand Transport Agency, 2019). Such space can take up significant area in a city. For example, land mapping of Pari-ā-Rua Porirua, a city in the Greater Wellington region, revealed that 24% of the land in the city centre was allocated to car parking (Hulme-Moir, 2010). Therefore, bicycle-oriented transportation planning returns space to local authorities to provide other amenities such as parks or businesses to the public.

Such mode shift is not posited to completely replace the motor vehicle for all trips but only those trips that are suitable. However, this is more trips than the public may reasonably expect. In a survey of Ōtepoti Dunedin adolescent school students, only 2.1% biked to school despite living less than 4 km away (Mandic et al., 2019) – a 15-minute bicycle ride – and half of all trips in Aotearoa New Zealand are less than 7 km (Waka Kotahi New Zealand Transport Agency, 2011) – a 30-minute bicycle ride. There is significant potential for reductions in congestion if people feel empowered to use a bicycle for these short trips in lieu of a motor vehicle.

2.2 History of Transportation Planning – How Did We Get Here?

There are several historical factors which influence contemporary planning for bicycle networks. We explore here a non-exhaustive list, including land use planning, public transportation reforms, and vehicular cycling.

In response to the introduction of the motor vehicle, cities in both North America (Weiner, 2016) and Europe (Urban, 2023) began to rapidly transform. Previously, rural roads that formed the connections between cities were typically unpaved; the new motorways were unlike in scale any road that had come before, not only forming connections between cities but indeed within cities, occasionally requiring the demolition of entire neighbourhoods and communities (Weiner, 2016). By the time that such infrastructure was developed in Aotearoa New Zealand, this was considered best practice, and low density planning was prioritised (Miller, 2011). During the construction of early suburbs, developers were generally required to 'gift' open space reserves, and it was and still is culturally expected that each houses include a generous amount of land. While such provision of open green space has no doubt contributed to the 'clean, green' Aotearoa New Zealand image, it has had the dual outcome of enforcing urban sprawl which in turn manufactures car dependence.

Deregulation of public transport in the late 1990s and early 2000s further entrenched car dependency in Aotearoa New Zealand (Miller, 2011). With a view of enabling market efficiencies, the reforms delegated operation of the public transportation network to the sixteen regional authorities, who were required to tender for contracts with private bus companies to provide services. So, while there is one national organisation that plans for the road network (namely

Waka Kotahi New Zealand Transport Agency), there is no such equivalent organisation for the provision of the public transportation network. This leads to poor integrated and interregional transport (Waka Kotahi New Zealand Transport Agency, 2019). For instance, each network has separate transportation cards, fares, and concessions[4] – Tāmaki Makaurau Auckland uses the AT HOP card which costs $4.20 per ride within the city centre (Auckland Transport, 2023), Kirikiriroa Hamilton uses the Bee Card which costs $2.00 per ride (Busit, 2023), and Pōneke Wellington uses a Snapper Card which costs $4.03 per ride (Metlink, 2023). Someone driving between Kirikiriroa Hamilton and Tāmaki Makaurau Auckland could use one road network and one national licensing system, but someone making use of the public transportation system would need to buy two cards and pay two fares.

The adoption of separated, dedicated cycleways was further delayed by the idea of 'vehicular cycling' in the 1990s. The architect of vehicular cycling, John Forester (2012), described it thusly: *"Cyclists fare best when they act and are treated as drivers of vehicles."* While Forester was understandably operating in a context where American state legislators were restricting the use of bicycles on public roadways, the adoption of his ideas resulted in widespread opposition to cycleways with a preference for people on bikes to ride in shared traffic (Furth, 2012). It is widely acknowledged today that this type of road environment discourages cycling. Conversely, Dutch infrastructure guidelines state that people on bikes should only ride in mixed traffic when the speed limit is equal to or less than 30 kph, traffic volumes are low, and the road has no marked centreline. In all other road environments, separated infrastructure is provided. Such guidelines were adopted following an organised campaign for safer roads in the 1960s and 1970s called called "Stop de Kindermoord" ("Stop the Child Murder") (Dekker, 2021). The two diverging planning practices are in the process of reuniting, with many cities that were former proponents of vehicular cycling transitioning towards the European style of separated cycleways; however, their late start in developing separated cycle networks has meant that they are many decades behind.

---

[4] Fares are calculated for a single adult passenger with no concessions travelling within the core city. Fares are higher when travelling to the outer suburbs of the city. For instance, while travel within Tāmaki Makaurau Auckland City Centre is $4.20, travel to the North Shore or Pukekohe may be as much as $7.18.

2.3 What is a Cycling Network?

Transportation systems inevitably form networks, which form the basis of the links between people, cities, and nations (Rodrigue et al., 2013). In its most simple conception, a network is composed of elements and the connections between those elements (Rodrigue et al., 2013; Brandes, 2005). These are called nodes and edges, respectively. In the context of transportation systems, nodes are locations, both origins and destinations, while roads are edges, which connect them together. In practice, nodes are used to broadly represent intersections (i.e., places where two or more roads meet). In this sense, nodes represent the point at which a user of the transport network can change from using one edge to using another. This is preferred over using nodes for each legitimate starting point and ending point because such a network would have so many nodes and edges (i.e., every shop, every office building, every park, every house, etc.) as to be incomprehensible.

While transportation networks are typically conceptualised as being road networks for motor vehicles, other types of transportation networks also exist, such as walking networks, composed primarily of footpaths. Figure 2 shows an example of this for the surrounds of the University of Waikato Te Whare Waananga o Waikato, highlighting both the road network and the footpath

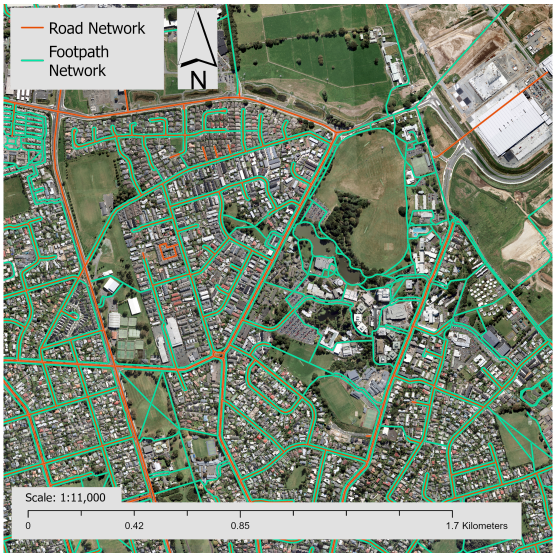

Figure 2: The road and footpath network surrounding the University of Waikato Te Whare Waananga o Waikato.

network. Note how the footpath network follows the road for the most part, with footpaths available on either side of the road, but also includes access through parks that are not available to motor vehicles. Likewise, there are some roads, particularly the road at the north of the extent, where footpaths are not provided and walking is not permitted.

It can seem obvious to assume that a cycling network is composed of bicycle infrastructure, however, there are a few elements that make cycling networks unique from both road and walking networks. In Aotearoa New Zealand law, cycling is permitted on any roadway[5], which already expands our definitions, but there are also places where cycling is permitted but driving is not – principally bike lanes and shared paths (Land Transport (Road User) Rule 2004). The distinction between these types of infrastructure will be clarified in the next subsection. Bicycles can also make use of modal filters (Furth, 2012). These are pieces of infrastructure that in effect filters for traffic modes that can pass through the barrier, making a route that is discontinuous for motor vehicles continuous for people on bikes. Figure 3 shows an example of a modal filter. Therefore, we can conceptualise the cycling network as a network between a road network and a footpath network, able to make use of road connections shared with motor vehicles but also shortcuts through parks and shared paths alongside pedestrians.

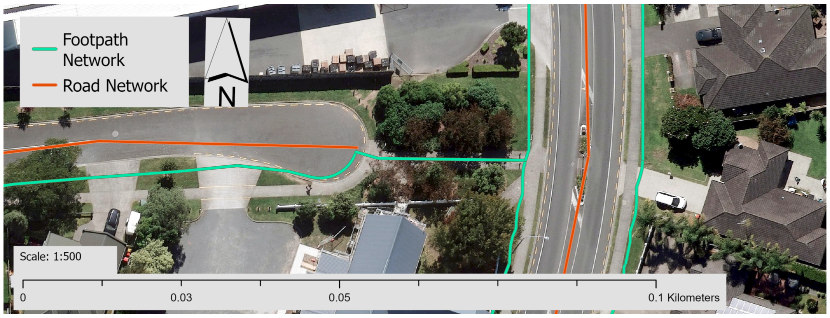

Figure 3: A modal filter in Rototuna, Kirikiriroa Hamilton which permits pedestrian and cycle traffic but not motorised traffic.

---

[5] This is not stated explicitly in the cited Rule but is derived from the definition of a vehicle in the Land Transport Act 1998, which includes bicycles as a type of vehicle. ‘Plain English’ resources communicating driving law to the public also support this interpretation. For more details, the online New Zealand Road Code can be perused: https://www.nzta.govt.nz/roadcode.

2.3.1 Bicycle Infrastructure and Key Network Factors that Influence Its Use

Bicycle infrastructure varies in both structure and quality. Furth (2012) outlines four main categories of bicycle infrastructure:

1. Shared streets – no delineated space for people on bikes but traffic calming may be in place (i.e., mixed traffic), sometimes called bicycle boulevards
2. Bike lanes – delineated on-road space for people on bikes designated with paint
3. Separated bike lanes – delineated on-road space for people on bikes with physical separation such as bollards, curb steps, or plantar boxes
4. Shared paths – off-road paths typically shared with pedestrians

The former three are 'on-road' while the latter is 'off-road'. Figure 4 shows an example of each type of bicycle infrastructure across Kirikiriroa Hamilton.

(a) Shared street – North City Road (b) Bike lane – Borman Road (c) Separated bike lane – Ward Street (d) Shared path – Wairere Drive Shared Path

Figure 4: There are four main categories of bicycle infrastructure, ranging from mixed traffic to full separation.

Photos by the thesis author.

Traffic calming features elements such as but not limited to narrow lanes, chicanes, removal of on-street car parking, and raised speed tables for the purpose of discouraging motorised through traffic and prioritising people on bikes (Buehler and Dill, 2016). Shared streets often feature this type of infrastructure, but can also refer to environments in which there is no traffic calming in place but traffic volumes are low enough that there is little to no conflict between people on bikes and people in cars (Furth, 2012). Interestingly, while shared streets are specified as a type of infrastructure by Furth (2012), there is no widespread consensus on whether this is considered to be dedicated bicycle infrastructure as there is still a requirement to ride in mixed traffic. Such infrastructure is included in studies investigating the relative influence of different types of bicycling infrastructure (see: Buehler and Dill, 2016; Broach et al., 2012), but conversely, some studies of the networks formed by bicycle infrastructure explicitly exclude bicycle boulevards (see: Schoner and Levinson, 2014). For the purpose of this work, such streets are considered to be bicycle infrastructure, and the reasons for this will be made more clear in the section on the Level of Traffic Stress Framework.

Broadly, dedicated cycling infrastructure such as bike lanes and separated bike lanes is correlated to an increased in the number of people who choose to cycle. Both stated-preference (see: Caulfield et al., 2012; Larsen and El-Geneidy, 2011) and revealed-preference (see: Habib et al., 2014) studies have shown this. Bicycle infrastructure alone, however, is not sufficient. For instance, several works investigating factors relating to bicycle uptake note the distance between origins and destinations as a variable to which cyclists are particularly sensitive (Handy and Xing, 2011; Zhao, 2014; Cervero et al., 2019; Broach et al., 2012). Distance can be due to urban sprawl caused by car dominated transport planning, which pushes origins and destinations apart, or due to a lack of safe, direct cycling routes which forces people on bikes to take undue detours.

The greater the separation between traffic modes, the safer the bicycle infrastructure is perceived by its users. In a survey by Waka Kotahi New Zealand Transport Agency (2018) of residents across several cities in Aotearoa New Zealand, more than half of respondents agreed that it is safe to cycle on separated bike lanes. This is in contrast to roads without bicycle infrastructure that feature high traffic volumes and potentially multiple lanes of traffic per direction, which only one-fifth of respondents perceived as safe. The same survey also found that while bike lanes are perceived as safer than roads with no bicycle infrastructure, they are perceived as less comfortable than shared streets and separated paths. In effect, they are “better than nothing”. Results from Larsen and El-Geneidy (2011) corroborate this result, finding that people on bikes will ride a longer route to access a separated bike lane than a bike lane. However, this does not imply that shared paths are necessarily superior in all cases; shared paths often follow park or river settings, and even on occasion abandoned rail right-of-ways (Furth, 2012). While providing obvious recreational value, these sorts of paths can occasionally be meandering and fail to take people on bikes to practical destinations within a suitable time or distance. In such cases, they do not have much transportation utility.

Connectivity is also important element of a cycling network. Connectivity is a nebulous term, occasionally used interchangeably with terms such as accessibility, directness, or continuity. Definitions tend to fall into two categories: mathematical and trip-based. In the realm of mathematics, for instance, Kamel and Sayed (2020) use graph theory to define connectivity as "the minimum number of elements (nodes or edges) that need to be removed to separate the remaining nodes into two or more isolated subgraphs". We will explore graph theory more in the following subsection. Schoner and Levinson (2014) and Osama et al. (2017) also make use of graph theory, using ratios between nodes and edges as definitions of connectivity. Departing from the realm of edges and nodes, Cabral et al. (2019) use a bikeshed (analogous to a pedshed i.e., the area encompassed by distance travelled along accessible network edges) measure to determine connectivity, and Lowry and Hadden-Loh (2017) define connectivity as "the proportion of amenities that can be reached from an address by low stress links". It is evident that connectivity does not encompass a singular, mathematical definition, but a general collection of measures representing the ease of reaching destinations. As we are interested in the construction of networks, we will focus on mathematical definitions of connectivity and make use of graph theory.

Unsurprisingly, all the aforementioned studies reveal connectivity as a statistical significant variable. Schoner and Levinson (2014) analyse biking facilities across seventy-four cities in the United States to quantify the relationship between bicycle network measures and bicycle mode share for commuting. Their analysis finds connectivity and density to be statistically significant variables. However, the analysis was focused on bicycle infrastructure only (i.e., excluding shared streets and bicycle boulevards). Meanwhile, Kamel and Sayed (2020) and Osama et al. (2017) also find connectivity, in addition to other variables such directness, length, continuity, and complexity have positive correlations to bicycle ridership.

2.3.2 Using Graph Theory to Measure and Compare Networks

Graph theory is concerned by elements and the connections between those elements (Rodrigue et al., 2013; Brandes, 2005). Formally, these elements are referred to as nodes v, their connections as edges e, and the entire structure as a graph. Graphs are also occasionally called networks; this thesis will use the terms interchangeably. Figure 5 shows an example of a graph with five nodes and six edges ($v = 5$, $e = 6$).

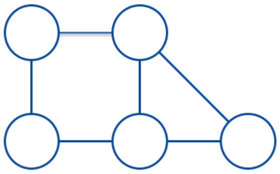

Figure 5: An example of a graph with five nodes and six edges.

Graph theory is used in many works to evaluate cycling networks (see: Kamel and Sayed, 2020; Schoner and Levinson, 2014; Osama et al., 2017). Several graph measures have been developed in order to compare graphs and networks. The relevant graph measures for any particular scenario will depend on the matter being investigated. For this thesis, we are interested in connectivity, and we will therefore compare measures of connectivity.

The Beta Index is a simple mathematical ratio of the edges and nodes,

$$\beta = \frac{e}{v} \tag{1}$$

where e is the number of edges and v is the number of nodes (Rodrigue et al., 2013). A graph with $\beta < 1$ is called a simple graph or a tree graph. This occurs in the case where there are more nodes than edges ($v > e$). Meanwhile, a graph with $\beta > 1$, where there are more edges than nodes ($e > v$), is called a complex graph. A complex graph is considered to be more connected than a simple graph. Figure 6 demonstrates the difference between a simple graph and a complex graph; note how travelling between node A and node B in the simple graph requires travelling along two edges, whereas in the complex graph, the trip can be achieved with one edge. In a graph with a fixed number of nodes v, increasing the number of edges will always increase the number of paths and therefore the value of β.

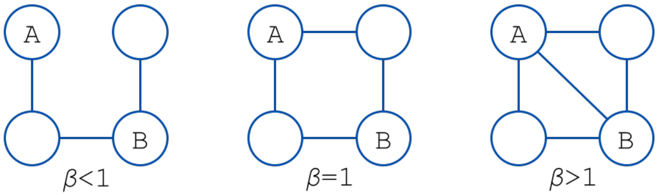

Figure 6: An example of graphs with varying β.

Figure adapted from Rodrigue et al. (2013).

Another element that can be investigated is the number of subgraphs. A subgraph p is formed by a subset of edges and nodes of a graph (Brandes, 2005). Any subset of edges and nodes can form a subgraph. For example, in the context of transportation systems, a municipal road network is a part of a regional road network, which is itself part of a wider national road network. The municipal network can be considered a subgraph of the regional network which can be considered a subgraph of the national network (Rodrigue et al., 2013). Each subgraph forms a part of the larger graph. However, subgraphs can also be used to refer to a subset of edges and graphs that are not connected, meaning that there are no possible paths between nodes that are on different subgraphs (Schoner and Levinson, 2014). These subgraphs are effectively isolated from one another – "islands of connectivity", a key concept of the Level of Traffic Stress Framework (Mekuria et al., 2012) that we will explore later. We will use this definition of a subgraph. In this case, a higher number of subgraphs would indicate high fragmentation and therefore low connectivity. Figure 7 shows an example of a graph composed of two subgraphs ($p = 2$).

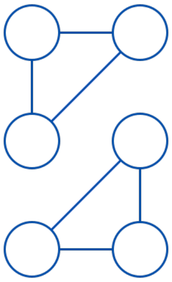

Figure 7: An example of graph with two subgraphs.

The distribution of nodes and edges within subgraphs is equally important. If d_p is the length contained within a subgraph, then

$$p_r = \frac{d_{p,max}}{\sum^{p} d_p} \quad ; \quad 0 \leq p_r \leq 1 \tag{2}$$

is the subgraph ratio, or the percentage of the network that is contained within the largest subgraph (Schoner and Levinson, 2014). A large subgraph ratio indicates that most of the graph is contained within one subgraph with surrounding, small fragments, while a small subgraph ratio indicates that the network is composed of primarily small fragments. Figure 8 shows two graphs, each composed of two subgraphs, with varying subgraph ratios. The graph on the left has a smaller subgraph ratio than the graph on the right. While they both have the same number of subgraphs, the graph on the right with the higher p_r has more of its nodes and edges contained within the larger subgraph with the rest of the network contained in a so-called ‘satellite subgraph’. Practically, this means that someone on this graph has access to more routes. Meanwhile, the network on the left with the lower p_r has two subgraphs of equal size, which makes it less connected as each subgraph has fewer available routes.

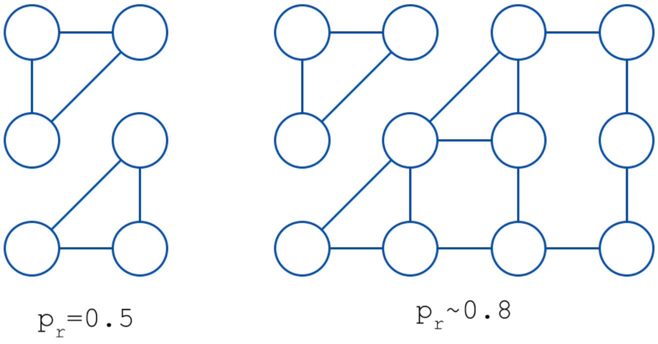

Figure 8: An example of two graphs, each composed of two subgraphs, with varying subgraph ratios.

The Beta Connectivity Index, the number of subgraphs, and the subgraph ratio are by no means an exhaustive list of all network measures, however together, they provide broad coverage of the aspects of connectivity that we are investigating here. For instance, as demonstrated in Figure 8, the subgraph ratio is crucial for distinguishing the connectivity between two graphs with the same number of subgraphs. The Beta Connectivity Index provides another dimension. Using the same graph as in Figure 8, Figure 9 features an additional edge connecting nodes A and B. Where previously a path between A and B would require a minimum of travel across two edges, this path can now be accomplished across only one edge. This graph is indisputably more connected than the previous, which is reflected in the increased β even while p and p_r remain constant.

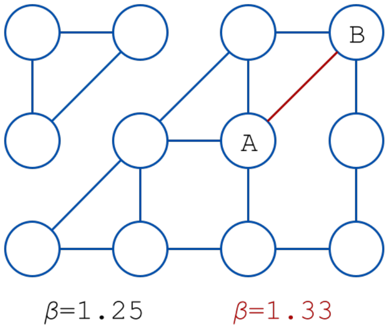

Figure 9: An example of how the Beta Connectivity Index β distinguishes between graphs with similar connectivity.

In brief, the Beta Connectivity Index informs the structure of the graph, the subgraph count informs the fragmentation of the graph, and the subgraph ratio informs the distribution of the graph. With respect to transportation systems, the Beta Connectivity tells us how many different ways we can travel between two nodes, with simple graphs offering less options and complex graphs offering more options. The subgraph count tells us the number of "islands" that exist in the network, and the subgraph ratio tells about the size of those islands. A well-connected network would have high Beta Connectivity, a high subgraph ratio, and a low subgraph count.

2.3.3 The Role of Socioeconomic Factors in Cycling Uptake

Although literature reviews on the subject find that the presence and density of bicycling infrastructure is the best predictor of cycling ridership (Buehler and Goel, 2022), demographic factors, such as income, gender, and age are found to influence cycling uptake in some contexts. Schoner and Levinson (2014) investigate several variables, including population, median income, proportion of households with children, proportion of college students, and motor vehicles per household, ultimately finding only the proportion of college students to have a statistically significant positive correlation to bicycle ridership. It is generally accepted that cities with a high proportion of college students have relatively high cycling ridership, however there also exists a number of college towns, particularly in the United States, that exhibit low cycling ridership (Buehler and Goel, 2022), so a propensity towards cycling is likely due to students tending to live closer to campus and having less disposable income to cover the costs of a motor vehicle rather than an inherent quality of attending college. Meanwhile, Wang et al. (2016) found race and home occupancy status (i.e., whether the home owner is also the home occupier) to be significant variables of those investigated, with the proportion of white households and owner-occupied homes having a positive correlation to cycling ridership. Imani et al. (2019) investigate variables previously noted in addition to age and gender but does not find the results for these variables to be statistically significant. However, there is evidence to suggest that gender may be significant in an Aotearoa New Zealand context, as women are noted to cycle at a lower rate than men[6] (Russell et al., 2021).

Much of this research is focused on low cycling countries such as the United States, Canada, and Australia (Buehler and Dill, 2016). The relationship between the choice to cycle and demographic elements are different in high cycling countries like the Netherlands (Ton et al., 2022). In transitioning from low cycling to high cycling, the relative contribution from socioeconomic variables like the ones explored here may become negligible. A study comparing cycling ridership in Germany and the United States and a series of socioeconomic factors found that the relationship between gender and cycling ridership was weaker in Germany than the United States (Buehler et al., 2011). This ‘tipping point’ may arise after a critical level of suitable bicycle infrastructure is reached within a city or region.

---

[6] Most of the work on the cycling gender gap focuses on people who identify as women or men with very few studies including transgender or non-binary people. This is a potential gap in the literature.

2.4 Frameworks for Evaluating Cycling Networks

Following from our exploration of the composition of cycling networks and the relationship between infrastructure and ridership, there is naturally a need to evaluate the effectiveness of cycling networks. Many Frameworks have emerged in an attempt to fill this need.

Bicycle Level of Service (BLOS) Framework. The BLOS Framework, developed by the United States Highway Capacity Manual, aims to assign a Level of Service (LOS) score of A through F, which "generally represents the average score that travelers would give a facility or service" (National Research Council (U.S.) Transportation Research Board, 2010). The purpose of the Framework is to provide a methodology for the analysis, design, and planning of road environments for cars and bicycles. The Highway Capacity Manual has been a reference document for American traffic engineers since the 1950s, with elements related to bicycles introduced in 1985. The edition of the Highway Capacity Manual referenced herein is the fifth edition from 2010. The score for bicycles is based on, in order of importance: the effective width of the outside through lane; motorised traffic volumes; motorised vehicle speeds; the percentage of traffic that are heavy vehicles (trucks); and the quality of the road surface. It is calculated by

$$BLOS = 0.507 \ln \nu + 0.1999 S_t (1 + 10.38 HV)^2 + \frac{7.066}{P^2} - 0.005 (W_e)^2 + 0.057 \tag{3}$$

where ν is the flow rate in the outside lane in vehicles per hour, S_t is the effective speed factor, HV is the percentage of heavy vehicle traffic, P is a value representing the quality of the pavement surface, and W_e is the effective width of the outside through lane in feet. The flow rate ν is calculated by

$$\nu = \frac{V}{PHF} \tag{4}$$

where V is the volume of traffic in vehicles per hour and PHF is the peak-hour-factor, a variable which represents peak 15-minute traffic volume and is determined experimentally. Finally, the effective speed factor S_t is calculated by

$$S_t = 1.1199 \ln(S_p - 20) + 0.8103 \tag{5}$$

where S_p is the posted speed limit. The LOS score is assigned using Table 1.

LOS Score	BLOS Value
A	≤ 1.5
B	2.5
C	3.5
D	4.5
E	5.5
F	> 5.5

Table 1: Level of Service (LOS) scores assigned by the Bicycle Level of Service (BLOS) Framework.

Bicycle Compatibility Index (BCI) Framework. Similar to the BLOS Framework, the BCI Framework aims to assign a LOS score based on several variables, namely the presence of a bicycle lane or paved shoulder, the width of that lane, the width of the curb (outside) lane, the volume of traffic, the speed of that traffic, and whether the area zoning is residential or not (Harkey et al., 1998). This Framework was intended to expand on the work of the BLOS system to develop an empirical model. The BCI Framework aimed to create a Framework that could be widely adopted by engineers to determine the "compatibility" of a roadway to both motor vehicle and bicycle use. It is calculated by

$$\begin{aligned} BCI =& 3.67 - 0.966BL - 0.125BLW - 0.152CLW + 0.002CLV + 0.0004OLV \\ &+ 0.035SPD + 0.506PKG - 0.264AREA + AF \end{aligned} \tag{6}$$

where BL is 1 if a bicycle lane or paved shoulder is present and 0 otherwise, BLW is the width of that bicycle lane or paved shoulder in feet, CLW is the curb lane width in feet, CLV is the curb lane volume in vehicles per hour, OLV is the traffic volume in vehicles per hour of the other lane if applicable, SPD is the 85th percentile of traffic speed in miles per hour, PKG is 1 if a parking lane with more than 30% occupancy is present and 0 otherwise, $AREA$ is 1 if the area is residential and 0 otherwise, and AF are adjustment factors,

$$AF = f_t + f_p + f_{rt} \tag{7}$$

where f_t is the adjustment factor based on the volume of heavy traffic, f_p is the adjustment factor based on the parking time limit, and f_{rt} is the adjustment factor based on the volume of traffic making right-hand turns (left-hand turns in Aotearoa New Zealand). The values of f_t, f_p, and f_{rt} are assigned as in Table 2. The LOS score is then assigned using Table 3.

Variable	Adjustment Factor
AF for Heavy Traffic	
Vehicles per Hour	f_t
< 10	0.0
20	0.1
30	0.2
60	0.3
120	0.4
≥ 121	0.5

Variable	Adjustment Factor
AF for Parking Turnover	
Parking Limit (minutes)	f_p
< 15	0.6
30	0.5
60	0.4
120	0.3
240	0.2
480	0.1
≥ 481	0.0

Variable	Adjustment Factor
AF for Right-Turning Traffic	
Vehicles per Hour	f_{rt}
< 270	0.0
≥ 271	0.1

Table 2: Adjustment Factors AF for the Bicycle Compatibility Index (BCI) Framework.

LOS Score	BCI Value
A	≤ 1.5
B	2.3
C	3.4
D	4.4
E	5.3
F	> 5.3

Table 3: Level of Service (LOS) score assigned by the Bicycle Compatibility Index (BCI) Framework.

Bicycle Stress Level (BSL) Framework. This Framework measures streets against the stress associated with using them (Sorton and Walsh, 1994). This could be considered a spiritual predecessor to the Level of Traffic Stress Framework discussed in the Introduction. At the time of its development, there were few similar contemporary Frameworks. The output ranges from 1 to 5, with 1 being the least stressful and reasonably safe for all cyclists and 5 being the most stressful and not appropriate for any cyclists.

Departing from the notion of LOS scores, the BSL Framework instead assigns stress values based on road characteristics, namely the curb (outside) lane traffic volume in vehicles per hour per lane, the curb lane width in metres, and the traffic speed in kilometres per hour, which is summarised in Table 4. The three stress values are averaged to produce the final stress value for the road.

Stress Level	Curb Lane Volume	Curb Lane Width	Traffic Speed	Category
1	≤ 50	≥ 4.6	≤ 40	Very low
2	150	4.3	50	Low
3	250	4.0	60	Moderate
4	350	3.7	65	High
5	≥ 450	≤ 3.3	≥ 75	Very high

Table 4: Stress scores assigned by the Bicycle Stress Level (BSL) Framework.

2.4.1 Comparison of Existing Frameworks

Let us compare the value produced by each Framework for a roadway with the following characteristics[7]: one lane per direction of width 3.6 m with a 0.6 m shoulder, no on-street parking, a posted speed limit of 80 kph, and a traffic volume of 500 vehicles per hour with 5% of that traffic being heavy vehicles. This example originates from the United States Highway Capacity Manual (National Research Council (U.S.) Transportation Research Board, 2010), the architect of the BLOS Framework. This example is helpful because it includes a value for PHF, which is an experimentally determined variable required to calculate $BLOS$. The calculations from the HCM are therefore used for $BLOS$, with calculations for the other Frameworks are done by the thesis author. The results are in Table 5. See Appendix A for a full explanation of calculations.

Framework	Value	Category
BLOS	5.2	LOS E
BCI	4.2	LOS C
BSL	4.7	High

Table 5: A comparison of the $BLOS$, BCI, and BSL scores for an example roadway.

---

[7] Two of the three Frameworks are of American origin. Units have been converted to metric for this exploration, but the equations for the American Frameworks remain scaled to imperial units.

2.4.2 Limitations of Existing Frameworks

Despite having similar inputs and structure to the BLOS Framework, the BCI Framework gives a substantively different output. Given that the LOS score represents "the average score that travelers would give a facility or service" (National Research Council (U.S.) Transportation Research Board, 2010), it is surprising that the BLOS Framework assigns a ranking close to the bottom (i.e., almost the worst) while the BCI Framework assigns a ranking closer to the top (i.e., almost the best).

There is little to no relationship between the scores assigned by the BLOS, BCI, and BLS Frameworks and the expected number of users or the experience and comfort of those users. Harkey (1998) states that the BCI Framework is appropriate for the 'average adult cyclist' but does not elaborate on what this means. All the Framework authors state that their models are developed from a survey of cyclists in the United States. It is possible that the responding cyclists, who are cyclists in those environments because they are already comfortable riding in such environments, overstated the comfort level of those roads. In fact, Sorton and Walsh (1994) note that two-thirds of their respondents self-identified as 'experienced cyclists', which is unlikely to be an accurate representation of the general public.

Carrying on from this idea, the BLOS and BCI Frameworks in particular seem to fundamentally misunderstand the needs of people riding bikes. As we have demonstrated, the BCI Framework would assign an 80 kph road a LOS C score. Although the BLOS Framework would assign the same road a LOS E score, the National Research Council (U.S.) Transportation Research Board (2010) outlines an example of 'improving' the road environment for people on bikes by increasing the speed limit to 88 kph, widening the shoulder to 1.8 m, and repaving the road surface ($P = 5$). This new environment earns a LOS C score[8]. In their words: *"Although the posted speed would increase as a result of the proposed design, this negative impact on bicyclists would be more than offset by the proposed shoulder widening, as indicated by the improvement from LOS E to LOS C."* While increased separation from motor traffic while cycling is an oft-cited desire from the public and therefore should not be understated as a positive element in the proposed road improvement, it is unconvincing to suggest that more people would cycle in an environment with such a high posted speed limit.

---

[8] For completeness, the new BCI score is $BCI = 3.3$ or LOS B.

2.5 The Level of Traffic Stress Framework

We briefly discussed the idea of the Four Types of Cyclists and the Level of Traffic Stress Framework in the Introduction; we will now present and explore these ideas in greater detail. An observation from our exploration of existing cycling network frameworks is that they are based on surveys of existing cycleway users. This is a gap that is addressed by the 'Four Types of Cyclists' typology (Geller, 2009). Geller, a transport planner based in Portland, Oregon, noted that utilitarian cycling behaviour tended to fall into four groups. Critically, his typology included people who did not currently cycle for utilitarian purposes – the so-called 'traffic-intolerant majority'. In doing so, he was able to acknowledge the needs of this group and, pertinently, the barriers that prevented them from cycling. His 'Four Types of Cyclists' are:

1. Strong and Fearless riders – people who will ride regardless of road conditions – approximately 4% of the population
2. Enthused and Confident riders – people who are comfortable riding with minimal road facilities but prefer separated facilities – approximately 9% of the population
3. Interested but Concerned riders – people who are uncomfortable sharing the road in mixed traffic conditions but would ride if they felt safe – approximately 56% of the population
4. No Way, No How riders – people who are completely uninterested in riding on the road for reasons of topography, inability, or simply a complete and utter lack of interest – approximately 31% of the population

The group sizes, initially an estimate by Geller, have been measured empirically for both a North American context (Dill and McNeil, 2013) and an Aotearoa New Zealand context (Koorey and Teather, 2016).

The intuition of this typology has seen its persistence in transportation planning research. Notably, the Level of Traffic Stress (LTS) Framework references the Four Types of Cyclists in its four levels of traffic stress. The stress of a road is determined by the speed limit, the number of lanes, and the type of bicycle infrastructure present, if any. A categorisation is also presented for off-road bicycle infrastructure. The LTS Framework is outlined in Table 6 with examples of roads at each stress level in Figure 10. Within this framework, the network composed of LTS1 and LTS2 edges are considered to be the 'low stress network'. Conversely, the edges characterised by LTS3 or LTS4 streets are considered ‘high stress’. This aids in the recontextualisation of cycling networks into the roads that are suitable for cycling rather than only the streets that feature dedicated bicycle infrastructure. We touched on this idea in our discussion of cycling networks, arguing that cycling networks can be conceptualised as more than only its dedicated infrastructure, but a mix between a road network and a footpath network. Now, we expand on that idea by acknowledging that not all streets with dedicated bicycle infrastructure are suitable for cycling. While many people report desiring dedicated bicycle infrastructure, proximity to high speed and high volume traffic present safety concerns

LTS1	Encompasses streets and paths that present little to no traffic stress, appropriate for “Interested but Concerned” riders, including children. Cyclists are either physically separated from traffic, are provided dedicated cycling infrastructure beside generally slow and low volume traffic, or share sufficiently traffic calmed streets.
LTS2	Encompasses streets and paths that present little or no traffic stress but require more attention than LTS1, appropriate for “Interested but Concerned” riders. Speeds and volumes may be somewhat higher, but cyclists are still provided either separated cycling infrastructure, dedicated space on low traffic streets, or traffic calmed streets.
LTS3	A level of traffic stress beyond LTS2, appropriate for “Enthused and Confident” riders. Cyclists may have a dedicated cycling lane beside moderate speed traffic or no infrastructure on low to moderate speed streets.
LTS4	A level of traffic stress beyond LTS3, appropriate only for those “Strong and Fearless” riders.

Table 6: Stress levels assigned by the Level of Traffic Stress (LTS) Framework.

(a) LTS1. Completely separate bicycle infrastructure. All cyclists, including children, would feel comfortable biking on a path like this. (Te Awa River Path – Kirikiriroa Hamilton)

(b) LTS2. Speeds and traffic volumes are low, and there is only one lane per direction. Most people would feel comfortable biking on a road like this. (Ashurst Avenue – Kirikiriroa Hamilton)

(c) LTS3. Dedicated bicycle infrastructure is unprotected and beside high speed, multi-lane traffic. Only a few people would feel comfortable biking on a road like this. (Te Rapa Straight – Kirikiriroa Hamilton).

(d) LTS4. No dedicated bicycle infrastructure, high speeds, and multiple through lanes per direction. Most people would avoid biking on this road. (Cobham Drive – Kirikiriroa Hamilton)

Figure 10: A range of roads and paths with different stress levels as assigned by the Level of Traffic Stress (LTS) Framework.

Photos by the thesis author.

(Waka Kotahi New Zealand Transport Agency, 2018). Such a road would receive an LTS3 or LTS4 score. In effect, the LTS Framework distinguishes between ‘good’ cycling infrastructure and ‘bad’ cycling infrastructure.

If only the low stress edges are considered, so-called “islands of low stress connectivity” are revealed. This refers to how a large swathe of low stress infrastructure exists, composed of local streets and recreational paths, but fail to connect together in a way that would allow people to make reasonable trips without requiring the use of those higher stress edges. Indeed, using San José, California as a case study, Mekuria et al. (2012) find that $\sim 64\%$ of the network consists of edges of the lowest stress, however only 4.7% of origin-destination trips were accessible to “Interested but Concerned” cyclists. One source of this is the structure of the road network. Roads are generally laid out in a way to prevent though traffic on local streets. For cross-city travel, traffic is directed toward arterial roads, which, much like the arteries of the body, carry high volume and high speed traffic around the city. Inevitably, a person riding a bike would have to ride on these arterial roads to access important destinations, and since most people will not tolerate such levels of stress, they will make use of another mode of transport – which, in Aotearoa New Zealand, is typically the motor vehicle. This is generally misinterpreted by local authorities as a lack of demand for utilitarian cycling.

2.5.1 What Does LTS Do Differently?

There is evidence to support the low stress/high stress distinction for cycling infrastructure. Real world on-road measurements of psychological stress validate that cyclists feel more stress in mixed traffic environments than in off-road environments (Caviedes and Figliozzi, 2018), and high stress edges are statistically associated with an increased risk and severity of crashes involving cyclists (Chen et al., 2017). Indeed, this is the justification from Sorton and Walsh (1994) in their development of the Bicycle Stress Level (BSL) Framework. The primary difference between BSL and LTS is their calculation of stress: the BSL Framework returns the average of the stress contributed from each part, whereas the LTS Framework returns the maximum value. Since all variables are weighted equally by the BSL Framework, this allows the score to be ‘pulled down’ by low values. For instance, a road with high traffic volume and speed but a wide shoulder – such as most motorways[9] in Aotearoa New Zealand – would receive a score that is too low. Conversely, the LTS Framework focuses assessment of bicycle

---

[9] A motorway is used here in contrast to a rural highway, which typically has one lane per direction and no other engineered elements. A motorway typically has multiple through lanes, a well-paved surface, and safety elements such as escape lanes and median barriers.

infrastructure on its weakest part – the part that is most likely to deter people from using it.

The LTS Framework, through its utilisation of the Four Types of Cyclists typology, creates a classification scheme that is suitable for the entire population, whereas the BLOS, BCI, and even the BSL Frameworks state that their classification schemes are suitable for adult cyclists, with no elaboration on what this means. As we discussed in the previous subsection, these Frameworks were developed empirically based on responses from cyclists in the United States (National Research Council (U.S.) Transportation Research Board, 2010; Harkey, 1998; Sorton and Walsh, 1994). We can now recognise that these cyclists, which we previously argued were unlikely to be representative of the population, were likely part of that 'Strong and Fearless' group that are comfortable riding in all road conditions. This is likely how such conditions that are not suitable for the majority of people merited acceptable scores from these Frameworks. It is clear that these Frameworks, developed primarily for the use of traffic engineers, are inspired by the concept of vehicular cycling (Forester, 2012) and therefore prioritise mixed traffic environments. While the LTS Framework allows for low stress classifications in mixed traffic, this is only allowed under certain conditions, and separated bicycle infrastructure, which is consistently reported as the preferred type of bicycle infrastructure by the 'Interested but Concerned' majority (Waka Kotahi New Zealand Transport Agency, 2018), is prioritised by receiving the lowest stress score.

Existing Frameworks, particularly the BLOS Framework and the BCI Framework, have expensive data inputs, requiring data on not only on the geometry of the road space but the number of motor vehicle users and the percentage of those users who represent heavy traffic. These data requirements are legitimate challenges for local authorities in assessing their cycling networks. Callister and Lowry (2013) reviewed data requirements for several existing roadway classification schemes, including the BLOS Framework, the BCI Framework, and the BSL Framework, by sending a survey to all cities and counties in the state of Idaho, totalling 115 respondents. They found that none of the authorities had all the required data and many had very little data. Therefore, a critical element of the LTS Framework that has seen its rising popularity in the field of transportation planning is its simplicity. Input variables – speed limit, number of lanes, and cycling infrastructure – are relatively straightforward to collect.

2.5.2 Criticisms of the Level of Traffic Stress Framework

Traffic volume is not included as a variable despite significant literature suggesting that this affects cycling route choice (Wang et al., 2016). For example, it is possible for a road to have a high speed limit but low traffic volume, such as a rural road, making the edge relatively low stress, and conversely, for a street to have a low speed limit but high traffic volume, making the edge more stressful. The LTS makes a stress determination based on the speed limit only in these cases, which would incorrectly designate the first road as more stressful and the second street as less stressful. Furth et al. (2018) use traffic volume data in an adapted Level of Traffic Stress Framework.

Another limitation of the LTS Framework is the assertion that high stress edges are completely inaccessible to cyclists who do not tolerate them. It is plausible that people who are "Interested but Concerned" would be willing to use a edge that is beyond their acceptable tolerance of stress for limited stretches. Works such as Lowry et al. (2016) and Furth et al. (2018)[10] allow a limited tolerance for high stress edges by introducing a maximum cumulative distance across such edges before a route becomes inaccessible.

Even the 'Four Types of Cyclists' typology has seen refinement. Damant-Sirois et al. (2014) and Cabral (2019) use survey data from cyclists in Montreal and Edmonton respectively to empirically determine a cyclist typology. A criticism of Geller (2009) from both studies is that his categories are subjectively rather than empirically determined. Cabral also criticises the label of "Fearless" as a cycling typology, writing: *"Informal discussions with members of the Edmonton cycling community highlighted that many cyclists who are very comfortable in high stress environments feel this way because they have extensive experience, know what to look out for, and how to behave to be predictable and be seen. Having no fears has little to do with their comfort; rather they master fears by taking control of the situation as much as possible."* The typology developed by Cabral is the Level of Cycling Comfort (LCC) Framework. This differs from the LTS Framework in that it focuses on scenarios that invoke comfort rather than stress. In comparing high comfort LCC networks compared to low stress LTS networks, Cabral finds that the LCC connectivity is less optimistic in the number of edges that are available to the average person riding a bicycle.

---

[10] Furth is an author on the original Mekuria et al. (2012) paper.

2.5.3 Low Stress Connectivity

Many researchers have used the Level of Traffic Stress Framework to evaluate cycling networks across North America (see: Cabral et al., 2019; Imani et al., 2019; Boisjoly et al., 2020) and Europe (see: Cervero et al., 2019; Abad and Van der Meer, 2018). Results generally find that connectivity among low stress edges is low and that routes utilising only low stress edges are considerably longer or not possible compared to the most direct route. This highlights a lack of coherent bicycle network planning in those cities and countries.

This leads naturally into studies that aim to improve connectivity. Many studies make use of low stress network analysis to develop prioritisation tools for cycling improvement projects. A variety of approaches which incorporate different connectivity measures and adaptations to the LTS Framework are explored. For example, Lowry et al. (2016) use an altered LTS Framework that includes traffic volume as a variable and a connectivity measure defined as the sum of amenities available with a comfortable 20-minute bicycle ride to calculate how connectivity would change if a suite of improvement projects in Seattle, Washington were implemented. Kent and Karner (2019) use a low stress bikeshed approach in combination with performance measures for accessibility to public amenities such as supermarkets, pharmacies, banks, and libraries to evaluate potential cycling projects in Baltimore, Maryland. Gehrke et al. (2020) take a similar bikeshed and cumulative amenity accessibility approach to connectivity while also including travel time into their prioritisation matrix.

There is an implication in these works that the increase in connectivity is an important result because it will enable more people to cycle for transportation purposes. As discussed previously, it is generally agreed in the literature that the presence of cycling infrastructure is the strongest indicator for cycling, so it is intuitive that low-stress infrastructure would be an as strong if not a stronger indicator. However, there are few studies that attempt to quantify the relationship between cycling volumes and low-stress infrastructure. This is a potential gap given that many studies are using the low stress framework to build prioritisation tools, so it is important to understand this relationship. This is the motivation of our research question.

Wang et al. (2016) are among the first to investigate this relationship. Applying the LTS Framework to Salem and Keizer, two continuous cities in Oregon, United States, the relationship between the resulting low stress network and both a household travel survey and journey-to-work data is investigated, specifically the number of people and jobs that could be reached from low stress islands. Results suggest that as low stress accessibility to destinations increase, walking and biking mode share similarly increases, though Wang stresses that the high mode share could be attributed to land use and attractive destinations rather than solely the provision of low stress infrastructure. Further, modelling validates data for the general travel behaviour but not commuting behaviour. This indicates that the LTS Framework is more useful to cities and regions looking to increase cycling generally but not commuting specifically. That being said, Wang confirms that the Framework provides an indication to a household's propensity to cycle. Wang et al. (2020) and Cervero et al. (2019) also touch on the topic. Wang et al. (2020) investigate the relationship between low stress network in Franklin County, Ohio and all commuting mode shares, finding that the proportion of LTS2 edges is a statistically significant and positive indicator with the share of people commuting by bicycle. Cervero et al. (2019) investigate the relative contributions of several cycling network variables to cycling commuting mode share, including but not limited to levels of traffic stress, finding all variables to have some statistical significance. Their results also highlight the importance of other variables such as land use and the local perception of cycling. It is not surprising that the results in both cases are restricted to commuting, as this is the most commonly available data on cycling mode share.

3 Methodology

3.1 Sample of Cities

The cities included in this research are, from northernmost to southernmost, Tāmaki Makaurau Auckland, Kirikiriroa Hamilton, Tauranga, Pōneke Wellington, Ōtautahi Christchurch, Ōtepoti Dunedin, and Waihōpai Invercargill.

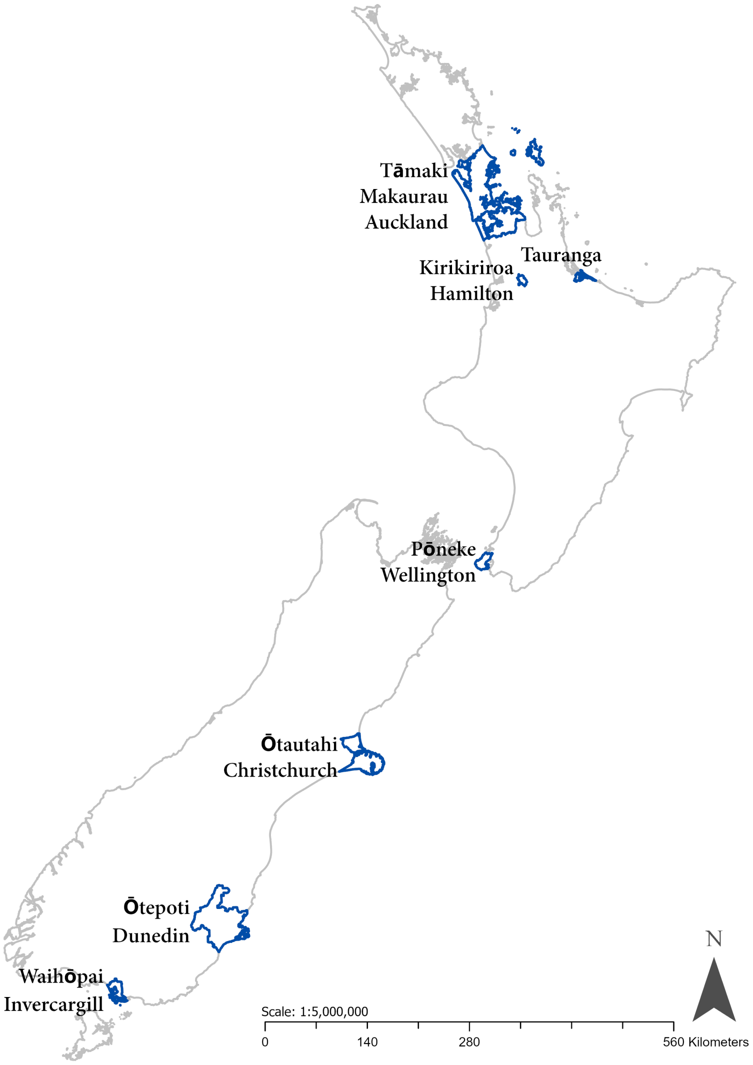

Figure 11: The cities across Aotearoa New Zealand that are involved in this model.

City	Population	Cycling (%)	Driving (%)	Public Transport (%)	Walking (%)
Tāmaki Makaurau Auckland	1571718	1.00%	73.93%	10.73%	4.32%
Kirikiriroa Hamilton	160911	2.37%	80.76%	2.84%	4.75%
Tauranga	136713	2.29%	79.29%	1.66%	2.88%
Pōneke Wellington	202737	4.02%	44.77%	21.33%	19.31%
Ōtautahi Christchurch	369006	5.59%	76.06%	4.21%	3.87%
Ōtepoti Dunedin	126255	2.08%	73.27%	3.45%	9.90%
Waihōpai Invercargill	54204	2.00%	83.84%	0.50%	3.95%
National	4699719	1.96%	73.02%	6.46%	5.21%

Data from Statistics New Zealand Tatauranga Aotearoa (2018a; 2018b).
Percentage values are based on working population. Percentages do not add to 100% as some transport modes are excluded.

Table 7: Commuting patterns across the cities included in the model.

The selected cities represent a range of populations, climates, topographies, commitment to investments for cycling, and existing commuting patterns, with those patterns summarised in Table 7. For example, Waihōpai Invercargill has the highest percentage of workers commuting by motor vehicle, whereas Ōtautahi Christchurch has the highest number of bicycle commuters and Pōneke Wellington has an above average number of public transport and walking commuters. Additionally, these are the urban areas for which cycling network data was readily available. This introduces some bias, as cities that have already invested in or are favourable towards urban cycling are more likely to have a cycle network dataset compared to those which are not, which means that the dataset is biased towards cities already likely to have higher commuting ridership. That being said, interestingly, cycle network data for Ōtautahi Christchurch, the city with the highest number of bicycle commuters in the country, was not available from Christchurch City Council. Open-source data from OpenSourceMap (OSM) is used in lieu.

In Aotearoa New Zealand, the most granular geographic scale available for analysis is the Statistical Area (SA2). Statistical Area geographies aim to represent communities that interact socially and economically (Statistics New Zealand Tatauranga Aotearoa, 2018c). This is in contrast to the the Territorial Authority (TA) level which represents local government boundaries. The number of Statistical Areas for analysis is detailed in Table 8.

City	SA2s (#)
Tāmaki Makaurau Auckland	539
Kirikiriroa Hamilton	62
Tauranga	50
Pōneke Wellington	78
Ōtautahi Christchurch	169
Ōtepoti Dunedin	66
Waihōpai Invercargill	27
Total	991

Table 8: Summary of Statistical Areas available in each city for analysis.

3.2 Building a Low Stress Network

Three principle attributes are required for analysis: speed limit, number of lanes, and type of bicycle infrastructure. Table 10 at the end of this section will show the source of each dataset. These attributes are required to be combined for LTS assignment. Figure 12 shows the overlay of these attributes in the Tauranga South and Brookfield suburbs in Tauranga.

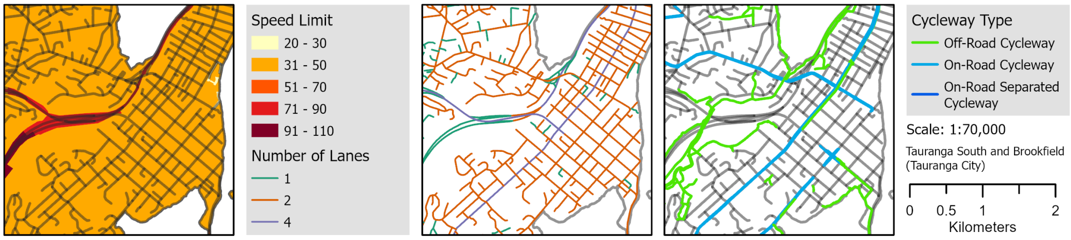

Figure 12: An overlay of geographic input variables using Tauranga South and Brookfield (Tauranga) as a case site – speed limit, number of lanes, cycleway type.

3.2.1 Determining the Speed Limit

The National Speed Limit Register (NSLR) is a dataset maintained by Waka Kotahi New Zealand Transport Agency (2022) that contains the speed limit records for all roads across the country. There are four categories of speed limit recorded:

1. Permanent speed limit – the speed limit in force when no other temporary speed limit is in place
2. Variable speed limit – the speed limit that takes force under certain conditions, such as temporary school zone speed limits
3. Seasonal speed limit – the speed limit that takes force on a seasonal basis
4. Emergency speed limit – the speed limit that takes force during a natural disaster or other emergency

Wherever possible, the permanent speed limit is used as this is the speed limit that is most likely to be in force at any given time. While many schools have variable speed limits in place, these are often only in force for an hour in the morning and the afternoon. If someone is commuting by bicycle outside of those times, then the standard speed limit would apply.

The speed limits are stored as polygons. The `Pairwise Intersect` function in `ArcGIS Pro` is used to identify which roads intersect which speed limit polygons and attach that speed limit value to the road. There are some areas, notably northern Tāmaki Makaurau Auckland, where there is no speed limit data stored. It is unclear why this is the case. These edges are removed from the analysis as it is not possible to calculate the LTS value without the speed limit.

3.2.2 Finding the Number of Lanes

The number of lanes is stored as an attribute of the road geometry. It is described as "number of paths available side by side for the simultaneous passage of vehicles on a road" (Toitu Te Whenua Land Information New Zealand, 2011). This indicates that a road with one lane in each direction would have a lane count of 2, a road with one lane for one direction and two lanes for the other would have a lane count of 3, a road with two lanes per direction would have a lane count of 4, and so forth. A lane count of 1 indicates that the road is narrow but does not preclude bidirectional traffic.

3.2.3 Identifying the Type of Bicycle Infrastructure

Dataset attributes for cycling infrastructure is varied as each dataset is maintained by a distinct territorial authority. For example, the data provided by Auckland Council has attribute "On-road unbuffered cycle lane" for on-road cycleways without separation, while the data provided by Dunedin City Council calls this same infrastructure a "Painted Carway Lane". Where possible, the meaning of these terms are clarified with the respective territorial authority. Additionally, as noted in the city summary, Ōtautahi Christchurch does not have an available dataset identifying the location and type of cycling infrastructure. Data from OpenStreetMap (OSM) is therefore used. This dataset contains all the cycleways identified by users since the inception of OpenStreetMap. To determine whether the cycleway was on-road or off-road, a `Buffer` of 5 m is employed. If the road network is within the buffer, the cycleway is considered to be on-road. Otherwise, it is off-road. This is a crude and brute-force method. Unfortunately, this method is not capable of distinguishing between on-road cycleways and on-road separated cycleways.

Following this, all infrastructure is categorised into three groups: "On-Road Separated Cycleway", "On-Road Cycleway", and "Off-Road Cycleway". This data now needs to be attached to the road geometry. For the on-road infrastructure, the `Buffer` and `Pairwise Intersect` functions are used to identify with which roads the bicycle infrastructure is associated. For off-road infrastructure, the `Snap` function with a distance tolerance of 5 m connects these edges to the existing road network.

3.2.4 Calculating the Level of Traffic Stress

Finally, the Level of Traffic Stress for each edge can be calculated. The LTS values assigned is dictated in Table 9 for on-road infrastructure. Edges that are identified as an off-road cycleway or an on-road separated cycleway are assigned LTS1.

Note that units are converted from imperial to metric and rounded to speed limit increments common in Aotearoa New Zealand. For instance, the second smallest speed category in imperial units is 30 mph, which converts to 48 kph. As this is not a speed limit increment in Aotearoa New Zealand, this is rounded to 50 kph for use in the Framework. Furthermore, the LTS Framework makes a distinction between bike lanes that are alongside parking and bike lanes that are not alongside parking. However, this data is not available for the selected cities. Aligning with the principle that each edge is only as comfortable as its least comfortable part, the values for bike lanes alongside parking are used for all bike lanes.

Speed Limit	$\leq$ 2 lanes	3 lanes	4 lanes	5 lanes	$\geq$ 6 lanes
On-Road Cycleway (alongside Parking Lane)					
$\leq$ 40 kph	LTS1	LTS3	LTS3	LTS3	LTS3
50 kph	LTS2	LTS3	LTS3	LTS3	LTS3
60 kph	LTS3	LTS3	LTS3	LTS3	LTS3
$\geq$ 70 kph	LTS4	LTS4	LTS4	LTS4	LTS4
In Mixed Traffic (No Cycleway)					
$\leq$ 40 kph	LTS2	LTS2	LTS3	LTS3	LTS4
50 kph	LTS2	LTS2	LTS4	LTS4	LTS4
60 kph	LTS4	LTS4	LTS4	LTS4	LTS4
$\geq$ 70 kph	LTS4	LTS4	LTS4	LTS4	LTS4

Table 9: Level of Traffic Stress (LTS) values assigned for on-road infrastructure based on speed limit and number of through lanes.

This results in a network such as in Figure 13, which features the same area (Tauranga South and Brookfield in Tauranga City) as Figure 12 from the start of this subsection now classified according to the Level of Traffic Stress Framework. Once each edge has an associated LTS value attribute, the edges containing $LTS \leq 2$ are selected. This is the final, low stress network for analysis. In Figure 13, this is only the green edges.

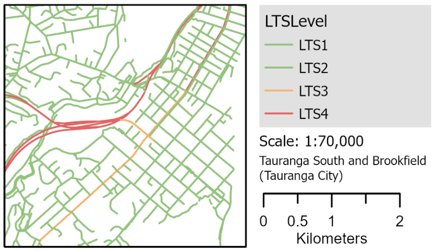

Figure 13: The final road network classified with the Level of Traffic Stress (LTS) Framework in Tauranga South and Brookfield (Tauranga).

3.3 Model Variables

Now that a low stress network has been constructed, data can be collected for input into a model. The source for data in variable data can be found in Table 11 at the end of this section.

As noted previously, the model is regressed at the SA2 level. However, SA2s with a population less than three hundred people are excluded. This is to exclude outlying statistical areas that may cause the model to behave poorly. This population criteria is chosen because it represents a population size of more than two standard deviations from the population mean (μ=2600, σ=1143) and thus removes less than 5% of the total data. Note that excluding low population SA2s does not exclude all SA2s with no people commuting to work by bicycle. The final dataset contains 947 SA2s across the seven TAs.

3.3.1 Dependent Variable – Number of Cyclists

The dependent variable is the number of people who use a bicycle to commute to work as reported by the New Zealand Census. It asks: *"What is the one main way you usually travel to work - that is, the one you use for the greatest distance?"* This captures the number of people who are travelling by bicycle, and, importantly, can be disaggregated into SA2s for analysis. To account for population differences between SA2s, it is converted to a percentage value (in other words, the number of people per hundred people in that SA2 who reported biking to work).

There are some limitations introduced into the analysis from the use of this data. Firstly, Census data only captures information about commuting by bicycle. It is possible that someone may drive or take public transport to work but use a bicycle for other trips, such as grocery shopping or visiting a friend. The latter trips would not be reflected in the Census data. Secondly, the Census only allows one response. This means that respondents who use multiple modes to commute to work or change mode based on season, weather conditions, or other factors are not counted.This is problematic because cyclists tend to be more multimodal than other groups (Heinen, 2011).

Two potential alternative dependent variables were considered but ultimately discarded: the New Zealand Household Travel Survey and cycling count data. The New Zealand Household Travel Survey has been conducted by the Ministry of Transport since 2003. For the survey, each member of the selected households is asked to keep a record of all travel over two days. This method of data collection addresses the limitations of the previous dataset, as travel for all purposes is collected, including multimodal travel. However, data is summarised at a regional level instead of a SA2 level. This makes the Household Travel Survey inappropriate for analysis. Meanwhile, cycling count data reports the actual number of cyclists using a particular stretch of infrastructure. This is an improvement on both Census data and the Household Travel Survey data because it both reports trips for all purposes and is associated directly with a piece of infrastructure. However, as the data is held locally, it is not likely to be consistent across regions which presents challenges in analysis on a national scale. Additionally, of the cities that have cycling counter data available, the majority of those counters were located within 100 m of cycling infrastructure (89.3%)[11], which means that the number of people cycling on streets without cycling infrastructure – whether those be high stress streets or low stress streets – is not reported. Counts from both scenarios are needed to build a robust model. That being said, other studies of this nature (see: Wang et al., 2020; Cervero et al., 2019) also focus primarily or only on commuting data. Therefore, this is not an unusual approach, but appropriate and expanded data on cycling trips for all purposes will be critical to fully understanding the scope of this issue in the future.

3.3.2 Independent Variables – Geographic Elements

The Beta Connectivity Index β, the number of subgraphs p, and the subgraph ratio p_r as discussed in our section on graph theory are used as indicators of connectivity. In addition to these variables, the Low Stress Percentage Length LTS is calculated at the SA2 level and the TA level. The Low Stress Percentage Length is the percentage of lengths contained in the network that are low stress, as in

$$LTS = \frac{\sum_1^2 d_{LTS}}{\sum_1^4 d_{LTS}} \quad ; \quad 0 \leq LTS \leq 1 \tag{8}$$

where d_{LTS} is the total length of edges of a given LTS value. This is the only variable regressed at both the neighbourhood and the city level.

---

[11] This is calculated using data available from Waikato Open Data Portal: https://data-waikatolass.opendata.arcgis.com/datasets/hcc::cycling-counter-information/explore.

3.3.3 Independent Variables – Socioeconomic Elements

There are variables aside from the provision of bicycle infrastructure that influence the level of cycling. This model therefore includes certain socioeconomic variables at the SA2 level, namely the percentage of women, the percentage of Māori, the percentage of homeowners, and the average number of motor vehicles per household to account for those influences. Median income is traditionally an influence as well, but it is omitted in this case to avoid multicollinearity as it is highly correlated to the percentage of homeowners and the percentage of Māori.

3.4 Hurdle Model

The dependent variable, the percentage of people commuting to work by bicycle, contains more zeros than can be accounted for in a traditional negative binomial or Poisson modelling scheme (Zuur et al., 2009). Of the 947 SA2s, there are 65 zeros, which constitutes 6.8% of the dataset. This distribution is shown in Figure 14. A zero-inflated model, which accounts for this asymmetrical distribution, is required.

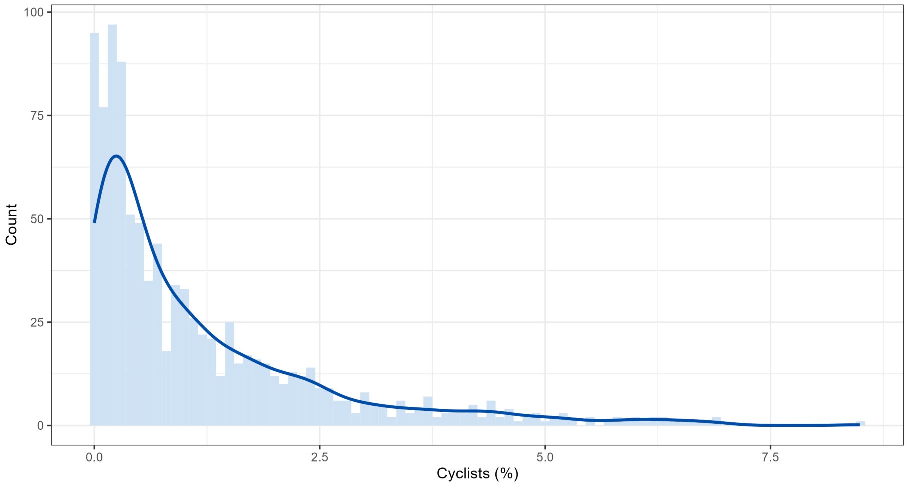

Figure 14: The distribution of values across all the Statistical Areas in the model showing a high proportion of zeros.

The Hurdle model is selected. This zero-inflated model consists of two parts (Kleiber and Zeileis, 2008), which are:

1. A binary model for $y_i = 0$ – What causes y_i to be zero or positive?

2. A Poisson model for $y_i > 0$ – What influences the size of positive y_i?

This approach not only accounts for the zeros in the dataset but provides insight into the generation of those zeros, as the model will output the variables that are significant in converting zeros to non-zeros (the "hurdle" in the Hurdle model – what variables are associated with people starting to bike?) in addition to the variables that influence the size of the non-zeros (what variables are associated with more people biking?).

This is represented mathematically as

$$f_{hurdle} = \begin{cases} f_{zero}, & y = 0 \\ \left[1 - f_{zero}\right] \dfrac{f_{count}}{1 - f_{count}}, & y > 0 \end{cases} \tag{9}$$

where f_{zero} is the function that results in zeros and f_{count} is the non-zero count model (Kleiber and Zeileis, 2008).

A zero-inflated negative binomial model is also considered but discarded. The dispersion of the dependent variable is greater than the mean ($\mu = 1.13$, $\sigma = 2.06$) which makes the negative binomial distribution appropriate[12], however the handling of zeros differs (Zuur et al., 2009). The Hurdle model separates the zeros and the non-zeros, as described above. However, the zero-inflated model takes a 'mixed' approach, as in addition to the binary model for determining what causes y_i to be zero or positive, zeros can be generated through the count process. Ultimately, this approach is not taken because the ability to investigate the zeros and non-zeros separately is useful for this work.

Two Hurdle models are run. The first includes only geographical elements (Model 1), and the second includes both geographical and socioeconomic elements (Model 2). This allows the relative contributions of infrastructure and socioeconomic variables to be evaluated. The `hurdle` function in the `pscl` package for R is used (Jackman, 2023).

---

[12] A Poisson distribution requires $\mu > \sigma$.

Data Source	Publisher	Year	Notes
LTS Classification – Data for Cycle Networks			
Auckland City Cycle Network[a]	Auckland Transport	2017	Available publicly
Hamilton City Cycle Network	Hamilton City Council	2023	Obtained through request
Tauranga City Cycle Network[a]	Tauranga City Council	2022	Available publicly
Wellington City Cycle Network	Wellington City Council	2023	Obtained through request. Two datasets are used – one for recreational trails (i.e. through parks) and one for on-road tracks
Christchurch City Cycle Network	OpenStreetMap	2023	Christchurch City Council did not have available data and so open-source data was used
Dunedin City Cycle Network	Dunedin City Council	2023	Available publicly
Invercargill City Cycle Network	Invercargill City Council	2023	Obtained through request
LTS Classification – Data for Road Geometry			
Road Centrelines (Topo, 1:50k)	Toitu Te Whenua Land Information New Zealand	2011	Contains lane count attribute and road geometry
National Speed Limit Register (NSLR)	Waka Kotahi New Zealand Transport Agency	2022	Contains speed limit attribute as polygons
Data for Model Boundaries			
Statistical Area 2 2018 Clipped (generalised)	Statistics New Zealand Tatauranga Aotearoa	2018	Data from 2018 is used to align with available Census data[b]
Territorial Authority 2018 Clipped (generalised)	Statistics New Zealand Tatauranga Aotearoa	2018	Data from 2018 is used to align with available Census data[b]

[a] Indicates that the territorial authority was contacted to clarify cycle infrastructure classification.

[b] Most recent available Census was conducted in 2018.

Table 10: Source of geographic data.

Data Source	Publisher	Year	Notes
Census Data – Dependent Variable			
Main means of travel to work by age group and sex, for the employed census usually resident population count aged 15 years and over, 2018 Census (RC, TA, SA2, DHB)[a]	Statistics New Zealand Tatauranga Aotearoa	2018	Contains number of bicycle commuters attribute
Census Data – Independent Variables			
Age and sex by ethnic group (grouped total responses), for census usually resident population counts, 2006, 2013, and 2018 Censuses (RC, TA, SA2, DHB)[a]	Statistics New Zealand Tatauranga Aotearoa	2018	Contains population, gender, and race attributes
Number of motor vehicles by tenure of household, for households in occupied private dwellings, 2006, 2013, and 2018 Censuses (RC, TA, DHB, SA2)[a]	Statistics New Zealand Tatauranga Aotearoa	2018	Contains number of motor vehicles attribute – converted to mean number of motor vehicles per household
Individual home ownership and ethnic group (grouped total responses) by age group and sex, for the usually resident population count aged 15 years and over, 2006, 2013, and 2018 Censuses (RC, TA, SA2, DHB)[a]	Statistics New Zealand Tatauranga Aotearoa	2018	Contains number of home owners attribute – sum of "Own or partly own" and "Hold in a family trust" variables

[a] Indicates geographic scales for which data is available (RC – Regional Council; TA – Territorial Authority; SA2 – Statistical Area; DHB – District Health Board)

Table 11: Source of socioeconomic data.

4 Results and Discussion

We begin with an exploration of the resulting low stress networks of each city. Then, we discuss the significance of the model results. Finally, we discuss limitations of these results and future research that could be undertaken.

4.1 Majority of Networks are Low Stress but Poorly Connected

In all the included territorial authorities except for Ōtepoti Dunedin, more than half of the edges are low stress, with three cities (Pōneke Wellington, Kirikiriroa Hamilton, and Tauranga) having more than 80% of their edges be low stress. This is shown in Figure 15. This result is especially significant because the application of the LTS Framework in this thesis assumed that all bike lanes were alongside a parking lane, which in turn enforces stricter conditions on an edge being low stress or not.

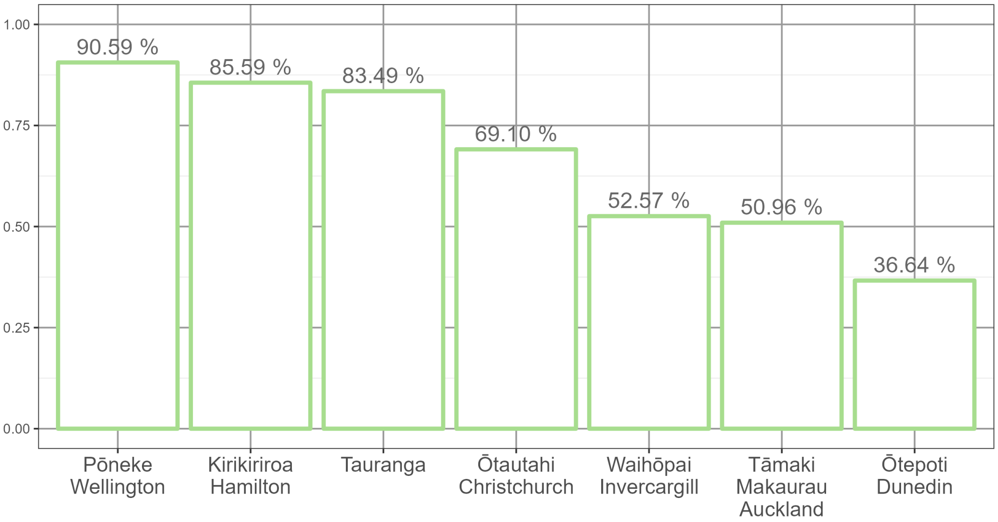

Figure 15: The proportion of low stress infrastructure in each territorial authority.

The distribution of input variables is shown in Table 12. The mean proportion of low stress infrastructure at the statistical area level is 0.86 with a standard deviation of 0.22, which means that approximately two-thirds of the statistical areas exhibit $LTS_{SA2} \geq 0.63$. Similarly, the mean number of subgraphs is 3.19 with a standard deviation of 3.96, which means that most statistical areas have $p \lesssim 7$ subgraphs. Similar indications of connectivity are seen for the subgraph ratio, with most statistical areas having more than 75% of the network contained within its largest subgraph. From the results for the Beta Connectivity Index β, the majority of neighbourhoods exhibit simple low stress network structure, with the majority of values clustered between $0.78 \leq \beta \leq 1.03$. Taken together, the distribution of these network measures indicates that a significant proportion of edges within cities and neighbourhoods are low stress but these networks may be fragmented and feature few connections between nodes.

That being said, for all variables, there is a long tail of values, evident from the size of the extreme values (the maximum or the minimum) compared to the standard deviation. This shows that while the most SA2s have low connectivity, there is significant variation in the provision of cycling infrastructure in different neighbourhoods, with some neighbourhoods being significantly more connected than others.

Variable	Min	Mean	Median	Max	Standard Deviation
Geographic Variables					
Low Stress Infrastructure (%) – SA2	0.00	0.86	0.94	1.00	0.22
Low Stress Infrastructure (%) – TA	0.37	0.60	0.51	0.91	0.15
Beta Connectivity Index	0.50	0.91	0.91	1.32	0.13
Subgraph Count	1.00	3.19	2.00	42.00	4.00
Subgraph Ratio	0.13	0.91	1.00	1.00	0.17

Table 12: Distribution of input geographic variables to the model.

4.1.1 Cycling Infrastructure is not Prerequisite for Low Stress

Of the edges that are designated as low stress, the majority of them do not contain dedicated bicycle infrastructure. Using Kirikiriroa Hamilton as a case study, of the 937 km of edges contained within the network, 797 km of those edges are designated as low stress with 367 km of dedicated bicycle infrastructure (on-road or off-road cycleways) – less than half. This indicates that the majority of low stress edges are designated so due to acceptable road design rather than the presence of bicycle infrastructure, confirming the notion that dedicated bicycle infrastructure is not required to make a a comfortable road environment for people on bikes. Meanwhile, the remaining 139 km of high stress infrastructure features 23 km of bicycle infrastructure. This bicycle infrastructure, which is ostensibly for the purpose of providing a more comfortable cycling experience for the majority of people, is unfortunately inaccessible to the majority of people due to a combination of intolerable speeds and a high number of lanes. The result is that bicycle infrastructure exists that is not accessible beyond those "Enthused and Confident" or "Strong and Fearless" riders.

This summary is provided for other cities in Table 13. Kirikiriroa Hamilton in fact has an atypical proportion of its low stress links occupied by bicycle infrastructure, with the next highest proportion being in Tauranga with 35%. Across all the edges in the studied cities, dedicated bicycle infrastructure occupies 22% of low stress edges, demonstrating that 78% of

City	Total Network Length (km)	Low Stress Network			High Stress Network		
		Length (km)	Cycleways (km)		Length (km)	Cycleways (km)	
Tāmaki Makaurau Auckland	11082	5602	742	13%	5480	100	2%
Kirikiriroa Hamilton	937	797	367	46%	139	23	17%
Tauranga	925	770	271	35%	156	19	12%
Pōneke Wellington	1245	1127	326	29%	118	7	6%
Ōtautahi Christchurch	3258	2237	624	28%	1022	156	15%
Ōtepoti Dunedin	2616	948	137	14%	1663	10	1%
Waihōpai Invercargill	807	415	129	31%	392	30	8%
National	20866	11896	2596	22%	8970	345	4%

Table 13: The total length and percentage length of bicycle infrastructure located within low stress and high stress edges in each city.

low stress edges are designated so due to their tolerable road conditions rather than the presence of bicycle infrastructure specifically.

In conjunction with the previous result, these results support the “islands of low stress connectivity” assertion (Mekuria et al., 2012). This is well illustrated by Figure 16 below, showing the low stress network constructed from the roads in Linwood East, Christchurch. Although $\sim 53\%$ of the network is composed of low stress edges, they are rendered isolated by intervening high stress edges. An ostensibly connected road network is therefore transformed into a segmented low stress bicycle network, which effectively leaves people who may have access to nearby low stress segments unable to access other low stress segments. They are effectively trapped on their “islands”.

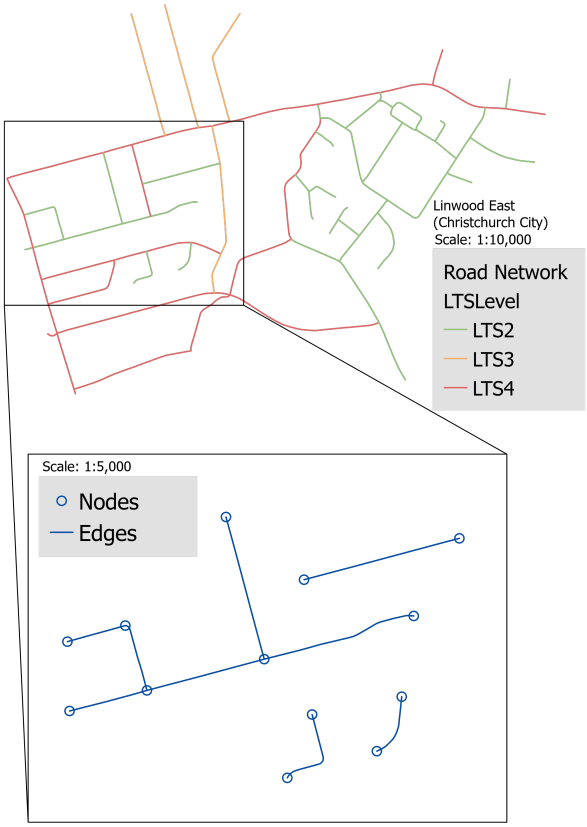

Figure 16: A typical low stress network using Linwood East (Ōtautahi Christchurch) as a case site, demonstrating “islands of low stress connectivity”.

4.2 Low Stress Infrastructure is Significant Variable in Cycling Uptake

The Low Stress Percentage at the TA and SA2 level are found to be statistically significant in both models, as well as the Beta Connectivity Index β in the zero model. That variables representing high connectivity are correlated to increased ridership is sensible and aligned to expected results based on existing literature (see: Schoner and Levinson, 2014; Kamel and Sayed, 2020; Osama et al., 2017). The Subgraph Count p and Subgraph Ratio p_r are not found to be statistically significant in either model. The Beta Connectivity Index β has statistical significance in the zero part of the model. This means that β is correlated to whether a non-zero number of people cycle (i.e., converting non-cycling commuters to cycling commuters) but not correlated to the number of people who cycle. The full set of coefficients from the model can be found in Table 14.

Furthermore, the Percentage of Low Stress Infrastructure at the TA level is relatively stronger than the Percentage of Low Stress Infrastructure at the SA2 level. This shows that infrastructure can be constructed anywhere in a city and still result in additional cycling in areas that did not receive new infrastructure.

Taken altogether, these results show that any increase to the Low Stress Percentage LTS, regardless of whether it forms connections between existing "islands" or not, as would be the case if new low stress infrastructure increases β or decreases p, will correlate to an increase in ridership. Any and all low stress infrastructure will encourage more people to bike. As low stress infrastructure encompasses more than only bicycle infrastructure, this result expands the allowable and encourage types of infrastructure that can encourage utilitarian cycling.

	Model 1		Model 2	
Variable	Count	Zero	Count	Zero
Geographic Variables				
Low Stress Infrastructure (%) – SA2	1.27 **	1.25 *	1.18 *	0.35
Low Stress Infrastructure (%) – TA	1.45 ***	8.56 ***	2.04 ***	9.33 ***
Beta Connectivity Index	-0.14	1.87 **	0.39	0.15
Subgraph Count	-0.01	0.02	0.00	-0.04
Subgraph Ratio	0.57	0.60	0.30	0.06
Socioeconomic Variables				
Proportion of Māori			-5.92 ***	-2.82 *
Proportion of Homeowners			-0.36	6.25 ***
Mean Motor Vehicle per Household			-0.13	-3.87 ***
Proportion of Women			-8.09 ***	-7.21
Coefficient of Determination (R2)	0.261		0.393	
Statistical Significance: ***0.000 **0.001 *0.05				

Table 14: Results from the model.

4.3 Socioeconomic Variables are Significant in Aotearoa New Zealand

For the socioeconomic variables, the minimum and maximum values fall more than one standard deviation from the mean, indicating that while the majority of statistical areas have a ‘typical demographic’, there are also statistical areas that feature very high or very low values. For example, while the average statistical area has a population with 12% Māori, some statistical areas have a population as low as 0.9% and others as high as 77%. A similar distribution can be seen in the mean motor vehicles per household variable. The mean number of motor vehicles is 1.84 (two motor vehicles per household), however some neighbourhoods have a mean value of 0.26 (one motor vehicle per four households) and others 2.91 (three motor vehicles per household). The values demonstrate a large range across the statistical areas.

In the count model, the proportion of Māori and the proportion of women have a negative correlation to the proportion of people commuting to work by bicycle. This is not surprising. Surveys in Aotearoa New Zealand identify a majority of current cyclists earn high income (more than $100K), are male, and are under 35 years of age (Waka Kotahi New Zealand Transport Agency, 2018). This contrasts to the Māori population, who tend to have lower income (Te Tai Ōhanga The Treasury, 2018). To understand trends in cycling across race and gender, Russell et al. (2021) interviewed 49 Māori and Pākehā women. It is found that while the cycling rate among Māori men were similar to Pākehā men ($\sim$ 5.9% for both groups) Māori women

Variable	Min	Mean	Median	Max	Standard Deviation
Socioeconomic Variables					
Proportion of Māori	0.01	0.12	0.10	0.77	0.09
Proportion of Homeowners	0.01	0.33	0.34	0.60	0.12
Mean Motor Vehicle per Household	0.26	1.84	1.85	2.91	0.36
Proportion of Women	0.23	0.51	0.51	0.62	0.02

Table 15: Distribution of input socioeconomic variables to the model.

tended to cycle approximately half as much (1.6%) as Pākehā women (2.5%). Additionally, Māori households were more likely to have a communal bicycle for the household (i.e., less likely to have a personal bicycle). They identified that cycling was viewed as a male-dominated and Pākehā-dominated domain. This precedes a negative perception of the activity, with associations of 'aggressive', 'competitive', and 'professional', which makes it unappealing to those who do not match the stereotypical image.

In the zero model, all socioeconomic variables are significant except for the proportion of women, with home ownership having a positive correlation with cycling and the average number of motor vehicles per household having a negative correlation with cycling. The correlation for the proportion of Māori is unchanged from the count model. The results for home ownership and motor vehicles are sensible and align with previous studies (see: Imani et al., 2019; Wang et al., 2016). Evidence from a report commissioned by the Minister of Housing and Urban Development[13] shows that household mobility (i.e., moving) is more common for those living in private rentals and state housing than for those who own their homes, which leads to a myriad of negative health, educational, and social outcomes (Johnson et al., 2018). It is therefore not surprising that those who have less connection and familiarity to their neighbourhoods are less likely to take up cycling as an everyday transport mode as they are less familiar with their local area. A similar logic can be considered for the motor vehicle variable. Those who have fewer vehicles are more likely to consider or rely on alternate modes of transport.

It is likely that the relative importance and strength of these variables will change if and as more people choose to bike. While socioeconomic variables such as the ones explored in this model are found to be significant in low cycling countries such as the United States, Australia, and indeed Aotearoa New Zealand, they are not found to be significant in high cycling countries such as the Netherlands and Denmark (Buehler and Goel, 2022). Indeed, the relative contributions of socioeconomic variables in explaining the distribution of input variables is less than the contribution from the geographic variables ($R2 = 26\%$ for the geographic only model and $R2 = 39\%$ for the mixed model – a difference of 15%). This indicates that there may be a tipping point at which there is enough cycling infrastructure that the contribution of socioeconomic variables like the ones explored here become negligible.

---

[13] At the time, this was the Hon Phil Twyford.

4.4 Limitations of Model and Results

Regression modelling only indicates correlation and not causation. Therefore, based on these results alone, we cannot be confident that the provision of low stress infrastructure is what causes people to bike more. That being said, there is evidence from longitudinal studies that ridership does increase after the installation of bicycle infrastructure (Hirsch et al., 2017). Therefore, while the results herein is not enough to make that assertion, based on the body of knowledge in this field, there is confidence that the installation of low stress infrastructure will cause an increase in the number of people choosing to cycle.

The coefficient of determination (R2) is 26% for Model 1 and 39% for Model 2. This means that the independent variables at most explain less than half of the variation in the data. This indicates that there are other variables that are contributing to the variance in the data. This could be other geographic or socioeconomic elements that this model did not consider. These will be explored in the following subsections.

4.4.1 Traffic Volume and Slope as Geographic Variables

Expansions of the standard LTS Framework have been explored by other works. For instance, as previously discussed, Furth et al. (2018) included traffic volume in their assignment of low stress and high stress edges. People riding bikes are known to be sensitive to traffic volumes when selecting routes (Broach et al., 2012). To simplify data collection, road classification could be used as a proxy to traffic volume, as arterial and collector roads are known to carry more motor vehicles than local roads, and so forth. Cabral (2019) used this approach to make an informed guess as to whether a road featured on-street parking. Topography it also another variable that could be included. Lowry et al. (2016) included average gradient as a classification variable, classifying roads with high gradients (i.e., very steep) as high stress. Such variables are known to have a negative correlation to cycling uptake (Kamel and Sayed, 2020; Osama et al., 2017). This has been cited as a barrier in some Aotearoa New Zealand cities (Waka Kotahi New Zealand Transport Agency, 2018).

4.4.2 Driver Attitude Towards Cyclists

The perception of cycling and the people who cycle has an impact on the likelihood of someone choosing to cycle for utilitarian purposes. Are people riding bikes perceived as annoying or as normal road users? Do drivers harass people riding bikes, or do they provide adequate clearance when passing? Heinen (2011) investigates how attitudes towards cycling impacts commuting by bicycle patterns. A belief in the social and environmental benefits of cycling and an enjoyment of cycling are likely to result in an individual cycling, but attitudes vary by country, social norms, and built environment. For example, both cyclists in Delft, Netherlands and Davis, California disliked cycling in the dark, but for different reasons; cyclists in Delft noted social reasons, such as unsafe neighbourhoods, while cyclists in Davis noted traffic concerns. In Aotearoa New Zealand, positive beliefs include that cycling benefits to the environment, promotes a healthy lifestyle, and constitutes a good form of exercise, while negative beliefs include that cycling is unsafe and dangerous, dedicated cycling infrastructure is a nuisance, and cyclists are ‘cocky’ or ‘arrogant’ (Waka Kotahi New Zealand Transport Agency, 2018; Mandic et al., 2017). In a review of driver attitudes towards cyclists and the role of the New Zealand Road Code, Barter and Isler (2019) argue that driver behaviour and is influenced by social norms, familiarity with road rules and cycling infrastructure, previous experiences with people riding bikes, and propensity towards distractions such as cellphones. Thus, for example, a survey could investigate the familiarity with road rules regarding cycling in an area as a proxy to driver attitude.

With regards to driver attitude, the National Research Council (U.S.) Transportation Research Board (2010) succinctly states: *“the likelihood of drivers slowing down or providing additional horizontal clearance while passing cyclists plays a significant role in the perceived quality of service of a facility”.* That being said, this is a difficult variable to quantify. The number of accidents between cyclists and drivers could be a reasonable proxy variable, but this presents challenges. Under New Zealand law, all traffic accidents involving injury to another person are required to be reported to Police (Land Transport Act 1998), however a report commissioned by Auckland Transport comparing hospitalisation data from the Ministry of Health and the Accident Compensation Corporation (ACC) to crash data from the Crash Analysis System (CAS) operated by Waka Kotahi New Zealand Transport Agency determined that the number of injuries requiring at least one night in hospital is higher than the number expected when only considering crash data (ViaStrada, 2022)[14]. The report concludes that there is a significant issue with under reporting in the system. In particular, near misses, which are scenarios in which a person riding a bike almost crashes but avoids injury, are found to occur up to approximately 32 times for each reported collision and are significantly related to perceptions of traffic risk (Sanders, 2015).

4.4.3 Exclusion of Footpaths

This model may not reflect the actual behaviour of cyclists in low cycling countries. Although riding on the footpath is illegal in Aotearoa New Zealand (Land Transport (Road User) Rule 2004), it is still common to see many cyclists doing so as it is perceived as safer than a road without accommodations (Waka Kotahi New Zealand Transport Agency, 2018). In Australia, where it is illegal for adults to ride on the footpath unless they are accompanying a child, a survey found that cyclists generally did so in areas where there was insufficient accommodations on the road (Haworth and Schramm, 2011).

In the context of LTS, footpaths may be used by "Interested but Concerned" cyclists to bypass high stress edges, which may be why the geographic model alone has a low coefficient of determination. Therefore, there is an argument to be made that these edges should be included. Consideration would need to be given to how the LTS value of the footpath is designated, since the width, proximity to driveways, and volume of pedestrians can all affect the stress of using the edge. However, with regard to evaluating accessibility for people riding bikes, this may give the impression that cycling infrastructure and the wider cycling network does not need as much improvement since the footpath is available for use, despite its use being illegal. Despite the perception of increased safety while riding on the footpath compared to riding on the road, there is no clear evidence that it is safer (MRCagney, 2018).

---

[14] Anecdotally, the thesis author was struck by a car while biking to work in February 2023 which caused injury requiring urgent care treatment. At the time of writing (November/December 2023), this crash does not appear in the CAS dataset despite reporting to New Zealand Police.

4.5 Future Research

This work is far from definitive nor complete. As discussed, both the model and the data have limitations that restrict the application of the results from this thesis.

A more sophisticated model could include additional variables as discussed in the previous subsections. In particular, a GPS study such as those in Broach et al. (2012) and Lowry et al. (2016) could empirically determine the cycling routes and environments that people in Aotearoa New Zealand tend towards and the ones that they avoid. A study of this type in Aotearoa New Zealand would illuminate the differences between cycling preferences locally and internationally and, more importantly, allow refinement of the LTS Framework in an Aotearoa New Zealand context and allow the analysis of utilitarian non-commuting cycling trips.

Additionally, the concept of a 'tipping point', wherein the relative strengths of the socioeconomic variables become negligible, has been discussed a few times throughout this thesis. A study of the effect of different socioeconomic variables across different countries where cycling is common (the Netherlands, Denmark) and those where cycling is less common (the United States, Canada, Aotearoa New Zealand) to test this idea and, if it proves valid, identify when and how the tipping point may occur in Aotearoa New Zealand, would be a worthy endeavour.

5 Implications for Planning and Policy

The results of this study demonstrate that the proportion of low stress infrastructure is a significant variable in the number of people choosing to bicycle. Since this variable is significant at both the city level and neighbourhood level, it is likely that new low stress infrastructure in a neighbourhood can be correlated to an increase in the number of people cycling in a different neighbourhood, regardless of how well connected it is to the existing network. While the exact distribution of low stress and high stress infrastructure will shift if a different LTS Framework is applied (for instance, a framework that incorporates traffic volume or slope), the key takeaway remains the same. Additionally, while this study is undertaken in Aotearoa New Zealand, it is likely that results are transferable to other jurisdictions.

Therefore, when planning for people to ride bikes on a particular street, elements other than dedicated bicycle infrastructure should be considered. The results here show that most of low stress networks in the studied cities are not composed of edges featuring dedicated bicycle infrastructure. This shows that such infrastructure is not always required. For instance, traffic calming elements such as road narrowing, chicanes, or raised safety platforms can be used instead to make it comfortable for people to ride bikes.

Focus must also be given to existing streets that are designated as high stress. There will always be a need for arterial roads in cities, but consideration must be given as to how people on bikes will interact with that environment so that high stress edges do not carve cities into "islands of low stress connectivity". This could be achieved through lowering the traffic stress by reducing the number of lanes or reducing the speed limit. Alternatively, separated bicycle infrastructure, which always has LTS1, can be installed. Bicycle infrastructure without separation, which we have called bike lanes, should never be installed in such an environment, as they will only be accessible to a minority of people who already ride bikes. A third option is to provide an alternative route. This could be through sufficiently traffic calmed local streets or a shared path through a park. In designing such an alternative, it is important that it is of equivalent distance to the original route. People on bikes are particularly sensitive to distance, and thus if a route is direct by motor vehicle but circuitous via bicycle, most people will opt to use a motor vehicle. A traffic calming technique that may be of particular use here is the Dutch cycling concept of "Ontvlechten" (roughly "disentanglement" in English). The mobility plan for the city of Amsterdam as outlined by Gemeente Amsterdam [Government of Amsterdam] (2013) demonstrates this: the city outlined different networks for different traffic modes, including cycling, walking, public transport, and private vehicles. These networks designate which transport mode has priority on the given street to provide guidance on how limited street space should be allocated. The effect of this is that in addition to sufficient separation between people biking and people driving, there is reduced interaction between modes generally. That is, people riding bikes and people driving choose different routes and therefore do not interact as much because the infrastructure that is welcoming to each mode is separated, creating equivalent but separate networks. Importantly, the networks are often designed to provide the shortest route to people on bikes which further encourages utilitarian cycling. The goal should not be for all street edges to be low stress but for enough streets to be low stress to ensure a connected and accessible cycling network that does not force undue detour to its users. Given limited resources and budgets, a method of prioritisation will need to be implemented; for instance, Lowry et al. (2016) use the relative contribution to increased connectivity to rank proposed projects in Seattle, United States, with the largest contributions warranting the highest priority. Such prioritisation is beyond the scope of the work but is encouraged in future research.

Effecting positive change to socioeconomic variables to improve cycling uptake can also be pursued by policy makers. The model explored here shows that neighbourhoods with a higher proportion of homeowners see a higher amount of cycling. Therefore, policies that remove barriers to home ownership may result in an increase in cycling. Alternatively, policies that improve security and tenure for renters may result in the same outcome. The model also shows that if there are fewer motor vehicles per household, bicycle commuting is more likely. Policies in this space could aim to make motor vehicle ownership less appealing, such as through increased fuel taxes or the introduction of congestion charges, or make alternate forms of transport more appealing, such as free public transport fares or electric bicycle subsidies. There is a lot of research into social policies that encourage or discourage particular modes of transport, but the focus of this thesis is infrastructure, so the recommendations here are brief and general.

6 Conclusion

Returning to our research question:

> ***To what extent does the provision of low stress cycling infrastructure relate to cycling uptake in major cities in Aotearoa New Zealand?***

We can now answer that the Level of Traffic Stress (LTS) Framework can indeed explain at least 25% of the variability in cycling uptake for commuting in Aotearoa New Zealand.

The modelling also reveals the percentage of low stress infrastructure at both the city and the neighbourhood level is the only significant variable for increasing bicycle commuting levels. Further, this variable is expressed stronger at the city level than the neighbourhood level, indicating that new low stress infrastructure is likely to increase cycling uptake regardless of where it is located. While these results are generated in an Aotearoa New Zealand context, these results are likely transferable to other jurisdictions.

An important result in corollary to this is that the majority of roads within the studied cities are designated as low stress but poorly connected due to intervening high stress edges, creating "islands of low stress connectivity". Interestingly, low stress infrastructure is not solely composed of bicycle infrastructure. Across all the studied cities, bicycle infrastructure composed only approximately 20% of the low stress infrastructure, indicating that most low stress roads were designated so due to acceptable road conditions. This shows that a holistic approach that considers the entire road environment is a critical element of improving ridership.

Altogether, we find that any new low stress infrastructure regardless of its location is likely to increase bicycle ridership, and, critically, this infrastructure need not be composed of dedicated bicycling facilities. Traffic calming through speed limit reductions and removal of traffic lanes can equally cultivate low stress environments.

Planners and policy makers can take comfort in that investment in low stress infrastructure and traffic calming is worthwhile because there is an empirical relationship between low stress bicycling infrastructure and cycling uptake.

7 References

[1] Abad, L., & Van der Meer, L. (2018). Quantifying Bicycle Network Connectivity in Lisbon Using Open Data. *Information, 9*(11), 287. https://doi.org/10.3390/info9110287

[2] Auckland Council Te Kaunihera o Tāmaki Makaurau. (2020). *Te Tāruke-ā-Tāwhiri: Auckland's Climate Plan*

[3] Auckland Transport. (2023). *Bus & train fares.* https://at.govt.nz/bus-train-ferry/fares-discounts/bus-train-fares

[4] Barter, A. R., & Isler, R. B. (2019, November 18-20). *Does the New Zealand Driver Licencing System Adequately Prepare and Test Drivers to Share the Road Safely with Cyclists?* [Conference Paper Presentation]. International Cycling Safety Conference, Brisbane, Australia.

[5] Boisjoly, G., Lachapelle, U., & El-Geneidi, A. (2020). Bicycle network performance: Assessing the directness of bicycle facilities through connectivity measures, a Montreal, Canada case study. *International Journey of Sustainable Transportation, 14*(8), 620-634. https://doi.org/10.1080/15568318.2019.1595791

[6] Brandes, U. (2005). *Network Analysis: Methodological Foundations.* Springer Science & Business Media.

[7] Broach, J., Dill, J., & Gliebe, J. (2012). Where do cyclists ride? A route choice model developed with revealed preference GPS data. *Transportation Research Part A: Policy and Practice, 46*(10), 1730-1740. http://dx.doi.org/10.1016/j.tra.2012.07.005

[8] Buehler, R., Pucher, J., Merom, D., & Bauman, A. (2011). Active Travel in Germany and the U.S.: Contributions of Daily Walking and Cycling to Physical Activity. *American Journal of Preventive Medicine, 41*(3), 241-250. https://doi.org/10.1016/j.amepre.2011.04.012

[9] Buehler, R., & Dill, J. (2016). Bikeway Networks: A Review of Effects on Cycling. *Transport Reviews, 36*(1). https://doi.org/10.1080/01441647.2015.1069908

[10] Buehler, R., & Goel, R. (2022). Chapter Seven: A global overview of cycling trends. In *Advances in Transport Policy and Planning: Cycling.* Academic Press.

[11] Busit. (2023). *Fares.* https://www.busit.co.nz/fares/

[12] Cabral, L. (2019). Analysing Network Connectivity by Cyclist Comfort: An Empirical Reappraisal of the Four Types of Cyclists Typology and Level of Traffic Stress Framework. [Masters Thesis, University of Alberta]. https://doi.org/10.7939/r3-dpht-zz13

[13] Cabral, L., Kim, A. M., Shirgaokar, M. (2019). Low-stress bicycling connectivity: Assessment of the network build-out in Edmonton, Canada. *Case Studies on Transport Policy, 7*(2), 230-238. https://doi.org/10.1016/j.cstp.2019.04.002

[14] Callister, D., & Lowry, M. B. (2013). Tools and Strategies for Wide-Scale Bicycle Level-of-Service Analysis. *Journal of Urban Planning and Development, 139*(4). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000159

[15] Caulfield, B., Brick, E., & McCarthy, O. T. (2012). Determining bicycle infrastructure preferences – A case study of Dublin. *Transportation Research Part D, 17*(5), 413-417. https://doi.org/10.1016/j.trd.2012.04.001

[16] Caviedes, A., & Figliozzi, M. (2018). Modelling the impact of traffic conditions and bicycle facilities on cyclists' on-road stress levels. *Transportation Research Part F: Traffic Psychology and Behaviour, 58*, 488-499. https://doi.org/10.1016/j.trf.2018.06.032

[17] Cervero, R., Denman, S., & Jin, Y. (2019). Network design, built and natural environments, and bicycle commuting: Evidence from British cities and towns. *Transport Policy, 74*, 153-164. https://doi.org/10.1016/j.tranpol.2018.09.007

[18] Chen, C., Anderson, J. C., Wang, H., Wang, Y., Vogt, R., & Hernandez, S. (2017). How bicycle level of traffic stress correlate with reported cyclist accidents injury severities: A geospatial and mixed logit analysis. *Accident Analysis & Prevention, 108*, 234-244. https://doi.org/10.1016/j.aap.2017.09.001

[19] Christchurch City Council. (2012). *Christchurch Transport Strategic Plan 2012–2042.*

[20] Damant-Sirois, G., Grimsrud, M., & El-Geneidy, A. M. (2014). What's your type: a multidimensional cyclist typology. *Transportation, 41*, 1153-1169. https://doi.org/10.1007/s11116-014-9523-8

[21] Dekker, H. (2021). *Cycling Pathways : The Politics and Governance of Dutch Cycling Infrastructure, 1920-2020.* Amsterdam University Press.

[22] Dill, J., & McNeil N. (2013). Four Types of Cyclists?: Examination of Typology for Better Understanding of Bicycling Behavior and Potential. *Transportation Research Record, 2387*(1), 129-138. https://doi.org/10.3141/2387-15

[23] Elliot, T., McLaren, S. J., & Sims, R. (2018). Potential environmental impacts of electric bicycles replacing other transport modes in Wellington, New Zealand. *Sustainable Production and Consumption, 16*, 227-236. https://doi.org/10.1016/j.spc.2018.08.007

[24] Forester, J. (2012). *Effective Cycling* (7th ed.). MIT Press.

[25] Furth, P. G. (2012). Chapter Six: Bicycle infrastructure for mass cycling: A transatlantic comparison. In *City Cycling.* MIT Press.

[26] Furth, P. G., Putta, T., & Moser, P. (2018). Measuring low-stress connectivity in terms of bike-accessible jobs and potential bike-to-work trips: A case study evaluating alternative bike route alignments in northern Delaware. *The Journal of Transport and Land Use, 11*(1), 815-831. http://dx.doi.org/10.5198/jtlu.2018.1159

[27] Gehrke, S. R., Akhaven, A., Furth, P. G., Wang, Q., & Reardon, T. G. (2020). A cycling-focused accessibility tool to support regional bike network connectivity. *Transportation Research Part D: Transport and Environment, 85.* https://doi-org.ezproxy.waikato.ac.nz/10.1016/j.trd.2020.102388

[28] Geller, R. (2009). *Four Types of Cyclists.* Portland Office of Transportation, OR.

[29] Gemeente Amsterdam. (2013). *Amsterdam Aantrekkelijk Bereikbaar: MobiliteitsAanpak Amsterdam 2030.*

[30] Habib, K. N., Mann, J., Mahmoud, M., & Weiss, A. (2014). Synopsis of bicycle demand in the City of Toronto: Investigating the effects of perception, consciousness and comfortability on the purpose of biking and bike ownership. *Transportation Research Part A, 70*, 67-80. https://doi.org/10.1016/j.tra.2014.09.012

[31] Hamilton City Council Te Kaunihera o Kirikiriroa. (2022a). *Access Hamilton Strategy Ara Kootuitui Kirikiriroa.*

[32] Hamilton City Council Te Kaunihera o Kirikiriroa. (2022b). *Our Climate Future: Te Pae Tawhiti o Kirikiriroa. Our strategy to respond to climate change.*

[33] Handy, S. L., & Xing, Y. (2011). Factors Correlated with Bicycle Commuting: A Study in Six Small U.S. Cities. *International Journal of Sustainable Transportation, 5.* https://doi.org/10.1080/15568310903514789

[34] Harkey, D. L., Reinfurt, D. W., & Knuiman, M. (1998). Development of the Bicycle Compatibility Index. *Transportation Research Record: Journal of the Transportation Research Board, 1636*(1). https://doi.org/10.3141/1636-03

[35] Hawley, G., Witten, K., Hosking, J., Mackie, H., & Smith, M. (2019). The journey to learn: Perspectives on active school travel from exemplar schools in New Zealand. *Journal of Transport & Health, 14.* https://doi.org/10.1016/j.jth.2019.100600

[36] Haworth, N., & Schramm, A. (2011). Adults cycling on the footpath: what do the data show? In Hellyer, S (Ed.) *Proceedings of the 2011 Australasian Road Safety Research, Policing and Education Conference.* Insurance Commission of Western Australia, Australia.

[37] Heinen, E. (2011). *Bicycle commuting.* IOS Press.

[38] Hillsdon, M., Thorogood, M., Anstiss, T., & Morris, J. (1995). Randomised controlled trials of physical activity promotion in free living populations: a review. *Journal of Epidemiology and Community Health, 49*, 448-453. https://pubmed.ncbi.nlm.nih.gov/7499985/

[39] Hirsch, J. A., Meyer, K. A., Peterson, M., Zhang, L., Rodriguez, D. A., & Gordon-Larsen, P. (2017). Municipal investment in off-road trails and changes in bicycle commuting in Minneapolis, Minnesota over 10 years: a longitudinal repeated cross-sectional study. *International Journal of Behavioural Nutrition and Physical Activity, 14.* https://doi.org/10.1186/s12966-017-0475-1

[40] Hulme-Moir, A. (2010). Making Way for the Car: Minimum Parking Requirements and Porirua City Centre [Masters Thesis, Victoria University of Wellington]

[41] Imani, A. F., Miler, E. J., & Saxe S. (2019). Cycle accessibility and level of traffic stress: A case study of Toronto. *Journal of Transport Geography, 80.* https://doi.org/10.1016/j.jtrangeo.2019.102496

[42] Jackman, S. (2023). Political Science Computational Laboratory (1.5.5.1) [Software]. https://CRAN.R-project.org/package=pscl

[43] Johan de Hartog, J., Boogaard, H., Nijland, H., & Hoek, G. (2010). Do the Health Benefits of Cycling Outweigh the Risks? *Environmental Health Perspectives, 118*(8) https://doi.org/10.1289/ehp.0901747

[44] Johnson, A., Howden-Chapman, P., & Eaqub, S. (2018). *A Stocktake of New Zealand's Housing.* New Zealand Government.

[45] Kamel, M. B., & Sayed, T. (2020). The impact of bike network indicators on bike kilometres travelled and bike safety: A network theory approach. *Environment and Planning B: Urban Analytics and City Science, 48.* https://doi.org/10.1177/2399808320964469

[46] Keall, M. D., Shaw, C., Chapman, R., & Howden-Chapman, P. (2018). Reductions in carbon dioxide emissions from an intervention to promote cycling and walking: A case study from New Zealand. *Transportation Research Part D: Transport and Environment, 65*, 687-969. https://doi.org/10.1016/j.trd.2018.10.004

[47] Kent, M., & Karner, A. (2019). Prioritising low-stress and equitable bicycle networks using neighbourhood-based accessibility measures. *International Journal of Sustainable Transportation, 13*(2), 100-110. https://doi.org/10.1080/15568318.2018.1443177

[48] Kleiber, C., & Zeileis, A. (2008). Chapter Five: Models of Microeconometrics. In *Applied Econometrics with R.* Springer New York.

[49] Koorey, G., & Teather, K. (2016, July 6-8). *Four Types of Cyclists in Christchurch?* [Conference Presentation]. 2 Walk and Cycle Conference 2016, Auckland, New Zealand.

[50] Land Transport Act 1998

[51] Land Transport (Road User) Rule 2004

[52] Larsen, J., & El-Geneidy, A. M. (2011). A travel behaviour analysis of urban cycling facilities in Montréal Canada. *Transportation Research Part D, 16*, 172-177. https://doi.org/10.1016/j.trd.2010.07.011

[53] Leung, C., Destremau, K., Pambudi, D., & Bealing, M. (2017). *Benefits from Auckland road decongestion.* NZ Institute of Economic Research.

[54] Lindsay, G., Macmillan, A., & Woodward, A. (2011). Moving urban trips from cars to bicycles: impact on health and emissions. *Australian and New Zealand Journal of Public Health, 35*(1), 54-60. https://doi.org/10.1111/j.1753-6405.2010.00621.x

[55] Litman, T., & Laube, F. (2002). *Automobile Dependency and Economic Development.* Victoria Transport Policy Institute. https://vtpi.org/ecodev.pdf

[56] Lowry, M. B., Furth, P. G., & Hadden-Loh, T. (2016). Prioritising new bicycle facilities to improve low-stress network connectivity. *Transportation Research Part A: Policy and Practice, 86*, 124-140. http://dx.doi.org/10.1016/j.tra.2016.02.003

[57] Lowry, M. B., & Hadden-Loh, T. (2017). Quantifying bicycle network connectivity. *Preventive Medicine, 95*, S134-S140. https://doi.org/10.1016/j.ypmed.2016.12.007

[58] Mandic, S., Hopkins, D., Bengoechea, E. G., Flaherty, C., Williams, J., Sloane, L., Moore, A., & Spence, J. C. (2017). Adolescents' perceptions of cycling versus walking to school: Understanding the New Zealand context. *Journal of Transport & Health, 4*, 294-304. https://doi.org/10.1016/j.jth.2016.10.007

[59] Mekuria, M. C., Furth, P. G., & Nixon, H. (2012). *Low-Stress Bicycling and Network Connectivity.* Mineta Transportation Institute Publications.

[60] Metlink. (2023). *Tickets and fares.* https://www.metlink.org.nz/getting-started/tickets-and-fares-2/

[61] Miller, C. L. (2011). *Implementing Sustainability: The New Zealand Experience.* Routledge.

[62] MRCagney. (2018). *Footpath Cycling Discussion Paper.*

[63] National Research Council (U.S.) Transportation Research Board. (2010). *HCM 2010: Highway Capacity Manual* (5th ed.). Transportation Research Board, 2010.

[64] Osama, A., Sayed T., & Bigazzi, A. Y. (2017). Models for estimating zone-level bike kilometres travelled using bike network, land use, and road facility variables. *Transportation Research Part A: Policy and Practice, 96*, 14-28. https://doi-org.ezproxy.waikato.ac.nz/10.1016/j.tra.2016.11.016

[65] Pucher, J., Buehler, R., Bassett, D. R., & Dannenberg, A. L. (2010). Walking and cycling to health: a comparative analysis of city, state, and international data. *American Journal of Public Health, 100*(10), 1986–1992. https://doi.org/10.2105/AJPH.2009.189324

[66] Rodrigue, J., Comtois, C., & Slack, B. (2013). *The Geography of Transport Systems.* (3rd ed.). Routledge.

[67] Russell, M., Davies, C., Wild, K., & Shaw, C. (2021). Pedalling towards equity: Exploring women's cycling in a New Zealand city. *Journal of Transport Geography, 91.* https://doi.org/10.1016/j.jtrangeo.2021.102987

[68] Tauranga City Council. (2021). *The Western Bay of Plenty Transport System Plan.*

[69] Te Tai Ōhanga The Treasury. (2018). *Statistical Analysis of Ethnic Wage Gaps in New Zealand.*

[70] Sanders, R. L. (2015). Perceived traffic risk for cyclists: The impact of near miss and collision experiences. *Accident Analysis & Prevention, 75*, 26-34. https://doi.org/10.1016/j.aap.2014.11.004

[71] Schoner, J. E., & Levinson D. M. (2014). The missing link: bicycle infrastructure networks and ridership in 74 US cities. *Transportation, 41*, 1187-1204. http://dx.doi.org/10.1007/s11116-014-9538-1

[72] Sorton, A., & Walsh, T. (1994). Bicycle Stress Level as a Tool To Evaluate Urban and Suburban Bicycle Compatibility. *Transportation Research Record, 1438*, 17-24.

[73] Statistics New Zealand Tatauranga Aotearoa. (2018a). *Main means of travel to work by age group and sex, for the census usually resident population count attending, studying, or enrolled in education, 2018 Census (RC, TA, SA2).* [Dataset]

[74] Statistics New Zealand Tatauranga Aotearoa. (2018b). *Age and sex by ethnic group (grouped total responses), for census usually resident population counts, 2006, 2013, and 2018 Censuses (RC, TA, SA2, DHB).* [Dataset]

[75] Statistics New Zealand Tatauranga Aotearoa. (2018c). *Statistical Area 2 2018 Clipped (generalised).* [Dataset]

[76] Statistics New Zealand Tatauranga Aotearoa. (2020). *Household expenditure statistics: Year ended June 2019.* https://www.stats.govt.nz/information-releases/household-expenditure-statistics-year-ended-june-2019

[77] Ton, D., Gavriilidou, A., Yuan Y., Schneider, F., Hoogendoorn, S., & Daamen, W. (2022). Chapter Eight: Modelling of cycling behaviour. In *Advances in Transport Policy and Planning: Cycling.* Academic Press.

[78] Urban, F. (2023). Chapter 3.7: The End of the Planned City? Urban Planning after 1989. In *European Planning History in the 20th Century: A Continent of Urban Planning.* Taylor & Francis.

[79] ViaStrada. (2022). *Safety of People Travelling Outside Vehicles. Deep Dive Review: First and Second Phase.*

[80] Volker, J. M. B., & Handy, S. (2021). Economic impacts on local businesses of investments in bicycle and pedestrian infrastructure: a review of the evidence. *Transport Reviews 41*(4), 401-431, https://doi.org/10.1080/01441647.2021.1912849

[81] Waka Kotahi New Zealand Transport Agency. (2011). *Travel Planning Toolkit Guidelines and Resources.* https://www.nzta.govt.nz/resources/travel-planning-toolkit/

[82] Waka Kotahi New Zealand Transport Agency. (2018). *Understanding attitudes and perceptions of Cycling & Walking.*

[83] Waka Kotahi New Zealand Transport Agency. (2019). *Keeping Cities Moving: Increasing the wellbeing of New Zealand's cities by growing the share of travel by public transport, walking and cycling.*

[84] Wang, H., Palm, M., Chen, C., Vogt, R., & Wang, Y. (2016). Does bicycle network level of traffic stress (LTS) explain bicycle travel behaviour? Mixed results from an Oregon case study. *Journal of Transport Geography, 57*, 8-18. https://doi.org/10.1016/j.jtrangeo.2016.08.016

[85] Wang, K., Akar, G., Lee, K., Sanders, M. (2020). Commuting patterns and bicycle level of traffic stress (LTS): Insights from spatially aggregated data in Franklin County, Ohio. *Journal of Transport Geography, 86.* https://doi.org/10.1016/j.jtrangeo.2020.102751

[86] Weiner, E. (2016). *Urban Transportation Planning in the United States: History, Policy, and Practice.* (5th ed.). Springer International Publishing AG.

[87] Wild, K., & Woodward, A. (2018). *Electric City: E-bikes and the future of cycling in New Zealand.* University of Auckland.

[88] Zhao, P. (2014). The Impact of the Built Environment on Bicycle Commuting: Evidence from Beijing. *Urban Studies, 51*(5), 1019-1037. https://doi.org/10.1177/0042098013494423

[89] Zuur, F. A., Ieno, E. N., Walker, N. J., Saveliev, A. A., Smith, G. M. (2009). Chapter Eleven: Zero-Truncated and Zero-Inflated Models for Count Data. In *Mixed Effects Models and Extensions in Ecology with R*. Springer New York.

A Calculations for Comparison of Frameworks

The road we are calculating for has the following characteristics: one lane per direction of width 3.6 m with a 0.6 m shoulder, no on-street parking, a posted speed limit of 80 kph, and a traffic volume of 500 vehicles per hour with 5% of that traffic being heavy vehicles. This example originates from the United States Highway Capacity Manual (National Research Council (U.S.) Transportation Research Board, 2010).

Bicycle Level of Service (BLOS) Framework. Firstly, $PHF = 0.9$ is given by National Research Council (U.S.) Transportation Research Board (2010). With $V = 500$ and Equation 4, we find $\nu = 556$.

As there is no on-street parking, the effective width is the width of the outside lane is the sum of the travel lane and the shoulder, which is $w_e = 4.2$ m.

For the pavement quality, the National Research Council (U.S.) Transportation Research Board (2010) suggests a 'fair' quality, which has $P = 3$.

We calculate the effective speed factor as $S_t = 4.62$ using Equation 5.

The LOS score is therefore $BLOS = 5.20$ by Equation 3, which is LOS E.

Bicycle Compatibility Index (BCI) Framework. We take the 85th percentile of traffic speed SPD as the posted speed limit, as in North America, this is usually how the speed limit is set (National Research Council (U.S.) Transportation Research Board, 2010).

We take $AREA = 0$ as speeds of 80 kph are not common to residential areas, $OLV = 0$ as there is only one lane per direction, and $PKG = 0$ as there is no on-street parking.

With heavy vehicle traffic percentage at 5%, we can calculate the hourly volume of heavy traffic as $V_{HT} = 25$.

Given heavy traffic, we also calculate $f_t = 0.2$ from Table 2. Given that there is no-street parking, we can also assign $f_p = 0$ and as this is not a residential area, we do not expect a lot of turning traffic (i.e., into residential driveways), we will take $f_{rt} = 0$. Therefore, $AF = 0.2$ by Equation 7.

Finally, we calculate $BCI = 4.2$ by Equation 6 which gives a final score of LOS C.

Bicycle Stress Level (BSL) Framework. The process for calculating the BSL is more straightforward than the $BLOS$ and the BCI.

Referring to Table 4, a traffic volume of greater than 450 vehicles per hour yields a stress value of 5, a curb lane width of 3.6 m yields a stress value of 4, an a traffic speed of greater than 75 kph finally yields a stress level of 5.

This therefore gives a final stress value of $BSL = 4.7$.

B Low Stress Network Maps

Tāmaki Makaurau Auckland

Low Stress Infrastructure (%) = 50.96%. Cycling Commuters (%) = 1.00%.

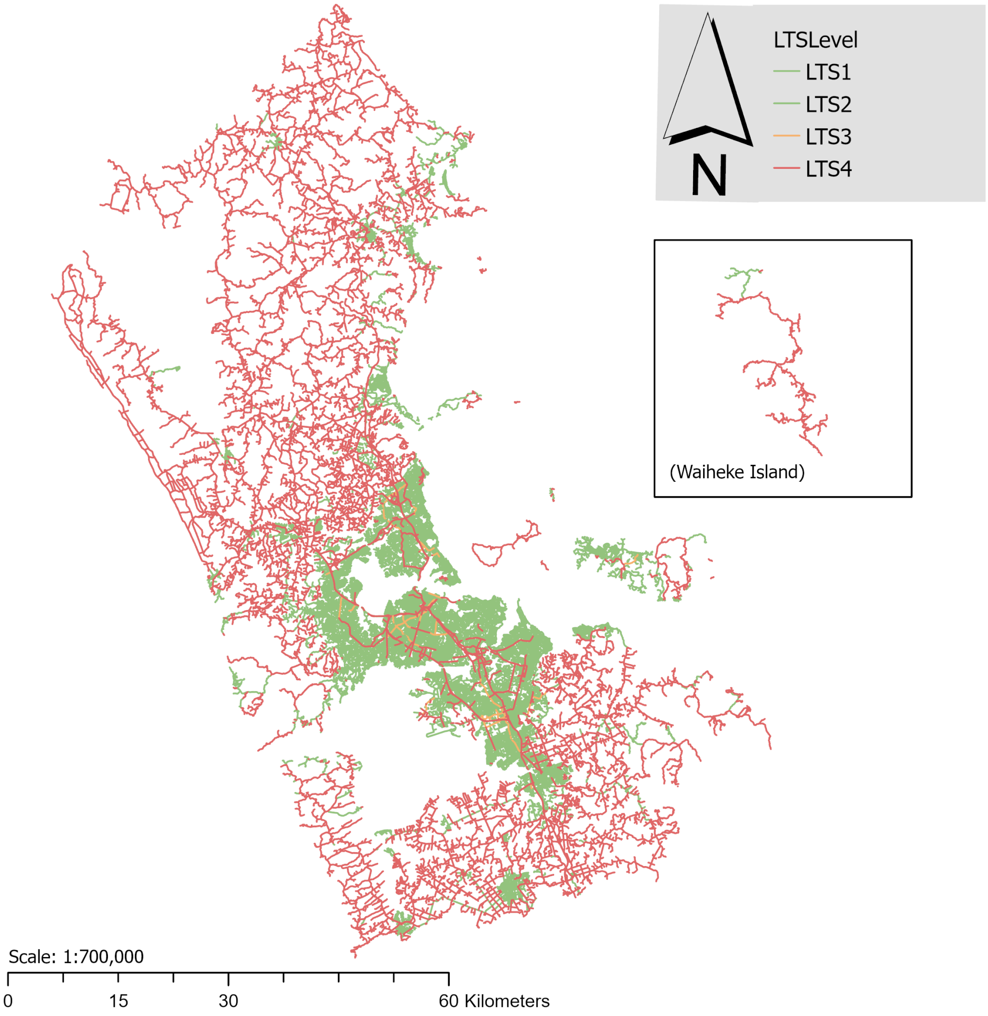

Figure 17: The Level of Traffic Stress (LTS) Framework classified for Tāmaki Makaurau Auckland.

Kirikiriroa Hamilton

Low Stress Infrastructure (%) = 85.59%. Cycling Commuters (%) = 2.37%.

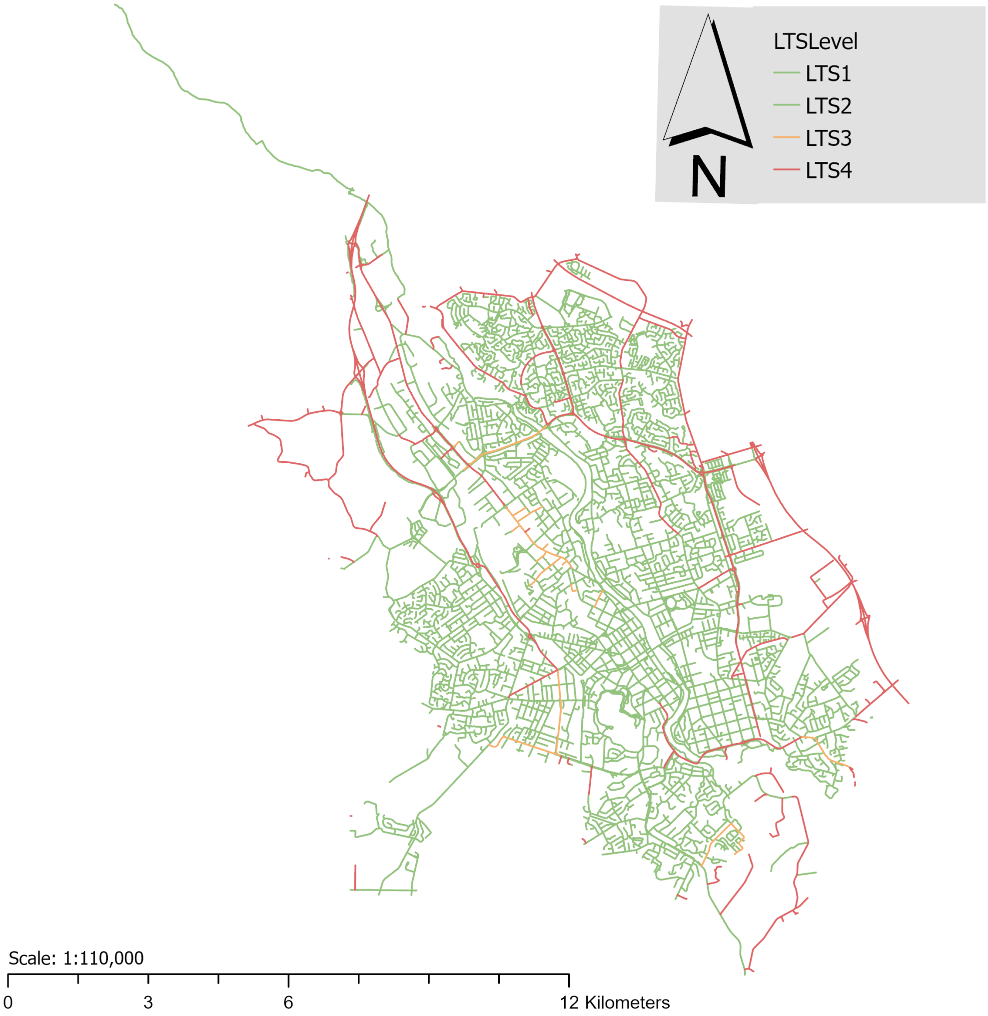

Figure 18: The Level of Traffic Stress (LTS) Framework classified for Kirikiriroa Hamilton.

Tauranga

Low Stress Infrastructure (%) = 83.49%. Cycling Commuters (%) = 2.29%.

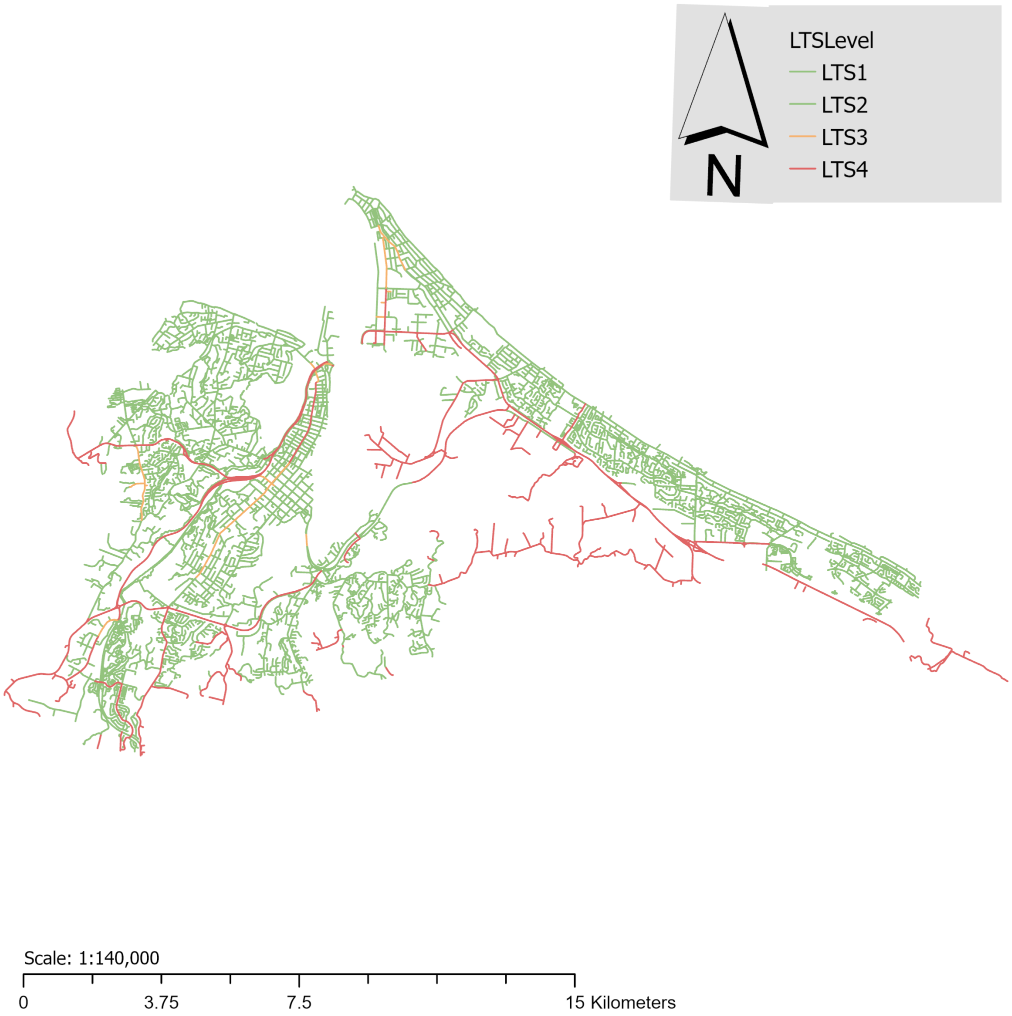

Figure 19: The Level of Traffic Stress (LTS) Framework classified for Tauranga.

Pōneke Wellington

Low Stress Infrastructure (%) = 90.59%. Cycling Commuters (%) = 4.02%.

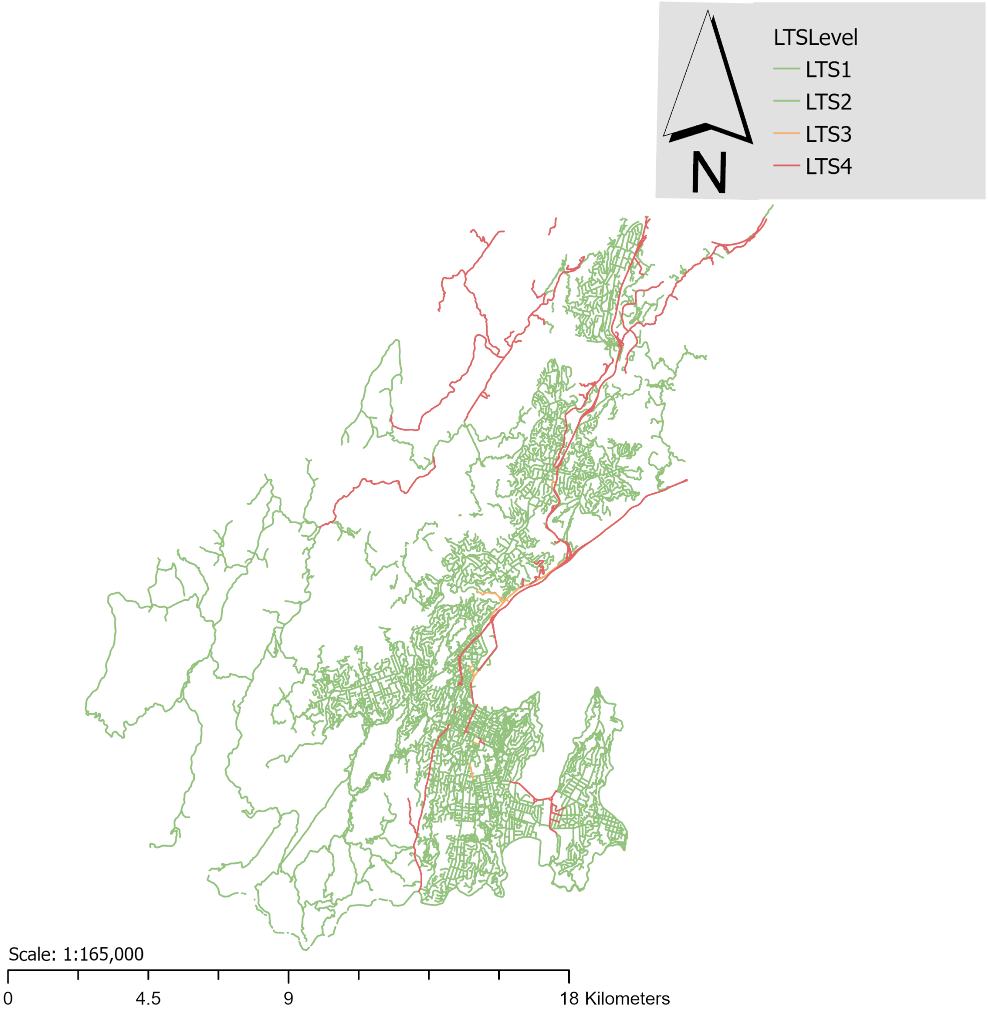

Figure 20: The Level of Traffic Stress (LTS) Framework classified for Pōneke Wellington.

Ōtautahi Christchurch

Low Stress Infrastructure (%) = 69.10%. Cycling Commuters (%) = 5.59%.

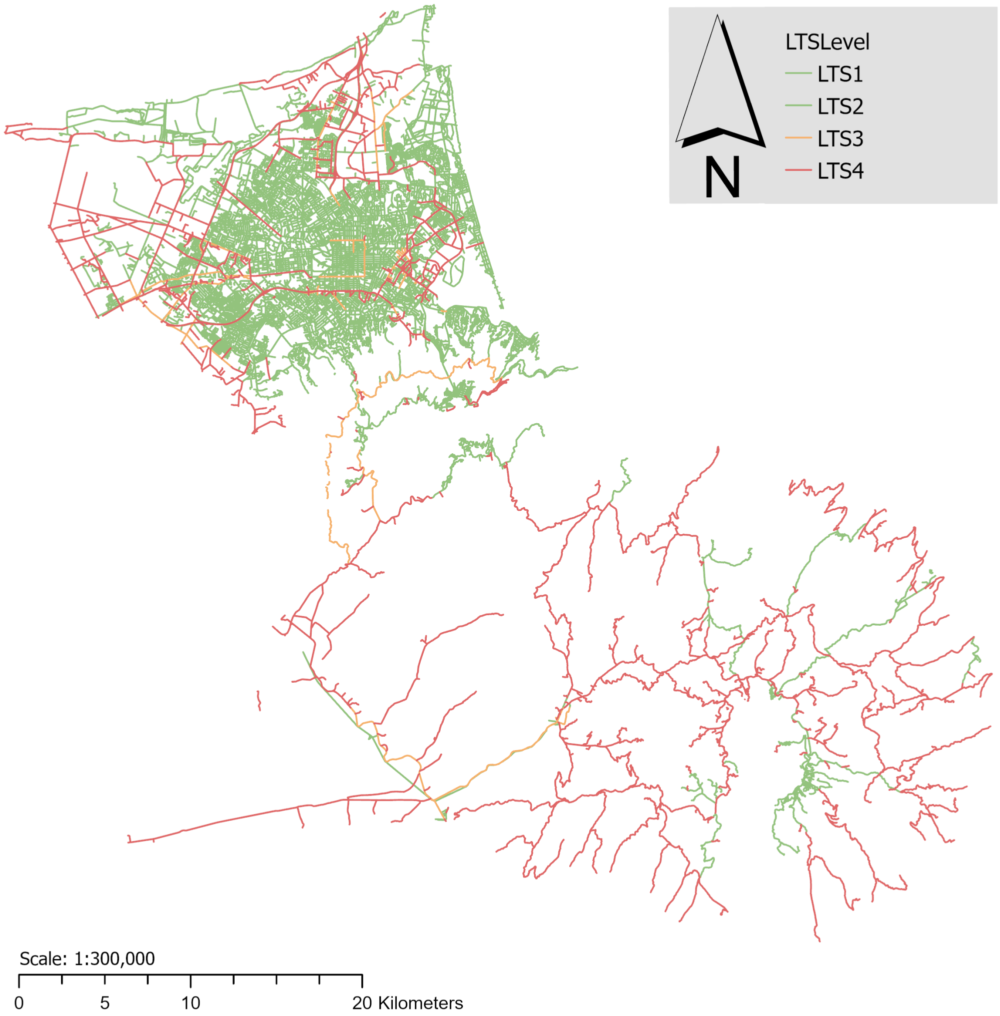

Figure 21: The Level of Traffic Stress (LTS) Framework classified for Ōtautahi Christchurch.

Ōtepoti Dunedin

Low Stress Infrastructure (%) = 36.64%. Cycling Commuters (%) = 2.08%.

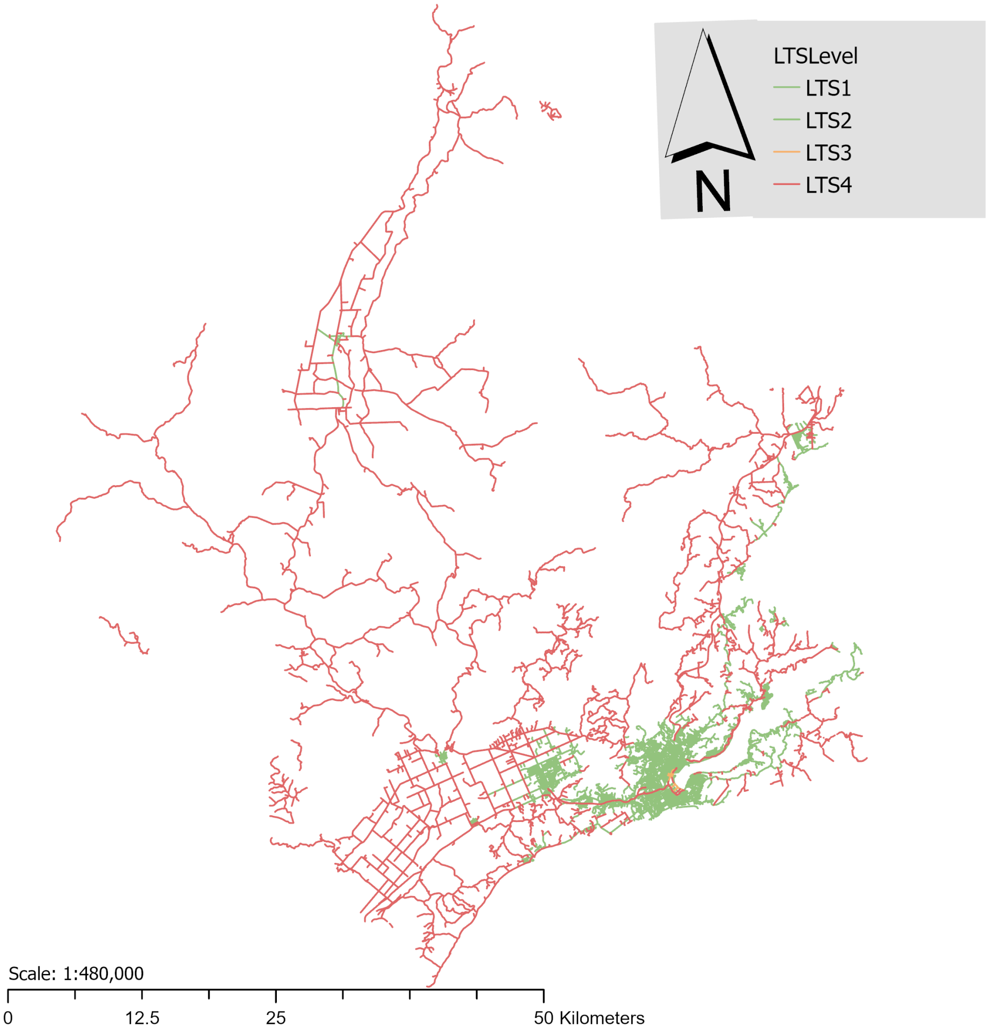

Figure 22: The Level of Traffic Stress (LTS) Framework classified for Ōtepoti Dunedin.

Waihōpai Invercargill

Low Stress Infrastructure (%) = 52.57%. Cycling Commuters (%) = 2.00%.

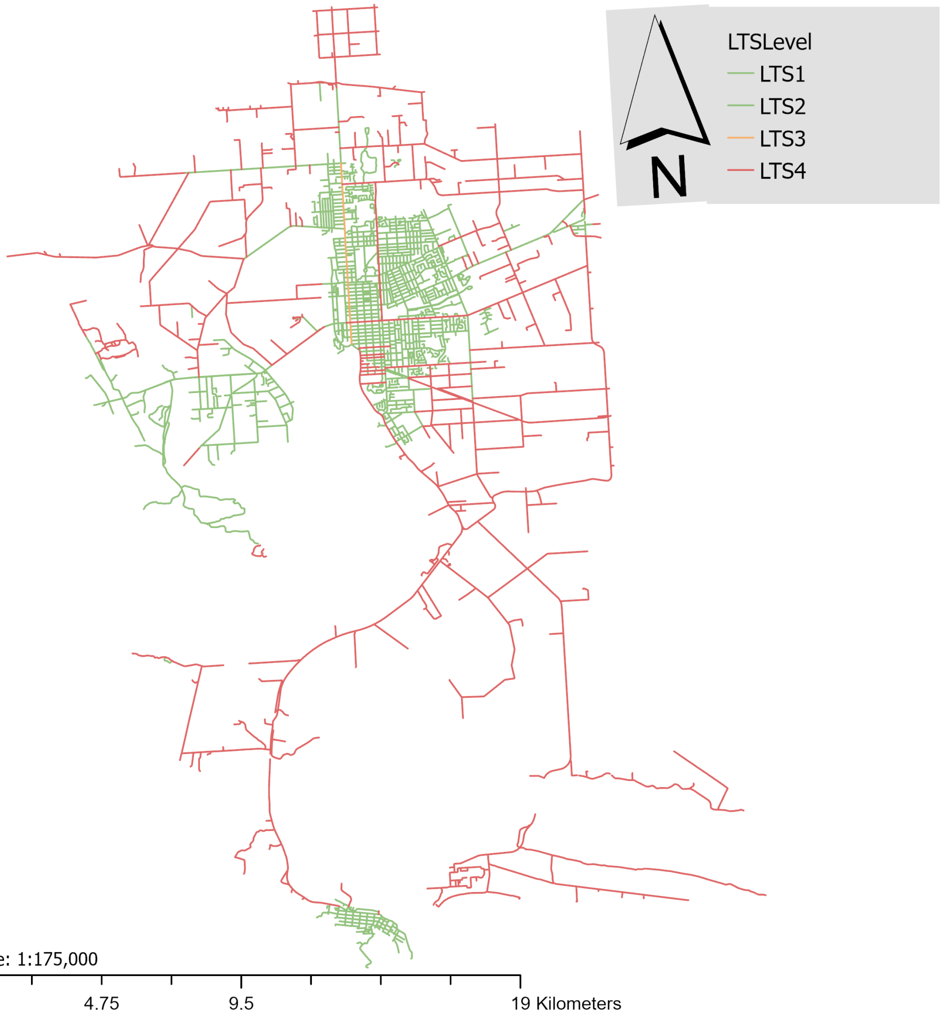

Figure 23: The Level of Traffic Stress (LTS) Framework classified for Waihōpai Invercargill.