Assessing the impacts of ‘all ages and abilities’ cycling infrastructure: Insights from mid-sized Canadian cities

by

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Abstract

This thesis assessed cycling activity, perceived safety, and cycling accessibility after investments in cycling infrastructure in mid-sized Canadian cities. The research team worked with practitioners to conduct a natural experiment study investigating the 'all ages and abilities' network in Victoria, with Kelowna and Halifax as control cites. Cycling activity increased, marginally, in all three cities over 2016-2021. In Victoria, women experienced a greater increase in perceived safety. Unexpected events, such as COVID-19, influenced the ability to capture impacts using difference-in-difference approaches. For cycling accessibility, OpenStreetMap data and the r5r routing tool were used to identify complete communities based on access to destinations via low traffic stress cycling routes. Cycling accessibility increased in Victoria from 2016-2023, however, neighbourhoods that were not considered complete communities had a greater proportion of racialized residents and residents without post-secondary education. These findings underscore why cycling infrastructure must be equitably implemented to grow and diversify ridership.

Keywords: population health intervention research; active transportation; built environment; socio-spatial; distributional equity; planning

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List of Acronyms

AAA	All Ages and Abilities
DA	Dissemination Area
FHS	Faculty of Health Sciences
IBIMS	Impacts of Bicycle Infrastructure in Mid-Sized cities
IKT	Integrated Knowledge Translation
LTS	Level of Traffic Stress
OSM	OpenStreetMap
PHIR	Population Health Intervention Research
SFU	Simon Fraser University

Preface

This is a manuscript-based thesis conforming to guidelines set by the Faculty of Health Sciences at Simon Fraser University. This statement is to confirm that Tessa Williams is the first author of both manuscripts. Citations and author contributions are listed below.

Williams, T., Whitehurst, D. G. T., Nelson, T., Fuller, D., Therrien, S., Gauvin, L., & Winters, M. (2023). All ages and abilities cycling infrastructure, cycling activity, and perceived safety: Findings from a natural experiment study in three mid-sized Canadian cities. Journal of Cycling and Micromobility Research, 1, 100005. https://doi.org/10.1016/j.jcmr.2023.100005

MW developed the study design with DGTW, TN, DF, and LG. TW executed the analyses and interpreted the results under the supervision of MW and DF. TW led manuscript writing with guidance from MW. All authors (MW, TW, DGTW, TN, DF, ST and LG) reviewed the draft manuscript and provided feedback before approving the final revised manuscript.

Williams, T., Bonsma-Fisher, M., Whitehurst, D. G. T., Nelson, T., & Winters, M. (2023). Cycling towards complete communities: Estimating access to destinations via low traffic stress cycling with open-source data and routing tools. Manuscript submitted for publication.

TW developed the study design and methodology with guidance from MW. TW completed the r5r and demographic analyses. MBF completed the transportation network data analysis. TW interpreted the results under the supervision of MW, TN, and MBF. TW led manuscript writing with guidance from MW. All authors (TW, MW, MBF, TN, and DGTW) reviewed the draft manuscript and provided feedback before approving the final revised manuscript.

Chapter 1. Introduction

1.1. Background

Cycling has the proven potential to support healthy lifestyles (Götschi et al., 2015; Henriques-Neto et al., 2020; Mueller et al., 2015). In 2017, the Chief Public Health Officer of Canada called for public health and community planning practitioners to collaborate on upstream interventions to the built environment, with the aim of incentivizing active transportation, increasing levels of physical activity, and reducing rates of chronic disease (Public Health Agency of Canada, 2017). Since then, climate-induced disasters have devastated communities around the world, highlighting the urgent need to transition to sustainable transportation (Tammaru et al., 2023).

Despite the strong health and climate rationale for cycling, safety concerns persist as a major barrier to cycling uptake (Pearson et al., 2022). Groups underrepresented in cycling, such as older adults and women, express stronger preferences for cycling infrastructure separated from vehicles (Aldred, Elliott, et al., 2016). Cities that provide cycling-supportive infrastructure typically have higher levels of cycling, and the cycling populations tend to be more age and gender representative, compared to cities where cycling infrastructure is uncommon (Goel et al., 2022). In this way, the construction of cycling infrastructure networks designed to the safety standards of underrepresented groups could increase cycling overall and attract a more diverse ridership (Aldred, Woodcock, et al., 2016; Pucher & Buehler, 2017).

‘All ages and abilities’ (AAA) design approaches strive to create cycling infrastructure that is safe, comfortable, and equitable for a wide range of people (National Association of City Transportation Officials, 2017). AAA networks often aim to provide convenient access to common destinations to support cycling for transport (Laberee et al., 2023). Many Canadian cities are building AAA cycling networks, but the implementation has not been studied thoroughly (Laberee et al., 2023), particularly in mid-sized cities (Winters, Branion-Calles, et al., 2018). To address this evidence gap, this thesis investigated the impacts of a major AAA cycling investment; in 2016, the City of Victoria, British Columbia committed to build a 33 km AAA cycling network (City of Victoria, 2023c). This substantial intervention created an opportunity for researchers to evaluate the impacts and generate evidence that is directly relevant for practice.

1.2. Relationship to IBIMS project

My thesis is nested within the “Impacts of Bicycle Infrastructure in Mid-sized Cities Study (IBIMS)” project. IBIMS was a partnership with local governments that investigated the impacts of cycling infrastructure investments over 2016-2021 in three mid-sized cities:

- Victoria, British Columbia, located on the traditional, unceded territory of the Lək̓ʷəŋən (Lekwungen) peoples, including the Xwsepsum (Esquimalt) First Nation and Songhees First Nation
- Kelowna, British Columbia, located on the traditional, unceded territory of the Syilx Okanagan people
- Halifax, Nova Scotia, located on the traditional, unceded territory of the Mi’kmaq people

The IBIMS project was specifically focused on assessing the impacts of cycling infrastructure in Victoria (where the AAA network was planned) compared to the control cities of Kelowna and Halifax (where there were few planned changes to cycling infrastructure). The project scope was developed with input from study city partners to identify objectives relevant to practice (Winters, Branion-Calles, et al., 2018). The broader project focused on three main objectives: (1) quantify population-level changes in cycling activity, perceived safety, and cycling collisions; (2) evaluate the spatial distribution of cycling infrastructure and cycling collisions; and (3) appraise the health-related economic benefits of the intervention (Winters, Branion-Calles, et al., 2018). To work towards these objectives, the IBIMS project team designed a survey to collect travel behaviour and sociodemographic data, created a spatial dataset to document the change in quality, quantity, and connectivity of the cycling network (Fischer & Winters, 2021; Winters, Fischer, et al., 2018), and estimated the monetary value of public health benefits associated with investments into AAA cycling infrastructure using the World Health Organization’s Health Economic Assessment Tool (HEAT) (Whitehurst et al., 2021). Data from the survey and spatial dataset are used within this thesis.

1.3. Guiding approach

My research fits within a Population Health Intervention Research (PHIR) approach. PHIR assesses an action, program, or policy with potential to impact population-level health outcomes, even if the intervention is implemented outside of the health sector (Hawe & Potvin, 2009). PHIR often aims to produce evidence useful for practitioners and policy makers (Moore et al., 2019). To achieve this aim, PHIR integrates interdisciplinary methods and theories to study why, for whom, how, and under what circumstances an intervention works (Moore et al., 2019). In other words, PHIR seeks to understand more than just the impact of an intervention, but also the contextual factors that influenced its success or failure (Craig et al., 2018; Hawe & Potvin, 2009). PHIR approaches are well suited to uncover inequalities, due to the established methods for identifying differential impacts amongst populations and growing guidance to account for context (Craig et al., 2018). The IBIMS project leveraged the strengths of PHIR to generate practical evidence on the overall impacts of cycling infrastructure investments in the mid-sized city context and impacts amongst different population groups.

1.4. Research Question

The aim of my thesis was to contribute evidence on the impacts of investments in AAA cycling infrastructure that is relevant to decision makers in the mid-sized city context, and ultimately support the transition to sustainable, healthy, and equitable communities. My thesis was guided by the following research question: **how does AAA cycling infrastructure impact cycling activity, perceived safety, and cycling accessibility overall and amongst different populations**? I completed two manuscripts that explored different aspects of this research question. The first manuscript examined cycling activity and perceived safety, to address the following objectives:

- Assess if the change in cycling activity and perceived safety over time in the intervention city (Victoria) was significantly different from change over time in the control cities (Kelowna and Halifax)
- Assess if change in cycling activity and perceived safety over time was significantly different between respondents closer and farther to AAA cycling infrastructure in the intervention city (Victoria), compared to the change over time in the control cities (Kelowna and Halifax)
- Characterize how change in cycling activity and perceived safety over time may vary for specific subgroups of the population

The second manuscript examined cycling accessibility, to address the following objectives:

- Identify areas in the intervention city (Victoria) that can be considered complete communities based on their access to destinations via low traffic stress cycling routes
- Assess how the intervention (the City of Victoria AAA cycling network) impacted access to destinations via low traffic stress cycling routes
- Assess distributional equity impacts by characterizing the sociodemographics of those who live in areas considered complete communities Victoria, compared with those who do not

1.5. Rationale

There is a strong practical, knowledge mobilization, and equity rationale for studying cycling infrastructure. From a practical perspective, cycling infrastructure warrants attention because it requires considerable public funds to build and maintain, it has a long life cycle and therefore enduring impact on the public realm, and it consumes valuable right-of-way space which faces competing demands from different modes. From a knowledge mobilization perspective, cycling infrastructure projects have opportunities for community engagement, and sharing study results in the public domain means research can be used directly by decision makers and advocates to inform future projects. From an equity perspective, the design of cycling infrastructure can be tailored to the preferences of certain groups, enabling the use of targeted strategies to increase diversity in who cycles (Huyen et al., 2019).

This thesis is well positioned to address key gaps in the literature. First, mid-sized cities present distinct planning considerations (Sotomayor & Flatt, Jo, 2018), yet natural experiment studies of cycling infrastructure in Canada have tended to focus on major urban centres (Frank et al., 2021; McGavock et al., 2022). Second, the transportation community is paying more attention to equity considerations (Doran et al., 2021), but there are gaps in the evidence on the equity impacts of cycling infrastructure. Numerous studies investigate the distribution of cycling infrastructure, but few take into account the quality of the cycling infrastructure and its effect on perceived safety across different population groups (Jahanshahi et al., 2021). There is also a lack of studies that capture who benefits from cycling infrastructure interventions over time (Houde et al., 2018). Thus, researchers have the opportunity to develop natural experiment studies in collaboration with city partners, produce context-specific evidence, and capture equity impacts.

1.6. Structure

This is a manuscript-based thesis structured around two manuscripts. Chapter 2 provides an overview of the literature to orient the reader. Chapter 3 presents the first manuscript, which combined survey data, spatial analysis, and statistical analysis to assess change in cycling activity and perceived safety over time. Chapter 4 presents the second manuscript, which leveraged open-source data and routing tools to assess change in accessibility over time. Chapter 5 summarizes the findings from both manuscripts and proposes takeaways for practice.

Chapter 2. Literature Review

2.1. Benefits of cycling

Cycling is a means of transportation and recreational activity that offers a variety of benefits to both the individual cyclist and wider population, as illustrated by the conceptual model developed by Krizek et al. (2009) in Figure 2.1. At the individual-level, there is a large body of evidence documenting the pathways between cycling, increased physical activity, and improved health outcomes, such as reduced risk of chronic disease (Götschi et al., 2015; Henriques-Neto et al., 2020; Mueller et al., 2015). Additionally, population-level health outcomes may arise through increased physical activity induced by cycling and translate to reduced health system costs (Whitehurst et al., 2021). In Canada, chronic disease is on the rise (Public Health Agency of Canada, 2017) and fewer than one in five adults meet the recommended amount of weekly physical activity (Colley et al., 2018); this clearly highlights the potential impact of cycling as a health-promoting behaviour.

In addition to health benefits, cycling can offer individuals an affordable, flexible alternative to public transit and car ownership (Heinen et al., 2010; Parker, 2019). Increasing the quality and quantity of cycling infrastructure can also improve access to essential services (Lin et al., 2021) and opportunities for social connection (Leger et al., 2019). At the population-level, bicycles do not generate the harmful externalities that are commonly associated with motor vehicles, such as noise pollution, air pollution, and congestion. Furthermore, shifting driving trips to cycling trips decreases greenhouse gas emissions (Zahabi et al., 2016), which is particularly important in the context of a climate emergency. On the whole, cycling offers net benefits to society, as demonstrated by consistent cost-benefit analyses (Gössling et al., 2019; Gössling & Choi, 2015).

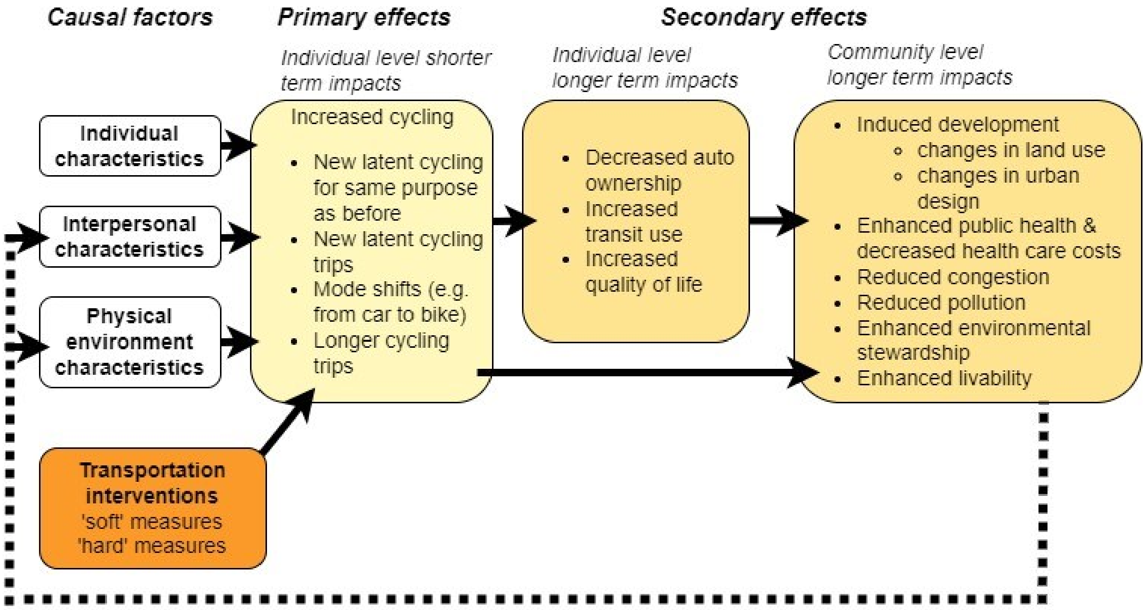


Figure 2.1 **Conceptual model of cycling causal factors and effects adapted from Krizek et al. (2009)**

2.2. Motivators and barriers to cycling

There are a variety of individual, interpersonal, and physical environment characteristics that can act as motivators or barriers to cycling, as summarized in Table 2.1. When it comes to the physical environment, there is consensus that the presence or absence of safe cycling infrastructure is one of the strongest drivers of cycling activity (Winters et al., 2017; Yang et al., 2019). In contrast, the influence of interpersonal relationships (Willis et al., 2015) and intersecting individual identities such as age, gender, race, and socioeconomic status yield more complex patterns of cycling activity (Yuan et al., 2023). For example, research indicates that gender may be associated with decisions to cycle, because women are more likely to be responsible for caregiving and therefore more likely to complete complex trips, sometimes with children, elderly family members, and goods in tow (Sersli et al., 2020; Shaw et al., 2020). This body of research informed the selection of priority population groups when assessing the impacts of cycling investments in this thesis.

Table 2.1 Characteristics that relate to cycling activity

Individual	Interpersonal	Physical environment
• Age • Bicycle ownership • Car ownership • Education • Employment status • Gender • Health, fitness, & disability • Income • Personal values • Race • Trip complexity & distance	• Community attitudes & social norms • Workplace attitudes & social norms	• Climate & weather • Connectivity • Cycling infrastructure ○ Quality ○ Quantity • End of trip facilities • Intersection controls • Land use diversity & density • Scenery • Topography • Traffic volumes & speeds

Sources: Heinen et al., 2010; Martens et al., 2021; Winters et al., 2010.

2.3. Cycling infrastructure, cycling activity, and safety

There is a large body of research on the complementary relationship between cycling infrastructure, cycling activity, and safety. Cities that build more cycling infrastructure experience greater increases in cycling activity overall, and larger decreases in cycling fatalities and severe injuries (Buehler & Pucher, 2021a). The provision of cycling infrastructure and low rates of injury help explain why cycling activity flourishes across population groups in certain European cities (Buehler & Pucher, 2021a). In contrast, unsafe cycling conditions persist as a major barrier to uptake in Canadian cities (Desjardins et al., 2021; Winters, Davidson, et al., 2010) and mode share remains low, particularly amongst women, older adults, and racialized people (MacEacheron et al., 2023).

Applying the Krizek et al. (2009) conceptual framework, cycling infrastructure is a hard measure intended to modify the safety of the physical environment for cycling and increase the perceived safety of cycling at the individual-level. The specific design of cycling infrastructure matters, because people prefer cycling infrastructure that is separated from motor vehicle traffic (Clark et al., 2019; Desjardins et al., 2021; Winters & Teschke, 2010). Groups that are underrepresented in cycling, such as women and older adults, express particularly strong preferences for cycling facilities separated from vehicles (Aldred, Elliott, et al., 2016). This preference is supported by epidemiological research that demonstrates separated cycling facilities improve actual safety outcomes

(Ling et al., 2020; Teschke et al., 2012; Zangenehpour et al., 2016). As a result, building cycling infrastructure that is separated or protected from vehicles is a promising strategy for increasing cycling activity overall, as well as attracting different populations to cycling (Pucher & Buehler, 2017).

This thesis focused on perceived safety because of the association with cycling infrastructure (Branion-Calles et al., 2019) and cycling activity (Boakye et al., 2023) described above. It is important to note that perceived safety of cycling infrastructure does not always align with actual safety outcomes (Winters et al., 2012), but data on actual safety outcomes was not available in comparable formats across study cities. Further, perceived safety is a complex construct influenced by individual, interpersonal, and physical environment characteristics (Campos Ferreira et al., 2022; Ravensbergen et al., 2020). It was outside of the scope of this thesis to exhaustively cover the full range factors that influence perceived safety.

2.4. Cycling and equity

Governments have limited resources to build transportation systems, therefore infrastructure is typically distributed unequally across communities (Pereira & Karner, 2021). Patterns of unequal infrastructure investments can disproportionately benefit some groups and create disadvantages for others, ultimately contributing to inequity (Martens et al., 2021). In Canada, a recent policy scan suggests efforts to address and operationalize equity in transportation planning are growing (Doran et al., 2021). Likewise, more transportation researchers are calling for approaches that explicitly consider *equity* and *justice* (Agyeman & Doran, 2021; Karner et al., 2020; Martens, 2016).

At a high level, *transportation equity* approaches focus on the fair distribution of the benefits and burdens of transportation systems across people and place (Karner et al., 2020). In contrast to equality, equitable approaches to (re)distribution are needs-based and prioritize the most disadvantaged (Lee et al., 2017). *Transportation justice* approaches aim to reform the societal structures and institutions that underpin transportation systems (Karner et al., 2020). While transportation equity approaches tend to focus on *distributive* issues, *transportation justice* approaches also consider issues of *process* (e.g., who participates in decision making?) and *recognition* (e.g., whose identities, knowledge, and history are valued?) (Karner et al., 2020). Both equity and justice approaches are critical in the effort to improve transportation systems. Language for equity and justice in the transportation field will continue to evolve with contemporary discussions and emerging practices.

This thesis aligns with a *transportation equity* approach more than the *transportation justice* approach, because of its focus on understanding the distribution of intervention benefits amongst different social groups and spatial neighbourhoods. Researchers and practitioners typically consider two scales of distribution: *social,* the (un)fair distribution of benefits and burdens across different demographic groups, and *spatial,* the (un)fair distribution of benefits and burdens across different geographic areas (Cunha & Silva, 2023; Lee et al., 2017) Thus, *socio-spatial approaches* to studying cycling equity may overlay maps of cycling infrastructure with neighbourhood-level demographics to identify areas and groups within the community that could benefit from improved transportation options (Doran et al., 2021).

Both social and spatial inequity exist in the Canadian cycling context. Women and certain racialized groups (Black, Indigenous, and South Asian) report less recreational cycling (Firth, Branion-Calles, et al., 2021) and commute cycling (Hosford & Winters, 2022). This disparity in who cycles translates into missed opportunities for individuals to experience the health, mobility, and social benefits of cycling. There are also spatial patterns of inequitable access to cycling infrastructure in Canadian cities (Firth, Hosford, et al., 2021; Fischer & Winters, 2021; Houde et al., 2018; Winters, Fischer, et al., 2018). To unpack these socio-spatial patterns of inequity, researchers and practitioners must consider the local history of land use and transportation system development, as well the intersectional factors that influence cycling.

Intersectionality is a concept developed by Dr. Kimberlé Crenshaw (1989) to describe how a person's identities can combine to amplify advantage and disadvantage in society. For example, although Black women share experiences of sexism with white women and racism with Black men, they experience the combined effects of sexism and racism differently (Crenshaw, 1989). In the context of cycling, past research focused on investigating differences between men and women, however, more research is starting to draw on the concept of intersectionality to explore the motivators and barriers to cycling for women of different racial, cultural, and class backgrounds (Lam, 2022; Yuan et al., 2023). Intersectionality underscores the need for transportation researchers and practitioners to consider differences within social groups, not just differences between groups.

2.5. Cycling accessibility

The fundamental value of transportation is its ability to help people reach destinations, fulfill basic needs, and participate in society (Litman, 2021; Martens et al., 2021; Pereira & Karner, 2021). As follows, providing people with spatial access to quality cycling infrastructure is an important starting point, but cycling networks must also connect people to everyday destinations. Within research and practice we see transportation metrics shifting away from measures of infrastructure availability and performance to holistic measures of accessibility (Litman, 2021; Siddiq & Taylor, 2021). In this context, accessibility can be defined as "*the ability to reach relevant activities, individuals or opportunities, which might require traveling to the place where those opportunities are located"* (Handy, 2005, as cited in Vale et al., 2016).

Amongst the different measures of accessibility, cumulative opportunities are most common in practice, followed by gravity-based (Boisjoly & El-Geneidy, 2017). Both measures estimate the number of destinations that can be reached from a given place within a certain time or distance (e.g., number of grocery stores accessible within 15 minutes of walking from the subway station at 4 km/hr). Gravity-based measures use distance-decay functions to prioritize destinations based on proximity to the origin point, whereas measures of cumulative opportunities weight all destinations the same, regardless of proximity (Levinson & King, 2020).

Some argue that gravity-based measures are more theoretically sound, because they capture the attractiveness of closer destinations (Palacios & El-Geneidy, 2022). However, recent studies demonstrated that cumulative opportunities approaches yield comparable results to the more complex gravity-based measures (Kapatsila et al., 2023; Palacios & El-Geneidy, 2022). Furthermore, current guidance (Levinson & King, 2020) recommends cumulative opportunity measures over alternatives, due to their relative ease of interpretation, usefulness for benchmarking, and capacity to leverage readily available datasets.

Accessibility analyses require information on the transportation network and destinations within a community. This information is typically sourced from government, proprietary, or open-source data such as OpenStreetMap (OSM), an online map of built environment features curated by volunteer data contributors around the world. The basic OSM data structure is known as a tag, which is composed of keys (the high-level category, for example, public_transport) and values (the detailed description, for example, bus_stop). Recently, researchers have leveraged OSM data to create measures of the built environment, such as the Canadian Active Living Environment (Can-ALE) dataset (Herrmann et al., 2019), the Canadian Bikeway Comfort and Safety Classification System (Can-BICS) (Ferster et al., 2023), and City Access Map, a global map of access to opportunities via walking (Nicoletti et al., 2022).

Ultimately, the choice of a dataset depends on the project aims. OSM is a crowdsourced dataset, and recent attention has turned to understanding the quality of OSM data. When it comes to transportation network data, the global road network is considered largely complete (Barrington-Leigh & Millard-Ball, 2017). In Canada, the length and location of the OSM road network and cycling infrastructure data are spatially comparable to reference data sources, but attribute accuracy has been shown to vary between cities and cycling infrastructure types (Ferster et al., 2023; H. Zhang & Malczewski, 2018). For the destination data, evidence suggests the quality of OSM destination data varies between categories. For example, a study of 49 German cities found that public-facing shops (e.g., retail) were more completely mapped than private businesses (e.g., offices) in OSM (Klinkhardt et al., 2023). Measures of temporal accuracy are rare, but a study of coffee shops in New York City found that the data was accurate enough to model trends over time (L. Zhang & Pfoser, 2019). Due to the wide variety of results across contexts and laborious process of ground-truthing data, there is a need for further research on indicators of OSM data quality (Klinkhardt et al., 2023).

Chapter 3. All ages and abilities cycling infrastructure, cycling activity, and perceived safety: Findings from a natural experiment study in three mid-sized Canadian cities

3.1. Introduction

Many cities set ambitious mode share targets for cycling as a strategy to address the interconnected challenges of chronic disease, climate change, and traffic congestion. Nevertheless, the private motor vehicle remains the predominant mode of transportation in Canada (Government of Canada, 2022), and safety concerns about cycling in traffic persist as a barrier to cycling uptake (Pearson et al., 2022). Transformational changes to the transportation system are required to make cycling safe and accessible. Since local decision makers have limited resources to make these required changes to achieve ridership goals, they look to research for strong evidence on intervention effectiveness.

Research shows an association between the built environment and cycling (Yang et al., 2019); cities that have more cycling infrastructure tend to have higher cycling mode share (Winters et al., 2016). However, the quality of infrastructure matters; designs that separate cyclists from vehicle traffic improves both perceived (Branion-Calles et al., 2019; Winters et al., 2012) and recorded safety outcomes (Ling et al., 2020; Teschke et al., 2012; Zangenehpour et al., 2016). Furthermore, this type of infrastructure is preferred by potential cyclists (Clark et al., 2019) and groups underrepresented in cycling who are more likely to express safety concerns, such older adults, women, and people cycling with children (Aldred, Elliott, et al., 2016; Buehler & Pucher, 2021b). In addition to quality, infrastructure proximity and connectivity also influence cycling behaviour (Teschke et al., 2017). Thus, the construction of networks of cycling infrastructure designed to be comfortable for a range of ages and abilities could address safety concerns, attract different people to cycling, and increase ridership, particularly for those with better access to the infrastructure (Buehler & Dill, 2016).

Cycling infrastructure has clear potential to support cycling, yet ridership remains low in mid-sized Canadian cities, suggesting stronger evidence is required. Randomized controlled trials (RCTs) are rarely feasible when assessing extensive population health interventions. Natural experiments present a promising alternative, because real world interventions with naturally-occurring differences in exposure enable researchers to emulate experimental designs and compare impacts on different groups (Craig et al., 2017). However, study designs for causal inference in cycling are still evolving (Aldred, 2019). A 2018 systematic review of 11 studies (Stappers et al., 2018) and a 2019 systematic review of 31 studies (Mölenberg et al., 2019), both investigating cycling infrastructure, revealed that many of these studies did not include methods to mitigate bias, such as control sites, individual-level exposure measurement, follow-up periods longer than one year, or testing for statistical differences. Consequently, there are opportunities to improve the internal validity of the existing evidence base, by designing studies with more comprehensive controls for bias. Furthermore, investigating contexts outside of the USA has the potential to enhance external validity (Benton et al., 2016). Natural experiments in Canada have tended to focus on standalone interventions (i.e., new bike lanes or multi-use trails) in major urban centres (Frank et al., 2021; McGavock et al., 2022), rather than full networks.

In 2017, the City of Victoria in British Columbia, Canada started to build a 33 kilometre 'all ages and abilities' (AAA) network. The IBIMS project was a natural experiment study, co-designed with municipal partners, to provide a rigorous evidence base on the impacts of this investment (described in detail in (Winters, Branion-Calles, et al., 2018)). The study design compared the intervention in Victoria with two control cities: Kelowna, British Columbia and Halifax, Nova Scotia. This work falls within population health intervention research, an area of research that studies a population-level action, program, or policy, often outside of the health sector, and assesses the impacts on health and equity (Hawe & Potvin, 2009).

In this paper, our aim was to assess how investments in AAA infrastructure impacted the outcomes of self-reported cycling activity and perceived safety. We started with a difference-in-difference approach, to compare changes in the outcomes over time, in the intervention versus control cities. Then, to better reflect individual-level exposures (not only city-level exposures), we used a triple-difference approach to compare the difference in the change in these outcomes over time between respondents who live closer and farther from AAA cycling facilities in the intervention city of Victoria, compared with the control cities. Finally, we looked at how changes may vary for specific subgroups of the population.

3.2. Methods

3.2.1. Study cities

Kelowna, British Columbia and Halifax, Nova Scotia were selected as control cities based on similarities with the intervention city (see Table 3.1). All three cities are regional hubs for employment and education with climate, transportation, and land use patterns influenced by large bodies of water. In 2016, Victoria had a cycling commute mode share that was more than double that of Kelowna and four times that of Halifax (Table 3.1). There were no plans to build AAA cycling networks in Kelowna or Halifax when the study was conceived.

We acknowledge that in observational studies there is never a perfect control site. At the outset of the study, we assessed potential municipalities based on size, urban layout and climate, and importantly, input from local governments indicating that these were ‘peer’ cities which they would use for comparisons in a transportation context (Winters, Branion-Calles, et al., 2018). Kelowna, located in Interior BC, falls under the same provincial jurisdiction and has an urban core surrounded by lower density areas, similar to Victoria. Although not on the ocean, Kelowna also experiences climate moderation from a major lake. Halifax is a regional municipality, but the metropolitan core (Peninsula, Mainland and Dartmouth) is a suitable comparator to Victoria and adjacent municipalities. Both Halifax and Victoria are provincial capitals, coastal settings, and share more moderate climates relative to other Canadian cities. We originally considered Nanaimo, another mid-sized city closer to Victoria, but our study city partners indicated this was an unsuitable comparison due to its sprawling, linear layout and the highway cutting through the city.

Table 3.1 Key characteristics of study cities at baseline (2016) and 2021

	2016			2021		
	Halifax [a]	**Kelowna [b]**	**Victoria [c]**	**Halifax [a]**	**Kelowna [b]**	**Victoria [c]**
Count of dissemination areas	320	167	390	325	167	395
Land Area (km^2)	121.5	211.8	140.6	121.5	211.8	140.4
Population [d]	204,709	127,380	234,955	228,028	144,576	244,403
Population density (people/km^2) [d]	1,685	601	1,671	1,877	683	1,741
Proportion of residents that cycle to work [d]	1.7%	3.7%	8.6%	0.9%	2.4%	6.9%
Total cycling infrastructure (km) [e]	83	247	193	89	277	207
Total AAA infrastructure (km) [e]	45	86	74	54	106	89
Proportion (95% CI) of survey respondents that live, work, or study within 500 m of AAA infrastructure [e]	44% (40-48%)	61% (57-64%)	51% (47-54%)	53% (50-57%)	63% (59-66%)	64% (61-68%)

AAA = all ages and abilities, CI = confidence interval.

[a] Limited to the core of the regional municipality including Peninsular Halifax, Mainland Halifax, and Dartmouth.

[b] Excludes neighbouring municipality of West Kelowna.

[c] Includes Victoria as well as neighbouring municipalities of Esquimalt, Oak Bay, and Saanich.

[d] Source: 2016 & 2021 Census of Canada, profile data for Victoria, Kelowna, and Halifax at the dissemination area level (Statistics Canada, 2016).

[e] Source: Impacts of Bicycle Infrastructure in Mid-Sized Cities (IBIMS) spatial dataset.

3.2.2. Study sample

Details of the population survey are published elsewhere (Winters, Branion-Calles, et al., 2018). In brief, a market research firm administered a city-wide phone survey that collected sociodemographic, postal code, and cycling data from 1000 adults ($\geq$ 18 years) in each study city at three timepoints: 2016 (‘before’ AAA network), 2019, and 2021 (considered ‘after’ AAA network) for a total sample of 9000. Respondents were recruited using age and gender quotas. The proportion of adults that were contacted, deemed eligible, and completed the phone survey decreased in each wave (cooperation rates were 15.7% in 2016, 11.3% in 2019, and 10.8% in 2021). We geocoded the postal code data and excluded 1681 respondents from the analytic dataset because they did not live, work, or study within the study area boundaries. We then used census data to calculate post-stratification weights, so that the sample reflected the age and gender distribution of each study city (weights ranged from 0.61 to 4.65). The weighted analytic dataset comprised 7314 respondents in total: 2432 in 2016, 2413 in 2019 and 2469 in 2021. This sample size is sufficient to detect small changes in the mean difference in outcomes (~700 respondents per study city per year), based on the power calculation published in the protocol paper (Winters, Branion-Calles, et al., 2018). The Simon Fraser University Office of Research Ethics approved the IBIMS project (study number 2016s0401).

3.2.3. Infrastructure data

We created a spatial dataset of the location, length, and type of infrastructure in each study city from 2016 to 2021, based on data provided by study city partners. Infrastructure was digitized along the road centreline, so roads with infrastructure on both sides were only recorded once in this dataset (Fischer & Winters, 2021). We did not consider sharrows, demarcating road segments shared by people on bicycles and people in motor vehicles, as infrastructure in our dataset (Winters, Fischer, et al., 2018). We standardized the different types of infrastructure across study cities, through a combination of reviewing Google Streetview, Google Earth, site visits, and discussions with study city partners (Winters, Fischer, et al., 2018). We used the following categories for cycling infrastructure types: local street bikeways, off-street paths, protected bike lanes, painted bike lanes, and suggested bike routes (see Appendix A for definitions).

There is no consistent definition of AAA infrastructure across local design guidelines (e.g., British Columbia's Active Transportation Guidelines (Ministry of Infrastructure and Transportation, 2019), Can-BICS (Winters et al., 2020), Level of Traffic Stress (Mekuria et al., 2012), and NACTO's Designing for All Ages & Abilities (National Association of City Transportation Officials, 2017). Consequently, we adopted the City of Victoria's approach and deemed local street bikeways, off-street paths, and protected bike lanes as AAA for the purposes of measuring exposure. These types of infrastructure reduce cyclists' interactions with vehicles through protection, separation, or traffic calming treatments. Painted bike lanes and suggested bike routes with only signs or sharrows do not reduce cyclists' interaction with vehicles in the same way, therefore they were not considered AAA.

3.2.4. Measures

Our primary outcomes are cycling activity and perceptions of cycling safety. These outcomes were identified as important by city government partners, and are outcomes that are associated with cycling infrastructure (Campos Ferreira et al., 2022; Yang et al., 2019). Thus, we derived two outcomes of interest from the survey data: the proportion of respondents that reported cycling activity (i.e., responded "yes" to the survey question, "In the previous 12 months, have you used a bicycle?"), and the proportion of respondents that reported safe perceptions of cycling in their study city (i.e., responded '1- very safe' or '2 - safe' to the survey question, "On a scale of 1 to 5 (1 being very safe and 5 being very dangerous"), overall, how safe do you think cycling is in your city?"). Respondents answering 'don't know' or 'refused' for the outcome questions were excluded from modelling (*n* = 3 for the cycling activity model, *n* = 159 for the perceived safety model).

All survey respondents with outcome data were included in the analysis and classified as 'exposed' or 'unexposed' to AAA infrastructure. Exposure was defined as living, working, or studying within 500 metres of AAA infrastructure, to include a range of regular destinations. Only one of these destinations had to meet the distance threshold for the respondent to be considered exposed to AAA infrastructure. We selected the 500 metre threshold to align with the City of Victoria's target: at full build out, 95% of the municipality will have access to AAA infrastructure within 500 metres (City of Victoria, n.d.); this threshold was of policy relevance to our study partners. Furthermore, 500 metres has been used to define exposure in past investigations of built environment interventions and cycling (Hosford et al., 2019; Hosford & Winters, 2018). Past work in urban contexts suggest that cyclists may travel an additional 7-10% of the trip distance, making these detours in order to reach cycling infrastructure (Krenn et al., 2014; Winters, Teschke, et al., 2010).

We measured exposure as the road network distance between the respondent's geocoded place of home, work, or study and the nearest AAA infrastructure, using the Closest Facility Analysis tool (ArcGIS Pro version 2.9.0). We used the Statistics Canada Road Network File (Statistics Canada, 2021) to build a separate network dataset for each study city and study year. We used our cycling infrastructure dataset and converted the linear segments to points at 50-metre intervals for use in the Closest Facility Analysis tool. In this way, we measured the distance to the nearest AAA infrastructure for each respondent and converted this continuous measure to a binary exposure variable (≤ 500 metres = exposed, or 'closer' within the text that follows; > 500 metres = unexposed or 'farther').

We identified potential confounders based on a literature review of cycling barriers and facilitators. The covariates in the analytic dataset (Table 3.2) included age, gender, bike access, car access, having children under the age of 16 living at home, having a disability that limits cycling, highest level of education attained, employment status, household income before taxes, and race.

Many respondents did not provide complete income information (*n* = 1111, 15% of weighted and pooled sample), therefore we retained this as a separate category. For other variables, approximately 4% of respondents provided at least one "don't know", "refused", or an ambiguous "other" response that did not relate to the question. We imputed these values using the multiple imputation by chained equation (MICE) algorithm. Responses for outcome variables were not imputed. We generated 10 imputed datasets using the mice package version 3.14 (Buuren & Groothuis-Oudshoorn, 2011) at default settings in RStudio version 2022.07.01+554. We did not use the respondent ID, weight, or exposure variables to predict the missing values. We used the analytic dataset prior to imputation to calculate the descriptive statistics shown in Table 3.2. We used the imputed datasets for modelling. Parameters were pooled according to Rubin's rules (Buuren & Groothuis-Oudshoorn, 2011).

Table 3.2 Weighted sociodemographic characteristics of baseline (2016) survey respondents that live, work, or study within study boundaries by study city

Sample characteristics	Halifax N = 764 *n* (%)	Kelowna N = 826 *n* (%)	Victoria N = 842 *n* (%)
Age (years)			
18-34	268 (35)	225 (27)	236 (28)
35-54	226 (30)	251 (30)	249 (30)
55-75+	270 (35)	351 (42)	358 (42)
Gender (reference = men) [a]			
Women	402 (53)	431 (52)	442 (52)
Bike access (reference = access)			
No bike access	344 (45)	225 (27)	228 (27)
Birth country (reference = Canada)			
Born outside Canada	154 (20)	126 (15)	176 (21)
Car access (reference = access)			
No car access	110 (14)	43 (5)	83 (10)
Children <16 years at home (reference = none)			
At least one child <16 years at home	152 (20)	198 (24)	189 (22)
Disability (reference = none)			
Disability that might limit ability to bike	137 (18)	155 (19)	158 (19)
Education			
High school or less	154 (20)	198 (24)	131 (16)
Post secondary [b]	458 (60)	518 (63)	528 (63)
Graduate/Professional degree	145 (19)	103 (12)	170 (20)
Employment (reference = working for pay)			
Not working for pay [c]	229 (30)	316 (38)	318 (38)
Household income			
Less than \$50k	207 (27)	212 (26)	223 (26)
\$50k to < \$100k	209 (27)	230 (28)	239 (28)
\$100k to < \$150k	112 (15)	148 (18)	135 (16)
\$150k or more	94 (12)	95 (12)	99 (12)
Other [d]	143 (19)	141 (17)	146 (17)
Race (reference = White)			
Racialized [e]	141 (18)	68 (8)	99 (12)

Total “don’t know”, “refused”, or “other” responses by variable: bike access = 0, birth country = 10, car access = 0, children at home = 0, disability = 16, education = 27, employment = 33, race = 44.

[a] The instrument was not originally designed to reflect gender diversity beyond the gender binary.

[b] Combines responses: “college/vocational/technical school”, “some university”, and “graduated university”.

[c] “Not working for pay” combines responses: “homemaker”, “student”, “retired” and “unemployed”.

[d] Combines responses: “don’t know”, “refused”, and “other”.

[e] Combines responses: “Indigenous (First Nations, Metis, Inuk/Inuit)”, “South Asian”, “Black”, “Latinx”, “East/Southeast Asian”, “Middle Eastern”, and “Multiracial”.

3.2.5. Statistical analysis

We used the gtsummary package (Sjoberg et al., 2021) to run descriptive analysis on sociodemographic characteristics, outcomes, and exposure over time in each study city. We completed chi square tests to test associations between the proposed covariates and potential trends. For multivariable modeling, we fit a series of logistic regression models to examine the association between of living, working, or studying within 500 metres of AAA cycling infrastructure. In the first series of models, the outcome variable was self-reported cycling activity within the last year (*n* = 7316 after imputation and before weighting). In the second series, the outcome variable was perceived safety of cycling (*n* = 7157 after imputation and before weighting).

We started with a difference-in-difference approach to estimate how the interaction between time and study city impacted cycling activity and perceived safety. An alternative approach would have been a time*exposure interaction to test the main effect of cycling interventions across all cities, but our research specifically aimed to test the effect of the AAA cycling intervention in Victoria, compared to the control cities Kelowna and Halifax. The intent behind our choice to start with the time*study city interaction was to compare the city-level response to the intervention, regardless of individual-level access to AAA cycling infrastructure. This approach considers all respondents in Victoria (intervention city) as exposed and assumes all respondents in Kelowna and Halifax (control cities) are unexposed. In reality, the control cities had some AAA infrastructure at baseline (see Table 3.1). Additionally, even within the study cities, some residents live closer to the infrastructure, and some farther. Proximity to infrastructure is associated with higher cycling (Zahabi et al., 2016), particularly separated infrastructure (Teschke et al., 2017). Consequently, our primary analysis adds another 'difference' level for comparison: respondents who live, work or study closer to AAA infrastructure ($\leq$ 500 metres) and those farther from AAA infrastructure (i.e., unexposed to the intervention).

This additional variable enabled a triple-difference analysis to ascertain how the interaction between time (year), study city, and exposure (proximity to AAA) impacted cycling activity and perceived safety. Essentially, this model compares people living in different locations in the same city as well as across cities, over time. The triple-difference approach was operationalized through an interaction term (time*study city*exposure). The reference level was set at year = 2016, study city = Halifax, and exposure = unexposed. In this analysis, we expected cycling activity and perceived safety to increase over time (difference in baseline and follow up), to increase more for respondents living, working, or studying closer to AAA cycling infrastructure compared to respondents farther away (difference in exposed and unexposed groups), and to increase more for respondents in Victoria compared to Halifax and Kelowna (difference across intervention and control cities). As follows from our hypothesis, we anticipated the odds ratio for the term 2021*Victoria*Exposed to be greater than those for the 2021*Halifax*Exposed, 2021*Kelowna*Exposed, and 2021*Victoria*Unexposed terms.

We used the interactions package (Long, 2019) to plot the model coefficients as point estimates and understand how the predicted probability of the outcomes of interest changed over time, based on the interaction between time, study city, and exposure. We also used the gtsummary package (Sjoberg et al., 2021) to calculate odds ratios for comparison with the plots and to aid interpretation of the results. The odds ratios estimate the odds of the outcome for a particular group of respondents, compared to the odds of the outcome in the reference group.

We completed sensitivity analysis to better understand the effect of time, study city, and exposure to AAA infrastructure on subgroups of the sample, including older adults (≥ 55 years) and women. We selected these subgroups prior to analysis based on the AAA rationale of the intervention (Winters, Branion-Calles, et al., 2018). We did not complete a stratified analysis for people with children living at home as originally planned in our protocol paper, because the sample size was too small for this subgroup. For another sensitivity analysis, we lowered the exposure threshold from 500 metres to 100 metres, as a stricter definition for determining proximity to AAA infrastructure.

3.3. Results

3.3.1. Descriptives

Table 3.1 provides an overview of how the cycling network evolved over time in each study city. From 2016 to 2021, Halifax built 9 kilometres of new AAA infrastructure, Kelowna built 20 kilometres, and Victoria built 15 kilometres, reflecting an overall growth in their network distance by 7%, 12% and 7%, respectively. The proportion of respondents living closer to AAA infrastructure increased by 9% in Halifax, 2% in Kelowna, and 13% in Victoria.

Table 3.2 summarizes sociodemographic characteristics of respondents that lived, worked, or studied within the study area at baseline (see Appendix B for all study years). Within each study city, there were negligible changes in sample characteristics over time, meeting a core assumption of difference-in-difference analysis. The age, gender, race, and employment composition of the sample generally reflects the underlying population (see Appendix C). However, people with less education and income were underrepresented in each study city.

Table 3.3 shows that cycling activity was higher at all three timepoints in Victoria and Kelowna compared to Halifax. All study cities experienced modest increases in cycling over time from baseline to the second follow up (8% in Halifax, 8% in Kelowna, and 2% in Victoria). Table 3.4 shows that the cities started with different baseline proportions of perceived safety; ~9% more respondents in Victoria reported perceived safety than in Kelowna, and ~19% more than in Halifax. Over the study period there were only small shifts in perceived safety (3%, 1%, and 0% respectively).

Table 3.3 Cycling activity by year, study city, and exposure to AAA cycling infrastructure [a]

Year & study city	All respondents weighted *n* = 7314 % (95% CI)	Exposed [b] weighted *n* = 4211 % (95% CI)	Unexposed weighted *n* = 3103 % (95% CI)
2016, Halifax	33 (30-37)	35 (30-40)	32 (27-36)
2019, Halifax	34 (30-37)	36 (31-41)	31 (26-37)
2021, Halifax	41 (37-44)	44 (39-49)	37 (33-42)
2016, Kelowna	50 (46-53)	50 (46-54)	49 (43-54)
2019, Kelowna	56 (52-59)	58 (53-62)	53 (47-58)
2021, Kelowna	58 (54-61)	60 (55-64)	55 (49-61)
2016, Victoria	51 (48-54)	54 (49-58)	48 (43-53)
2019, Victoria	55 (51-59)	58 (53-62)	50 (45-56)
2021, Victoria	53 (49-57)	53 (48-57)	53 (47-60)

AAA = all ages and abilities, CI = confidence interval.

[a] Based on the survey question: “In the previous 12 months, have you used a bicycle?”

[b] Exposed indicates living, working, or studying $\leq$ 500 metres from AAA cycling infrastructure, while unexposed is > 500 metres.

Table 3.4 Perceived safety by year, study city, and exposure to AAA cycling infrastructure [a]

Year & study city	All respondents weighted *n* = 7143 % (95% CI)	Exposed [b] weighted *n* = 4135 % (95% CI)	Unexposed weighted *n* = 3008 % (95% CI)
2016, Halifax	27 (24-30)	28 (23-33)	26 (22-31)
2019, Halifax	25 (22-29)	24 (20-30)	26 (21-32)
2021, Halifax	27 (24-29)	31 (26-35)	23 (19-28)
2016, Kelowna	37 (34-41)	35 (30-38)	40 (35-46)
2019, Kelowna	35 (31-38)	36 (31-39)	33 (27-38)
2021, Kelowna	38 (35-41)	39 (34-43)	37 (30-41)
2016, Victoria	46 (43-49)	49 (45-54)	43 (38-47)
2019, Victoria	47 (43-51)	48 (43-53)	45 (40-51)
2021, Victoria	49 (46-53)	49 (45-54)	50 (44-57)

AAA = all ages and abilities, CI = confidence interval.

[a] Based on the survey question “On a scale of 1 to 5 (1 being very safe and 5 being very dangerous”), overall, how safe do you think cycling is in your city?”, where ”safe” combines responses ‘1- very safe’ and ‘2 – safe’.

[b] Exposed indicates living, working, or studying $\leq$ 500 metres from AAA cycling infrastructure, while unexposed is > 500 metres.

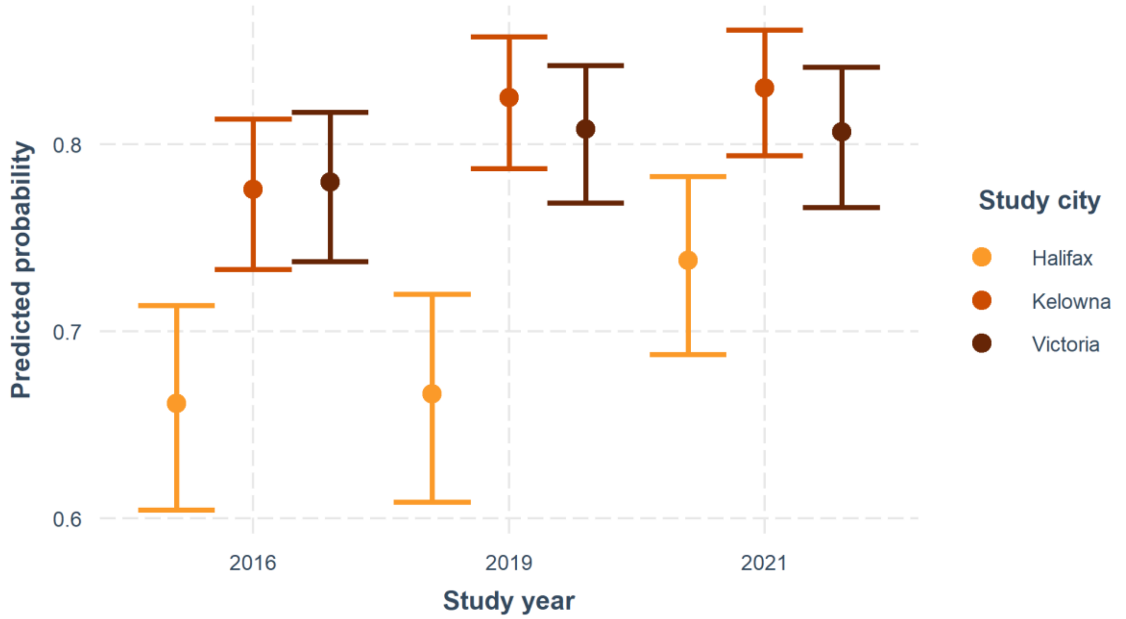
3.3.2. Difference-in-difference approach

The first difference-in-difference analysis estimated how the interaction between time and study city affects cycling activity. These results compare the effect of the intervention at the city-level, regardless of individual-level access to AAA infrastructure. Figure 3.1 Panel A shows that, at baseline, Halifax had the lowest predicted probability of cycling (0.66, 95% CI: 0.61-0.72), while Kelowna and Victoria started with approximately the same predicted probability (~0.78, 95% CI: 0.74-0.82). At the study mid-point, in 2019, there was negligible change in the predicted probability in Halifax (0.67, 95% CI: 0.61-0.72), while Kelowna and Victoria experienced modest increases in predicted probability to 0.83 (95% CI: 0.79-0.86) and 0.81 (95% CI: 0.77-0.84), respectively. In 2021, Halifax experienced the largest increase in predicted probability, reaching 0.74 (95% CI: 0.69-0.79), while predicted probability in Kelowna and Victoria remained stable at 0.83 (95% CI: 0.80-0.86) and 0.81 (95% CI: 0.77-0.84).

The odds ratios in Table 3.5 show there were significant baseline differences in cycling activity between the study cities. In 2016, the adjusted odds of cycling were 1.77 greater in Kelowna (95% CI: 1.38-2.27) and 1.81 greater in Victoria (95% CI: 1.42-2.32), compared to Halifax. Over time, only Halifax experienced a significant increase in the adjusted odds of cycling (OR: 1.44, 95% CI: 1.12-1.86). The significant interaction term between year and study city (2021*Halifax) indicates that cycling increased more over time in Halifax than in other cities.

For the second outcome of interest, there were significant differences in perceived safety between the study cities at baseline, as evidenced by both the predicted probability plot (Figure 3.1 Panel B) and odds ratios (see terms 2016*Kelowna and 2016*Victoria in Table 3.6). Halifax had the lowest predicted probability of perceived safety of cycling (0.26, 95% CI: 0.21-0.30), followed by Kelowna (0.37, 95% CI: 0.32-0.42), then Victoria (0.45, 95% CI: 0.40-0.50). This sequence did not change at the first or second follow up. The difference-in-difference analysis showed no significant changes in perceived safety over the study period in any study city.

A. Cycling activity (weighted n = 7314)



B. Perceived safety (weighted n = 7143)

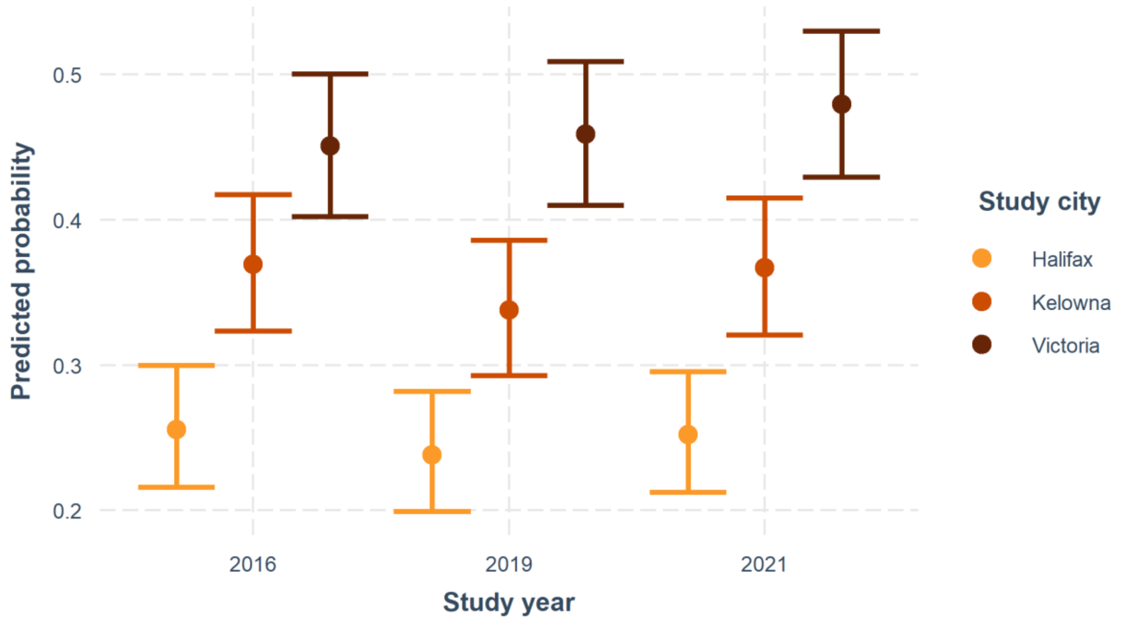


Figure 3.1 **Panel A. Predicted probability of cycling activity by year and study city. Panel B. Predicted probability of perceived safety by year and study city.**

Results of adjusted and weighted difference-in-difference logistic regression models estimating associations between the outcome, time, study city, and the interaction between time and study city, where the point represents the predicted probability and the bars represent the 95% confidence interval.

Table 3.5 Odds of cycling activity from the difference-in-difference analysis (weighted *n* = 7314)

Year * Study city	Unadjusted OR	95% CI	Adjusted OR [a]	95% CI
2016 * Halifax	reference	-	reference	-
2019 * Halifax	1.02	0.83, 1.27	1.02	0.78, 1.33
2021 * Halifax	**1.40**	**1.14, 1.71**	**1.44**	**1.12, 1.86**
2016 * Kelowna	**1.98**	**1.62, 2.43**	**1.77**	**1.38, 2.27**
2019 * Kelowna	1.25	0.94, 1.67	1.33	0.93, 1.90
2021 * Kelowna	1.00	0.76, 1.32	0.98	0.69, 1.39
2016 * Victoria	**2.10**	**1.72, 2.57**	**1.81**	**1.42, 2.32**
2019 * Victoria	1.15	0.86, 1.53	1.16	0.82, 1.65
2021 * Victoria	0.78	0.59, 1.03	0.82	0.58, 1.15

CI = confidence interval, OR = odds ratio.

Bold indicates odds ratio that is significantly different than 1.00 (i.e., confidence interval does not include 1.00).

[a] Adjusted for age, gender, bike access, birth country, car access, children at home, disability, education, employment, household income, and race.

Table 3.6 Odds of perceived safety from the difference-in-difference analysis (weighted *n* = 7143)

Year * Study city	Unadjusted OR	95% CI	Adjusted OR [a]	95% CI
2016 * Halifax	reference	-	reference	-
2019 * Halifax	0.91	0.72, 1.15	0.91	0.72, 1.15
2021 * Halifax	1.00	0.80, 1.26	0.98	0.78, 1.23
2016 * Kelowna	**1.59**	**1.28, 1.98**	**1.71**	**1.37, 2.13**
2019 * Kelowna	0.99	0.73, 1.35	0.96	0.70, 1.31
2021 * Kelowna	1.03	0.76, 1.39	1.01	0.74, 1.37
2016 * Victoria	**2.30**	**1.86, 2.85**	**2.39**	**1.93, 2.97**
2019 * Victoria	1.14	0.84, 1.54	1.13	0.84, 1.54
2021 * Victoria	1.14	0.85, 1.54	1.14	0.85, 1.55

CI = confidence interval, OR = odds ratio.

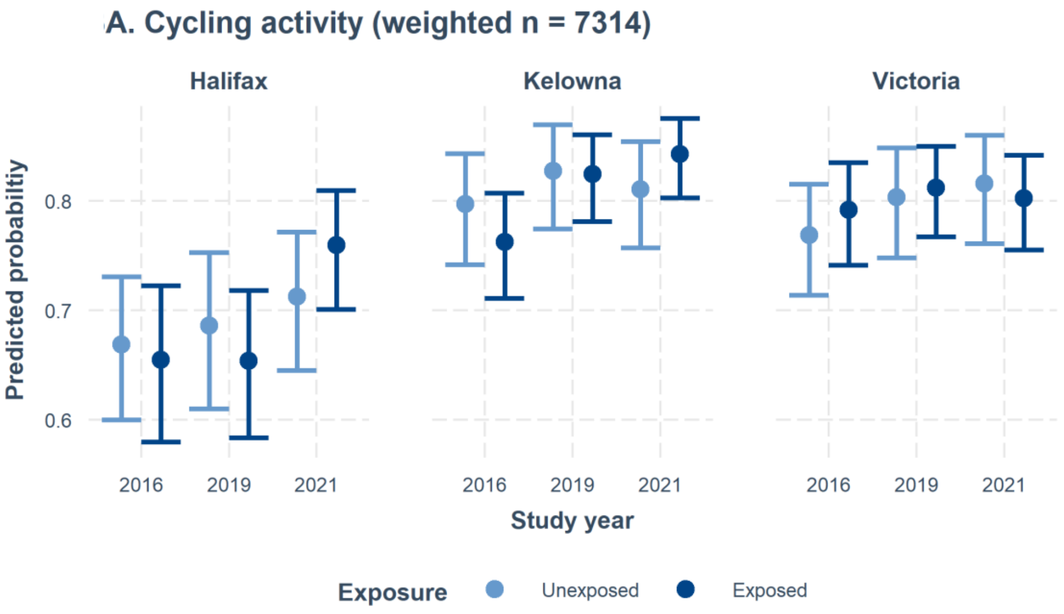
Bold indicates odds ratio that is significantly different than 1.00 (i.e., confidence interval does not include 1.00).

[a] Adjusted for age, gender, bike access, birth country, car access, children at home, disability, education, employment, household income, and race.

3.3.3. Triple-difference approach

The first triple-difference analysis estimated how the interaction between time, study city, and exposure impacts cycling activity. These results account for individual-level access to AAA infrastructure. Figure 3.2 Panel A illustrates that respondents closer and farther from AAA infrastructure started with similar predicted probabilities of cycling activity in all three cities (~2-4% difference between the exposed and unexposed groups). Across study cities, the predicted probability of cycling increased over time. In 2021, Halifax had a slightly larger difference between respondents closer to AAA infrastructure and those farther away (~5%), compared to Kelowna (~3% difference) and Victoria (~2% difference). The odds ratios presented in Table 3.7 suggest there were no statistically significant differences in the change over time between respondents living closer and farther from AAA infrastructure.

Similar to the difference-in-difference analysis, baseline variation in perceived safety between the three study cities was also apparent in the triple-difference analysis. In Halifax and Kelowna, the predicted probability of perceived safety decreased over time for respondents farther from AAA infrastructure and increased slightly over time for respondents closer to AAA infrastructure. At the end of the study, there was almost no difference between the predicted probability of respondents closer and farther from AAA infrastructure in Victoria, due to the lack of change in the exposed group and steady increase in the unexposed group over time. The triple-difference analysis yielded a statistically significant odds ratio shown in Table 3.8 that suggests living, working, or studying farther from AAA bicycle infrastructure is associated with larger increases of perceived safety over time in Victoria (OR 1.59, 95% CI: 1.01-2.50).


A. Cycling activity (weighted n = 7314)

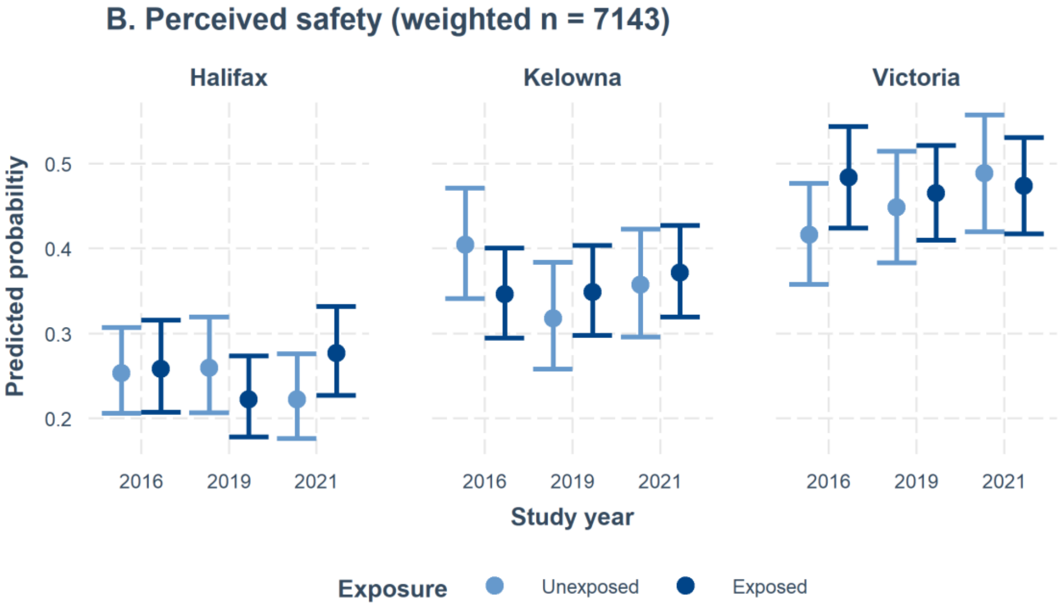

B. Perceived safety (weighted n = 7143)

Figure 3.2 Panel A: Predicted probability of cycling activity by year, study city, and exposure. Panel B: Predicted probability of perceived safety by year, study city, and exposure

Results of adjusted and weighted triple-difference logistic regression models estimating associations between the outcome, time, study city, exposure, and the interaction between time, study city, and exposure, where the point represents the predicted probability and the bars represent the 95% confidence interval. Unexposed indicates living, working, or studying > 500 metres from AAA (all ages and abilities) cycling infrastructure, while exposed is ≤ 500 metres.

Table 3.7 **Odds of cycling activity from the triple-difference analysis (weighted *n* = 7314)**

Year * Study city * Exposure	Unadjusted OR	95% CI	Adjusted OR [a]	95% CI
2016 * Halifax * Unexposed	reference	-	reference	-
2019 * Halifax * Unexposed	0.97	0.71, 1.33	1.08	0.74, 1.59
2021* Halifax * Unexposed	1.29	0.96, 1.72	1.23	0.86, 1.77
2016 * Halifax * Exposed	1.15	0.85, 1.56	0.94	0.65, 1.36
2019 * Halifax * Exposed	1.06	0.69, 1.64	0.92	0.54, 1.57
2021 * Halifax * Exposed	1.13	0.75, 1.71	1.35	0.81, 2.26
2016 * Kelowna * Unexposed	**2.05**	**1.52, 2.76**	**1.95**	**1.35, 2.82**
2019 * Kelowna * Unexposed	1.19	0.77, 1.86	1.12	0.65, 1.94
2021 * Kelowna * Unexposed	1.00	0.65, 1.54	0.88	0.52, 1.49
2016 * Kelowna * Exposed	0.91	0.61, 1.38	0.87	0.53, 1.43
2019 * Kelowna * Exposed	1.10	0.61, 1.98	1.30	0.63, 2.68
2021 * Kelowna * Exposed	1.01	0.57, 1.79	1.13	0.56, 2.29
2016 * Victoria * Unexposed	**2.01**	**1.51, 2.66**	**1.65**	**1.17, 2.32**
2019 * Victoria * Unexposed	1.12	0.73, 1.71	1.13	0.67, 1.91
2021 * Victoria * Unexposed	0.96	0.63, 1.45	1.08	0.65, 1.81
2016 * Victoria * Exposed	1.08	0.72, 1.62	1.22	0.74, 2.00
2019 * Victoria * Exposed	1.03	0.58, 1.84	1.00	0.49, 2.04
2021 * Victoria * Exposed	0.70	0.39, 1.23	0.59	0.29, 1.19

CI = confidence interval, OR = odds ratio.

Bold indicates odds ratio that is significantly different than 1.00 (i.e., confidence interval does not include 1.00).

Unexposed indicates living, working, or studying > 500 metres from AAA (all ages and abilities) cycling infrastructure, while exposed is ≤ 500 metres.

[a] Adjusted for age, gender, bike access, birth country, car access, children at home, disability, education, employment, household income, and race.

Table 3.8 Odds of perceived safety from the triple-difference analysis (weighted *n* = 7143)

Year * Study city * Exposure	Unadjusted OR	95% CI	Adjusted OR [a]	95% CI
2016 * Halifax * Unexposed	reference	-	reference	-
2019 * Halifax * Unexposed	1.02	0.73, 1.42	1.03	0.74, 1.45
2021* Halifax * Unexposed	0.85	0.61, 1.17	0.84	0.61, 1.18
2016 * Halifax * Exposed	1.10	0.79, 1.52	1.03	0.74, 1.42
2019 * Halifax * Exposed	0.81	0.51, 1.30	0.89	0.50, 1.28
2021 * Halifax * Exposed	1.34	0.85, 2.11	1.30	0.82, 2.07
2016 * Kelowna * Unexposed	**1.91**	**1.40, 2.62**	**2.00**	**1.45, 2.76**
2019 * Kelowna * Unexposed	0.71	0.44, 1.14	0.66	0.41, 1.07
2021 * Kelowna * Unexposed	1.01	0.63, 1.60	0.97	0.61, 1.55
2016 * Kelowna * Exposed	0.72	0.47, 1.12	0.76	0.49, 1.18
2019 * Kelowna * Exposed	1.78	0.95, 3.35	1.85	0.98, 3.51
2021 * Kelowna * Exposed	1.03	0.56, 1.91	1.05	0.56, 1.95
2016 * Victoria * Unexposed	**2.08**	**1.55, 2.80**	**2.10**	**1.56, 2.84**
2019 * Victoria * Unexposed	1.09	0.70, 1.71	1.10	0.70, 1.73
2021 * Victoria * Unexposed	**1.58**	**1.01, 2.47**	**1.59**	**1.01, 2.50**
2016 * Victoria * Exposed	1.20	0.79, 1.84	1.28	0.83, 1.97
2019 * Victoria * Exposed	1.05	0.57, 1.94	1.02	0.55, 1.90
2021 * Victoria * Exposed	0.56	0.30, 1.02	0.55	0.30, 1.01

CI = confidence interval, OR = odds ratio.

Bold indicates odds ratio that is significantly different than 1.00 (i.e., confidence interval does not include 1.00).

Unexposed indicates living, working, or studying > 500 metres from AAA (all ages and abilities) cycling infrastructure, while exposed is ≤ 500 metres.

[a] Adjusted for age, gender, bike access, birth country, car access, children at home, disability, education, employment, household income, and race.

3.3.4. Sensitivity analyses

Given the AAA rationale for the intervention, we fit additional triple-difference models to understand how cycling activity and perceived safety changed over time in specific subsets of the population: older adults (≥ 55 years) and women. Appendices D and E show that the trends for these subgroups mirrored the results from the entire population, with larger confidence intervals, as is expected with smaller sample sizes. Point estimates suggest that for both older adults and women, the difference between cycling activity in respondents closer and farther from AAA infrastructure appeared to change the most over time in Halifax, although these were not statistically significant. In Victoria, the predicted probability of perceived safety increased over time for women living, working, or studying farther from AAA infrastructure (OR 2.08, 95% CI: 1.07 –

4.04). We also compared the results with another triple-difference model that used a lower exposure threshold, reduced from 500 metres to 100 metres, as a stricter definition for determining proximity to AAA infrastructure. The results in Appendix F show that this approach yielded a larger magnitude increase in cycling activity over time for the 2021 exposed group in Halifax. This sensitivity analysis did not generate any significant changes over time for perceived safety.

3.4. Discussion

In this natural experiment study, we leveraged the City of Victoria's investment in AAA infrastructure to assess the impacts on cycling activity and perceived safety. All three of the study cities – Halifax, Kelowna, and Victoria – added AAA infrastructure, grew the proportion of respondents living, working, or studying close to AAA infrastructure, and experienced increases in cycling activity over 2016 to 2021. However, the difference-in-difference analysis suggested these impacts were more substantial in Halifax, and the triple-difference analysis did not indicate that the rate of change was greater for people who lived closer to AAA infrastructure versus those that did not, as we had hypothesized. Living farther from AAA infrastructure was associated with increases in perceived safety over time in Victoria, suggesting a potential far-reaching effect of the network. These findings were unexpected, and below we explore design considerations and unanticipated events that affected the outcomes of this natural experiment study.

3.4.1. Population health intervention research

We embarked on this natural experiment study to gather rigorous evidence on the self-reported cycling activity and perceived safety impacts of AAA infrastructure. Our study design included various methods to increase the quality of the evidence, including data collection at multiple time points, age and gender representative sampling of both cyclists and non-cyclists, and consistent exposure assignment based on standardized infrastructure data. These study components enhance the robustness of our findings in comparison to other study designs and offer valuable insight on cycling in mid-sized cities, an understudied context with unique potential for cycling uptake (Galway et al., 2021).

However, applying population health intervention research methodologies to real-world infrastructure projects is challenging because the intervention may not proceed as planned (Leatherdale, 2019), and unexpected changes can undermine the suitability of the control cities (Foley et al., 2017). Our study was influenced by three factors that were not anticipated: first, construction of the AAA network in Victoria only reached partial completion (~50%) during the study period. The final segments are targeted for completion in 2024 (City of Victoria, 2023c). Second, the control cities built more AAA infrastructure than expected, and third, the COVID-19 pandemic disrupted transportation, spurring rapid investments in cycling infrastructure projects worldwide (Combs & Pardo, 2021). It is widely thought the pandemic will have lasting impacts on active travel behaviour (van Wee & Witlox, 2021).These external factors manifested in the cities under investigation here: during the study period, Halifax approved the Integrated Mobility Plan, a policy prioritizing sustainable transportation, and secured $25 million of funding to build a AAA network (Rutgers, 2019). At the onset of the pandemic, Halifax temporarily reallocated 16 kilometres of right-of-way for cycling, the most of any of the three study cities (Fischer & Winters, 2021), and built 9 kilometres of new AAA infrastructure (Table 3.1). These two unanticipated factors may explain why the difference-in-difference analysis indicated the change in cycling activity was greater in Halifax than in other cities.

The unexpected events also highlight the value of control cities, which are not often included in evaluations of infrastructure interventions. We worked together with partners on the challenge of selecting control cities. Ideally, control cities would emulate the same transportation context and built form as the intervention city, but these conditions do not exist. We were able to improve comparability of data within our study by standardizing cycling infrastructure across study cities, but consistent safety data and household travel survey data were unavailable. There have been calls for a national household survey in Canada; a resource such as this could facilitate more and larger-scale natural experiment studies, and allow for a larger set of intervention and control cities (Branion-Calles et al., 2021). This can enable researchers to pivot when interventions are not implemented as originally planned (Fuller et al., 2014).

3.4.2. Cycling activity

All three cities experienced modest increases in cycling activity over time, yet the triple-difference results indicate there was no difference in the change between respondents living closer and farther from AAA infrastructure in any study city. These results do not support the hypothesis that respondents closer to AAA infrastructure in the intervention city would experience a larger increase over time compared to those further away, mainly because Victoria started with high cycling activity (51% had cycled at least once in the previous year in 2016, 95% CI: 48-54%) but experienced minimal change in cycling activity over time (53% in 2021, 95% CI 49-57%). It is possible that the intervention had minimal impact. Alternatively, the nature of the outcome measure (cycling in the past year) may have limited the ability to detect impacts of the intervention. Measuring the change in respondents who self-report any cycling activity within the last year can capture people who newly start cycling, but does not capture people who start cycling more, or for different purposes. The baseline survey (2016) included a trip diary to capture more detailed transportation behaviours, however, costs to repeat this component were prohibitive. Cycling rates were already high in Victoria in 2016, therefore change in this outcome may have been hard to detect. Interestingly, we also saw cycling activity increased substantially in Halifax. The fact that Halifax had the lowest level of cycling in 2016 (0.33, 95% CI: 0.30-0.37) and the highest proportion of respondents without access to a bicycle (45%) may suggest there was more room for growth. This finding aligns with a natural experiment that collected pre-post data on 73 new or upgraded active transportation routes in the UK and found that higher relative increases in cycling were associated with lower baseline levels of cycling (Le Gouais et al., 2021).

3.4.3. Perceived safety

The triple-difference analysis provides evidence that the intervention achieved some of its goal to make cycling approachable to a wider range of people, given the increase in perceived safety over time for respondents living farther away from AAA infrastructure in Victoria (OR 1.59, 95% CI: 1.01 – 2.50), and the sensitivity analysis that showed the magnitude of increase was even greater for women (OR 2.08, 95% CI: 1.07 – 4.04). These findings are consistent with studies that indicate the provision of protected infrastructure may rectify the gendered disparity in perceived safety (Goddard et al., 2014; Graystone et al., 2022). Furthermore, the fact that AAA infrastructure was not associated with significant increases in perceived safety over time in the control cities, even though they built more than originally expected, may suggest there is something about the quality of the design and implementation of the network in Victoria that differentiates it from the infrastructure built in Kelowna and Halifax.

Although we cannot explain this finding *per se*, the literature offers some possible explanations for the counter-intuitive finding that perceived safety increased more over time for respondents living farther away from AAA infrastructure in Victoria; research shows that most people choose less direct cycling routes in order to access infrastructure (Krenn et al., 2014; Winters, Teschke, et al., 2010) and that this tendency is stronger for women (Broach & Dill, 2016). Thus, it is possible that the location of the AAA infrastructure in Victoria improved access to key destinations, and therefore overall network connectivity was better for respondents living further away from AAA infrastructure, even if network entry points remained unchanged. This finding hints at important spatial nuances and future work could look to distinguish the relationship between individual-level access to cycling infrastructure, and perceptions of city-wide cycling safety, compared to perceptions of neighbourhood cycling safety.

3.4.4. Limitations

There are several limitations to this study. First, this study focuses on the role of infrastructure, but there are other policy interventions (Pucher et al., 2010) and sociodemographic factors that intersect to influence motivators and barriers for cycling (Jahanshahi et al., 2022). Rich qualitative research illuminates how class, gender, and race combine in complex ways to influence cycling experiences and perceptions (Lubitow et al., 2019; Ravensbergen, 2022). Thus, decision makers must adopt an intersectional perspective if the goal of these interventions is to attract more people – of all ages, abilities, and experiences – to cycling (Lam, 2022). Second, our methods for measuring exposure may be subject to misclassification bias, given the accuracy of geocoding postal codes (Khan, 2018), difficulty capturing the connectivity of permeable street networks, and broad exposure definition that included home, work, and study locations. Third, triple-difference relies on a parallel trend assumption for causal inference; the difference between outcomes for exposed and unexposed groups in the intervention group must trend the same way as the comparison group (Olden & Møen, 2022). In all three study cities, we hypothesized that cycling activity and perceived safety would increase over time as more AAA infrastructure was built, and the difference between outcomes for exposed and unexposed groups would get larger over time. This assumption holds for the cycling activity outcome, but not for perceived safety because unexposed respondents in the control cities experienced decreases over time. Further, we modeled cycling activity and perceived cycling safety as separate outcomes; each of these were of primary interest to municipal partners. Future work could also explore how perceived safety may modify the association between cycling infrastructure and cycling activity, where people who feel cycling is safer may show larger changes in behaviour.

3.4.5. Conclusion

This natural experiment study demonstrates that collaborations between researchers and practitioners can generate valuable for evidence on cycling interventions. However, in real-world research, events often unfold differently than anticipated. Consequently, the study results were influenced by a slight delay in the implementation of the AAA network in Victoria, substantial infrastructure investment in the control cities, and the global COVID-19 pandemic. Across study cities, cycling increased marginally during the study period, however the triple-difference analysis showed no significant difference in the change over time between respondents closer and farther from AAA infrastructure. The triple-difference analysis provides evidence that the AAA infrastructure in Victoria increased perceived safety over time, particularly for women, thereby making progress toward the goal of making cycling more approachable for a wider range of people. Since only ~15 kilometres of Victoria's proposed 33 kilometres AAA network were built during the study period, there is ample opportunity to expand upon this study. Future studies could assess the AAA network in Victoria and elsewhere by considering not only by access to infrastructure, but also how infrastructure supports access to destinations. Finally, we recommend that researchers and practitioners continue to collaborate on the collection of data to assess the impacts of interventions, to ensure evidence is rigorous and relevant for practice.

Chapter 4. Cycling towards complete communities: Estimating access to destinations via low traffic stress cycling with open-source data and routing tools

4.1. Introduction

Cities are facing complex, interrelated challenges when it comes to climate, public health, and equity. The search for holistic solutions to today’s pressing issues has renewed interest in proximity-based planning concepts such as complete communities (Marchigiani & Bonfantini, 2022). Complete communities and similar concepts promote neighborhoods where residents can walk or wheel safely to access daily destinations within a short distance, instead of driving (Tammaru et al., 2023). Many local governments in Canada have already adopted complete community policy goals (Grant, 2023).

Measurement of community “completeness” is needed to monitor progress towards policy goals, yet assessments and standard measures are lacking in practice (Gower & Grodach, 2022). One approach cities use to quantify completeness is measuring access to destinations (Lu & Diab, 2023). A growing number of cities are also seeking to operationalize equity when developing complete community policies and measures (Lu & Diab, 2023), given concerns that retrofitting neighbourhoods with dense, mixed-use development and cycling infrastructure could spur displacement (Agyeman & Doran, 2021) and segregate communities by income (Tammaru et al., 2023).

In this study, we aimed to demonstrate an approach to measuring complete communities that captures the impact of transportation network changes over time and assesses equity. We quantified access to destinations via low traffic stress cycling routes in Victoria, British Columbia, Canada. Our work sits within the IBIMS project, a partnership between researchers and practitioners to study investments in cycling infrastructure. The study reported here had three objectives: first, to identify areas that can be considered complete communities based on their access to destinations via low traffic stress cycling routes. Second, to assess how the implementation of Victoria’s AAA cycling network, 33 km of cycling infrastructure built out over 2017-2024, impacts access to destinations. Third, to assess distributional equity impacts by characterizing the sociodemographics of those who live in areas considered complete communities compared with those who do not. In the process, we also tested open-source data (OpenStreetMap) and routing tools (r5r) for estimating accessibility, with the aim of appraising their utility for practice-based inquiry.

4.2. Literature Review

4.2.1. Policy context

The ‘complete community’ is a flexible concept that local governments can adapt to their context and goals (Grant, 2023). The foundation of the concept is a combination of diverse land uses connected by sustainable transportation systems that enable people to meet their daily needs without driving. Across policies, there are variations in the specific types of land uses and modes of transportation used to operationalize complete communities (Lu & Diab, 2023). Similar proximity-based planning concepts have garnered academic and public attention in recent years. For example, in 2020, Paris Mayor, Anne Hidalgo, championed the concept of 15-minute cities, which sets a specific target for accessing opportunities in walkable neighbourhoods (Moreno et al., 2021).

Within the Victoria region, three levels of government have provided policy direction on complete communities. The provincial government developed a guide for assessing the state of complete communities at a local level, with a focus on access to destinations via walking (B.C. Ministry of Housing & Urban Systems Ltd., 2023). The Capital Regional Growth Strategy, which encompasses the City of Victoria and its neighbouring communities of Saanich, Esquimalt, and Oak Bay, has the creation of complete communities as one of seven overarching objectives (Regional and Strategic Planning, Capital Regional District, 2018). The strategy specifically states that daily destinations should be accessible within a 15-minute bike ride (Regional and Strategic Planning, Capital Regional District, 2018). This strategy informed the City of Victoria’s Official Community Plan, which provides guidelines on the specific destinations in complete communities, including commercial services (e.g., restaurants, banks, hairdressers), community services (e.g., recreation centres, schools, medical clinics), and green spaces (City of Victoria, 2023a).

4.2.2. Accessibility measures

The ability to access destinations using sustainable modes of transportation is the foundation of complete communities. In this context, cycling accessibility can be defined as the ability to reach destinations by cycling alone (Vale et al., 2016). There are different approaches to measuring accessibility, but one of the most common in planning practice is to measure cumulative opportunities (Boisjoly & El-Geneidy, 2017). These measures estimate the number of opportunities accessible from a set starting point given certain trip conditions such as mode of transportation, maximum distance, maximum travel time, speed, and time of day (Levinson & King, 2020).

Measurement of cumulative opportunities requires two main inputs: land use data and transportation network data (Siddiq & Taylor, 2021). The land use data represents the origin and destination points in the study area under investigation. Some studies focus on a single type of destination, such as grocery stores (Hosford et al., 2022). Other studies create a ‘basket’ of destinations to estimate the variety of accessible destinations (Kent & Karner, 2019; Radzimski, 2023), which is more aligned with the complete communities concept. The transportation network data represents the potential routes between origins and destinations. For cyclists, it is critical to consider the exposure to traffic and availability of cycling infrastructure along these routes, because it influences perceived safety (Branion-Calles et al., 2019), actual safety outcomes (Marshall & Ferenchak, 2019), and cycling mode choice (Winters et al., 2016; Zahabi et al., 2016).

Level of traffic stress (LTS) is a measure commonly used in studies of cycling accessibility to account for the relationship between cycling, safety, and the built environment (Faghih Imani et al., 2019; Kent & Karner, 2019; Lin et al., 2021). The LTS criteria was developed to codify a transportation network based on the cyclist experience. The criteria were informed by Dutch design guidelines and account for the presence of bike lanes, on-street parking, number of lanes, speed limit, traffic volume, traffic signals, turning movements, and blockages of bike lanes (Furth et al., 2016). There are four levels of traffic stress, which mirror the “four types of cyclists” (Geller, 2006). The lowest level (LTS 1) represents a low-stress environment suitable for most cyclists, including children; LTS 2 represents an environment comfortable for most adult cyclists, but may not be suitable for children; LTS 3 represents an environment navigable for confident adult cyclists, but may not be suitable for adults concerned about cycling on the same road as vehicles without protection; finally, the highest level (LTS 4) represents a high-stress environment only suitable for “strong and fearless” adult cyclists (Furth et al., 2016). Accessibility to more destinations on a low-stress network (LTS <= 2) is strongly predictive of cycling mode choice (Faghih Imani et al., 2019).

4.2.3. Equity considerations for complete communities

Planners are responsible for guiding the distribution of land uses and transportation infrastructure. Hence, the concept of equity in planning research and practice is often informed by distributional equity, which strives for the fair allocation of resources in society (Meerow et al., 2019). Planning literature also considers issues of procedural equity (i.e., how are decisions made?) and recognitional equity (i.e., whose identities, cultures, and histories are valued?) (Meerow et al., 2019). Distributive analyses typically consider how resources are allocated across different groups of people and neighbourhoods to identify socio-spatial patterns of (in)equity (Cunha & Silva, 2023). In this way, accessibility analyses are well suited to investigate distributive equity impacts, but less so for procedural and recognitional equity impacts.

Some scholars have criticized complete community approaches for their potential to increase property values and displace low-income residents to peripheral neighbourhoods with poor access to destinations (Agyeman & Doran, 2021; Tammaru et al., 2023). Cycling infrastructure investments can be particularly fraught because they are framed as a low-cost alternative to car ownership, yet some community members view them as symbols of gentrification (Lubitow et al., 2019). The evidence on the association of cycling infrastructure and displacement in North America is mixed (Ferenchak & Marshall, 2021; Flanagan et al., 2016; Kiani et al., 2023). Nevertheless, these critiques underscore the need to apply an equity lens to complete community policy goals.

4.3. Methods

4.3.1. Context

The IBIMS project focused on Victoria, British Columbia, a mid-sized city located on the traditional, unceded territory of the Lək̓ʷəŋən (Lekwungen) peoples, including the

Xwsepsum (Esquimalt) First Nation and Songhees First Nation. In 2016, the City of Victoria committed to construct a 33 km AAA cycling network (City of Victoria, n.d.). The AAA design aimed to make cycling safer and more convenient for a wider ridership, such as older adults and people cycling with children (City of Victoria, n.d.). The first segment of the network opened in 2017 (City of Victoria, 2023b) and the last segments are set for completion in 2024 (City of Victoria, 2023c). Approximately 23 km of new AAA cycling infrastructure was constructed between 2016 and 2023, according to City of Victoria (2022) open data.

The study area included Victoria's neighbouring communities of Esquimalt, Oak Bay, and Saanich, to better reflect regional transportation dynamics, hereby referred to as Greater Victoria. Halifax, Nova Scotia and Kelowna, British Columbia were also included in the IBIMS project as control cities. These cities were not included in the analysis reported in Chapter 4 because exploratory analysis indicated OSM data was of a lower quality and quantity than in Greater Victoria.

4.3.2. Complete community definition

We decided measuring access to a range of destinations that fall within common amenity categories best reflected the intent of the complete communities policy goal in the Regional Growth Strategy (Regional and Strategic Planning, Capital Regional District, 2018). In this study, a complete community was defined as a dissemination area (DA) where at least one active living, community, education, food, health, and shopping destination was accessible within 15 minutes of cycling on low traffic stress routes. We developed the six amenity categories within our complete community definition based on the approach of Nicoletti et al (2022), who used OSM data to analyze walking access to destinations in major cities across six continents. This approach was modified to better align with the destinations identified in the City of Victoria Official Community Plan, including adding a shopping category. We also eliminated the entertainment and mobility categories due to poor data availability in our study area.

4.3.3. Data

For the origin points, we used the coordinates of the population-weighted centroid of DAs in Statistics Canada's Geographic Attribute File for Census year 2021

(Statistics Canada, 2022). We chose DAs because they are the smallest spatial unit available for detailed Census data (Statistics Canada, 2019) and remain relatively stable over time. DAs cover smaller areas in urban contexts, therefore it is important to note that the routing tool also considered destinations located outside of the DA of origin, as long as they were accessible within 15 minutes of cycling on low traffic stress routes.

For the destination points, we used OSM, a global map of built environment features based on volunteered geographical information. As a crowdsourced database, OSM data quality and completeness continuously improves over time (Barrington-Leigh & Millard-Ball, 2017). Thus, applications of OSM data to study the built environment (Herrmann et al., 2019), and cycling specifically (Ferster et al., 2019, 2023; Murphy & Owen, 2019; Wasserman et al., 2019), are growing. In OSM, information about built environment features are provided in tags, composed of keys (the high-level category, for example, public_transport) and values (the detailed description, for example, bus_stop). We used the ohsome package (Raifer et al., 2019) to extract built environment features from OSM. This package enables the user to filter the data by geometry, key, value, date, and spatial boundary.

We extracted both point (node) and polygon (closed way) data tagged with an amenity, leisure, or shop key as of January 1, 2023. We used the study area with a 4 km buffer zone as the spatial boundary in order to mitigate edge effects. This distance approximates a 20-minute bicycle ride and enables the routing algorithm to travel outside of the IBIMS study area boundary to reach destinations. To reduce duplicate datapoints, we removed overlapping points and polygons. For example, this step removed playgrounds that were mapped as points or polygons within larger park polygons, and individual stores that were mapped as points within a larger shopping centre polygon. We assigned each destination point in our dataset to one of the six broader amenity categories within our complete community definition (active living, community, education, food, health, and shopping). See Appendix G for a breakdown of the destinations within each amenity category.

For the transportation network, we used Geofabrik to download historical OSM data in a pbf file format for British Columbia at two timepoints: January 1, 2016 (considered pre-AAA cycling network) and January 1, 2023 (considered post-AAA cycling network). We used the osmconvert tool to limit the data to the spatial extent of the buffered study area. We also downloaded OSM data at the same two timepoints using the Python package osmnx (Boeing, 2017) because it comes in a format more suitable for descriptive analysis. We first extracted all OSM way tags (linear built environment features) in the study area by using the Overpass API, then created a custom osmnx filter to ensure that any tags relating to cycling infrastructure were captured.

4.3.4. Routing tool

We used the Rapid Realistic Routing (r5r) package (Pereira et al., 2021), an increasingly common tool for estimating access in sustainable transportation and urban planning research (Hosford et al., 2022; Negm et al., 2023; Radzimski, 2023). r5r leverages the existing R5 routing engine and open-source data to calculate accessibility measures in an R environment. The r5r package requires three main inputs: origin points, destination points, and a transportation network. The r5r package is designed to use OSM in a pbf file format as the transportation network data source, while the data source is flexible for origin and destination points (Pereira et al., 2021).

The r5r package adopts the existing R5 method for assigning LTS to account for the important role road design plays in cyclist safety. The underlying code uses road characteristics recorded in OSM to systematically assign LTS based on road classification, total number of traffic lanes, posted speed limit, and available cycling infrastructure (Eldred, 2020). Compared to the LTS criteria developed by Furth et al (2016), the criteria used by r5r are simplified, as they do not account for on-street parking, and they approximate road widths based on road classification and number of lanes. OSM's road classification is based on function; motorways are highest in this hierarchy, because they are used to move high volumes of vehicles at high speeds, whereas residential roads are lowest in this hierarchy, because they typically provide access to housing without connecting neighbourhoods (*Key:highway - OpenStreetMap Wiki*, n.d.).

We set the maximum LTS at 2, as per the default r5r settings and common practice in cycling accessibility literature (Faghih Imani et al., 2019; Kent & Karner, 2019; Wasserman et al., 2019). LTS 1 and LTS 2 (considered low stress in this study) include roads that do not allow cars, residential roads, tertiary roads with cycling infrastructure, tertiary roads with three or fewer lanes, and tertiary roads with a posted speed limit less than ~40 km/hr (Eldred, 2020). Motorways, trunks, primary, or secondary roads are always considered high stress (LTS 3 or LTS 4). Given these default settings, the r5r LTS assignment does not always match the AAA definition used by the City of Victoria; specifically, within r5r assignment, slower and narrower roads without cycling infrastructure can be considered part of the low-stress network. Conversely, faster and wider roads with cycling infrastructure can be considered part of the high-stress network. See Appendix H for a summary of the sequential logic behind LTS assignment in r5r.

In addition to LTS, r5r allows users to specify other mode parameters. We selected a 15-minute travel time maximum to align with the Regional Growth Strategy criteria for complete communities (Regional and Strategic Planning, Capital Regional District, 2018). We used the default cycling speed of 12 km/hr. Given these travel time and speed parameters, the routing tool could consider routes up to 3 km in distance. Thus, potential cycling routes could travel through several DAs to access destinations in an urban context such as downtown Victoria. By default, r5r will switch from cycling to walking when it cannot identify a route that meets the LTS parameters. Since we were interested in cycling specifically, we set the walk speed to 0.01 km/hr, effectively ending routes at breaks in the low traffic stress network.

4.3.5. Analysis

To identify areas that could be considered complete communities we ran the accessibility function from the r5r package. This function created a routable transportation network, identified potential routes between origins and destination points, and then calculated the number of destinations from each amenity category that could be accessed within 15 minutes of cycling on low-stress traffic routes. Based on the accessibility function results, we determined which DAs had access to at least one destination point from each amenity category in our complete community definition and created a binary outcome variable (complete community = yes/no).

To assess how the implementation of the AAA cycling network impacted cycling accessibility, we estimated accessibility as of January 1, 2016 (before construction began), and January 1, 2023 (after construction began). We used different transportation network data but the same origin and destination points for both the 2016 and 2023 analysis. Consequently, this analysis did not capture the impact of changes to land use over time, but it isolated the impact of the change in the transportation network, in line with the study objective. Completing cross-sectional analyses enabled us to compare accessibility over time and determine which DAs became complete, which DAs were always considered complete, and which DAs were never considered complete.

We examined the underlying data to understand if the changes in the transportation network data supported the estimated changes in access and complete communities. We looked closely at four road characteristics that influence LTS assignment: road classification, speed limit, number of lanes, and cycling infrastructure. We started by looking at change at the road network level to understand high-level trends. Next, we looked at change at the road segment level to gain a better understanding of if trends were driven by improvements in data completeness. We identified segments with records of explicit lane and speed limit reductions between 2016 and 2023, in comparison to segments where road characteristics were missing in 2016 and then added in 2023.

To assess distributional equity impacts, we looked at which population groups live in areas considered complete communities and those that lived in areas with insufficient cycling accessibility to meet the definition. We extracted 2021 census data at the DA level using the cancensus package (von Bergmann & Shkolnik, 2021). To compare area-level measures of sociodemographics, we divided the DAs into two groups: ‘complete communities’ and ‘not complete communities’. The sociodemographic characteristics of interest were: youth (0-14 years), older adults (65 years and older), labour force status (employed), highest level of education (at least post-secondary), low income (based on the low-income cut-offs, after tax variable [LICO-AT] from Statistics Canada), racialized (based on the visible minority variable from Statistics Canada), recent immigrant (within the last five years), and Indigenous identity. We calculated the average proportion for each sociodemographic characteristic for the DAs within each group. Four DAs with supressed Census data were removed from the dataset. We used t-tests to compare proportions between groups, using a statistical significance level of 0.05. All analyses were completed in R Studio version 4.3.1 and Python 3.

4.4. Results

4.4.1. Origins, destinations, and transportation network

Our dataset included 391 DAs containing a population of 242,960 in Greater Victoria. We extracted and retained 2891 destination points from OSM after cleaning. Based on the OSM values, we divided the destination dataset into the following amenity categories: 1248 (43%) active living, 179 (6%) community, 91 (3%) education, 631 (22%) food, 70 (2%) health, and 672 (23%) shopping features. The highest concentrations of destination points were found in downtown Victoria and along major transportation corridors.

For the 2023 transportation network (see Figure 4.1), we found that 900.6 km of the 2890.5 total km (31.2%) had complete data on road characteristics needed for LTS assignment (i.e., number of lanes and posted speed limit, or the presence of cycling infrastructure). For the transportation network that did not have complete data, the underlying code in r5r applied assumptions about road characteristics to assign LTS based on the road classification (see Appendix H). In this way, r5r assigned 2028.1 km (70.2%) as low traffic stress, and 862.4 km (29.8%) as high traffic stress. While there was a greater proportion of low traffic stress roads overall, the high traffic stress roads were often located along major corridors, creating barriers for connectivity between pockets of low traffic stress roads.

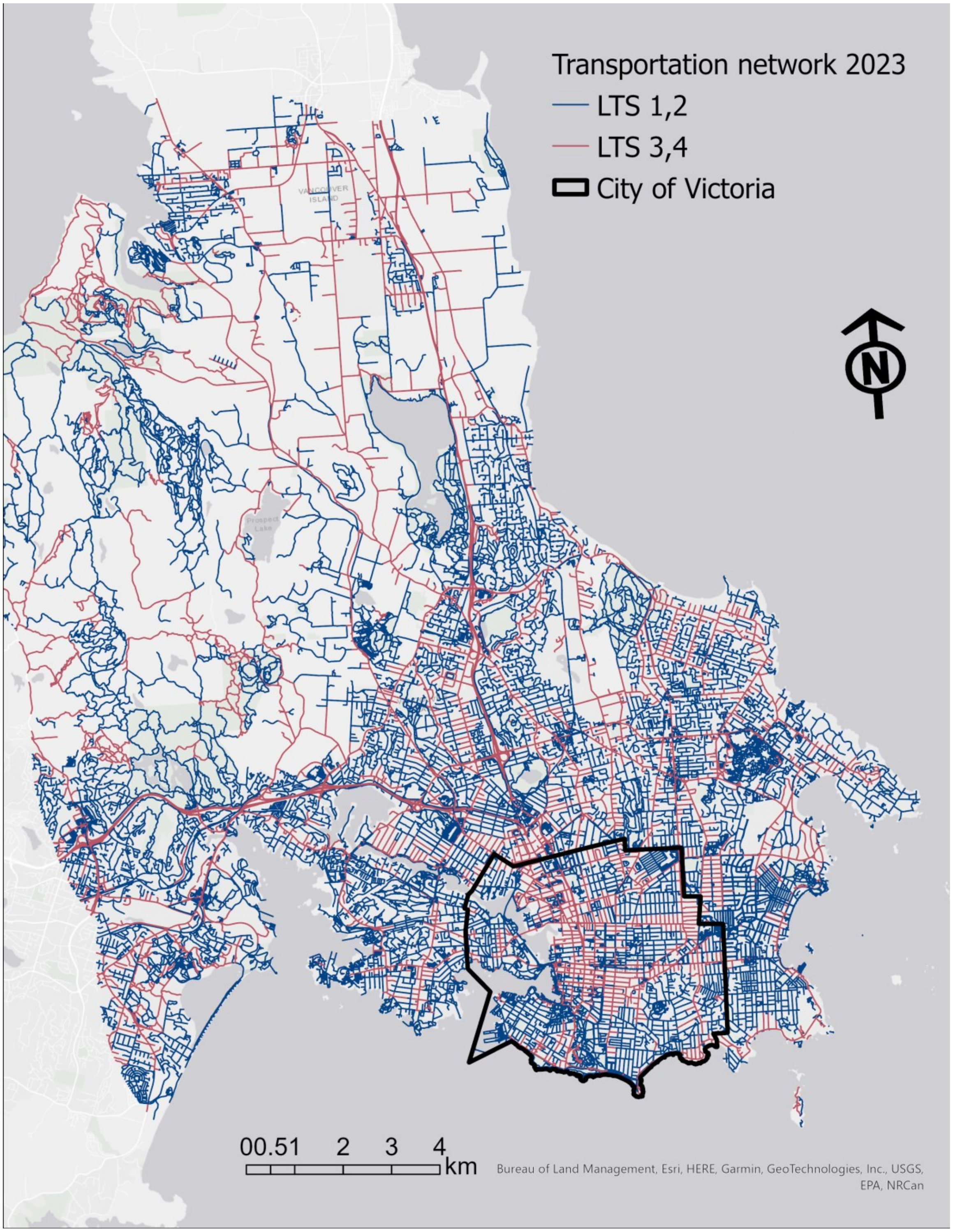


Figure 4.1 Transportation network in Greater Victoria 2023
LTS = level of traffic stress.
LTS 1 and 2 includes roads that do not allow cars, residential roads, tertiary roads with cycling infrastructure, tertiary roads with three or fewer lanes, and tertiary roads with a posted speed limit less than ~40 km/hr, while LTS 3 and 4 includes motorways, trunks, primary, or secondary roads (Eldred, 2020).

4.4.2. Access to destinations

In the majority of DAs, there was access to more than one destination from each amenity category within 15 minutes of cycling on low traffic stress routes. Active living destinations were the most numerous in our dataset derived from OSM. Table 4.1 shows that active living destinations were also the most accessible destination type; 76% of DAs (75% of the population) had access to at least one active living destination. In contrast, health destinations were the most frequently missing. A similar number of DAs lacked access to community, education, health, and shopping destinations. The majority of DAs (230/391) were missing access to at least two of the six amenity categories that make up our complete community definition.

Table 4.1 Access to destinations (within amenity categories) via 15 minutes of cycling on low traffic stress routes for 391 Greater Victoria DAs

	Amenity category					
	Active living	**Community**	**Education**	**Food**	**Health**	**Shopping**
Mean (SD)	17 (20)	3 (3)	2 (2)	7 (13)	1 (2)	7(10)
Proportion of DAs with/without access	76/24	57/43	56/44	57/43	45/55	54/46
Population with/ without access	183,329/ 59,631	139,772/ 103,188	134,188/ 108,772	140,818/ 102,142	109, 211/ 133,749	134,781/ 108,179

DA = dissemination area; SD = standard deviation

4.4.3. Complete communities

In 2023, 40% (155/391) of DAs in Greater Victoria could be considered complete communities, having at least one active living, community, education, food, health, and shopping destination within 15 minutes of cycling on low traffic stress routes. These complete communities were clustered in areas with concentrations of destinations, low-traffic stress routes, or both (see Figure 4.2). In 2016, before the implementation of the AAA cycling network, 21% (81/391) of DAs in Greater Victoria met our definition of complete communities. In 2023, we identified 85 additional DAs that could be considered complete communities, meaning these areas experienced increases in access to destinations over time. The majority of the DAs that became complete communities over time (53/85 [62%]) were located within the City of Victoria, where the AAA cycling network was implemented.

Our analysis identified a small number of DAs (11/391 [3%]) where cycling accessibility appeared to decrease over time. In most of these areas of concern, breaks in the 2023 low traffic stress network that were not present in the 2016 low traffic stress network seemed to limit entry/egress from the DA. Further analysis comparing OSM data with ground-truthed data is required to determine if these breaks in the low traffic stress network reflect real-world change, or changes in data quality and completeness.

In 2016, 64% of the transportation network was considered low stress, and this increased to 70% in 2023. Road characteristics at the network level were trending in a direction to support expansions in the low traffic stress network, and thereby facilitate better access to destinations via cycling. Table 4.2 shows there were increases in the total kilometres of lower class roads (roads with three or fewer lanes, roads with speed limits less than 40 km/hr, and roads with cycling infrastructure).

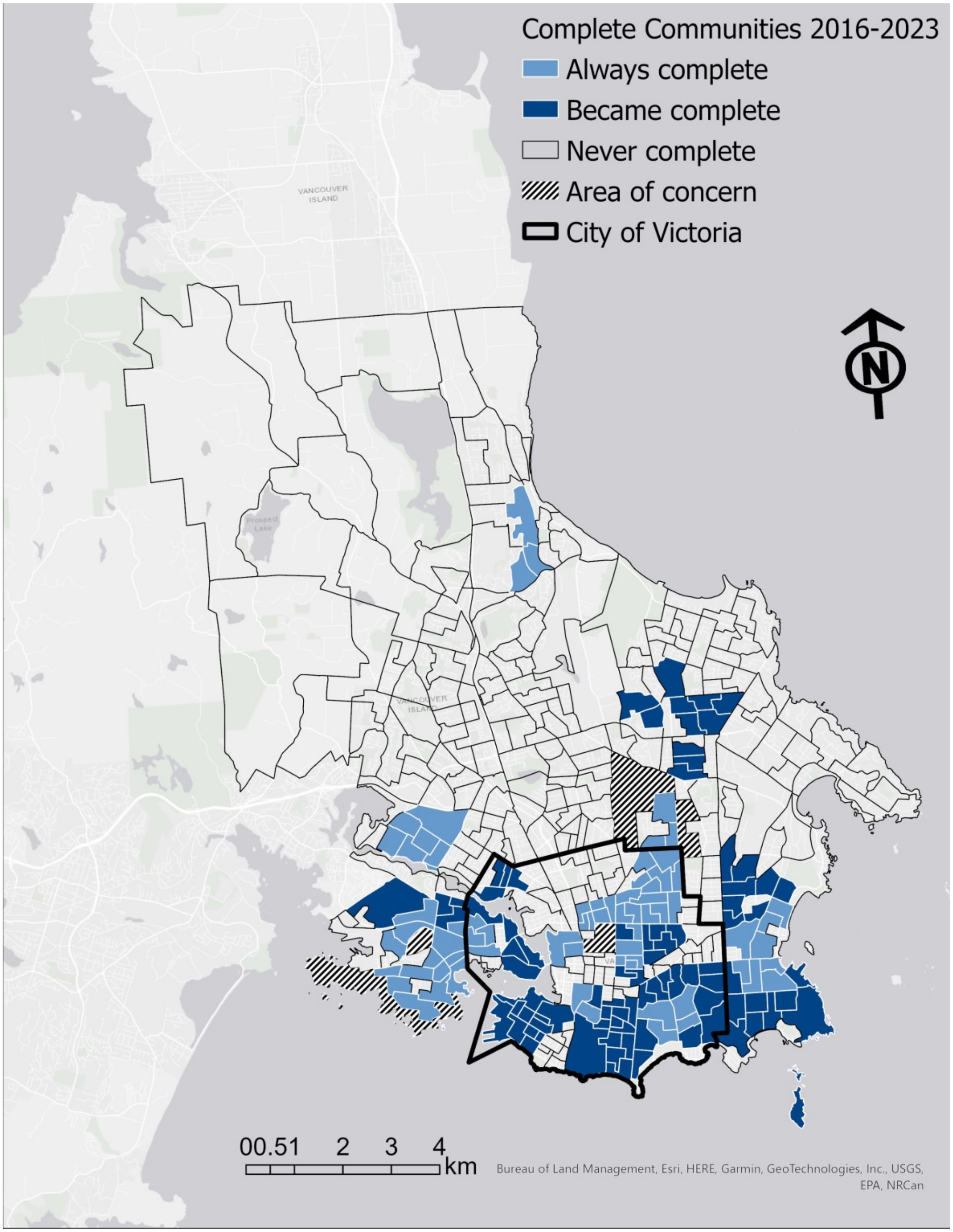


Figure 4.2 **Change in complete communities at the dissemination area-level in Greater Victoria 2016-2023**

Complete communities are defined as dissemination areas where at least one active living, community, education, food, health, and shopping destination was accessible within 15 minutes of cycling on low traffic stress routes.

Table 4.2 Select road characteristics recorded in OSM for Greater Victoria, 2016 and 2023

Road characteristic	Year	
	2016	2023
Lower road class [a]	1697.7	1906.5
Lanes <u><</u>3	520.5	547.4
Speed limit <40 km/hr	76.1	150.9
Cycleway [b]	556.6	638.2
Complete road data [c]	741.5	900.6
LTS 1 & LTS 2 (low stress)	1566.2	2028.1
LTS 3 & LTS 4 (high stress)	869.2	862.4
Total	2435.4	2890.5

OSM = OpenStreetMap, LTS = level of traffic stress

[a] Minor roads, defined as OSM tags highway = tertiary, residential, bridleway, pedestrian, living_street, or footway.
[b] Cycling infrastructure, defined as OSM tags cycleway, path, track, or footway where cycling is permitted.
[c] Defined as segments with number of lanes AND speed limit recorded, OR cycling infrastructure.
Values as kilometres aggregated by road centreline.

Our review of changes at the road segment level found one explicit lane reduction recorded in the data (26 metres out of the estimated 27 km total), where a segment with more than three lanes in 2016 decreased to three or fewer lanes in 2023. Similarly, there was a small number of explicit speed limit reductions recorded in the data (17 km of the estimated 75 km), where the speed limit exceeded 40 km/hr in 2016, then decreased in 2023. We found no explicit instances of speed limits increasing. The rest of the changes occurred on road segments that did not have any lane counts or speed limits recorded as of 2016. As a result, it is possible that the trend of increasing low stress segments between 2016 and 2023 was driven by the addition of road characteristics to OSM that were previously missing from the data (i.e., improvements in data completeness). Further analysis would be required to determine which road characteristic changes correspond with the implementation of built environment interventions at the road segment level.

We found an increase of 81.6 km in the length of cycleways recorded in OSM data between 2016 and 2023, where a cycleway is defined as cycling infrastructure physically separated from vehicles. The City of Victoria AAA cycling network includes 33 km of new infrastructure, therefore some of this increase probably represents new infrastructure built in neighboring communities, or recently added tags for existing cycling infrastructure that was not previously recorded in OSM.

4.4.4. Sociodemographic comparison

Table 4.3 compares area-level measures of sociodemographic characteristics for people living in DAs deemed complete communities with those living in DAs that did not meet the criteria. These results show that, on average, there was a greater proportion of racialized people and people without post-secondary education living in areas that did not meet our definition of complete community (6.1% and 4.2% higher, respectively). Otherwise, the demographic profile of people living within complete communities was comparable to those who did not.

Table 4.3 Sociodemographics of Greater Victoria dissemination areas by access to destinations (2023)

Sociodemographics [a]	Complete community [b]	Not complete community	Overall
Dissemination areas, n (%)	155 (40)	236 (60)	391 (100)
0-14 years % (SD)	11.8 (4.5)	11.7 (4.1)	11.7 (4.3)
65 years and over % (SD)	23.2 (11.5)	23.6 (10.7)	23.5 (11.0)
Employed % (SD)	59.7 (10.4)	58.6 (9.6)	59.1 (9.9)
At least post-secondary education % (SD)	**67.0 (8.9)**	**62.8 (8.4)**	64.4 (8.8)
Low income [c] % (SD)	5.4 (2.6)	5.4 (2.7)	5.4 (2.6)
Racialized [d] % (SD)	**16.2 (9.6)**	**22.3 (11.7)**	19.9 (11.3)
Recent immigrant [e] % (SD)	2.7 (2.7)	2.7 (3.1)	2.7 (2.9)
Indigenous identity % (SD)	4.2 (3.9)	3.7 (3.2)	3.9 (3.5)

SD = standard deviation.

Bold indicates a statistically significant difference based on t tests (p<0.05 threshold).

[a] Source: Statistics Canada 2021 Census: Profile data for the Victoria, British Columbia Census Metropolitan Area at the Dissemination Area level.

[b] Complete communities are defined as dissemination areas where at least one active living, community, education, food, health, and shopping destination was accessible within 15 minutes of cycling on low traffic stress routes.

[c] Based on the low-income cut offs, after tax (LICO-AT) variable from Statistics Canada (2021).

[d] Based on the visible minority variable from Statistics Canada (2021).

[e] Based on the immigration status and 2016-2021 period of immigration variable from Statistics Canada (2021).

4.5. Discussion

In this study we leveraged open-source data and routing tools to estimate cycling accessibility. Our findings contribute to the growing conversation on complete communities and other proximity-based planning concepts, with the goal of creating more sustainable, equitable, and healthy cities. We developed a definition of complete communities that resonated with local policy language and used it to identify areas with access to a range of common destinations via low traffic stress cycling routes in Greater Victoria. We found there was an increase in access to definitions and estimated a 91% increase over time in the proportion of areas that meet the definition of complete communities. Despite this increase, the majority (60%) of the population couldn't cycle on low traffic routes to reach an active living, community, education, food, health, and shopping destination. Moreover, census data suggests that, on average, there was a significantly higher proportion of racialized people and people without post-secondary education living in areas with lower cycling accessibility (6.1% and 4.2% higher, respectively). Below we share our learnings, with a focus on what practitioners should consider when conceptualizing complete communities, using open-source data and routing tools to assess the cycling accessibility impacts of infrastructure investments, and assessing distributional equity impacts of the design of communities and transportation networks.

4.5.1. Conceptualizing complete communities

We identified complete communities based on access to active living, community, education, food, health, and shopping destinations via low traffic stress cycling routes. Our empirical results offer practitioners a measure to gauge progress towards complete community policy goals in Greater Victoria. A strength of this study is our use of cumulative opportunities measures. These measures tend be more intuitive for practitioners and the public (Levinson & King, 2020; Siddiq & Taylor, 2021). Furthermore, these measures yield comparable results to more theoretically complex, data-intensive alternatives (Kapatsila et al., 2023; Palacios & El-Geneidy, 2022). Our use of readily available data and tools also means practitioners can recreate similar approaches.

A drawback is that this analysis provides a high level, simplified picture of cycling accessibility. Cumulative opportunities measures cannot determine if the accessible destinations actually meet the preferences and constraints of individuals (Siddiq & Taylor, 2021), which may vary depending on social identity. For instance, having access to a grocery store may not be useful if the products are too expensive, or if it doesn't carry culturally appropriate food. Additionally, a definition focusing on another set of destinations would have yielded different results. For example, while workplaces are mentioned in some complete community policies (Grant, 2023; Lu & Diab, 2023) we excluded them from our analysis, in part because jobs are not explicitly recorded in OSM. The destination types we included may be considered proxies for jobs because they require employees (e.g., gyms, libraries, schools, restaurants, hospitals, and retail outlets).

Researchers and practitioners can build off our work by exploring more nuanced conceptualizations of complete communities. Alternative approaches challenge the "neutral" perspective of many accessibility analyses by exploring the diverse transport needs of specific groups (Willberg et al., 2023). For example, Hosford et al (2022) estimated access at different speeds to project access for older and younger cyclists. Additionally, many local governments use public engagement to inform their definition of complete communities (Lu & Diab, 2023). Researchers have opportunities to support this dialogue, by creating interactive maps that enable users to visualize and weight access to different destinations, in the style of City Access Map (Nicoletti et al., 2022).

4.5.2. Estimating cycling accessibility

Past investigations of changes in access to cycling infrastructure over time found that improvements were distributed inequitably across different groups of people (Ferenchak & Marshall, 2021; Firth, Hosford, et al., 2021; Houde et al., 2018). However, few studies explore how the build out of cycling infrastructure impacts access to destinations via cycling over time. We were able to address this gap in the literature by comparing access to destinations via low traffic stress cycling routes before and after the implementation of the AAA cycling network. Our results suggest that Greater Victoria is making progress towards increasing cycling accessibility over time and cultivating complete communities. Our results can help practitioners identify islands of low traffic stress roads, prioritize interventions to connect these areas, and improve access to destinations. In doing this work, we uncovered important points about data completeness in OSM and LTS assignment in r5r that may impact these results. We expand on these points below, to assist those considering using this data source and tool in the future.

In Canada, the positional accuracy of OSM road network data is generally trusted by researchers because its accuracy is comparable with reference datasets (H. Zhang & Malczewski, 2018). However, the accuracy and completeness of characteristics within the road network data varies (H. Zhang & Malczewski, 2018). Thus, a limitation of our approach is that inaccurate and/or incomplete road characteristic data in OSM may skew LTS assignment. Wasserman et al (2019) evaluated the quality of OSM-derived LTS and found that secondary and tertiary roads were more susceptible to incorrect LTS assignment. They suspected this bias was due to the variable design of these roads (Wasserman et al., 2019). Traffic signals also influence the assignment of LTS in r5r, yet little is known about the quality of OSM data on traffic signals in Canada. When analyzing change over time, low data accuracy and completeness can make it difficult to parse increases in data quality from additions to the data that represent changes in the built environment. Future work could investigate the accuracy and completeness of road characteristics mapped in OSM at the neighbourhood scale, then estimate pre-post accessibility in neighbourhoods where cycling infrastructure was built.

Data completeness aside, the LTS assignment can be generous in the sense it includes residential roads within the low traffic stress classification. Notably, the inclusion of residential roads adds more routing options than if one only considered routes with cycling infrastructure. For example, according to OSM data there were ~638.2 km of cycleways in Greater Victoria in 2023, and the r5r LTS assignment of residential roads expanded the low traffic stress network by ~1,389.9 km (~218%). Conversely, we suspect r5r may underestimate cycling accessibility gains from investments on busier roads, because any road with a higher class than tertiary is considered high stress (LTS 3 or 4), even if it has cycling infrastructure (Eldred, 2020). We reviewed the source code and it appears to treat all cycling infrastructure the same regardless of separation or protection from vehicles (Byrd, 2022). For this reason, r5r may not be sensitive enough to capture infrastructure upgrades. Other studies have drawn on OSM data to assign LTS, but used tags to differentiate between facilities that separate cyclists from vehicles (e.g., protected bike lanes, paths), and facilities where facilities share space with vehicles (e.g., painted lanes, shared lanes, and shared busways) (Murphy & Owen, 2019; Wasserman et al., 2019).

In summary, an open-source approach offered many strengths, but there were also limitations. OSM's global coverage makes it easier to mitigate edge effects by including data beyond administrative boundaries. In contrast, using government data can make it difficult to consider data outside the administrative boundary. Furthermore, researchers can use OSM data and r5r to greatly reduce the time and effort to produce cycling accessibility analyses that consider traffic stress. That said, r5r's automatic assignment of LTS may be problematic for practice-based inquiry, especially if the goal is to assess the impact of infrastructure investments along busy roads. To address these shortcomings, those with data management and coding skills can manually assign LTS (Eldred, 2020). Alternatively, researchers and practitioners could identify priority areas of the transportation network, document road characteristics, and contribute this ground-truthed data to OSM to improve data quality and completeness (Wasserman et al., 2019). The combined power of the research and practice communities has the potential to vastly improve OSM data (Ferster et al., 2023). We argue it is in the interests of researchers and practitioners to become OSM contributors, and champion its use for the study of our communities and transportation systems.

4.5.3. Assessing distributional equity

The lack of dedicated cycling infrastructure is a prevailing barrier to cycling for transport (Pearson et al., 2022). Accordingly, an established body of work has studied spatial access to cycling infrastructure for equity-deserving groups in American (Braun et al., 2019; Ferenchak & Marshall, 2021) and Canadian (Firth, Hosford, et al., 2021; Houde et al., 2018) cities. In Greater Victoria, past research has found that low-income areas had better access to cycling infrastructure overall, but that there were specific areas with more low-income people that could benefit from investment (Winters, Fischer, et al., 2018). However, the primary benefit of access to transportation infrastructure is arguably improved access to destinations (Pereira & Karner, 2021). In this way, accessibility measures offer an advantage over measures of access to infrastructure, because they capture what people actually want from their transportation system (Litman, 2021; Martens, 2016).

Our study enhances past work by measuring access to destinations instead of access to infrastructure. Our findings indicate that in Greater Victoria, there tended to be higher proportions of racialized people and people without post-secondary education living in areas not considered complete communities. These results can help practitioners prioritize land use policy and cycling infrastructure investments for these areas. We did not investigate population change over time, but draw attention to the conversation about potential unintended consequences of sustainable mobility interventions intended to advance proximity-based planning concepts such as complete communities (Tammaru et al., 2023).

While this study focused on cycling infrastructure and the transportation network, there are other elements of the built environment that influence cycling accessibility, including end of trip facilities, wayfinding, lighting, and slope (Yang et al., 2019). Moreover, the uptake (Braun, 2021) and perception (Jahanshahi et al., 2022) of cycling infrastructure investments may vary across subgroups of the population. The equitable distribution of cycling infrastructure alone may not lead to equitable participation in cycling across population groups (Jahanshahi et al., 2022). Thus, practitioners must consider the contextual factors that influence the decision to cycle and how they vary across gender, race, and class (Yuan et al., 2023). While quantitative approaches prevail in the study of cycling equity (Cunha & Silva, 2023), qualitative approaches that value lived expertise may be better equipped to advance our understanding of the barriers and facilitators to improving accessibility for structurally marginalized groups (Lowe et al., 2023).

In addition to the general cautions explored above, we highlight a few limitations to our work. Firstly, OSM contributors can be inconsistent in their approach to tagging built environment features, including cycling facilities (Ferster et al., 2019). Furthermore, biased contribution patterns can influence the quality and completeness of OSM data. For example, women are underrepresented as OSM contributors (Gardner et al., 2020), and this may have implications for the kinds of built environment features, and areas of a community, that are mapped. Another consideration is that the access points we used for routing may not represent actual access points on the ground. We used the centroids of polygon features such as parks because it’s efficient, but this may be an oversimplification of reality (Spangler et al., 2023). Finally, decision makers have two main levers to advance complete community policies: land use and transportation. Our analysis did not capture the impacts of changes in land use over time. Future work could explore the impacts of complementary efforts to improve accessibility through transportation and land use changes.

4.5.4. Conclusion

Our cities must transform radically to address climate, public health, and equity challenges. In this context, we welcome the resurgence of complete community policies that explore holistic solutions to these complex, interrelated problems, by encouraging active travel, curtailing emissions, and reducing barriers to accessing daily destinations. Our study of Greater Victoria shows that progress towards complete communities is possible. We also found that the benefits of these investments were not shared equitably across population groups in Greater Victoria. Looking ahead, researchers and practitioners need to consider how the transition towards healthier, more sustainable communities can be guided by equity.

Chapter 5. Conclusion

5.1. Summary of findings and takeaways for practice

In this thesis I assessed the impacts of AAA cycling infrastructure investments on cycling activity, perceived safety, and cycling accessibility. Guided by PHIR approaches, I produced findings that provide evidence relevant to the mid-sized city context and highlight differential impacts between population groups. Below, I summarize the key findings and propose takeaways for practice. These takeaways are geared towards decision makers seeking to grow ridership by making cycling safer and more convenient for a wide range of people.

The manuscript in Chapter 3 presented findings from a natural experiment study of the implementation of the City of Victoria's 33 km AAA cycling network. I used difference-in-difference analysis to examine if the changes in cycling activity and perceived safety in the intervention city (Victoria) were significantly different from the changes observed in the control cities (Kelowna and Halifax). I measured how far survey respondents lived, worked, or studied from AAA cycling infrastructure. Then I completed a triple-difference analysis to examine if the change over time in cycling activity and perceived safety was significantly different between respondents closer and farther to AAA cycling infrastructure in the intervention city, compared to the control cities. Takeaways for practice include:

- **Cycling activity is growing in mid-sized cities that invest in AAA cycling infrastructure**. Even though the triple-difference analysis found no significant difference in the rate of change between people closer and farther to AAA cycling infrastructure, descriptive analysis showed signs of growth in all three study cities. Over 2016-2023, Victoria, Kelowna, and Halifax added AAA cycling infrastructure, expanded the proportion of respondents living, working, or studying close to AAA cycling infrastructure, and experienced marginal increases in cycling activity.
- **Impacts of AAA cycling infrastructure investments may vary depending on baseline cycling activity**. Difference-in-difference analysis indicated impacts were more substantial in Halifax, which had the lowest level of cycling activity in 2016 and possibly more room for growth. This finding aligns with another natural experiment study that found higher relative increases in cycling were associated with lower baseline levels (Le Gouais et al., 2021).

- **People living, working, or studying father away from AAA cycling infrastructure can still experience increases in perceived safety.** Triple-difference analysis showed there was a significant increase in perceived safety over time for respondents living farther away from AAA infrastructure in Victoria. The sensitivity analysis showed that the magnitude of increase was even greater for women, indicating the intervention made progress towards goals to make cycling approachable to a wider range of people.

- **Unanticipated events may affect the impacts of AAA cycling infrastructure interventions.** The findings of this natural experiment study were influenced by a delay in the implementation of the AAA network in Victoria, substantial infrastructure investment in the control cities, and the COVID-19 pandemic.

The manuscript in Chapter 4 presented findings from an investigation of cycling accessibility before and after the implementation of the AAA cycling network in Greater Victoria. I reviewed local policy documents guiding growth and developed a definition of complete communities. I operationalized this definition by using open-source data (OSM) and routing tools (r5r) to identify areas with access to a range of common destinations via 15 minutes of cycling on low traffic stress routes. I assessed distributional equity impacts by comparing the sociodemographics of people who lived in areas considered complete communities to those who do not. Takeaways for practice include:

- **Cycling accessibility increased over time, after the investments in the AAA cycling network**. We estimated a 91% increase from 2016 to 2023 in the areas that could be considered complete communities in Greater Victoria. However, increasing data completeness in OSM made it difficult to parse true built environment changes based on this analysis alone.

- **Most people still cannot reach common destinations via 15 minutes of cycling on low traffic stress routes.** In 2023, the majority (60%) of Greater Victoria residents lived in areas that didn’t meet the study definition of complete communities. Practitioners should continue to work to improve cycling accessibility and collaborate with residents to identify important destinations for daily travel.

- **The benefits of cycling accessibility are not distributed equitably**. Census data suggests that, on average, there is a higher proportion of racialized people and people without post-secondary education living in areas with lower cycling accessibility. Practitioners should consider prioritizing future cycling infrastructure investments in these areas.

- **The r5r method for assigning traffic stress may not be sensitive enough to capture impacts from infrastructure interventions on busier roads, or upgrades to existing infrastructure.** Researchers and practitioners should manually assign LTS if they want to use this tool to measure the impacts of cycling infrastructure investments.

The collective findings of these manuscripts demonstrate that investments in AAA cycling infrastructure can increase cycling activity, perceived safety, and cycling accessibility. Both manuscripts found that investments in AAA cycling infrastructure impacted population groups differently. Practitioners need to consider equity when planning, designing, and implementing cycling projects to avoid perpetuating differential impacts that compound to create unfair transportation disadvantages. Although both manuscripts captured signs of progress towards cycling in mid-sized Canadian cities, there is ample room for improvement; many people (i) did not cycle within the last year, (ii) perceived cycling as unsafe, and (iii) could not access common destinations via 15 minutes of cycling on low traffic stress routes. Cities must take more action to continue to grow cycling and diversify ridership.

5.2. Contributions

This thesis advances our understanding of the impacts of AAA cycling infrastructure in mid-sized cities. Each manuscript identifies individual contributions. Together, these manuscripts offer the following cross-cutting contributions to the field of cycling research, PHIR more broadly, and transportation practice.

5.2.1. Exploring different methods

In both manuscripts, I explored methods that are not typically used to study cycling infrastructure interventions. In Chapter 3, I used triple-difference analysis to compare impacts between study cities and impacts within cities based on exposure to AAA cycling infrastructure. Most studies do not include control cities, or individual-level measures of exposure, and even fewer combine these strategies in a triple-difference analysis (Mölenberg et al., 2019; Stappers et al., 2018). The results of my analysis showed nuances between study cities and exposure groups, highlighting the value of studying different scales.

In Chapter 4, I leveraged open-source data and routing tools for estimating cycling accessibility over time. I initially chose these methods because researchers are starting to use OSM and r5r to study the built environment. During my analysis, I encountered issues with data quality and LTS assignment that revealed strengths and weaknesses of my approach that were not well documented in the literature. As a result, I decided to appraise the utility of my approach for practice-based inquiry and share these learnings with the research community. In this way, my thesis identifies important considerations that researchers and practitioners need to be aware of when choosing methods for measuring impacts of cycling infrastructure investments.

5.2.2. Championing integrated knowledge translation

The integrated knowledge translation (IKT) approach used by the IBIMS project team is uncommon in the field of cycling research. My thesis demonstrates that IKT can make research more relevant to practice. For example, in Chapter 4, I assessed cycling accessibility, even though this was not originally identified as an outcome of interest for the IBIMS project (Winters, Branion-Calles, et al., 2018). The IKT approach enabled us to be responsive to partner needs and explore a new area of inquiry. I contributed a unique perspective to the IBIMS project as a planner turned graduate researcher. My practitioner experience was particularly valuable for knowledge mobilization. I met with each study city partner over the course of my thesis work. To close out my thesis work, I will present the findings from both manuscripts to study city partners on November 24, 2023. Thus, my thesis offers a model for future graduate researchers seeking to use their professional experience to contribute to academia and practice.

5.2.3. Highlighting importance of context

The paucity of research on mid-sized cities (Sotomayor & Flatt, Jo, 2018) was a major motivation for the IBIMS project. Consequently, context was a central consideration in both manuscripts. I visited each study city and spent time there cycling to gain a firsthand perspective on the investments in AAA cycling infrastructure. It is important to note my perspective was influenced by my positionality as a white, cisgender woman and others may have different experiences cycling in these cities. Future work could explore methods to capture the cycling experiences of people with diverse identities, such as ride along interviews, and photovoice. The interpretation of my results was aided through discussion with IBIMS project team members that lived and worked in the study cities. In contrast, many studies are completed by researchers who have never been to area of study. The steps I took to better understand context enabled me to contribute evidence that is more applicable to mid-sized cities, compared to the existing body of literature that focuses on cycling in large cities (Galway et al., 2021).

In addition, the findings from Chapter 3 suggest there can be differences within the mid-sized city context, given investments in AAA cycling infrastructure had different impacts on cycling activity and perceived safety in each study city. Cities are complex systems influenced by past and present development patterns, therefore researchers and practitioners need to consider how local context influences the impacts of cycling infrastructure interventions.

5.3. Limitations and future work

Each manuscript identified limitations in their respective chapters. Here, I describe two overarching limitations to this thesis: the focus on cycling infrastructure, and the narrow analysis of equity.

My thesis concentrated on the impacts of AAA cycling infrastructure and did not account for other interventions that can support cycling. In reality, many cities pursue ‘soft measures’ to complement ‘hard measures’. For example, the City of Victoria offered a free bike valet program in 2022 to address concerns of bike theft downtown and expanded hours in 2023 to meet demand (van der Zwan, 2023). Reviews of the literature suggest that investments in cycling infrastructure are more successful when paired with a suite of interventions (Pucher et al., 2010; Winters et al., 2017). The combined impact can exceed the individual impact of each intervention (Pucher et al., 2010). Thus, researchers and practitioners need to consider strategies to address the individual and interpersonal factors that influence cycling activity, in addition to the physical environment. Future work should explore how a wider range of interventions work together to support cycling.

I assessed distributional equity impacts in my thesis by analyzing the impacts of AAA cycling infrastructure amongst different populations and identifying differential impacts. This quantitative approach enabled me to speak to issues of distributional equity, but did not yield insight on procedural or recognitional issues. As a result, we do not know how the planning process behind the cycling infrastructure investments may have influenced the impacts of the intervention. We also don’t know how intersecting identities and historical injustices may have altered the impacts of cycling infrastructure for different individuals. Interviews with women and racialized people that cycle suggest cycling infrastructure investments alone are not enough to address the full range of barriers, such as exclusion from mainstream cycling culture, poor representation in transportation planning processes, gendered harassment, and racial profiling by police (Lubitow et al., 2019; Ravensbergen et al., 2020). Future work should adopt qualitative and mixed-method approaches to elucidate the procedural and recognitional issues surrounding cycling infrastructure investments.

5.4. Concluding thoughts

Our cities need to transform radically in the face of complex, interrelated challenges such as the climate emergency and the rise of chronic disease. Cycling offers clear sustainability and health benefits, yet driving tends to be safer and more convenient than cycling in most North American cities. People who choose to cycle in these unsupportive conditions don’t typically represent the entire population. Different approaches to the design and delivery of cycling infrastructure are required to grow and diversify cycling ridership. In this dynamic context, this thesis assessed the impacts of AAA cycling infrastructure investments overall and amongst different populations. This thesis offered valuable contributions, including testing different methods for cycling research, demonstrating the value of integrated knowledge translation between researchers and practitioners, and providing evidence specific to the mid-sized city context. The thesis findings indicate that investments in AAA cycling infrastructure can increase cycling activity, perceived safety, and cycling accessibility in mid-sized Canadian cities. Both manuscripts in this thesis found that investments in AAA cycling infrastructure impacted population groups differently. Researchers and practitioners need to collaborate with community to make cycling safe and convenient for all. To paraphrase Jane Jacobs (2011), our communities are capable of becoming sustainable and healthy for everybody, only when our communities are created by everybody.

References

Agyeman, J., & Doran, A. (2021). “You want protected bike lanes, I want protected Black children. Let’s link”: Equity, justice, and the barriers to active transportation in North America. *The International Journal of Justice and Sustainability*, *26*(12), 1480–1497. https://doi.org/10.1080/13549839.2021.1978412

Aldred, R. (2019). Built Environment Interventions to Increase Active Travel: A Critical Review and Discussion. *Current Environmental Health Reports*, *6*(4), 309–315. https://doi.org/10.1007/S40572-019-00254-4

Aldred, R., Elliott, B., Woodcock, J., & Goodman, A. (2016). Cycling provision separated from motor traffic: A systematic review exploring whether stated preferences vary by gender and age. *Transport Reviews*, *37*(1), 29–55. https://doi.org/10.1080/01441647.2016.1200156

Aldred, R., Woodcock, J., & Goodman, A. (2016). Does More Cycling Mean More Diversity in Cycling? *Transport Reviews*, *36*(1), 28–44. https://doi.org/10.1080/01441647.2015.1014451

Barrington-Leigh, C., & Millard-Ball, A. (2017). The world’s user-generated road map is more than 80% complete. *PLOS ONE*, *12*(8), 1–20. https://doi.org/10.1371/journal.pone.0180698

B.C. Ministry of Housing & Urban Systems Ltd. (2023). *Complete Communities: A guide to geospatial land use assessments for British Columbia’s communities*. https://www2.gov.bc.ca/assets/gov/housing-and-tenancy/tools-for-government/publications/complete-communities-guide.pdf

Benton, J. S., Anderson, J., Hunter, R. F., & French, D. P. (2016). The effect of changing the built environment on physical activity: A quantitative review of the risk of bias in natural experiments. *International Journal of Behavioral Nutrition and Physical Activity*, *13*(1), Article 1. https://doi.org/10.1186/s12966-016-0433-3

Boakye, K., Bovbjerg, M., Schuna, J., Branscum, A., Mat-Nasir, N., Bahonar, A., Barbarash, O., Yusuf, R., Lopez-Jaramillo, P., Seron, P., Rosengren, A., Yeates, K., Chifamba, J., Alhabib, K. F., Davletov, K., Keskinler, M. V., Diaz, M., Kruger, L., Li, Y., … Hystad, P. (2023). Perceived built environment characteristics associated with walking and cycling across 355 communities in 21 countries. *Cities*, *132*, 104102. https://doi.org/10.1016/j.cities.2022.104102

Boeing, G. (2017). OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. *Computers, Environment and Urban Systems*, *65*, 126–139. https://doi.org/10.1016/j.compenvurbsys.2017.05.004

Boisjoly, G., & El-Geneidy, A. M. (2017). The insider: A planners’ perspective on accessibility. *Journal of Transport Geography*, *64*, 33–43. https://doi.org/10.1016/j.jtrangeo.2017.08.006

Branion-Calles, M., Nelson, T., Fuller, D., Gauvin, L., & Winters, M. (2019). Associations between individual characteristics, availability of bicycle infrastructure, and city-wide safety perceptions of bicycling: A cross-sectional survey of bicyclists in 6 Canadian and U.S. cities. *Transportation Research Part A: Policy and Practice*, *123*, 229–239. https://doi.org/10.1016/j.tra.2018.10.024

Branion-Calles, M., Teschke, K., Koehoorn, M., Espin-Garcia, O., & Harris, M. A. (2021). Estimating walking and bicycling in Canada and their road collision fatality risks: The need for a national household travel survey. *Preventive Medicine Reports*, *22*, 101366. https://doi.org/10.1016/j.pmedr.2021.101366

Braun, L. M. (2021). Disparities in Bicycle Commuting: Could Bike Lane Investment Widen the Gap?: *Journal of Planning Education and Research*, 1–16. https://doi.org/10.1177/0739456X21993905

Braun, L. M., Rodriguez, D. A., & Gordon-Larsen, P. (2019). Social (in)equity in access to cycling infrastructure: Cross-sectional associations between bike lanes and area-level sociodemographic characteristics in 22 large U.S. cities. *Journal of Transport Geography*, *80*. https://doi.org/10.1016/j.jtrangeo.2019.102544

Broach, J., & Dill, J. (2016). Using Predicted Bicyclist and Pedestrian Route Choice to Enhance Mode Choice Models. *Transportation Research Record: Journal of the Transportation Research Board*, *2564*(1), 52–59. https://doi.org/10.3141/2564-06

Buehler, R., & Dill, J. (2016). Bikeway Networks: A Review of Effects on Cycling. *Transport Reviews*, *36*(1), 9–27. https://doi.org/10.1080/01441647.2015.1069908

Buehler, R., & Pucher, J. (2021a). Cycling to a more sustainable transport future. In *Cycling for Sustainable Cities* (pp. 327–240). MIT Press.

Buehler, R., & Pucher, J. (2021b). International Overview of Cycling. In R. Buehler & J. Pucher (Eds.), *Cycling for Sustainable Cities* (pp. 11–34). MIT Press.

Buuren, S. van, & Groothuis-Oudshoorn, K. (2011). mice: Multivariate Imputation by Chained Equations in R. *Journal of Statistical Software*, *45*, 1–67. https://doi.org/10.18637/jss.v045.i03

Byrd, A. (2022, December). *Source code for the Level of traffic stress labeler in conveyal's r5 routing algorithm*. https://github.com/conveyal/r5/blob/dev/src/main/java/com/conveyal/r5/labeling/LevelOfTrafficStressLabeler.java

Campos Ferreira, M., Dias Costa, P., Abrantes, D., Hora, J., Felício, S., Coimbra, M., & Galvão Dias, T. (2022). Identifying the determinants and understanding their effect on the perception of safety, security, and comfort by pedestrians and cyclists: A systematic review. *Transportation Research Part F: Traffic Psychology and Behaviour*, *91*, 136–163. https://doi.org/10.1016/j.trf.2022.10.004

City of Victoria. (n.d.). *Victoria's AAA Cycling Network | Victoria*. Retrieved November 10, 2021, from https://www.victoria.ca/EN/main/residents/streets-transportation/walk-roll-transit/cycling/victoria-s-aaa-cycling-network.html

City of Victoria. (2022). *Bike lanes* [dataset]. https://opendata.victoria.ca/datasets/VicMap::bike-lanes/about

City of Victoria. (2023a). *Official Community Plan*. https://www.victoria.ca/assets/Departments/Planning~Development/Community~Planning/OCP/Up~to~date~OCP~and~Design~Guidelines/OCP_WholeBook.pdf

City of Victoria. (2023b). *Current Projects*. Https://Www.Victoria.Ca. https://www.victoria.ca/EN/main/residents/streets-transportation/walk-roll-transit/cycling/current-projects.html

City of Victoria. (2023c, February 23). *All Ages and Abilities Cycling Network | Have Your Say*. https://engage.victoria.ca/aaa-cycling-network

Clark, C., Mokhtarian, P., Circella, G., & Watkins, K. (2019). User Preferences for Bicycle Infrastructure in Communities with Emerging Cycling Cultures. *Transportation Research Record*, *2673*(12), 89–102. https://doi.org/10.1177/0361198119854084

Colley, R., Butler, G., Prince, S., Garriguet, D., & Roberts, K. (2018). *Comparison of self-reported and accelerometer-measured physical activity in Canadian adults*. https://www150.statcan.gc.ca/n1/pub/82-003-x/2018012/article/00001-eng.htm

Combs, T. S., & Pardo, C. F. (2021). Shifting streets COVID-19 mobility data: Findings from a global dataset and a research agenda for transport planning and policy. *Transportation Research Interdisciplinary Perspectives*, *9*, 100322. https://doi.org/10.1016/J.TRIP.2021.100322

Craig, P., Di Ruggiero, E., Frohlich, K. L., Mykhalovskiy, E., White, M., on behalf of the Canadian Institutes of Health Research (CIHR)–National Institute for Health Research (NIHR) Context Guidance Authors Group (listed alphabetically), Campbell, R., Cummins, S., Edwards, N., Hunt, K., Kee, F., Loppie, C., Moore, L., Ogilvie, D., Petticrew, M., Poland, B., Ridde, V., Shoveller, J., Viehbeck, S., & Wight, D. (2018). *Taking account of context in population health intervention research: Guidance for producers, users and funders of research*. https://doi.org/10.3310/CIHR-NIHR-01

Craig, P., Katikireddi, V., Leyland, A., & Popham, F. (2017). Natural Experiments: An Overview of Methods, Approaches, and Contributions to Public Health Intervention Research. *Annual Review of Public Health*, *38*(39–56). https://doi.org/10.1146/annurev-publhealth

Crenshaw, K. (1989). Demarginalizing the Intersection of Race and Sex: A Black Feminist Critique of Antidiscrimination Doctrine, Feminist Theory and Antiracist Politics. *University of Chicago Legal Forum*, *1989*(1). http://chicagounbound.uchicago.edu/uclf/vol1989/iss1/8

Cunha, I., & Silva, C. (2023). Equity impacts of cycling: Examining the spatial-social distribution of bicycle-related benefits. *International Journal of Sustainable Transportation*, *17*(6), 573–591. https://doi.org/10.1080/15568318.2022.2082343

Desjardins, E., Apatu, E., Razavi, S. D., Higgins, C. D., Scott, D. M., & Páez, A. (2021). "Going through a little bit of growing pains": A qualitative study of the factors that influence the route choice of regular bicyclists in a developing cycling city. *Transportation Research Part F: Traffic Psychology and Behaviour*, *81*, 431–444. https://doi.org/10.1016/j.trf.2021.06.005

Doran, A., El-Geneidy, A., & Manaugh, K. (2021). The pursuit of cycling equity: A review of Canadian transport plans. *Journal of Transport Geography*, *90*, 102927. https://doi.org/10.1016/j.jtrangeo.2020.102927

Eldred, J. (2020, August 28). *Modeling Bicycle Comfort with Conveyal Analysis (Part 1)*. https://blog.conveyal.com/bike-lts-with-single-point-analysis-in-conveyal-55eecff8c0c7

Faghih Imani, A., Miller, E. J., & Saxe, S. (2019). Cycle accessibility and level of traffic stress: A case study of Toronto. *Journal of Transport Geography*, *80*, 102496. https://doi.org/10.1016/j.jtrangeo.2019.102496

Ferenchak, N. N., & Marshall, W. E. (2021). Bicycling facility inequalities and the causality dilemma with socioeconomic/sociodemographic change. *Transportation Research Part D: Transport and Environment*, *97*, 102920. https://doi.org/10.1016/J.TRD.2021.102920

Ferster, C., Fischer, J., Manaugh, K., Nelson, T., & Winters, M. (2019). Using OpenStreetMap to inventory bicycle infrastructure: A comparison with open data from cities. *International Journal of Sustainable Transportation*, *14*(1), 64–73. https://doi.org/10.1080/15568318.2018.1519746

Ferster, C., Nelson, T., Manaugh, K., Beairsto, J., Laberee, K., & Winters, M. (2023). Developing a national dataset of bicycle infrastructure for Canada using open data sources. *Environment and Planning B: Urban Analytics and City Science*, 23998083231159905. https://doi.org/10.1177/23998083231159905

Firth, C. L., Branion-Calles, M., Winters, M., & Harris, M. A. (2021). Who Bikes? An Assessment of Leisure and Commuting Bicycling from the Canadian Community Health Survey. *Findings*. https://doi.org/10.32866/001c.22163

Firth, C. L., Hosford, K., & Winters, M. (2021). Who were these bike lanes built for? Social-spatial inequities in Vancouver's bikeways, 2001–2016. *Journal of Transport Geography*, *94*, 103122. https://doi.org/10.1016/j.jtrangeo.2021.103122

Fischer, J., & Winters, M. (2021). COVID-19 street reallocation in mid-sized Canadian cities: Socio-spatial equity patterns. *Canadian Journal of Public Health 2021 112:3*, *112*(3), 376–390. https://doi.org/10.17269/S41997-020-00467-3

Flanagan, E., Lachapelle, U., & El-Geneidy, A. (2016). Riding tandem: Does cycling infrastructure investment mirror gentrification and privilege in Portland, OR and Chicago, IL? *Research in Transportation Economics*, *60*, 14–24. https://doi.org/10.1016/J.RETREC.2016.07.027

Foley, L., Prins, R., Crawford, F., Humphreys, D., Mitchell, R., Sahlqvist, S., Thomson, H., & Ogilvie, D. (2017). Effects of living near an urban motorway on the wellbeing of local residents in deprived areas: Natural experimental study. *PLOS ONE*, *12*(4), e0174882. https://doi.org/10.1371/journal.pone.0174882

Frank, L. D., Hong, A., & Ngo, V. D. (2021). Build it and they will cycle: Causal evidence from the downtown Vancouver Comox Greenway. *Transport Policy*, *105*, 1–11. https://doi.org/10.1016/j.tranpol.2021.02.003

Fuller, D., Gauvin, L., Dubé, A.-S., Winters, M., Teschke, K., Russo, E. T., Camden, A., Mee, C., & Friedman, S. M. (2014). Evaluating the impact of environmental interventions across 2 countries: The International Bikeshare Impacts on Cycling and Collisions Study (IBICCS) Study protocol. *BMC Public Health*, *14*(1), 1103. https://doi.org/10.1186/1471-2458-14-1103

Furth, P. G., Mekuria, M. C., & Nixon, H. (2016). Network Connectivity for Low-Stress Bicycling. *Transportation Research Record: Journal of the Transportation Research Board*, *2587*(1), 41–49. https://doi.org/10.3141/2587-06

Galway, L. P., Deck, E., Carastathis, J., & Sanderson, R. (2021). Exploring social-ecological influences on commuter cycling in a midsize northern city: A qualitative study in Thunder Bay, Canada. *Journal of Transport Geography*, *92*, 102995. https://doi.org/10.1016/j.jtrangeo.2021.102995

Gardner, Z., Mooney, P., De Sabbata, S., & Dowthwaite, L. (2020). Quantifying gendered participation in OpenStreetMap: Responding to theories of female (under) representation in crowdsourced mapping. *GeoJournal*, *85*(6), 1603–1620. https://doi.org/10.1007/S10708-019-10035-Z/FIGURES/7

Geller, R. (2006). *Four Types of Cyclists*. Portland Office of Transportation. https://www.portlandoregon.gov/transportation/article/264746

Goddard, T., Dill, J., Monsere, C., & McNeil, N. (2014, November). Can Protected Bike Lanes Help Close the Gender Gap in Cycling? Lessons from Five Cities. *Urban Studies and Planning Faculty Publications and Presentations*.

Gössling, S., Choi, A., Dekker, K., & Metzler, D. (2019). The Social Cost of Automobility, Cycling and Walking in the European Union. *Ecological Economics*, *158*, 65–74. https://doi.org/10.1016/J.ECOLECON.2018.12.016

Gössling, S., & Choi, A. S. (2015). Transport transitions in Copenhagen: Comparing the cost of cars and bicycles. *Ecological Economics*, *113*, 106–113. https://doi.org/10.1016/J.ECOLECON.2015.03.006

Götschi, T., Garrard, J., & Giles-Corti, B. (2015). Cycling as a Part of Daily Life: A Review of Health Perspectives. *Transport Reviews*, *36*(1), 45–71. https://doi.org/10.1080/01441647.2015.1057877

Government of Canada, S. C. (2022, November 30). *The Daily—Has the COVID-19 pandemic changed commuting patterns for good?* https://www150.statcan.gc.ca/n1/daily-quotidien/221130/dq221130c-eng.htm

Grant, J. L. (2023). Complete Community. *Journal of the American Planning Association*, *0*(0), 1–17. https://doi.org/10.1080/01944363.2023.2207619

Graystone, M., Mitra, R., & Hess, P. M. (2022). Gendered perceptions of cycling safety and on-street bicycle infrastructure: Bridging the gap. *Transportation Research Part D: Transport and Environment*, *105*, 103237. https://doi.org/10.1016/j.trd.2022.103237

Hawe, P., & Potvin, L. (2009). What is Population Health Intervention Research? *Canadian Journal of Public Health*, *100*(1), 8–14. https://doi.org/10.1007/BF03405503

Heinen, E., van Wee, B., & Maat, K. (2010). Commuting by bicycle: An overview of the literature. *Transport Reviews*, *30*(1), 59–96. https://doi.org/10.1080/01441640903187001

Henriques-Neto, D., Peralta, M., Garradas, S., Pelegrini, A., Pinto, A. A., Sánchez-Miguel, P. A., & Marques, A. (2020). Active Commuting and Physical Fitness: A Systematic Review. *International Journal of Environmental Research and Public Health*, *17*(8), 2721. https://doi.org/10.3390/IJERPH17082721

Herrmann, T., Gleckner, W., Wasfi, R. A., Thierry, B., Kestens, Y., & Ross, N. A. (2019). A pan-Canadian measure of active living environments using open data. *Health Reports*, *30*(5), 16–25. https://doi.org/10.25318/82-003-X201900500002-ENG

Hosford, K., Beairsto, J., & Winters, M. (2022). Is the 15-minute city within reach? Evaluating walking and cycling accessibility to grocery stores in Vancouver. *Transportation Research Interdisciplinary Perspectives*, *14*, 100602. https://doi.org/10.1016/j.trip.2022.100602

Hosford, K., & Winters, M. (2018). Who Are Public Bicycle Share Programs Serving? An Evaluation of the Equity of Spatial Access to Bicycle Share Service Areas in Canadian Cities. *Transportation Research Record*, *2672*(36), 42–50. https://doi.org/10.1177/0361198118783107

Hosford, K., & Winters, M. (2022, February 22). *How the Canadian population gets to work*. Mobilizing Justice. https://mobilizingjustice.ca/how-the-canadian-population-gets-to-work/

Hosford, K., Winters, M., Gauvin, L., Camden, A., Dubé, A.-S., Friedman, S. M., & Fuller, D. (2019). Evaluating the impact of implementing public bicycle share programs on cycling: The International Bikeshare Impacts on Cycling and Collisions Study (IBICCS). *International Journal of Behavioral Nutrition and Physical Activity*, *16*(1), 1–11. https://doi.org/10.1186/S12966-019-0871-9

Houde, M., Apparicio, P., & Séguin, A. M. (2018). A ride for whom: Has cycling network expansion reduced inequities in accessibility in Montreal, Canada? *Journal of Transport Geography*, *68*, 9–21. https://doi.org/10.1016/j.jtrangeo.2018.02.005

Huyen, L., Quinn, F., West, A., & Hankey, S. (2019). Advancing cycling among women: An exploratory study of North American cyclists. *Journal of Transport and Land Use*, *12*(1), 355–374. https://doi.org/10.5198/jtlu.2019.1461

Jacobs, J. (2011). *The death and life of great American cities: 50th anniversary edition*. Modern Library.

Jahanshahi, D., Chowdhury, S., Costello, S. B., & van Wee, B. (2021). Review of Key Findings and Future Directions for Assessing Equitable Cycling Usage: *Transportation Research Record*, *2675*(6), 453–464. https://doi.org/10.1177/0361198121995193

Jahanshahi, D., Costello, S. B., Dirks, K. N., Chowdhury, S., & Wee van, B. (2022). Understanding Perceptions of Cycling Infrastructure Provision and its Role in Cycling Equity. *Transportation Research Record*, 1–16. https://doi.org/10.1177/03611981221117821

Kapatsila, B., Palacios, M. S., Grisé, E., & El-Geneidy, A. (2023). Resolving the accessibility dilemma: Comparing cumulative and gravity-based measures of accessibility in eight Canadian cities. *Journal of Transport Geography*, *107*, 103530. https://doi.org/10.1016/j.jtrangeo.2023.103530

Karner, A., London, J., Rowangould, D., & Manaugh, K. (2020). From Transportation Equity to Transportation Justice: Within, Through, and Beyond the State: *Journal of Planning Literature*, *35*(4), 440–459. https://doi.org/10.1177/0885412220927691

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

Key:highway—OpenStreetMap Wiki. (n.d.). Retrieved August 30, 2023, from https://wiki.openstreetmap.org/wiki/Key:highway

Khan, S. (2018). Positional accuracy of geocoding from residential postal codes versus full street addresses. *Health Reports*, *29*(82), 9.

Kiani, B., Mamiya, H., Thierry, B., Firth, C., Fuller, D., Winters, M., & Kestens, Y. (2023). The temporal sequence between gentrification and cycling infrastructure expansions in Montreal, Canada. *Habitat International*, *139*, 102899. https://doi.org/10.1016/j.habitatint.2023.102899

Klinkhardt, C., Kühnel, F., Heilig, M., Lautenbach, S., Wörle, T., Vortisch, P., & Kuhnimhof, T. (2023). Quality Assessment of OpenStreetMap's Points of Interest with Large-Scale Real Data. *Transportation Research Record*, 1–14. https://doi.org/10.1177/03611981231169280

Krenn, P. J., Oja, P., & Titze, S. (2014). Route choices of transport bicyclists: A comparison of actually used and shortest routes. *International Journal of Behavioral Nutrition and Physical Activity*, *11*(1), 31. https://doi.org/10.1186/1479-5868-11-31

Krizek, K. J., Handy, S. L., & Forsyth, A. (2009). Explaining Changes in Walking and Bicycling Behavior: Challenges for Transportation Research: *Environment and Planning B: Urban Analytics and City Science*, *36*(4), 725–740. https://doi.org/10.1068/B34023

Laberee, K., Zanotto, M., Funk, A., Kirk, S. F. L., Moore, S. A., & Winters, M. (2023). 'All Ages and Abilities': Exploring the language of municipal cycling policies. *Urban, Planning and Transport Research*, *11*(1), 2264365. https://doi.org/10.1080/21650020.2023.2264365

Lam, T. (2022). Towards an Intersectional Perspective in Cycling. *Active Travel Studies*, *2*(1), Article 1. https://doi.org/10.16997/ats.1264

Le Gouais, A., Panter, J. R., Cope, A., Powell, J. E., Bird, E. L., Woodcock, J., Ogilvie, D., & Foley, L. (2021). A natural experimental study of new walking and cycling infrastructure across the United Kingdom: The Connect2 programme. *Journal of Transport & Health*, *20*, 100968. https://doi.org/10.1016/j.jth.2020.100968

Leatherdale, S. T. (2019). Natural experiment methodology for research: A review of how different methods can support real-world research. *International Journal of Social Research Methodology*, *22*(1), 19–35. https://doi.org/10.1080/13645579.2018.1488449

Lee, R. J., Sener, I. N., & Jones, S. N. (2017). Understanding the role of equity in active transportation planning in the United States. *Transport Reviews*, *37*(2), 211–226. https://doi.org/10.1080/01441647.2016.1239660

Leger, S. J., Dean, J. L., Edge, S., & Casello, J. M. (2019). “If I had a regular bicycle, I wouldn’t be out riding anymore”: Perspectives on the potential of e-bikes to support active living and independent mobility among older adults in Waterloo, Canada. *Transportation Research Part A: Policy and Practice*, *123*, 240–254. https://doi.org/10.1016/j.tra.2018.10.009

Levinson, D. M., & King, D. A. (2020). *Transport Access Manual: A guide for measuring connection between people and places*. http://www.apache.org/licenses/

Lin, B., Chan, T. C. Y., & Saxe, S. (2021). The Impact of COVID-19 Cycling Infrastructure on Low-Stress Cycling Accessibility: A Case Study in the City of Toronto. *Findings*. https://doi.org/10.32866/001c.19069

Ling, R., Rothman, L., Cloutier, M. S., Macarthur, C., & Howard, A. (2020). Cyclist-motor vehicle collisions before and after implementation of cycle tracks in Toronto, Canada. *Accident Analysis and Prevention*, *135*. https://doi.org/10.1016/j.aap.2019.105360

Litman, T. A. (2021). *Evaluating Accessibility for Transport Planning Evaluating Accessibility for Transportation Planning* (pp. 1–64). Victoria Transport Policy Institute. www.vtpi.org

Long, J. A. (2019). *interactions: Comprehensive, User-Friendly Toolkit for Probing Interactions* (1.1.5) [Computer software]. https://CRAN.R-project.org/package=interactions

Lowe, K., Barajas, J., & Coren, C. (2023). “It’s annoying, confusing, and it’s irritating”: Lived expertise for epistemic justice and understanding inequitable accessibility. *Journal of Transport Geography*, *106*, 103504. https://doi.org/10.1016/j.jtrangeo.2022.103504

Lu, M., & Diab, E. (2023). Understanding the determinants of x-minute city policies: A review of the North American and Australian cities’ planning documents. *Journal of Urban Mobility*, *3*, 100040. https://doi.org/10.1016/j.urbmob.2022.100040

Lubitow, A., Tompkins, K., & Feldman, M. (2019). Sustainable Cycling For All? Race and Gender-Based Bicycling Inequalities in Portland, Oregon. *City & Community*, *18*(4), 1181–1202. https://doi.org/10.1111/cico.12470

MacEacheron, C., Hosford, K., Manaugh, K., Smith-Lea, N., Farber, S., & Winters, M. (2023). Is Canada’s commuter bicycling population becoming more representative of the general population over time? A national portrait of bicycle commute mode share 1996–2016. *Active Travel Studies*, *3*(2), Article 2. https://doi.org/10.16997/ats.1393

Marshall, W. E., & Ferenchak, N. N. (2019). Why cities with high bicycling rates are safer for all road users. *Journal of Transport & Health*, *13*, 100539. https://doi.org/10.1016/j.jth.2019.03.004

Martens, K. (2016). Transport Justice: Designing fair transportation systems. *Transport Justice*. https://doi.org/10.4324/9781315746852

Martens, K., Golub, A., & Hamre, A. (2021). Social Justice and Cycling. In R. Buehler & J. Pucher (Eds.), *Cycling for Sustainable Cities* (pp. 257–280). MIT Press.

McGavock, J., Hobin, E., Prior, H. J., Swanson, A., Smith, B. T., Booth, G. L., Russell, K., Rosella, L., Isaranuwatchai, W., Whitehouse, S., Brunton, N., & Burchill, C. (2022). Multi-use physical activity trails in an urban setting and cardiovascular disease: A difference-in-differences analysis of a natural experiment in Winnipeg, Manitoba, Canada. *International Journal of Behavioral Nutrition and Physical Activity*, *19*(1), 1–14. https://doi.org/10.1186/S12966-022-01279-Z/FIGURES/5

Meerow, S., Pajouhesh, P., & Miller, T. R. (2019). Social equity in urban resilience planning. *Local Environment*, *24*(9), 793–808. https://doi.org/10.1080/13549839.2019.1645103

Mekuria, M. C., Furth, P. G., & Nixon, H. (2012). *Low-Stress Bicycling and Network Connectivity*. Mineta Transportation Institute. https://scholarworks.sjsu.edu/cgi/viewcontent.cgi?article=1073&context=mti_publications

Ministry of Infrastructure and Transportation. (2019). *British Columbia Active Transportation Design Guide*. https://www2.gov.bc.ca/gov/content/transportation/transportation-infrastructure/engineering-standards-guidelines/traffic-engineering-safety/active-transportation-design-guide

Mölenberg, F. J. M., Panter, J., Burdorf, A., & van Lenthe, F. J. (2019). A systematic review of the effect of infrastructural interventions to promote cycling: Strengthening causal inference from observational data. *International Journal of Behavioral Nutrition and Physical Activity*, *16*(1), 93. https://doi.org/10.1186/s12966-019-0850-1

Moore, G., Cambon, L., Michie, S., Arwidson, P., Ninot, G., Ferron, C., Potvin, L., Kellou, N., Charlesworth, J., Alla, F., Blaise, P., Bonell, C., Boutron, I., Campbell, R., Carrieri, P., Chauvin, F., Dabis, F., Edwards, N., Guevel, M. R., … Thabane, L. (2019). Population health intervention research: The place of theories. *Trials*, *20*(1), 1–6. https://doi.org/10.1186/S13063-019-3383-7/PEER-REVIEW

Moreno, C., Allam, Z., Chabaud, D., Gall, C., & Pratlong, F. (2021). Introducing the "15-Minute City": Sustainability, Resilience and Place Identity in Future Post-Pandemic Cities. *Smart Cities*, *4*(1), Article 1. https://doi.org/10.3390/smartcities4010006

Mueller, N., Rojas-Rueda, D., Cole-Hunter, T., De Nazelle, A., Dons, E., Gerike, R., Götschi, T., Panis, I., Kahlmeier, S., & Nieuwenhuijsen, M. (2015). Health impact assessment of active transportation: A systematic review. *Preventative Medicine*, *76*, 103–114. https://doi.org/10.1016/j.ypmed.2015.04.010

Murphy, B., & Owen, A. (2019). Implementing Low-Stress Bicycle Routing in National Accessibility Evaluation. *Transportation Research Record*, *2673*(5), 240–249. https://doi.org/10.1177/0361198119837179

National Association of City Transportation Officials. (2017). *Designing for All Ages & Abilities: Contextual Guidance for High-Comfort Bicycle Facilities*. https://nacto.org/wp-content/uploads/2017/12/NACTO_Designing-for-All-Ages-Abilities.pdf

Negm, H., Miller, H., & El-Geneidy, A. (2023). Exploring the X-Minute City by Travel Purpose in Montréal, Canada. *Findings*. https://doi.org/10.32866/001c.77506

Nicoletti, L., Sirenko, M., & Verma, T. (2022). Disadvantaged communities have lower access to urban infrastructure. *Environment and Planning B: Urban Analytics and City Science*, 23998083221131044. https://doi.org/10.1177/23998083221131044

Olden, A., & Møen, J. (2022). The triple difference estimator. *The Econometrics Journal*, *25*(3), 531–553. https://doi.org/10.1093/ectj/utac010

Palacios, M. S., & El-Geneidy, A. (2022). Cumulative versus gravity-based accessibility measures: Which one to use? *Findings*, 32444. https://doi.org/10.32866/001C.32444

Parker, C. (2019). Bicycle use and accessibility among people experiencing homelessness in California cities. *Journal of Transport Geography*, *80*, 102542. https://doi.org/10.1016/J.JTRANGEO.2019.102542

Pearson, L., Berkovic, D., Reeder, S., Gabbe, B., & Beck, B. (2022). Adults' self-reported barriers and enablers to riding a bike for transport: A systematic review. *Transport Reviews*, 1–29. https://doi.org/10.1080/01441647.2022.2113570

Pereira, R. H. M., & Karner, A. (2021). Transportation Equity. In *International Encyclopedia of Transportation* (pp. 271–277). Elsevier. http://dx.doi.org/10.1016/B978-0-08-102671-7.10053-3

Pereira, R. H. M., Saraiva, M., Herszenhut, D., Braga, C. K. V., & Conway, M. W. (2021). r5r: Rapid Realistic Routing on Multimodal Transport Networks with R5 in R. *Findings*, 21262. https://doi.org/10.32866/001C.21262

Public Health Agency of Canada. (2017). *Designing Heathy Living: The Chief Public Health Officer's Report on the State of Public Health in Canada 2017*. https://www.canada.ca/content/dam/phac-aspc/documents/services/publications/chief-public-health-officer-reports-state-public-health-canada/2017-designing-healthy-living/PHAC_CPHO-2017_Report_E.pdf

Pucher, J., & Buehler, R. (2017). Cycling towards a more sustainable transport future. *Transport Reviews*, *37*(6), 689–694. https://doi.org/10.1080/01441647.2017.1340234

Pucher, J., Dill, J., & Handy, S. (2010). Infrastructure, programs, and policies to increase bicycling: An international review. *Preventive Medicine*, *50*, S106–S125. https://doi.org/10.1016/j.ypmed.2009.07.028

Radzimski, A. (2023). Accessibility of social housing by sustainable transport modes: A study in Poznań, Poland. *Journal of Transport Geography*, *111*, 103648. https://doi.org/10.1016/j.jtrangeo.2023.103648

Raifer, M., Troilo, R., Kowatsch, F., Auer, M., Loos, L., Marx, S., Przybill, K., Fendrich, S., Mocnik, F.-B., & Zipf, A. (2019). OSHDB: A framework for spatio-temporal analysis of OpenStreetMap history data. *Open Geospatial Data, Software and Standards*, *4*(1), 3. https://doi.org/10.1186/s40965-019-0061-3

Ravensbergen, L. (2022). 'I wouldn't take the risk of the attention, you know? Just a lone girl biking': examining the gendered and classed embodied experiences of cycling. *Social & Cultural Geography*, *23*(5), 678–696. https://doi.org/10.1080/14649365.2020.1806344

Ravensbergen, L., Buliung, R., & Laliberté, N. (2020). Fear of cycling: Social, spatial, and temporal dimensions. *Journal of Transport Geography*, *87*, 102813. https://doi.org/10.1016/j.jtrangeo.2020.102813

Regional and Strategic Planning, Capital Regional District. (2018). *Regional Growth Strategy, Capital Regional District*. https://www.crd.bc.ca/docs/default-source/crd-document-library/bylaws/regionalgrowthstrategy/4017--capital-regional-district-regional-growth-strategy-bylaw-no-1-2016.pdf?sfvrsn=ecb611ca_10

Rutgers, J.-S. (2019, July 29). *Halifax bikeway network kicks into high gear with government funding*. Thestar.Com. https://www.thestar.com/halifax/2019/07/29/halifax-bike-network-gets-25-million-boost-from-three-levels-of-government.html

Sersli, S., Gislason, M., Scott, N., & Winters, M. (2020). Riding alone and together: Is mobility of care at odds with mothers' bicycling? *Journal of Transport Geography*, *83*, 102645. https://doi.org/10.1016/j.jtrangeo.2020.102645

Shaw, C., Russell, M., Keall, M., Macbride-Stewart, S., Wild, K., Reeves, D., Bentley, R., & Woodward, A. (2020). Beyond the bicycle: Seeing the context of the gender gap in cycling. *Journal of Transport & Health*, *18*, 100871. https://doi.org/10.1016/j.jth.2020.100871

Siddiq, F., & Taylor, B. D. (2021). Tools of the Trade? *Journal of the American Planning Association*, *87*(4), 497–511. https://doi.org/10.1080/01944363.2021.1899036

Sjoberg, D., D., Whiting, K., Curry, M., Lavery, J., A., & Larmarange, J. (2021). Reproducible Summary Tables with the gtsummary Package. *The R Journal*, *13*(1), 570. https://doi.org/10.32614/RJ-2021-053

Sotomayor, L. & Flatt, Jo. (2018). *At a Turning Point: A New Era for Mid-Sized Cities* (Leveraging Ontario's Urban Potential: Mid-Sized Cities Research Series). Evergreen. https://www.evergreen.ca/downloads/pdfs/2017/01_MSC_RC_Flatt_Sotomayor.pdf

Spangler, K. R., Brochu, P., Nori-Sarma, A., Milechin, D., Rickles, M., Davis, B., Dukes, K. A., & Lane, K. J. (2023). Calculating access to parks and other polygonal resources: A description of open-source methodologies. *Spatial and Spatio-Temporal Epidemiology*, *47*, 100606. https://doi.org/10.1016/j.sste.2023.100606

Stappers, N. E. H., Van Kann, D. H. H., Ettema, D., De Vries, N. K., & Kremers, S. P. J. (2018). The effect of infrastructural changes in the built environment on physical activity, active transportation and sedentary behavior – A systematic review. *Health & Place*, *53*, 135–149. https://doi.org/10.1016/j.healthplace.2018.08.002

Statistics Canada. (2016). *2016 & 2021 Census of Canada: Profile Data for Victoria, Kelowna, and Halifax at the Dissemination Area level.* [dataset]. cancensus. https://mountainmath.github.io/cancensus/

Statistics Canada. (2021). *Road network file, 2016, 2019 and 2021.* [dataset]. https://www12.statcan.gc.ca/census-recensement/2011/geo/RNF-FRR/index-eng.cfm

Statistics Canada. (2022). *Geographic Attribute File, Reference Guide, Census year 2021* (978-0-660-41716–5). https://www150.statcan.gc.ca/n1/en/pub/92-151-g/92-151-g2021001-eng.pdf?st=rLkNrKLj

Statistics Canada. (2019). *Dictionary, Census of Population, 2016—Dissemination area (DA)*. https://www12.statcan.gc.ca/census-recensement/2016/ref/dict/geo021-eng.cfm

Tammaru, T., Sevtsuk, A., & Witlox, F. (2023). Towards an equity-centred model of sustainable mobility: Integrating inequality and segregation challenges in the green mobility transition. *Journal of Transport Geography*, *112*, 103686. https://doi.org/10.1016/j.jtrangeo.2023.103686

Teschke, K., Chinn, A., & Brauer, M. (2017). Proximity to four bikeway types and neighborhood-level cycling mode share of male and female commuters. *Journal of Transport and Land Use*, *10*(1), 695–713. http://dx.doi.org/10.5198/jtlu.2017.943

Teschke, K., Harris, M. A., Reynolds, C. C. O., Winters, M., Babul, S., Chipman, M., Cusimano, M. D., Brubacher, J. R., Hunte, G., Friedman, S. M., Monro, M., Shen, H., Vernich, L., & Cripton, P. A. (2012). Route Infrastructure and the Risk of Injuries to Bicyclists: A Case-Crossover Study. *American Journal of Public Health*, *102*(12), 2336. https://doi.org/10.2105/AJPH.2012.300762

Vale, D. S., Saraiva, M., & Pereira, M. (2016). Active accessibility: A review of operational measures of walking and cycling accessibility. *Journal of Transport and Land Use*, *9*(1), 209–235. https://doi.org/10.5198/jtlu.2015.593

van der Zwan, A. (2023, March 7). *Victoria reopens and expands its free downtown bike valet service | CBC News*. CBC. https://www.cbc.ca/news/canada/british-columbia/victoria-free-downtown-valet-bike-service-1.6770049

van Wee, B., & Witlox, F. (2021). COVID-19 and its long-term effects on activity participation and travel behaviour: A multiperspective view. *Journal of Transport Geography*, *95*, 103144. https://doi.org/10.1016/J.JTRANGEO.2021.103144

von Bergmann, J., & Shkolnik, D. (2021). *Cancensus: R package to access, retrieve, and work with Canadian Census data and geography. V0.4.2.* https://mountainmath.github.io/cancensus/authors.html#citation

Wasserman, D., Rixey, A., Zhou, X. (Elynor), Levitt, D., & Benjamin, M. (2019). Evaluating OpenStreetMap's Performance Potential for Level of Traffic Stress Analysis. *Transportation Research Record*, *2673*(4), 284–294. https://doi.org/10.1177/0361198119836772

Whitehurst, D. G. T., DeVries, D. N., Fuller, D., & Winters, M. (2021). An economic analysis of the health-related benefits associated with bicycle infrastructure investment in three Canadian cities. *PLOS ONE*, *16*(2), e0246419. https://doi.org/10.1371/journal.pone.0246419

Willberg, E., Fink, C., & Toivonen, T. (2023). The 15-minute city for all? – Measuring individual and temporal variations in walking accessibility. *Journal of Transport Geography*, *106*, 103521. https://doi.org/10.1016/j.jtrangeo.2022.103521

Willis, D. P., Manaugh, K., & El-Geneidy, A. (2015). Cycling Under Influence: Summarizing the Influence of Perceptions, Attitudes, Habits, and Social Environments on Cycling for Transportation. *International Journal of Sustainable Transportation*, *9*(8), 565–579. https://doi.org/10.1080/15568318.2013.827285

Winters, M., Babul, S., Becker, H. J. E. H. (Jack), Brubacher, J. R., Chipman, M., Cripton, P., Cusimano, M. D., Friedman, S. M., Harris, M. A., Hunte, G., Monro, M., Reynolds, C. C. O., Shen, H., Teschke, K., Beaupré, E., Blakely, N., Dalton, J., Jazmaji, V., Kang, M., … Sztabinski, F. (2012). Safe Cycling: How Do Risk Perceptions Compare With Observed Risk? *Canadian Journal of Public Health*, *103*(Supplement 3), 42–47.

Winters, M., Branion-Calles, M., Therrien, S., Fuller, D., Gauvin, L., Whitehurst, D. G. T., & Nelson, T. (2018). Impacts of Bicycle Infrastructure in Mid-Sized Cities (IBIMS): Protocol for a natural experiment study in three Canadian cities. *BMJ Open*, *8*(1), e019130. https://doi.org/10.1136/BMJOPEN-2017-019130

Winters, M., Buehler, R., & Götschi, T. (2017). Policies to Promote Active Travel: Evidence from Reviews of the Literature. *Current Environmental Health Reports*, *4*(3), 278–285. https://doi.org/10.1007/S40572-017-0148-X/TABLES/2

Winters, M., Davidson, G., Kao, D., & Teschke, K. (2010). Motivators and deterrents of bicycling: Comparing influences on decisions to ride. *Transportation 2010 38:1*, *38*(1), 153–168. https://doi.org/10.1007/S11116-010-9284-Y

Winters, M., Fischer, J., Nelson, T., Fuller, D., & Whitehurst, D. G. T. (2018). Equity in Spatial Access to Bicycling Infrastructure in Mid-Sized Canadian Cities. *Transportation Research Record*, *2672*(36), 24–32. https://doi.org/10.1177/0361198118791630

Winters, M., & Teschke, K. (2010). Route Preferences Among Adults in the Near Market for Bicycling: Findings of the Cycling in Cities Study. *American Journal of Health Promotion*, *25*(1), 40–47. https://doi.org/10.4278/ajhp.081006-QUAN-236

Winters, M., Teschke, K., Brauer, M., & Fuller, D. (2016). Bike Score®: Associations between urban bikeability and cycling behavior in 24 cities. *International Journal of Behavioral Nutrition and Physical Activity*, *13*(1), 18. https://doi.org/10.1186/s12966-016-0339-0

Winters, M., Teschke, K., Grant, M., Setton, E. M., & Brauer, M. (2010). How Far Out of the Way Will We Travel?: Built Environment Influences on Route Selection for Bicycle and Car Travel. *Transportation Research Record*, *2190*(1), 1–10. https://doi.org/10.3141/2190-01

Winters, M., Zanotto, M., & Butler, G. (2020). The Canadian bikeway comfort and safety (Can-BICS) classification system: A common naming convention for cycling infrastructure. *Health Promotion and Chronic Disease Prevention in Canada*, *40*(9), 288–293. https://doi.org/10.24095/HPCDP.40.9.04

Yang, Y., Wu, X., Zhou, P., Gou, Z., & Lu, Y. (2019). Towards a cycling-friendly city: An updated review of the associations between built environment and cycling behaviors (2007–2017). *Journal of Transport & Health*, *14*, 100613. https://doi.org/10.1016/j.jth.2019.100613

Yuan, Y., Masud, M., Chan, H., Chan, W., & Brubacher, J. R. (2023). Intersectionality and urban mobility: A systematic review on gender differences in active transport uptake. *Journal of Transport & Health*, *29*, 101572. https://doi.org/10.1016/j.jth.2023.101572

Zahabi, S. A. H., Chang, A., Miranda-Moreno, L. F., & Patterson, Z. (2016). Exploring the link between the neighborhood typologies, bicycle infrastructure and commuting cycling over time and the potential impact on commuter GHG emissions. *Transportation Research Part D: Transport and Environment*, *47*, 89–103. https://doi.org/10.1016/J.TRD.2016.05.008

Zangenehpour, S., Strauss, J., Miranda-Moreno, L., & Saunier, N. (2016). Are signalized intersections with cycle tracks safer? A case-control study based on automated surrogate safety analysis using video data. *Accident; Analysis and Prevention*, *86*, 161–172. https://doi.org/10.1016/J.AAP.2015.10.025

Zhang, H., & Malczewski, J. (2018). Accuracy Evaluation of the Canadian OpenStreetMap Road Networks. *International Journal of Geospatial and Environmental Research*, *5*(2). https://dc.uwm.edu/ijger/vol5/iss2/1

Zhang, L., & Pfoser, D. (2019). Using OpenStreetMap point-of-interest data to model urban change—A feasibility study. *PLOS ONE*, *14*(2). https://doi.org/10.1371/JOURNAL.PONE.0212606

Appendix A.

Cycling infrastructure definitions

Local street bikeways	People on bicycles share the roadway with motor vehicles but traffic-calming elements reduce motor vehicle speeds and volumes, and bicycle priority measures facilitate safe intersection crossings (Winters et al., 2020).
Off-street paths	People on bicycles share a paved or gravel trail located away from the roadway with other pedestrians (multi-use path), or cyclists use a dedicated lane (bike path) adjacent to a pedestrian path (Winters et al., 2020).
Protected bike lanes	People on bicycles travel on a dedicated roadway lane that is physically separated from both motor vehicles and the sidewalk, through a vertical barrier, street furniture, landscaping, or change in grade (Winters et al., 2020). These were referred to as “separated cycle tracks” in our previous work (Fischer & Winters, 2021).
Painted bike lanes	People on bicycles travel on a dedicated roadway lane that is not physically separated from motor vehicles. These were referred to as “on-street bicycle lanes” in our previous work (Fischer & Winters, 2021).
Suggested bike routes	People on bicycles are guided by signs or pavement markings to share the roadway with motor vehicles on local streets but there are not traffic-calming elements. These were combined in the same category as “local street bikeways” in our previous work (Fischer & Winters, 2021).

Appendix B.

Sample sociodemographic characteristics across study years and study cities

Table B1. Weighted sociodemographic characteristics of survey respondents that live, work, or study within study boundaries by study city in 2016, 2019, and 2021

	Halifax			Kelowna			Victoria		
Sample characteristics	**2016** **N = 764** ***n* (%)**	**2019** **N = 729** ***n* (%)**	**2021** **N = 816** ***n* (%)**	**2016** **N = 826** ***n* (%)**	**2019** **N = 824** ***n* (%)**	**2021** **N = 837** ***n* (%)**	**2016** **N = 842** ***n* (%)**	**2019** **N = 860** ***n* (%)**	**2021** **N = 816** ***n* (%)**
Age									
18-34	268 (35)	270 (37)	287 (35)	225 (27)	245 (30)	228 (27)	236 (28)	256 (30)	228 (28)
35-54	226 (30)	208 (29)	241 (30)	251 (30)	240 (29)	253 (30)	249 (30)	248 (29)	243 (30)
55-75+	270 (35)	251 (34)	288 (35)	351 (42)	339 (41)	356 (43)	358 (42)	355 (41)	345 (42)
Gender (reference = men) [a]									
Women	402 (53)	387 (53)	430 (53)	431 (52)	431 (52)	436 (52)	442 (52)	448 (52)	429 (53)
Bike Access (reference = access)									
No bike	344 (45)	329 (45)	350 (43)	225 (27)	207 (25)	195 (23)	228 (27)	228 (27)	225 (28)
Birth country (reference = Canada)									
Born outside Canada	154 (20)	158 (22)	183 (22)	126 (15)	143 (17)	148 (18)	176 (21)	182 (21)	178 (22)
Car access (reference = access)									
No car access	110 (14)	110 (15)	164 (20)	43 (5)	40 (5)	54 (6)	83 (10)	87 (10)	87 (11)
Children > 16 years at home (reference = no children)									
At least one child	152 (20)	195 (27)	183 (22)	198 (24)	226 (27)	207 (25)	189 (22)	207 (24)	181 (22)

	Halifax			Kelowna			Victoria		
Sample characteristics	**2016 N = 764 *n* (%)**	**2019 N = 729 *n* (%)**	**2021 N = 816 *n* (%)**	**2016 N = 826 *n* (%)**	**2019 N = 824 *n* (%)**	**2021 N = 837 *n* (%)**	**2016 N = 842 *n* (%)**	**2019 N = 860 *n* (%)**	**2021 N = 816 *n* (%)**
Disability (reference = none)									
Disability	137 (18)	130 (18)	130 (16)	155 (19)	180 (22)	157 (19)	158 (19)	170 (20)	183 (22)
Education									
High school or less	154 (20)	125 (17)	153 (19)	198 (24)	203 (25)	188 (22)	131 (16)	118 (14)	147 (18)
Post-secondary [b]									
Graduate/professional degree	145 (19)	167 (23)	225 (28)	103 (12)	153 (19)	154 (18)	170 (20)	222 (26)	223 (27)
Employment (reference = Working for pay)									
Not working for pay [c]	229 (30)	235 (32)	272 (33)	316 (38)	300 (36)	317 (38)	318 (38)	306 (36)	316 (39)
Income									
$50k or less	207 (27)	176 (24)	220 (27)	212 (26)	206 (25)	207 (25)	223 (26)	193 (22)	153 (19)
$50k-$100k									
$100k-$150k	112 (15)	119 (16)	136 (17)	148 (18)	138 (17)	150 (18)	135 (16)	165 (19)	140 (17)
$150k or more									
Other [d]	143 (19)	104 (14)	112 (14)	141 (17)	119 (14)	121 (14)	146 (17)	115 (13)	110 (13)
Race (reference = White)									
Racialized [e]	141 (18)	123 (17)	149 (18)	68 (8)	101 (12)	112 (13)	99 (12)	90 (10)	119 (15)

Total “don’ know”, “refused”, or “other” by variable: bike access = 2, birth country = 20, car access = 1, children at home = 1, disability = 48, education = 62, employment = 91, race = 183.

[a] The instrument was not originally designed to reflect gender diversity beyond the gender binary.

[b] Combines responses: “college/vocational/technical school”, “some university”, and “graduated university”.

[c] “Not working for pay” combines responses: “homemaker”, “student”, “retired” and “unemployed”, while “working for pay” combines responses~~-~~ “≥ 30 hours/week” and “<30 hours/week”.

[d] Combines responses: “don’t know”, “refused” and “other”.

[e] Combines responses: “Indigenous (First Nations, Metis, Inuk/Inuit)”, “South Asian”, “Black”, “Latinx”, “East/Southeast Asian”, “Middle Eastern”, and “Multiracial”.

Appendix C.

Sample representativeness analysis

Table C1. Comparison of 2016 Census data with select sociodemographic characteristics of survey respondents that live, work, or study within study boundaries by study city at baseline (2016)

	Halifax 2016		Kelowna 2016		Victoria 2016	
	Census [a]	IBIMS	Census [a]	IBIMS	Census [a]	IBIMS
# of dissemination areas	320	N/A	167	N/A	390	N/A
Sample characteristics	(%)	(%)	(%)	(%)	(%)	(%)
Education [b]						
High school or less	38	20	45	24	38	16
Post-secondary	50	61	48	63	48	64
Graduate/Professional degree	12	19	7	13	13	21
Employment						
Working for pay	60	70	61	61	60	62
Not working for pay	40	30	39	39	40	38
Income						
$50k or less	44	33	36	31	38	32
$50k-$100k	33	34	33	34	33	34
$100k-$150k	13	18	17	22	16	19
$150k or more	10	15	14	14	13	14
Race						
Racialized	16	19	9	8	18	12
White	84	81	91	92	82	88

IBIMS = Impacts of Bicycle Infrastructure in Mid-Sized Cities.

Age and gender quotas were used during recruitment, therefore they are not listed in this table.

“Don’t know”, “Refused”, and “Other” responses were removed from the dataset for this comparison.

[a] Source: 2016 Census of Canada, profile data for Victoria, Kelowna, and Halifax at the dissemination area level (Statistics Canada, 2016).

[b] The census sample includes respondents $\geq$ 15 years, while the IBIMS sample includes respondents $\geq$ 18 years. This difference in age is reflected in the greater proportion of people with high school education or less in the census.

Appendix D.

Population subgroup analysis with sample subset of older adults only (≥ 55 years)

Table D1. Odds of cycling activity (weighted *n* = 2919)

Year * Study city * Exposure	Unadjusted OR	95% CI	Adjusted OR [a]	95% CI
2016 * Halifax * Unexposed	reference	—	reference	—
2019 * Halifax * Unexposed	1.04	0.59, 1.83	0.79	0.39, 1.61
2021 * Halifax * Unexposed	1.49	0.88, 2.51	1.24	0.62, 2.46
2016 * Halifax * Exposed	0.81	0.42, 1.58	0.55	0.24, 1.23
2019 * Halifax * Exposed	1.61	0.66, 3.96	2.07	0.68, 6.25
2021 * Halifax * Exposed	1.50	0.65, 3.49	1.87	0.65, 5.39
2016 * Kelowna * Unexposed	**2.55**	**1.56, 4.17**	**1.91**	**1.02, 3.60**
2019 * Kelowna * Unexposed	1.24	0.61, 2.55	1.76	0.71, 4.41
2021 * Kelowna * Unexposed	0.94	0.47, 1.87	1.06	0.43, 2.61
2016 * Kelowna * Exposed	1.12	0.51, 2.49	1.75	0.65, 4.71
2019 * Kelowna * Exposed	0.62	0.21, 1.83	0.49	0.12, 1.92
2021 * Kelowna * Exposed	0.70	0.25, 1.98	0.51	0.14, 1.92
2016 * Victoria * Unexposed	**2.99**	**1.86, 4.79**	**2.01**	**1.09, 3.69**
2019 * Victoria * Unexposed	1.00	0.50, 2.01	1.17	0.49, 2.84
2021 * Victoria * Unexposed	0.73	0.37, 1.45	0.90	0.37, 2.19
2016 * Victoria * Exposed	0.92	0.42, 2.04	1.37	0.51, 3.65
2019 * Victoria * Exposed	0.84	0.29, 2.50	0.66	0.17, 2.55
2021 * Victoria * Exposed	0.81	0.29, 2.31	0.72	0.19, 2.69

Based on the survey question: “In the previous 12 months, have you used a bicycle?”

CI = confidence interval, OR = odds ratio.

Bold indicates significant confidence interval that does not include 1.00

Unexposed indicates living, working, or studying > 500 metres from AAA (all ages and abilities) cycling infrastructure, while exposed is ≤ 500 metres.

[a] Adjusted for gender, bike access, car access, birthplace, children at home, disability, highest level of education, employment, household income, and race

Table D2. Odds of perceived safety (weighted *n* = 2824)

Year * Study city * Exposure	Unadjusted OR	95% CI	Adjusted OR [a]	95% CI
2016 * Halifax * Unexposed	reference	—	reference	—
2019 * Halifax * Unexposed	0.83	0.50, 1.37	0.81	0.49, 1.35
2021 * Halifax * Unexposed	0.77	0.47, 1.26	0.76	0.46, 1.25
2016 * Halifax * Exposed	0.83	0.48, 1.46	0.85	0.48, 1.49
2019 * Halifax * Exposed	0.61	0.26, 1.42	0.61	0.26, 1.44
2021 * Halifax * Exposed	1.46	0.68, 3.15	1.43	0.66, 3.10
2016 * Kelowna * Unexposed	**1.58**	**1.01, 2.48**	**1.64**	**1.04, 2.59**
2019 * Kelowna * Unexposed	0.93	0.48, 1.82	0.90	0.46, 1.78
2021 * Kelowna * Unexposed	1.25	0.64, 2.44	1.23	0.63, 2.41
2016 * Kelowna * Exposed	1.59	0.79, 3.21	1.58	0.78, 3.21
2019 * Kelowna * Exposed	1.13	0.39, 3.26	1.18	0.41, 3.41
2021 * Kelowna * Exposed	0.44	0.16, 1.17	0.45	0.17, 1.20
2016 * Victoria * Unexposed	**1.79**	**1.17, 2.75**	**1.71**	**1.10, 2.64**
2019 * Victoria * Unexposed	1.32	0.69, 2.51	1.35	0.70, 2.57
2021 * Victoria * Unexposed	1.43	0.75, 2.74	1.45	0.75, 2.80
2016 * Victoria * Exposed	1.28	0.63, 2.58	1.33	0.65, 2.69
2019 * Victoria * Exposed	1.46	0.51, 4.12	1.40	0.49, 3.99
2021 * Victoria * Exposed	0.74	0.28, 1.96	0.73	0.27, 1.95

Based on the survey question “On a scale of 1 to 5 (1 being very safe and 5 being very dangerous”), overall, how safe do you think cycling is in your city?”, where ”safe” combines responses ‘1- very safe’ and ‘2 – safe’.

CI = confidence interval, OR = odds ratio.

Bold indicates significant confidence interval that does not include 1.00

Unexposed indicates living, working, or studying > 500 metres from AAA (all ages and abilities) cycling infrastructure, while exposed is ≤ 500 metres.

[a] Adjusted for gender, bike access, car access, birthplace, children at home, disability, highest level of education, employment, household income, and race

Appendix E.

Population subgroup analysis with sample subset of women only

Table E1. Odds of cycling activity (weighted *n* = 3716)

Year * Study city * Exposure	Unadjusted OR	95% CI	Adjusted OR [a]	95% CI
2016 * Halifax * Unexposed	reference	—	reference	—
2019 * Halifax * Unexposed	0.98	0.62, 1.56	1.13	0.65, 1.96
2021 * Halifax * Unexposed	1.13	0.74, 1.74	1.18	0.70, 2.00
2016 * Halifax * Exposed	1.05	0.67, 1.64	0.75	0.44, 1.28
2019 * Halifax * Exposed	1.13	0.59, 2.14	0.98	0.45, 2.10
2021 * Halifax * Exposed	1.64	0.89, 3.02	1.98	0.95, 4.14
2016 * Kelowna * Unexposed	**1.97**	**1.28, 3.03**	**2.00**	**1.18, 3.40**
2019 * Kelowna * Unexposed	1.16	0.61, 2.21	1.03	0.47, 2.26
2021 * Kelowna * Unexposed	1.09	0.59, 2.01	0.83	0.39, 1.76
2016 * Kelowna * Exposed	1.12	0.61, 2.04	0.93	0.45, 1.90
2019 * Kelowna * Exposed	0.93	0.40, 2.19	1.41	0.50, 3.94
2021 * Kelowna * Exposed	0.70	0.30, 1.59	0.97	0.36, 2.65
2016 * Victoria * Unexposed	**1.86**	**1.24, 2.81**	**1.39**	**0.85, 2.27**
2019 * Victoria * Unexposed	1.00	0.54, 1.86	1.19	0.56, 2.52
2021 * Victoria * Unexposed	1.30	0.70, 2.39	1.58	0.75, 3.33
2016 * Victoria * Exposed	1.19	0.66, 2.16	1.67	0.82, 3.37
2019 * Victoria * Exposed	1.05	0.45, 2.45	0.84	0.31, 2.32
2021 * Victoria * Exposed	0.43	0.19, 0.99	0.34	0.13, 0.94

Based on the survey question: “In the previous 12 months, have you used a bicycle?”
CI = confidence interval, OR = odds ratio.
Bold indicates significant confidence interval that does not include 1.00.
Unexposed indicates living, working, or studying > 500 metres from AAA (all ages and abilities) cycling infrastructure, while exposed is ≤ 500 metres.
[a] Adjusted for age, bike access, car access, birthplace, children at home, disability, highest level of education, employment, household income, and race.

Table E2. Odds of perceived safety (weighted *n* = 3617)

Year * Study city * Exposure	**Unadjusted OR**	**95% CI**	**Adjusted OR [a]**	**95% CI**
2016 * Halifax * Unexposed	reference	—	reference	—
2019 * Halifax * Unexposed	1.07	0.65, 1.76	1.10	0.67, 1.82
2021 * Halifax * Unexposed	0.88	0.54, 1.43	0.87	0.53, 1.42
2016 * Halifax * Exposed	1.14	0.70, 1.84	1.06	0.65, 1.72
2019 * Halifax * Exposed	0.77	0.38, 1.54	0.75	0.37, 1.51
2021 * Halifax * Exposed	1.25	0.63, 2.45	1.27	0.64, 2.52
2016 * Kelowna * Unexposed	**2.17**	**1.37, 3.44**	**2.28**	**1.43, 3.64**
2019 * Kelowna * Unexposed	0.57	0.29, 1.15	0.52	0.26, 1.06
2021 * Kelowna * Unexposed	0.86	0.44, 1.70	0.85	0.43, 1.68
2016 * Kelowna * Exposed	0.60	0.32, 1.14	0.62	0.33, 1.19
2019 * Kelowna * Exposed	2.45	0.97, 6.21	**2.63**	**1.03, 6.72**
2021 * Kelowna * Exposed	1.47	0.60, 3.64	1.43	0.57, 3.58
2016 * Victoria * Unexposed	**2.12**	**1.37, 3.28**	**2.11**	**1.36, 3.29**
2019 * Victoria * Unexposed	1.17	0.61, 2.25	1.23	0.64, 2.39
2021 * Victoria * Unexposed	**1.96**	**1.01, 3.79**	**2.08**	**1.07, 4.04**
2016 * Victoria * Exposed	1.27	0.68, 2.37	1.38	0.73, 2.58
2019 * Victoria * Exposed	1.00	0.41, 2.43	0.94	0.38, 2.31
2021 * Victoria * Exposed	0.51	0.21, 1.24	0.47	0.19, 1.15

Based on the survey question “On a scale of 1 to 5 (1 being very safe and 5 being very dangerous”), overall, how safe do you think cycling is in your city?”, where ”safe” combines responses ‘1- very safe’ and ‘2 – safe’.

CI = confidence interval, OR = odds ratio.

Bold indicates significant confidence interval that does not include 1.00

Unexposed indicates living, working, or studying > 500 metres from AAA (all ages and abilities) cycling infrastructure, while exposed is ≤ 500 metres.

[a] Adjusted for age, bike access, car access, birthplace, children at home, disability, highest level of education, employment, household income, and race.

Appendix F.

Sensitivity analysis with 100 metre exposure threshold

Table F1. Odds of cycling activity (weighted *n* = 7143)

Year * Study city * Exposure	Unadjusted OR	95% CI	Adjusted OR [a]	95% CI
2016 * Halifax * Unexposed	reference	—	reference	—
2019 * Halifax * Unexposed	0.92	0.71, 1.17	0.93	0.72, 1.19
2021 * Halifax * Unexposed	0.99	0.78, 1.25	0.97	0.76, 1.24
2016 * Halifax * Exposed	0.86	0.44, 1.67	0.88	0.45, 1.73
2019 * Halifax * Exposed	1.07	0.47, 2.42	0.96	0.42, 2.21
2021 * Halifax * Exposed	1.24	0.55, 2.78	1.15	0.51, 2.62
2016 * Kelowna * Unexposed	**1.57**	**1.25, 1.98**	**1.68**	**1.33, 2.13**
2019 * Kelowna * Unexposed	0.90	0.64, 1.25	0.85	0.61, 1.20
2021 * Kelowna * Unexposed	1.07	0.77, 1.48	1.04	0.75, 1.45
2016 * Kelowna * Exposed	1.18	0.54, 2.58	1.17	0.53, 2.59
2019 * Kelowna * Exposed	1.61	0.60, 4.31	1.78	0.66, 4.84
2021 * Kelowna * Exposed	0.73	0.27, 1.92	0.76	0.28, 2.03
2016 * Victoria * Unexposed	**2.29**	**1.83, 2.86**	**2.41**	**1.92, 3.02**
2019 * Victoria * Unexposed	1.15	0.83, 1.59	1.14	0.82, 1.57
2021 * Victoria * Unexposed	1.08	0.78, 1.48	1.05	0.76, 1.45
2016 * Victoria * Exposed	1.14	0.52, 2.50	1.01	0.45, 2.25
2019 * Victoria * Exposed	0.86	0.32, 2.31	0.96	0.35, 2.62
2021 * Victoria * Exposed	1.28	0.48, 3.43	1.58	0.58, 4.29

Based on the survey question: “In the previous 12 months, have you used a bicycle?”

CI = confidence interval, OR = odds ratio.

Bold indicates significant confidence interval that does not include 1.00.

Unexposed indicates living, working, or studying > 100 metres from AAA (all ages and abilities) cycling infrastructure, while exposed is $\leq$ 100 metres.

[a] Adjusted for age, gender, bike access, birthplace, car access, children at home, disability, highest level of education, employment, household income, and race.

Table F2. Odds of perceived safety (weighted *n* = 7143)

Year * Study city * Exposure	Unadjusted OR	95% CI	Adjusted OR [a]	95% CI
2016 * Halifax * Unexposed	reference	—	reference	—
2019 * Halifax * Unexposed	0.92	0.71, 1.17	0.93	0.72, 1.19
2021 * Halifax * Unexposed	0.99	0.78, 1.25	0.97	0.76, 1.24
2016 * Halifax * Exposed	0.86	0.44, 1.67	0.88	0.45, 1.73
2019 * Halifax * Exposed	1.07	0.47, 2.42	0.96	0.42, 2.21
2021 * Halifax * Exposed	1.24	0.55, 2.78	1.15	0.51, 2.62
2016 * Kelowna * Unexposed	**1.57**	**1.25, 1.98**	**1.68**	**1.33, 2.13**
2019 * Kelowna * Unexposed	0.90	0.64, 1.25	0.85	0.61, 1.20
2021 * Kelowna * Unexposed	1.07	0.77, 1.48	1.04	0.75, 1.45
2016 * Kelowna * Exposed	1.18	0.54, 2.58	1.17	0.53, 2.59
2019 * Kelowna * Exposed	1.61	0.60, 4.31	1.78	0.66, 4.84
2021 * Kelowna * Exposed	0.73	0.27, 1.92	0.76	0.28, 2.03
2016 * Victoria * Unexposed	**2.29**	**1.83, 2.86**	**2.41**	**1.92, 3.02**
2019 * Victoria * Unexposed	1.15	0.83, 1.59	1.14	0.82, 1.57
2021 * Victoria * Unexposed	1.08	0.78, 1.48	1.05	0.76, 1.45
2016 * Victoria * Exposed	1.14	0.52, 2.50	1.01	0.45, 2.25
2019 * Victoria * Exposed	0.86	0.32, 2.31	0.96	0.35, 2.62
2021 * Victoria * Exposed	1.28	0.48, 3.43	1.58	0.58, 4.29

Based on the survey question “On a scale of 1 to 5 (1 being very safe and 5 being very dangerous”), overall, how safe do you think cycling is in your city?”, where ”safe” combines responses ‘1- very safe’ and ‘2 – safe’.

CI = confidence interval, OR = odds ratio.

Bold indicates significant confidence interval that does not include 1.00.

Unexposed indicates living, working, or studying > 100 metres from AAA (all ages and abilities) cycling infrastructure, while exposed is ≤ 100 metres.

[a] Adjusted for age, gender, bike access, birthplace, car access, children at home, disability, highest level of education, employment, household income, and race.

Appendix G.

Complete community definition

Table G1. **Destination points within each amenity category**

Active living	Community	Education	Food	Health	Shopping
gym	community_centre	school	pub	pharmacy	convenience
fitness_centre	library	childcare	restaurant	dentist	bank
sports_centre	social_facility	kindergarten	cafe	clinic	clothes
park	social_centre	university	food_court	hospital	hairdresser
pitch	townhall	college	marketplace	doctors	car_repair
playground	place_of_worship		fast_food		alcohol
swimming_pool			supermarket		bicycle
garden			food		car
golf_course			grocery		gift
sports_centre			greengrocer		all other tags under shop key (shop=*)
ice_rink			health_food		
dog_park			wholesale		
nature_reserve			cheese		
fitness_centre			butcher		
marina			frozen_food		
recreation_ground			seafood		
fitness_station			bakery		
skate_park			coffee		
			tea		
			pastry		
			ice_cream		
			chocolate		
			confectionary		

Adapted from Nicoletti et al (2022)
Each destination point corresponds to a OSM (OpenStreetMap) tag, with an amenity, leisure, or shop key.
In this study, a complete community was defined as a dissemination area (DA) where at least one active living, community, education, food, health, and shopping destination was accessible within 15 minutes of cycling on low traffic stress routes.

Appendix H.

LTS assignment in r5r: Summary of sequential logic

- Does not allow cars: LTS 1
- Is a service road: Unknown LTS
- Is residential or living street: LTS 1
- Has 3 or fewer lanes and max speed 40 km/hr or less: LTS 2
- Has 3 or fewer lanes and unknown max speed: LTS 2
- Is tertiary or smaller road:
    - Has unknown lanes and max speed 40 km/hr or less: LTS 2
    - Has bike lane: LTS 2
    - Otherwise: LTS 3
- Is larger than tertiary road
    - Has bike lane: LTS 3
    - Otherwise: LTS 4

Adapted from Eldred, 2020