BUILT ENVIRONMENT INFLUENCES ON CYCLING IN HAMILTON

CYCLING IN HAMILTON, ONTARIO: A MIXED METHODS INVESTIGATION ON THE BUILT ENVIRONMENT AND ROUTE CHOICE

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Abstract

Cycling for transport is an increasingly popular mode of travel in Hamilton, Ontario. Between 2011 and 2016, the mode share of cycling grew from 0.6% to 1.2%. As of 2019, 46% of the planned cycling facilities network has been built, which suggests that the city is transitioning to a cycling city. However, less is known about the built environment factors that influence cycling trips or the routes travelled by people who cycle in Hamilton. Drawing on the strengths of quantitative and qualitative methods, this research explores the built environment correlates of cycling and the perceptions of people who regularly cycle. First, a spatial interaction model was developed to test the level of cycling flows against various built environment attributes using trips data from the *2016 Transportation Tomorrow Survey*. A novel feature of this analysis is the use of a cycle routing algorithm to infer routes as impedance factors. The most parsimonious model suggests that the shortest-path *quietest* routes best explain the pattern of travel by bicycle in Hamilton. To build upon these findings, objective built environment attributes were documented along select shortest-path *quietest* routes using environmental audits. The qualitative phase of the study then explores how well these approximated routes match where cyclists travel in Hamilton, as well as how the built environment more broadly in a growing city is perceived and experienced, by interviewing people who regularly travel by bicycle. The interviews highlight that the built environment is not yet bicycle-oriented and that cycling infrastructure influences mobility and route choice. As a result, people who cycle seek out routes that enable them to minimize interactions with cars, by incorporating quiet streets, and that have enjoyable environments. Policy implications and recommendations specific to these findings are discussed to further support the city of Hamilton's transition to a more bikeable city.

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Abbreviations

GTHA: Greater Toronto and Hamilton Area

TTS: Transportation Tomorrow Survey

Declaration of Academic Achievement

I, Elise Desjardins, am the primary author and was responsible for all data collection, data analysis, and the writing of this manuscript.

Chapter 1: Introduction

Introduction

The bicycle has been a common sight in Hamilton, Ontario far longer than the automobile. Hamiltonians have been cycling since as early as 1899 (see Figure 1, Hamilton Public Library 2020). However, like other North American cities, transportation planning informed by modernism in subsequent decades favoured the automobile and people who cycle were increasingly excluded from public spaces through policy and design (Koglin and Rye 2014). In line with planning priorities at the time, photos of bicycles in Hamilton after the 1920s typically featured automobiles (see Figure 2, Hamilton Public Library 2020) – a visual indication of the car's growing dominance on city streets, as driving became the mode of travel of the future (Brown, Morris, and AICP 2009). It cannot be ignored that the automobile solved many urban transportation and public health problems in the early 20th century, including the presence of animal refuse on city streets, but the prioritization of this mode over others led to many unforeseen costs to the urban landscape and mobility including sprawl and pollution (Brown, Morris, and AICP 2009). The automobile was the vehicle, both literally and figuratively, to enable people to leave crowded urban cores for the suburbs where life was portrayed as healthier and more leisurely (Brown, Morris, and AICP 2009). But it inevitably took a toll on life in cities as freeways that cut through neighbourhoods ultimately influenced their fabric and character (Brown, Morris, and AICP 2009).

The ability to accommodate other road users became increasingly difficult with more city space given to roads that moved automobiles, resulting in less space for human-powered modes and the creation of unfriendly streetscapes. Efforts to educate people who cycle about the "rules of the road" are one example of the extent to which cycling practices and behaviours have been shaped in relation to other road users. The City of Hamilton, for example, dedicated an entire week to bicycle safety education in 1959 (see Figure 3, Hamilton Public Library 2020). And while European countries with a tradition of cycling for transport, like the Netherlands and Denmark, eventually began to curb the impact of the automobile on city streets in the 1970s by enacting policies to restart the uptake of cycling and discourage driving (Bruhèze and Oldenziel 2011), Canada fully embraced the monoculture of driving. In most Canadian cities today, including Hamilton, driving represents the largest mode share, and cycling levels have always been low compared to Europe (Pucher, Buehler, and Seinen 2011). This, however, is beginning to change and we are now witnessing the rise in cycling for transport in many Canadian cities over the past two decades. In particular, cycling to work levels have increased most in urban areas such as Vancouver, Montréal, and Toronto (Statistics Canada 2017), but cycling has also become more popular in small to mid-sized communities as well. We might term these "transitional cities" from the perspective of cycling because, despite historical low levels, they are currently undergoing change at the individual, community, and policy levels to become more bicycle-friendly. Key informants in many Canadian communities suggest that cultural and demographic changes alongside infrastructure and policy developments have supported this growth, although much research remains to be conducted to ensure that we understand the processes that lead to it (Assunçao-Denis and Tomalty 2019).


Figure 1. Female cyclists at the beach in Hamilton in 1899. (Hamilton Public Library 2020).

Figure 2. A child riding a bicycle on a street in Hamilton in 1957. (Hamilton Public Library 2020)

Figure 3. Bicycle Safety Week in 1959, in front of the site of the new City Hall in Hamilton. (Hamilton Public Library 2020)

Fast forward to the 21st century - the automobile became the source of many problems that transport planners in the early 20th century did not foresee or ignored (Brown, Morris, and AICP 2009). For instance, a recent national study in Canada reported that "one-third of Canadians live within 250 metres of a major road and are thus exposed to traffic emissions" (Evans et al 2019, p. 3). This number is much higher in Ontario where it's nearly 50% of residents. Evans et al. (2019) note that traffic-related emissions are responsible for most of the pollution near major roads, meaning that many Canadians are exposed to poor air quality and high levels of pollutants. Opportunities and incentives for walking and physical activity have also been removed from Canadian life over the past few decades as a result of neighbourhoods and cities designed so that people have to drive (Mowat et al. 2014).

In response to these urban challenges present in the Greater Toronto and Hamilton Area (GTHA), the most population and growing region in Canada, there is particular interest in encouraging more people to cycle for transport. Increasing urbanization has led to traffic congestion and pollution (Mowat et al. 2014), and people in Toronto have the longest average commute time compared to Montréal and Vancouver (Statistics Canada 2017). Further, there are several immediate public health concerns related to these problems have drawn the attention of public health officials. It is now the norm for Canadians to live sedentary lifestyles which has led to rising rates of obesity and diabetes, and increased health care costs to manage these conditions (Mowat et al. 2014). Given its health and environmental benefits, which are discussed in more detail later in this chapter, Medical Officers of Health in the GTHA have promoted active travel, namely walking and cycling, as a potential solution to these connected issues. Mowat et al. note: "Over a period of decades, we have removed physical activity from people's lives, designing, for example, communities that require the use of cars […] We need to build physical activity back into people's lives […] Planning healthy, compact, complete communities is needed to support greater use of public transit and active transportation." (2014, p. iii). Transportation departments within GTHA municipalities also recognize that shifting a portion of motorized trips to human-powered modes is beneficial for the overall transport system (City of Hamilton 2018a; City of Toronto 2017). Many cities have stated goals to support active transportation or reduce the mode share of single-occupancy vehicles. The creation of transportation polycultures (see Lavery, Páez, and Kanaroglou 2013), whereby individuals perceive and are able to use a variety of modes of transport, is increasingly supported by government efforts to promote active travel where such modes are practical. There are many localized trips in the GTHA that can be feasibly made by modes other than cars (Mitra et al. 2016), and cities are exploring ways to encourage this shift so that driving becomes the default mode less often.

The interests of both transport planners and public health officials intersect at the built environment level given the evidence that it influences transport choices and health outcomes. As Sallis et al. note, "Neighbourhoods designed to be safe and attractive for pedestrians and cyclists may help increase active transportation, active recreation, social capital, and home values while reducing traffic congestion, pedestrian injuries, health care costs, air pollution, and loss of open space" (2006, p. 314). These changes to the built environment can in turn facilitate greater physical activity (Sallis et al. 2012).

Interventions that modify the built environment typically remove barriers to active travel and improve factors that enable people to choose to walk or cycle more often. As such, the field of public health would call these “upstream” interventions because they aim to address the root causes of a population health problem, and they target the community level not just individuals. The literature on the relationship between the built environment and cycling, which is discussed below and in subsequent chapters, provides evidence from which cities can make informed decisions about interventions to promote active modes of transport. In particular, researchers from diverse fields without a traditional background in transport planning, ranging from sociology to epidemiology to leisure studies, have contributed to this literature. These perspectives have helped to illuminate the influence of a range of factors significant to individuals that shape transport choices. Through the Ontario Public Health Association, public health officials from a range of public health units across the province are working to address a range of topics related to the built environment including active transportation and healthy community design. Therefore, leveraging the field's expertise and bringing a public health lens to transport planning and urban design can help to identify co-benefits, evaluate the impact of interventions, and incorporate behaviour change strategies to support the development of new transport habits or norms.

Cycling and Public Health

As mentioned above, cycling is seen as an important component of a healthier and more sustainable transportation system that is influenced by the built environment, but it also offers benefits to population health. First and foremost, sedentary lifestyles and inadequate physical activity are public health concerns not only in Hamilton but across Canada. The majority of Canadian adults do not meet the daily physical activity guidelines (Statistics Canada 2015) and over 60% are overweight or obese (Statistics Canada 2017). Data from the most recent *Canadian Community Health Survey* in 2014 has also shown that the rates of obesity are rising in the adult population (Statistics Canada 2017). In the GTHA alone, it is estimated that physical inactivity and obesity lead to annual health care costs of over $4 billion (Mowat et al. 2014). Increasing physical activity is important at both the individual and population-level; it can reduce mortality risk (Woodcock et al. 2011) and the risk of obesity, cardiovascular disease, and diabetes (Statistics Canada 2018). For this reason, Medical Officers of Health in the GTHA have emphasized that enabling people to build physical activity into their daily routines is an important solution to prevent serious health conditions like diabetes or premature deaths (Mowat et al. 2014).

A growing number of studies have been conducted to investigate the association between cycling for transport or active travel and various health outcomes. The main health benefit is derived from increased physical activity which, after adjusting for other forms of recreational physical activity, has been associated with decreases in all-cause mortality risk (Kelly et al. 2014; Sahlqvist et al. 2013). Due to its moderate intensity, cycling for transport has been found to have the potential to contribute to an individual's requirement of 150 minutes of physical activity per week (Dill 2009). In a prospective population-based longitudinal study in the United Kingdom, Celis-Morales et al. (2017) found that commuting to work by bike, compared to other modes, was associated with a lower risk of cardiovascular disease, cancer, and all-cause mortality. While cycling for transport may expose the cyclist to interactions that may be detrimental to health, such as traffic accidents, injuries, or exposure to harmful air pollution, the evidence suggests that increased physical activity leads to health benefits that outweigh these potential consequences (de Hartog Jeroen Johan et al. 2010; Mueller et al. 2015). Collaboration with other sectors, including transport planners, can also help to reduce the risk of traffic accidents or injuries through policy and design. Researchers have also estimated significant health gains of a modal shift from driving to cycling. For instance, Raustrop and Koglin (2019) estimated that if nearly half of the residents in Scania county, Sweden cycled to work then almost 20 percent of the sample would meet the physical activity guidelines from the World Health Organization.

Overall, this area of research has some methodological challenges such as the reliance on cross-sectional or case studies (Götschi, Garrard, and Giles-Corti 2016) and the lack of longitudinal pre- and post-intervention studies (Mueller et al. 2015). This is beyond the scope of this literature review but important to acknowledge. More robust evidence with stronger methodological rigour is needed to confirm any causality between active travel and specific health outcomes (Saunders et al. 2013), and to discern the cycling-related effects on active travel more broadly (Oja et al. 2011). This could be an important opportunity for the field of public health to lend its expertise; stronger evidence of the benefits of cycling to population health could strengthen political will for changes and increase resources for making communities more bikeable. Nonetheless, many reviews have emphasized that promoting cycling is worthwhile from a public health standpoint because it can provide benefits at the population-level and is accessible from childhood to older age (Götschi, Garrard, and Giles-Corti 2016).

Cycling and the Built Environment

While research from different disciplines suggests that the decision to cycle is determined by factors at all levels of the socio-ecological model of health (Sallis et al. 2006), the cultural and built environments have received a lot of attention because of their importance in influencing behaviours at the interpersonal and community levels. The interests of public health and transport planning have intersected at the built environment level because both fields implement interventions that seek to change behaviour. The built environment has been defined as "the human-made design and layout of the communities in which people live, work, and play, which includes: neighbourhoods, homes, workplaces, schools, shops and services, sidewalks and bike paths, streets and transit networks, green spaces, parks and playgrounds, buildings, and other infrastructure" (City of Ottawa 2020). These attributes have been studied more closely in different settings to determine the direction of their association with active travel. Built environment characteristics such as mixed land use, street connectivity, cycling infrastructure, density of people and destinations, green space, and proximity to destinations are positively associated with or influence cycling for transport (Buehler and Dill 2016; Heesch et al. 2012; Le, Buehler, and Hankey 2018; Mertens et al. 2017; Pucher and Buehler 2008; Titze et al. 2010; Winters et al. 2010). Revealed preference studies have shown that routes travelled by cyclists typically feature some kind of cycling facility (Broach, Dill, and Gliebe 2012; Chen, Shen, and Childress 2018; Dill 2009) and cyclists both current and potential report a strong preference for facilities that separate them from traffic (Aldred et al. 2017; Winters et al. 2011). However, environments that support active travel tend to have several concurrent characteristics, for example cycling facilities in a mixed-use neighbourhood, which suggests that their effects on behaviour are likely to be cumulative (Sallis et al. 2012). A more thorough review of this literature is presented in Chapters 2, 3, and 4.

Changing one's behaviour to incorporate more physical activity in daily routines is challenging in environments where barriers exist and supports are not adequately promoted (Sallis et al. 2012). A range of interventions, from building infrastructure to traffic calming policies, have been implemented to encourage and facilitate cycling for transport in cities across Canada (Assunçao-Denis and Tomalty 2019). Building cycling infrastructure is arguably the most common action taken by cities because it is more incremental in nature and requires resources on a smaller scale. King and Krizek (2020) have argued that street-level changes should be the focus because they can be implemented more rapidly than larger changes with land use that often take decades. But as Rauthorp and Koglin note (2019), land use is an important determinant of where people live and work, and it can also influence travel distances and preferred modes. Nonetheless, dedicated infrastructure can be perceived as a prerequisite for access to road space, since cyclists typically prefer not to mix with traffic. A recent health impact assessment in seven European cities concluded that building new cycling facilities to expand the network was associated with increases in cycling (Mueller et al. 2018). This finding is supported by other research that protected infrastructure is a motivator for potential cyclists (Winters et al. 2011). Furthermore, Mueller et al. also estimated that "if all 167 European cities achieved a cycling mode share of 24.7%, over 10,000 premature deaths could be avoided annually" (2018). This evidence suggests that greater investment in cycling infrastructure is justified given the health and economic benefits that cities will experience if their residents are more physically active and have lower risk of chronic disease. However, such infrastructure would only lead to the expected benefits if they are perceived to be appealing and useable. Thus, cyclist preferences ought to be considered in their implementation.

A review of the evidence on the effects of interventions to promote cycling suggests that cities that implement a suite of interventions to change factors at the individual, built environment, and policy level have been successful in increasing cycling trips (Pucher, Dill, and Handy 2010). It has been argued that efforts that address factors at multiple levels of the socio-ecological model are worth exploring and implementing by cities that want to increase the uptake of cycling (Sallis et al. 2006). A recent systematic review found that the evidence on the effects of interventions to promote cycling is mixed and unclear (Yang et al. 2010). However, interventions appear to have at least a weak positive effect on cycling or active travel levels but can also have larger impacts (Aldred 2019; Mölenberg et al. 2019; Smith et al. 2017). Similar to the research on the association between health benefits and active travel, measuring or evaluating the efficacy of interventions is challenging because of methodological complexities (Aldred 2019; Mölenberg et al. 2019). As a city grows its infrastructure base and culture, experimenting with interventions is an opportunity for learning what will be effective in different situations. However, these interventions may only lead to the expected benefits if they are perceived to be appealing and useable by current and potential cyclists.

Additional research on these topics is cited and explored more in-depth in the following three chapters; each paper has a background or literature review section that is unique to the content of each phase of the project.

Setting for Research: Hamilton, Ontario

Hamilton is a mid-sized city in the GTHA with over 550,000 residents where cycling for transport is becoming an increasingly popular mode of transport. According to the 2016 *Transportation Tomorrow Survey* (*TTS*), a regional travel survey conducted in the GTHA every 5 years, approximately 1.2% of all trips in Hamilton are made by bicycle (Data Management Group 2018). This is a twofold increase from 2011 when the cycling mode share was only 0.6% (Data Management Group 2014). In fact, it has been estimated that 35% of all current trips in Hamilton are 5 km or less, which means that these trips could be cycled (Mitra et al. 2016). Thus, there is the potential to incentivize modal shifts in Hamilton that specifically increase opportunities for physical activity. Over the duration of this 5-year growth in cycling, the City of Hamilton was recognized as a Silver-rated Bicycle-Friendly Community by Share the Road Cycling Coalition, a provincial cycling advocacy group in Ontario (City of Hamilton 2018b).

The city's current Cycling Master Plan was first released in 2009 to "guide the development and operation of [the city's] cycling infrastructure for the next twenty years" (City of Hamilton 2009, p. i). The proposed network was designed to support commuter, recreational, and utilitarian cyclists. The Cycling Master Plan was most recently updated in 2018 to report on the progress achieved since 2009. The Plan outlines the following considerations that currently guide the planning of the cycling facilities network: continuity, safety, demand, cost, property constraints, and project coordination (City of Hamilton 2018b, p. 6-7). The plan states that $51.5 million (in 2009 dollars) is needed to implement the network by 2029. However, it also acknowledges that this would require an annual investment of $2.5 million which is more than double what the city typically allocates per year. On the other hand, the City spends over $70 million per year on roads, bridges, traffic, and sidewalks. The City received over $6 million from the provincial government in 2018 through the Ontario Municipal Commuter Cycling Program, which increased implementation budgets for the subsequent two years and completed some important gaps in the network. As of 2019, approximately 46% of the planned city-wide cycling infrastructure, which includes on-street and off-street facilities [see Figure 1], has been built (City of Hamilton 2020). The majority of proposed signed routes (77% of the network complete) and major multi-use trails/paths (65% complete) have been implemented, but only 35% of the proposed bicycle lanes have been completed (City of Hamilton 2020). Around 15 to 20 km of new cycling facilities are built each year, amounting to an annual increase of 1-2% for the entire network (City of Hamilton 2020). The Social Planning and Research Council (2014) in Hamilton reported that the City is likely to finish building the network by 2053, not 2029, at this current rate of implementation.

The City of Hamilton has implemented a range of strategies to date to encourage people to cycle. One of the City's most successful efforts to date is the public bicycle share system, Hamilton Bike Share, which has over 120 hubs in the lower city and nearly 900 operational bikes. It was launched in 2015 and had over 26,000 subscribers by June 2020. Hamilton's bicycle share system is the only one in Canada that provides greater access in disadvantaged areas (Hosford and Winters 2018), and it launched an equity program in 2018 to provide subsidized memberships to individuals in financial need. The City also has a Cycling Committee made up of local representatives that advises City Council on matters relating to cycling, including promotion, safety, infrastructure design, and tourism. The City has implemented programs to promote and encourage cycling for transport including annual events like *Bike Month* and *Bike to Work Day*, discounted transit and bike share passes for select workplaces based on demand, and workplace-based carpooling programs across the GTHA.

As such, it is posited that Hamilton is currently in a phase of transition; efforts to grow Hamilton's cycling culture are already underway, and cycling levels have grown between 2011 and 2016, but there is still a lot of work to be done to develop as a cycling city. There is opportunity now to "take a snapshot" at this mid-way point and examine cycling experiences and behaviours more closely. With more concerted efforts to encourage cycling for transport in Hamilton, there is a need for more research at the local level to better understand where cyclists travel and how they experience the built environment to gather evidence that can inform the creation and implementation of place-based policies or new interventions to grow cycling as an ideal mode of transportation.

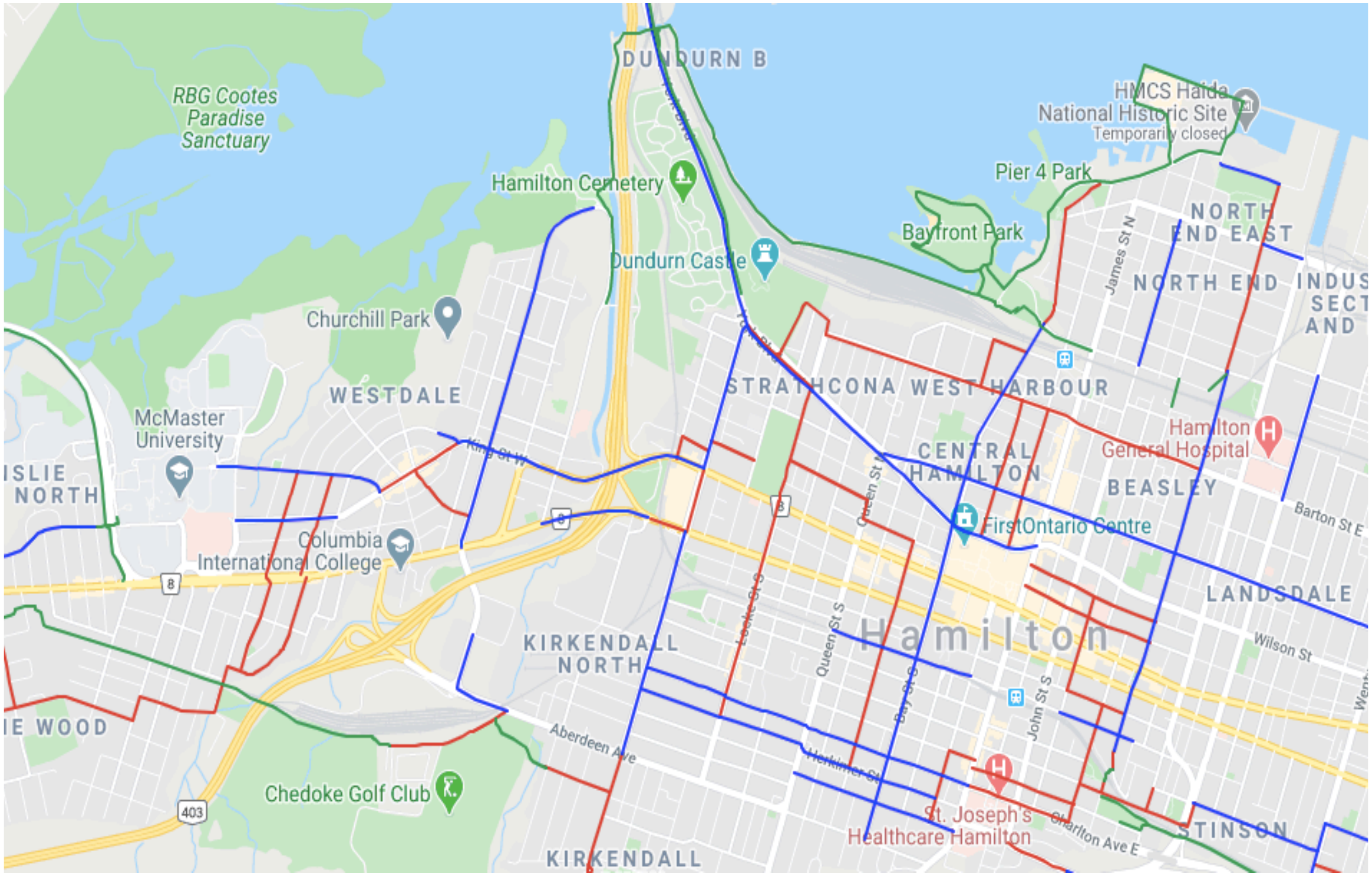

Figure 1. Road network and cycling facilities in the lower city in Hamilton. ***Legend****: blue lines indicate designated on-street bicycle lanes; red lines indicate signed on-street bike routes on streets with mostly low traffic volume; green lines indicate off-street paved multi-use trails that are shared with pedestrians; yellow lines represent highways;* *<u>white</u> lines represent arterial, collector, and residential roads.* (City of Hamilton 2020).

As a mid-sized city with low but growing cycling levels, and potential for increasing the mode share, Hamilton is a uniquely beneficial setting in Canada to study cycling. Large urban areas such as Vancouver, Montréal, and Toronto have attracted considerable attention for cycling research to date because of their higher mode shares (Statistics Canada 2017; Pucher, Buehler, and Seinen 2011). But small and mid-sized Canadian communities have also been proactive in supporting more cycling (see Assunçao-Denis and Tomalty 2019), despite less research in these areas. Given that nearly one third of all Canadians live in a mid-sized city, with a ranging from population from 100,000 to 1 million, a more complete understanding of the factors that influence cycling in these communities that differ from more dense and urbanized regions is warranted. Other recent interest in investigating cycling in mid-sized cities in Canada (for example, see Mayers and Glover 2019 and Winters et al. 2018) will also be informative. Further investigations can provide the evidence needed to inform strategic investments in these unique settings to facilitate cycling for transport. Beyond Canada, research in cities with emerging cycling cultures is also growing (*inter alia*, see Clark et al. 2019; Caulfield 2014; Félix, Moura, and Clifton 2019), and this thesis can contribute to the present body of research from a Canadian lens.

Cycling research conducted at McMaster University to date has helped to shed light on various aspects of the cycling experience in Hamilton. A recent study explored the challenges associated with cycling and the subjective identities of Hamilton's cyclists (van Miltenburg 2016). The study's finding that "cyclists are well-equipped to critically evaluate the urban spaces through which they travel" (van Miltenburg 2016, p. iii) suggests that the involvement of local cyclists in cycling research based in Hamilton is valuable and that their expertise can be leveraged to understand how the built environment influences route choice in a developing cycling city. Various studies have also analyzed data from the bicycle share system since it was launched in 2015. Scott and Ciuro found that the university is a major predictor of bike share trips (Scott and Ciuro 2019). Lu et al. (2018) conducted route choice analysis and reported that bike share users travel routes that are longer than the shortest path distance and are more likely to use local streets with low traffic and bicycle facilities. These studies have addressed different aspects of cycling in Hamilton, but more information about route choice preferences in the general population from a qualitative perspective can be informative about the types of environments that support cycling.

Rationale for Research

Most of what is known about the influences of the built environment on cycling for transport comes from quantitative methods. Data from travel surveys or census records form the bulk of sources used in exploratory individual or aggregate studies to infer how often people cycle, for which trip purposes, and where cycling trips start and end (Handy, Wee, and Kroesen 2014). Many studies make use of this data to explore the relationship between cycling levels or the likelihood of making a trip by bicycle and the presence or absence of urban form features at the meso-level around the origin and destination. While travel surveys and census data are less informative with respect to route choice and their characteristics, tools that collect revealed preferences, such as GPS or crowdsourced data from phone applications, are increasingly being used to capture information about route choice that can help to infer the types of infrastructure or environments that cyclists prefer (Pritchard 2018). Novel routing algorithms, such as *CycleStreets* (Lovelace and Lucas-Smith 2018), can also aid in our ability to infer and compare different routes between origins and destinations while considering aspects of the built environment that might influence cyclists to take such routes.

Qualitative research is increasingly common in the cycling literature given its suitability for answering a range of *why* and *how* questions about behaviour, culture, and identity. Cycling, similar to walking, allows for a more intimate and direct interaction with the built environment (Liu, Krishnamurthy, and Wesemael 2018; Moudon and Lee 2003) which lends itself well to the use of qualitative methods that can explore and describe its experiential nature in-depth. In Hamilton, where the cycling facilities network is still under development and there is currently limited infrastructure, qualitative methods can be useful for engaging with those who currently cycle to understand how the built environment is perceived at this stage and whether the changes to date support or hinder their ability to travel by bicycle. While both quantitative and qualitative approaches have merits on their own, they are complementary and ideally both can be used to answer different aspects of a research question (Steinmetz-Wood, Pluye, and Ross 2019). Quantitative data, when available, can be examined to identify travel patterns across the city while qualitative data can help to further interpret and contextualize these findings. The result is that both quantitative and qualitative research can be used together to develop a more holistic understanding of the cycling experience, as well as produce different types of evidence that can inform Hamilton's transition to a more bikeable city.

As a Hamiltonian and year-round cyclist since 2016, my interest in this topic was also driven by my own experiences and by my curiosity to better understand the experience of cycling in a city that is aiming to be more bicycle-friendly. More concretely, there is a need to understand how cycling for transport in developing cycling cities differs from or is similar to the evidence in the literature from other established cycling cities. One of the challenges in growing as a cycling city is determining what could be adapted from other cities with success and what unique contexts exist that require data from the local level. Given the evidence that cycling for transport is facilitated by the design and planning of our communities, and the health benefits associated with this mode, my focus on the built environment could inform policy or infrastructure solutions at the population-level in support of healthier and active modes. I also hope that this research project can contribute to the literature on this topic and produce practical findings for decision-makers in Hamilton. I acknowledge these motivations early on because my perspective and identity as a cyclist in this city has shaped how I approached this research. My connections to the cycling community have also strengthened my ability to do this research. As Hammersley and Atkinson (2007) have noted, "the researcher is the instrument" in qualitative data collection and analysis, and they are an active respondent to create space where others feel comfortable sharing their stories and experiences. It is therefore important to share that this project was planned, developed, and interpreted from the lens of a regular cyclist and advocate in Hamilton. I expand upon this further in Chapter 5.

Study Design

This study investigates cycling for transport in Hamilton, Ontario with a focus on the built environment and route choice. There are two large sources of data on cycling in Hamilton: the *Transportation Tomorrow Survey*, a regional travel survey carried out in the GTHA every 5 years by the University of Toronto's Data Management Group, and the ridership dataset from the city's public bicycle share program, Hamilton Bike Share. The former is publicly available and access to the data can be granted through the Data Management Group. Data from the bicycle share program is private and accessible only to the City of Hamilton and select researchers at McMaster University. Other types of cycling data include counters along select cycling facilities in the city. From the 2016 *Transportation Tomorrow Survey* dataset, it is possible to create an origin-destination matrix to demonstrate cycling trips between traffic zones[1] in Hamilton. These represent trip flows between different zones or within the same zone. However similar to many other travel surveys, this one does not ask for information about where cyclists travel from origin to destination.

Research Focus 1. With the exception of a GPS-based study in Hamilton of bike share users (Lu, Scott, and Dalumpines 2018), less is known about the built environment along the routes that cyclists choose to travel in Hamilton. However, research has shown that built environment factors at the route-level can be more influential on the likelihood of cycling than at the origin and destination (Winters et al. 2010). The lack of data on

[1] The traffic zone is the smallest spatial unit at which data are aggregated in the *Transportation Tomorrow Survey*. It is a polygon which typically falls along the centre line of roads or geographic boundaries.

route choice in the travel survey necessitates that potential routes be *inferred* instead. Therefore, a spatial interaction model can be developed to examine which built environment attributes at the zones of origin and destination of trips and to infer different types of routes between the zones by taking advantage of new technology, namely *CycleStreets*. The latter can help to explore which type of route best explains cyclist travel in Hamilton.

Research Focus 2. The *CycleStreets* algorithm captures some attributes of the built environment through data available from *Open Street Map* so the inferred routes in the spatial interaction model take these into account. Once the routes are inferred, the quality of the built environment can be documented using environmental audits. It is then possible to explore how well these approximated routes match where cyclists travel or would travel in Hamilton and to validate them through semi-structured interviews with people who regularly cycle.

Research Focus 3. Travel surveys, like the *Transportation Tomorrow Survey*, tend to be representative and are generalizable which make them useful for describing trends. However, they are less informative about motivations, experiences, and perceptions. Interviews and focus groups, although conducted in small sample sizes, allow for a deeper and more detailed understanding of aspects of transport behaviours that are not captured in travel surveys. Therefore, semi-structured interviews can further explore how the built environment more broadly in a transitional city is perceived and experienced by people who cycle.

Therefore, this research project aims to answer the following two questions using both quantitative and qualitative methods:

1. What attributes of the built environment influence cycling in Hamilton, Ontario?
2. What are cyclists' perceptions of the attributes in the built environment that influence their route choice?

This project was designed as an explanatory sequential mixed methods study. This design is a two-phased approach that includes the collection and analysis of quantitative and qualitative data, with the purpose of using the qualitative data to explain, interpret, and build upon the quantitative results (Creswell 2003). The qualitative phase is typically designed so that it connects to the findings from the quantitative phase (Figure 1, Creswell 2003). In this study, the second and third papers (Chapter 3 and 4) that describe the findings of the qualitative phase are used to interpret and build upon the results from the first paper (Chapter 2) in the quantitative phase. Among its strengths, this mixed methods design is easy for a single researcher to implement (Creswell 2003). Regardless of the design, mixed methods studies use complementary data to better understand a phenomenon.

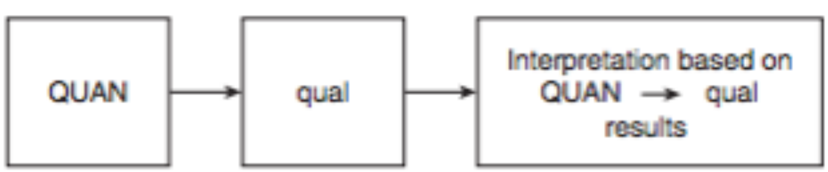

Figure 1. Explanatory sequential design in a mixed methods study (Creswell 2003).

This design was chosen because it would draw on the strengths of both quantitative and qualitative research to develop a comprehensive understanding of the influence of the built environment on travel by bicycle in Hamilton. Mixed methods have been identified as well suited for topics that explore the interactions between health or health outcomes and the built environment (Steinmetz-Wood, Pluye, and Ross 2019). Conceptually, this research is informed by Moudon and Lee's (2003) *behavioral model of environment* framework, which identifies three important spatial components of an active travel trip: i) the origin and destination; ii) the characteristics of the route taken for these trips; and iii) the attributes around the origin and destination.

A mixed methods design typically requires a lot of time to implement due to data collection and analysis being conducted in two separate phases (Creswell 2003). However, secondary data from the *Transportation Tomorrow Survey* was used here instead of collecting new data. The most recent survey was conducted in 2016, and the data were made publicly available through the University of Toronto's Data Management Group in spring 2018. Given that the 2016 survey had not yet been used for any cycling research in Hamilton as of May 2019, this data set was analyzed in the quantitative phase to investigate the built environment correlates of cycling trip flows and to explore which type of route, inferred by *CycleStreets*, best explained cyclist travel in Hamilton. This shortened the timeline of data collection in the quantitative phase which made it feasible to complete both phases within the duration of the Master of Public Health program.

Structure of Thesis

Each subsequent chapter in this thesis addresses one or both of the research questions outlined above using either quantitative or qualitative methods.

Quantitative Phase

Chapter 2

This paper describes the development of a spatial interaction model to test the level of cycling flows against various built environment attributes at the zones of origin and destination using bicycle trip records from the *Transportation Tomorrow Survey (TTS)*. The quantitative phase was informed by Moudon and Lee's (2003) framework as well as the work of Moniruzzaman and Páez (2012) who developed a model-based approach to identify and audit dissemination areas in Hamilton where there were higher and lower shares of walking than predicted by their travel behaviour model. A similar approach and methodology were adopted to examine cycling trips between zones of origin and destination for this research in Hamilton. The zones of origin and destination are known through the *TTS*, but there is no information about the routes taken by people who cycle or their true origins and destinations. Instead, the centroids of the traffic zones were used as approximate start and end points of each trip flow. To overcome this limitation, a novel feature of the analysis is the use of *CycleStreets* (Lovelace and Lucas-Smith 2018), a cycle routing algorithm created in the United Kingdom, to infer different types of routes for the cost function of the model.

Qualitative Phase

Chapter 3

This paper reports on the findings from environmental audits that were conducted along select inferred routes, as well as cyclists' perceptions of these routes which were explored through a photo activity in semi-structured interviews. The residuals of the spatial interaction model reveal which cycling trip flows were over- and under-estimated trip which were then examined in more detail (see Moniruzzaman and Paez's (2012) research on walking trips in Hamilton). It was hypothesized that discrepancies between the number of observed and expected trips for each flow are due to micro-level attributes along the routes that were not captured in the spatial interaction model. For instance, there may be built environment attributes that deter cycling along routes for trip flows that were over-estimated. The opposite may be true along routes for trip flows that were under-estimated; the built environment may be more supportive for cycling. This unexplained part of the model is explored further using qualitative methods to explain and interpret why these flows may have been over- or under-estimated.

Environmental audits were conducted along 12 inferred routes using the *Systematic Pedestrian and Cycling Environmental Scan* (*SPACES*) (Pikora et al. 2002) to investigate their characteristics. Given the large number of trip flows that were analyzed from the origin-destination matrix (n = 9,801), a selection of the most over- and under-estimated flows were chosen for further examination. These were looked at further since the model performed most poorly for these trip flows in particular, even after including various built environment attributes at the zonal level. This was followed by 90-minute individual semi-structured interviews with 14 people who regularly cycle in Hamilton. Participants completed an activity where they were asked to look at photos of routes that were audited and to share their perceptions of the route. The subjective likes and dislikes of participants were compared to the objective assessment of route attributes. These findings were triangulated with the results from the spatial interaction model.

Chapter 4

This qualitative description paper describes findings from the thematic analysis of part of the semi-structured interviews. The spatial interaction model was expected to identify built environment attributes at the zones of origin and destination that explained the pattern of cyclist travel. Routes between zones of origin and destination were estimated using *CycleStreets* to incorporate, at the very least, certain factors captured by the algorithm that are used to infer routes that a knowledgeable cyclist could travel. To further interpret the results from the spatial interaction model, participants were asked questions about their cycling behaviour and how they perceive the built environment more broadly in Hamilton. The interview questions were informed by the quantitative phase but were more general so as to determine which built environment attributes more readily came to mind as influential for cyclists' route choice.

Conclusion

The final chapter presents a synthesis of the findings, reflection on the thesis process, and outlines public health implications and future directions for research on cycling in Hamilton and other transitional cities.

Caveat Lector

This manuscript is structured as a sandwich thesis, which means that it consists of three papers that have been written for publication. For this reason, there will be some repetition throughout as details of the study design are included in each chapter, and the background or introduction sections have similar literature cited.

Contributions

Chapter 2: CRediT Author Statement

Elise Desjardins: Conceptualization; Methodology; Formal Analysis; Validation; Writing - Original Draft

Dr. Antonio Páez: Conceptualization; Methodology; Software; Formal Analysis; Validation; Visualization; Writing - Original Draft; Supervision

Dr. Darren Scott: Writing - Review & Editing

Dr. Chris Higgins: Writing - Review & Editing

Dr. Emma Apatu: Writing - Review & Editing

Chapter 3: CRediT Author Statement

Elise Desjardins: Conceptualization; Methodology; Investigation; Formal Analysis; Writing - Original Draft

Dr. Antonio Páez: Conceptualization; Methodology; Investigation; Writing - Original Draft; Supervision

Dr. Emma Apatu: Writing - Review & Editing

Chapter 4: CRediT Author Statement

Elise Desjardins: Conceptualization; Methodology; Investigation; Formal Analysis; Writing - Original Draft

Dr. Emma Apatu: Conceptualization; Methodology; Writing - Original Draft; Supervision

Dr. Antonio Páez: Conceptualization; Methodology; Writing - Original Draft

Dr. S. Donya Razavi: Methodology; Writing - Review & Editing

Dr. Chris Higgins: Visualization; Writing - Review & Editing

Dr. Darren Scott: Writing - Review & Editing

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Chapter 2: Spatial Interaction Model

Introduction

Cycling is becoming an increasingly popular mode of travel in Canadian urban areas. From 1996 to 2016 the number of people commuting to work by bicycle in Canadian census metropolitan areas increased by 87.9% and the share of bicycle commute trips grew from 1.2% to 1.6% (Statistics Canada 2017). Such modal shifts may been have prompted by the widely recognized health and environmental benefits associated with cycling. Compared to other transportation modes, travelling by bicycle is associated with better self-perceived health (Avila et al. 2018) and reduced risk of chronic disease (Celis et al. 2017; Oja et al. 2011]. It has also been associated with reduced greehouse gas emissions (Zahabi et al. 2016) and improved air and noise pollution (de Nazelle et al. 2011). These benefits serve as motivation for cities to encourage more travel by this mode, but this requires effort to put cycling on par with other modes of transportation at a policy level. For this reason, many Canadian cities have integrated cycling in their transportation plans in recent years (*inter alia*, see City of Calgary 2011; City of Montréal 2017; City of Vancouver 2012) and have implemented a range of interventions and strategies that have been effective in increasing cycling (Assunçao-Denis and Tomalty 2019; Verlinden et al. 2019].

The City of Hamilton, located in the Greater Toronto and Hamilton Area urban region, has been identified as a city where cycling levels could substantially increase (Mitra et al. 2016). Approximately one third of all trips in the city are 5 km or less, which is widely considered to be a bikeable distance. Within the GTHA, Hamilton is a mid-sized city, located approximately 50 km from Toronto, that has also recently experienced a rise in cycling. As of 2016, 1.2% of all trips in Hamilton are made by bicycle according to the latest *Transportation Tomorrow Survey*, the periodic travel survey in the region (Data Management Group 2018). This represents a two-fold increase from the 2011 survey results when the mode share of cycling was only 0.6% (Data Management Group 2014). The increase in cycling trips in Hamilton occurred over the same period that cycling interventions were implemented, such as building more dedicated infrastructure and launching a public bicycle-share program in 2015. Recent studies have used GPS data from the bicycle-share program to conduct route choice analysis (Lu, Scott, and Dalumpines 2018) or explore influences on bike share ridership (Scott and Ciuro 2019). However, we still know relatively little about trips in this transitional city beyond those made by bike share. To date, there has been no published research that has investigated the level and pattern of bicycle trips in Hamilton using data from the regional *Transportation Tomorrow Survey*. Our understanding of the spatial distribution of such trips at the meso-level and the influence of the built environment is also limited.

To address these gaps in knowledge, the objective of this study is to investigate the built environment correlates of cycling flows in Hamilton. This paper describes the development of a spatial interaction model to test the level of cycling against various built environment attributes at the zones of origin and destination. Conceptually, the analysis is informed by Moudon and Lee's (2003) *behavioral model of the environment*. The framework outlines three components: i) the origin and destination of a trip; ii) route characteristics; and iii) characteristics around the origin and destination. Travel surveys are typically rich in terms of information about zones of origin and destination of trips, but are less informative with respect to route characteristics, which often have to be inferred, or true origins and destinations. For this reason, a feature of the analysis is the use of an algorithm for cycle routing, i.e., *CycleStreets*, to infer and compare different routes between zones of origin and destinations. This algorithm identifies routes according to various attributes and characterizes them as *fastest*, *quietest*, and *balanced* routes based on their level of *busyness*. The distance and time from the zone of origin to zone of destination along each inferred route serves as measures of cost in the analysis. This paper investigates the second and third components of Moudon and Lee's (2003) framework since the true origin and destination of trips are typically not known through travel surveys. The following two questions are addressed: 1) *Which built environment attributes at the zone of origin and destination influence bicycle trip flows in Hamilton?* and 2) *Which type of route best explains the pattern of travel by bicycle in Hamilton?* In addition, residuals from the spatial interaction model are analyzed to investigate and describe trip flows that were under- and over-estimated. Future opportunities for research, including assessment of the built environment along select routes identified by the algorithm, are also discussed.

Note that all data and code used in this research are available online. The source for this paper is an R markdown document that can be obtained from the following anonymous Google Drive folder.

Literature Review

The built environment in which people live, work, and play influences the transport modes available to them, the destinations that they can access, and where they choose to travel to get from A to B. With respect to walking and cycling, the *behavioral model of the environment* was proposed as a theoretical framework for environmental audits to identify built environment determinants of walking and bicycling at three different scales that make up any trip (Moudon and Lee 2003) According to this model, all three spatial areas (i.e., the characteristics of the origin, destination, and route) are important and necessary to assess the influence of the built environment on walking and bicycling for transportation, since these modes, more so than motorized travel, allow a traveller to interact more intimately with the micro-level environment (Moniruzzaman and Páez 2012; Moniruzzaman and Páez 2016; Moudon and Lee 2003). This type of framework holds true for bicycle trip analysis - people who travel by bicycle are likely to directly experience different attributes of the built environment along their journey and seek routes or areas that offer enjoyable and interesting atmospheres. Winters et al. (2010, p. 988) conducted a study measuring built environment variables at three different spatial scales in Vancouver, Canada and found that "place was important, since in each zone different built environment factors influenced cycling." This emphasizes the need to understand how environmental attributes affect bicycling along different parts of the trip (Winters, Brauer, et al. 2010).

Among the factors that influence cycling, infrastructure is often identified as an important attribute for bicycle-friendliness. It is thought to be fundamental for encouraging more bicycle trips in cities that are predominantly auto-dominated (Adam, Jones, and te Brömmelstroet 2020). The provision of, or proximity to, infrastructure has been found to influence bicycling behaviour (*inter alia*, see Buehler and Pucher 2012; Buehler and Dill 2016; Dill 2003; Fraser and Lock 2010; Mertens et al. 2017). Infrastructure can be very influential - a new bicycle lane in Oslo, Norway attracted trips by shifting cyclists from other parallel routes (Pritchard, Bucher, and Frøyen 2019). This suggests that it is not uncommon for preferred routes to change as new facilities are built over time and they are incorporated into daily trips. Furthermore, infrastructure can also support the integration of physical activity into commuting trips (Dill 2009) and increase perceptions of cycling safety (Branion-Calles et al. 2019). At the very least, cycling infrastructure is a visual and physical sign that streets can accommodate people who choose to travel using this mode. Many studies also provide evidence that other factors beyond infrastructure influence cycling behaviour. For instance, urban form at the places where cycling trips originate and end is also important (Scott and Ciuro 2019). Among other factors in these spatial zones, land use mix (Cervero, Denman, and Jin 2019; Sallis et al. 2013; Winters, Brauer, et al. 2010; Zhao 2014], access to a public bike share station (Cole-Hunter et al. 2015), route connectivity (Cervero, Denman, and Jin 2019; Winters, Brauer, et al. 2010), close proximity to jobs (Heesch, Giles-Corti, and Turrell 2015), higher job (Le, Buehler, and Hankey 2018; Zhao 2014) and population densities (Fraser and Lock 2010; Nielsen and Skov-Petersen 2018; Nordengen et al. 2019; Schneider and Stefanich 2015; Winters, Brauer, et al. 2010), and natural features or green space (Cole-Hunter et al. 2015; Le, Buehler, and Hankey 2018; Mertens et al. 2017) have been reported to increase the likelihood of travelling by bicycle. In most studies, a combination of these attributes is found to influence cycling, which suggests that multiple factors are needed to create spaces that ultimately encourage people to cycle (Scott and Ciuro 2019). However, there is variation in the relative influence of these attributes across studies and across places, which might reveal different effects that are related to contextual behaviours or planning and transportation policies. For example, residential density is not always a significant attribute (Scott and Ciuro 2019; Zhao2014). Therefore, the effect of built environment attributes can be varied, and this requires additional analysis to determine their influence on local cycling levels where such studies have not been previously conducted.

The majority of the studies described above have documented how the built environment around the trip origin or at the neighbourhood-level influences the likelihood of cycling or is associated with higher cycling levels. Research investigating the built environment along routes selected and travelled by cyclists is, with some exceptions, more limited [*inter alia*, see Chen, Shen, and Childress 2018; Dill 2009; el-Assi, Mahmoud, and Habib 2017; Lu, Scott, and Dalumpines 2018; Skov-Petersen, Barkow, et al. 2019). To fill this gap, researchers have used a variety of methods to reveal the route preferences of cyclists including data obtained from GPS or smartphone applications (Pritchard 2018). In general, studies using such data confirm that bicyclists prefer separated facilities and incorporate infrastructure as part of their routes (Dill 2009; Lu, Scott, and Dalumpines 2018; Misra and Watkins 2018; Skov-Petersen, Barkow, et al. 2019; Pritchard, Bucher, and Frøyen 2019). One study using GPS data found that streets with bike lanes were comparable in attractiveness to streets with low traffic volume (Broach, Dill, and Gliebe 2012). By examining GPS data from Hamilton's bicycle-sharing program, Lu et al. (2018) found that bike share users travel routes that are significantly longer than the shortest path distance and are more likely to use local streets with low traffic and bicycle facilities. Similarly, Chen et al. (2018) also reported that people who travel by bicycle in Seattle prefer short and flat routes with connected facilities on roads that have low traffic speeds. Their study found more variability with respect to preference for views along routes with features like mixed land use, street trees, lighting, and city features.

Cycling facilities have most consistently been found to be an important attribute of the built environment for cyclists, however other attributes such as preferred types of views along the route or variables around the origin or destination appear to be more varied. However, few studies incorporate more than one component of the framework outlined by Moudon and Lee (2003) to capture a comprehensive view of the variability in the built environment that a cyclist might encounter. Winters et al.'s (2010) study is an exception, as is the recent study conducted by Cole-Hunter et al (2018). Nielsen and Skov-Petersen (2018) recently analyzed the influence of built environment attributes at three different scales on the probability of cycling in Copenhagen, which captured some of the spatial differentiation at which variables are important, however they did not include any route analysis. There is a need for more research to measure and understand the built environment attributes that affect cycling along different parts of the trip and at different spatial zones.

Methods, Context, and Data

Spatial Interaction Models

We use spatial interaction methods to analyze bicycle trip flows in Hamilton. In the form of a gravity model, this modelling approach can account for all three elements in the Behavioral Model of the Environment and is a more holistic approach than trip generation analysis (for example, de Dios and Willumsen 2011, Chapter 5). The *Transportation Tomorrow Survey* provides sufficient information to infer origins and destinations of all bicycle trips in Hamilton using centroids of the traffic zones. Environmental attributes at the zone of origin and zone of destination of such trips can be accessed through publicly available data. Finally, new algorithms for cycle routing now make it possible to infer route characteristics between origins and destinations, which can be considered when calculating the trip distances.

Spatial interaction models operate on principles of propulsion, attraction, and the friction of space. In other words, we can assume that there are factors within a particular geographic area that contribute to producing bicycle trips, such as residential density, and there are factors in other geographic areas that attract them like jobs or services. Finally, there is the friction of space, in other words, the cost incurred in reaching a destination from an origin. Spatial interaction models can be useful for estimating or explaining spatial flows in a particular system or to predict them in different scenarios.

The equation of the spatial interaction model:

$$U_{ij} = f(V_i, Wj, d_{ij})$$

where i represents the origin, j represents the destination, U_{ij} is the total interaction between origin and destination (i.e., for this analysis it is the number of bicycle trips recorded in the *TTS*), V_i is a vector of attributes at the zone of origin (i.e., the push factors), W_j is a vector of attributes at the zone of destination (i.e., the pull factors), and d_{ij} represents the cost of making the trip (i.e., often the distance or time as a measurement of spatial separation).

Poisson regression is commonly used in the estimation of a spatial interaction model when the dependent variable is available as a count (Chun 2008; Griffith 2011; Metulini, Patuelli, and Griffith 2018). This regression model is also suitable for datasets that contain many zero flows (Griffith 2011) as is the case where many zones of origin and destination did not generate trips. For our analysis, bicycle trip counts serve as the dependent variable and built environment or demographic attributes known to influence bicycling serve as independent variables.

The Poisson regression model can be written in linear form as:

$$ln(\mu_{ij}) = \lambda + \lambda_O ln(V_i) + \lambda_D ln(W_j) + \beta ln(d_{ij})$$

where μ_{ij} is the number of bicycle trips between zone of origin i and zone of destination j, V_i and W_j represent the push and pull factors at i and j respectively, d_{ij} is the cost or separation between the zone of origin and zone of destination, and λ are estimable parameters.

Testing for Network Autocorrelation

An important assumption to note is that the residuals of the spatial interaction model are random and uncorrelated. However, as highlighted by numerous studies (e.g., Chun 2008; Metulini, Patuelli, and Griffith 2018), spatial or network autocorrelation can occur in spatial interaction modeling, among other things, because of unobservable factors at the zone of origin or destination that are not included in the model or a misspecified cost function. For these reasons the presence of network autocorrelation can lead to unreliable findings or misleading interpretations of the behaviour modelled (Chun 2008). As a diagnostic tool, network autocorrelation in a spatial interaction model, is useful to detect the omission of relevant variables. In contrast, when no network autocorrelation is detected in the residuals of the model, this is a sign that all systematic variation has been accounted for with the variables used, and since no pattern remains to be explained the model can be considered a *sufficient* explanation of the pattern [for the criterion of sufficiency in statistical data analysis, see Griffith et al., p. 4 and p. 454; Griffith and Lagona 1998; Cordy and Griffith 1993].

Recent papers on modelling spatial interaction have proposed the use of eigenvector spatial filtering as a way of accounting for network autocorrelation (Chun 2008; Griffith 2011; Metulini, Patuelli, and Griffith 2018). In this respect, use of Moran's I has been criticized for the case of residuals of a Poisson regression model because it is based on a normality assumption and Poisson has distributional properties that are not well known (Chun 2008). Instead the T statistic (Jacqmin-Gadda, Commenges, et al.

1997) is recommended for applications in spatial interaction modelling (Chun 2008; Metulini, Patuelli, and Griffith 2018).

Study Area: Hamilton, Ontario

Hamilton is a growing mid-sized city located in the Greater Toronto and Hamilton Area, in Canada. The city is divided by the Niagara Escarpment, which separates the lower city and downtown core in Dundas Valley from the suburban/rural parts of the city on top of the escarpment and is approximately 100m tall in many places. The population was approximately 540,000 in 2016 at the time of the *TTS* but is expected to increase by 22.9% over the coming 15 years (City of Hamilton 2018a), indicating that transportation demand will likely also grow. The city's current Cycling Master Plan was released in 2009 to "guide the development and operation of [the city's] cycling infrastructure for the next twenty years" (City of Hamilton 2009, p. i) and was most recently updated in 2018 (City of Hamilton 2018b). As of 2019, approximately 46% of the planned city-wide cycling infrastructure, which includes on-street and off-street facilities, has been built (City of Hamilton 2020). Around 15 to 20 km of new cycling facilities are built each year, amounting to an annual increase of 1-2% for the entire network (City of Hamilton 2020).

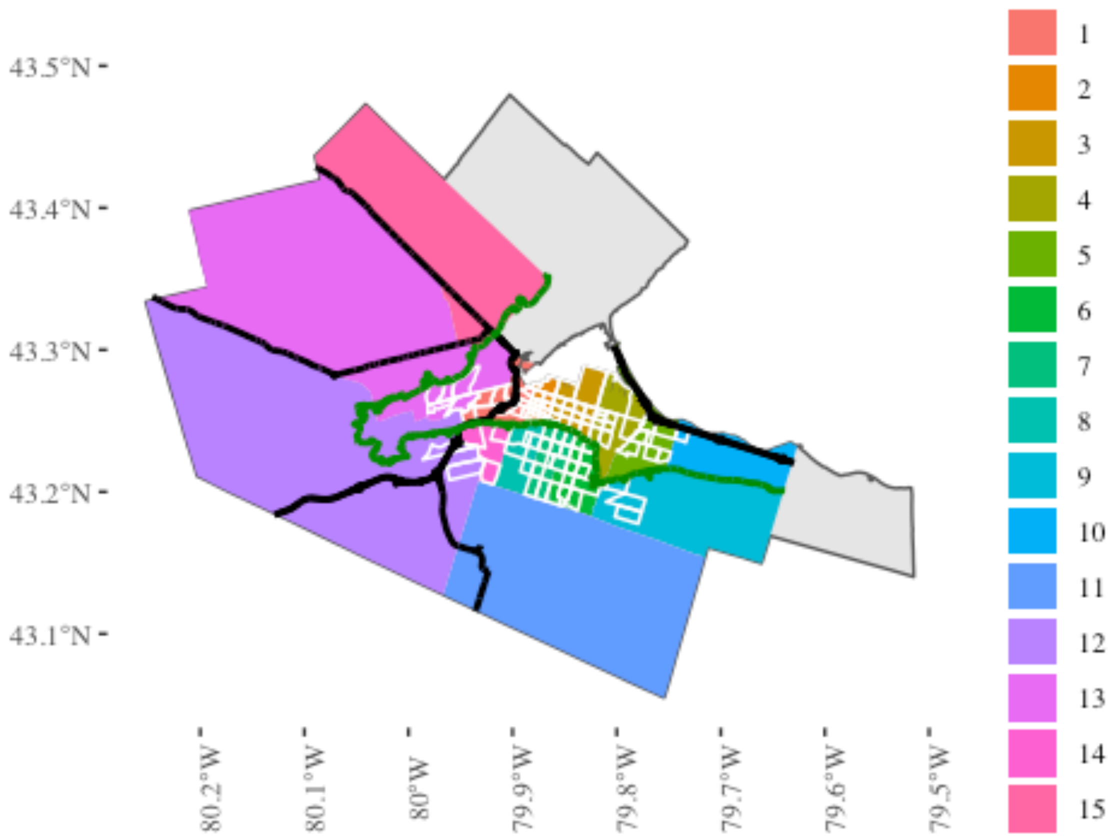

Figure 1. Wards in the city of Hamilton (Note: The smaller zones are traffic zones that generated at least one bicycle trip and are used in the analysis; black lines are provincial highways and green line is the Niagara Escarpment)

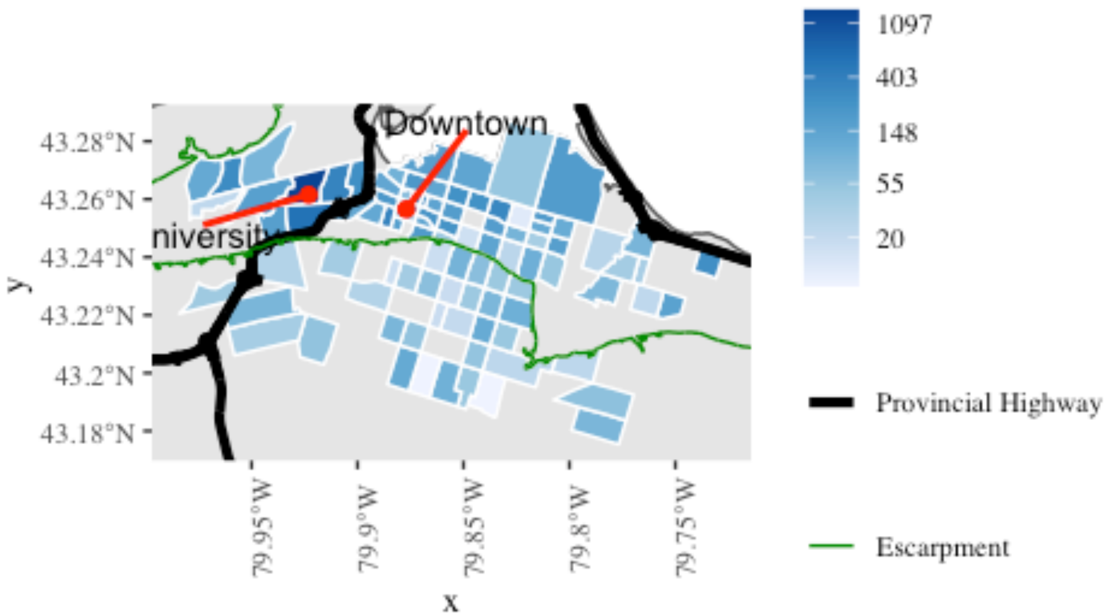

Figure 2. Number of Trips Produced by Each Traffic Zone (Black lines are provincial highways and green line is the Niagara Escarpment)

Data Sources

The *Transportation Tomorrow Survey* (*TTS*) is a voluntary travel survey conducted every 5 years since 1986 to collect information about urban travel for commuting purposes in Southern Ontario (Data Management Group 2018). The final dataset for the 2016 survey includes 6,424 completed surveys in Hamilton out of a total of 162,708 from the entire GTHA. The results from respondents in Hamilton serve as the primary dataset used in this analysis and were made available in Spring 2018. The *TTS* study employed a mixed sampling approach that was primarily address-based in response to changes in landline ownership and increasing households that only have a cell phone and no landline (Data Management Group 2018). The survey includes sampling weights to obtain population-level values of the variables (Data Management Group 2018). The survey was conducted between September and December 2016 online (64% of surveys completed) and by telephone (36% of surveys completed). Each participant was asked to provide household and demographic data (e.g., household size, number of vehicles, gender, etc.) and to describe all trips (e.g., origin, destination, transport mode, etc.) made the previous day by each member of the household aged 11 years or older. Trip data are aggregated for public use and the *traffic zone* is the finest level of spatial disaggregation. Hamilton has 234 traffic zones. Each traffic zone typically falls along the centre line of roads or the natural geographic boundaries but may or may not align with municipal ward boundaries.

In total, there are 13,635 bicycle trips in the 113 traffic zones within Hamilton, after the expansion factor to make it a representative sample. The trips occurred between a total of 294 origin-destination pairs. The true origins and destinations of trips are not included in the dataset, only the number of trips produced or attracted to each *traffic zone*. Cycling levels vary across different parts of the city. The geographical context for the analysis can be seen in Figures 1 and 2, which show the Wards in the city (each Ward has an elected representative in the City Council) that produced or attracted trips. Wards 1, 2, and 3, which include the local university and downtown core, produce the largest numbers of trips by bicycle in Hamilton. The maximum number of bicycle trips recorded to or from a traffic zone was 365 trips. This traffic zone is located in Ward 1, which has the highest bicycling mode share in the city, and predominantly features the local university. This aligns with Scott and Ciuro's (2019) findings that the university is a major generator and attractor of bike share trips. Due to low density and few destinations within a bikeable distance, the majority of traffic zones located in the rural areas of the city generated 0 bicycle trips. An average of 46 bicycle trips occurred per traffic zone that produced bicycle trips. The minimum number of bicycle trips recorded in a traffic zone that produce any bicycle trips at all was 6. Of the 113 traffic zones that produced bicycle trips, about 25% produced more than 55 trips, likely zones that feature built environment attributes, such as infrastructure or mixed land use, that are conducive to greater bicycling levels. Objectively measured demographic and environmental attributes at the zones of origin and destination that might explain the production or attraction of bicycle trips were included in the model. These explanatory variables were selected based on their known or potential influence on cycling behaviour, as identified in the literature above, but also on our ability to access such data. For instance, residential density at the zone of origin might explain why trips begin there, and the number of jobs or services at the zone of destination could explain why trips end there. We hypothesize that various land use mixes at the zone of destination will attract trips, while land use mixes at the zone of origin will compete and decrease the production of trips. Finally, other built environment attributes, such as street connectivity and percentage of arterial roads along the route, are hypothesized to be capture through the cost function as trips are inferred. When possible, the datasets used for this analysis come from 2016 to match the year of the *TTS* results. The *2016 Canadian Census*, which is publicly available information, provided population estimates at the census tract level. Land use data was accessed from *Teranet Inc.* and The City of Hamilton's Department of Planning and Economic Development. The latter dataset defines all land parcels in the city as well as the type of land use for each parcel. The 2016 *Enhanced Points of Interest* (EPOI), produced by DMTI Spatial Inc, is a national database of over 1 million business and recreational points of interest in Canada that featured over 32,000 points of interest located in Hamilton. Finally, The City of Hamilton's *Open Data Program* offered a dataset containing the number of transit stops and the number of existing and proposed cycling infrastructure segments, which can be thought of as attributes to gain entry to these respective transportation systems.

Data Preparation

Hamilton's bicycle trip records were accessed in July 2019 and exported as a contingency table with the traffic zones of origin and destination of all trips. The original table containing only trip information featured 294 origin-destination (O-D) pairs of traffic zones. This table was cleaned to remove 13 isolated zones, which produced trips only to neighbouring zones and not elsewhere in the city. This reduced the number of O-D pairs in our analysis from 294 to 262. Objective demographic and environmental variables were geographically organized in two different zoning systems, and areal interpolation was performed to convert census data from the tract level to traffic zones. Similarly, spatial subsetting was performed to select and organize environmental attributes based on their known coordinates and whether or not they intersected with a traffic zone. Zonal demographic and environmental variables were then joined to the origin-destination table. Table 1 shows the variables that were tested in the model to measure their relative and collective influence on bicycling trip flows.

Variable	Description	Source
Population	Persons residing in each traffic zone (1,000s)	2016 Canadian Census
Points of Interest	Points of interest (e.g., health care and educational facilities, restaurants, etc.) per traffic zone (1,000s)	DMTI Spatial Inc.
Bus Stops	Municipal bus stops per traffic zone (100s)	City of Hamilton Open Data
Infrastructure Segments	Existing and proposed cycling infrastructure segments per traffic zone (100s)	City of Hamilton Open Data
Institutions	Institutions (e.g., schools, places of worship, government, etc.) per traffic zone (1,000s)	Teranet Inc., Hamilton Parcel/Land Use Data
Commercial	Commercial locations (e.g., general retail, recreation, and sports clubs, etc.) per traffic zone (1,000s)	Teranet Inc., Hamilton Parcel/Land Use Data
Residential	Residences (e.g., detached house, semi-detached house, apartment, etc.) per traffic zone (1,000s)	Teranet Inc., Hamilton Parcel/Land Use Data
Industry	Industry locations per traffic zone (1,000s)	Teranet Inc., Hamilton Parcel/Land Use Data
Office	Office locations per traffic zone (1,000s)	Teranet Inc., Hamilton Parcel/Land Use Data
Full-Time Jobs	Persons employed full-time, outside of the home, by zone of employment (1,000s)	Transportation Tomorrow Survey
Part-Time Jobs	Persons employed part-time, outside of the home, by zone of employment (1,000s)	Transportation Tomorrow Survey

Table 1. Demographic and built environment variables used in the analysis.

In addition to the variables in Table 1, dummy variables were created to account for Hamilton's topography. Traffic zones were classified by geographic area, namely zones in the lower city and zones in the Niagara Escarpment or the suburban/rural parts of the city. This classification was used to code O-D pairs that were in the same different geographical classes, to capture that a bicyclist would need to navigate changes in elevation and natural features when travelling across different topographies in Hamilton. If both the zone of origin and zone of destination were in the lower city, this pair was labelled with 0. If the origin and destination were in different regions (i.e., lower city and escarpment/rural), the pair was labelled with 1. If both zones were in the escarpment or rural areas, the pair was labelled with 2.

Inferring Cycle Routes

The *TTS* does not ask respondents to state the routes that they travel, so this information is unknown. For this reason, we have to infer them using the centroids of each traffic zone as a start or end point for the trip flows. We use a novel routing service algorithm available for use in R, *CycleStreets* (Lovelace and Lucas-Smith 2018), to approximate routes as a cost function in the spatial interaction model. The algorithm relies on data that is publicly available through *Open Street Map*, so there are additional objectively measured environmental variables captured in the cost function. The algorithm infers three different types of routes: *fastest*, *quietest*, and *balanced*. The R package, which documents the use of the algorithm and was used for this analysis, states: "These represent routes taken to minimize time, avoid traffic, and compromise between the two, respectively" (Lovelace and Lucas-Smith 2018, p. 1). *CycleStreets* rates the *quietness* of a route as a score, with routes featuring cycle tracks and park paths rated as the quietest, and then decreasing to varying degrees of *quietness* depending on the extent that cyclists would have to interact with other road users. According to the algorithm's documentation, routes with shared facilities rate relatively high and busy roads have the lowest score. Overall, the algorithm tries to minimize the *busyness* of a route but there is a lack of transparency with respect to the rate of speed used for calculating the time of each route and which specific attributes are considered by the algorithm when minimizing *busyness*. *Quietness* scores are adjusted based on feedback from users, and help to determine whether a route is *fastest*, *quietest*, or *balanced*. The distance and time on each leg of a route can be obtained from *CycleStreets*, and from these the total travel distance and time for each type of route between zone of origin and destination can be calculated. Table 2 offers descriptive statistics of the different types of routes inferred by the algorithm, after removing intrazonal trips. Table 3 includes the average detour of the *quietest* and *balanced* routes compared to the Euclidean distance and using an average speed of 22.5 km/h. Distance and time along different cycle routes were used as measures of cost in our analysis. Testing each type of route as an impedance factor in the model yields six different cost variables for each origin-destination pair (i.e., *fastest-distance, fastest-time, quietest-distance, quietest-time, balanced-distance, and balanced-time)*. We also include the simplest measure of cost, the Euclidean distance, as a comparison. Each variable is incorporated into the spatial interaction model to test which cost variable best explains cycling flows in Hamilton.

Route	Minimum	Quartile.1	Median	Mean	Quartile.3	Max	SD
Quietest Distance (km)	0.412	4.950	7.944	8.293	11.085	25.523	4.419
Quietest Time (mins)	1.617	22.725	37.817	40.572	54.683	133.117	4.373
Balanced Distance (km)	0.412	4.829	7.688	8.127	10.784	24.908	4.424
Balanced Time (mins)	1.617	20.837	34.825	36.752	49.462	124.567	23.091
Fastest Distance (km)	0.412	4.851	7.715	8.179	10.834	24.865	20.376
Fastest Time (mins)	1.617	20.038	32.975	34.612	46.783	110.300	18.788

Table 2. Descriptive statistics of inferred routes using CycleStreets.

Route	Min	Quartile.1	Median	Mean	Quartile.3	Max
Quietest Distance (km)	0.9861	1.2782	1.3971	1.4388	1.5187	5.4321
Quietest Time (mins)	1.058	2.108	2.403	2.661	2.982	15.943
Balanced Distance (km)	0.9861	1.2574	1.3794	1.4064	1.4893	5.4149
Balanced Time (mins)	1.058	1.960	2.182	2.421	2.689	15.791

Table 3: Descriptive statistics of the average detour of inferred routes using Cycle Streets, as compared to the Euclidean distance.

Results and Discussion

Spatial Interaction Models Considered

Four spatial interaction models were estimated with bicycle flows between zones of origin and destination as the dependent variable. Various combinations of zonal attributes and the distance or time of inferred cycle routes between origins and destinations were experimented with. Each of these models went through a general-to-particular variable selection process. Starting with models that included all zonal attributes in Table 1, variables that did not meet a significance criterion of $p \leq 5\%$ were removed to obtain a more parsimonious model. For comparison purposes, a base model with a constant only was estimated to serve as a benchmark. This was followed by a model with only zonal variables (i.e., push-pull factors), then a model only with cost (time or distance), and then finally a full model with zonal and cost variables. The selection of initial variables for each model was deliberate and meant to investigate the performance of models that considered only certain aspects of the spatial interaction process. These models are described next and the results are presented in Table 5.

Model 1: Zonal Attributes Only

After the benchmark non-informative model, the first estimated spatial interaction model included zonal attributes as explanatory variables that might explain the production or attraction of bicycle trips but did not include a cost variable. These were the variables that met the significance criterion of $p \leq 5\%$ in the general-to-particular variable selection process. Therefore, this model did not include the second spatial zone of the *behavioral model of the environment*.

Model 2: Cost Variables Only

This model used only cost variables, which included our geographical classes for the zones. In other words, this model includes only the second spatial zone of the *behavioral model of the environment*. We estimated this model with one cost variable at a time (e.g., topography and fastest distance, topography and quietest time, etc.) which allowed for the comparison of how distance or time along specific inferred routes performed in each model.

Model 3: Full Model

In the final model, we combined the variables used in models 1 and 2, to include both zonal attributes and the cost function. This model includes zonal attributes that might explain the production or attraction of bicycle trips, topography classification, and measures of cost from inferred routes. Just like Model 2, we estimated this model using each cost variable at the time (i.e., all zonal attributes with *fastest-distance* as cost, etc.).

Results

Akaike's information criterion (AIC) is used to compare the various models. The model with the lowest AIC is selected as the model that minimizes information loss, while considering parsimony of the specification. In addition, AIC is used in the calculation of the relative likelihood, which is defined as:

$$e^{\frac{AIC_{min}-AIC_i}{2}}$$

In the above, AIC_{min} is the AIC of the model that minimizes this criterion, and AIC_i is the AIC of a competing model. This is measure of of goodness of fit is interpreted as the probability that the competing model minimizes information loss to the same extent as the best model. It is important to note that although comparison of AIC from a set of models indicates the model with the best fit, it does not reveal any information about the quality of each model, which is why analysis of the residuals is important as well.

Table 4 presents a summary of the goodness of fit of the models. For reference, the AIC of the base model is 95,808 and the AIC of Model 1 is 83,994. Model 1 is a significantly better fit than the base model, which indicates the explanatory power of zonal attributes as independent variables. Interestingly, as seen in the table, the use of cost as in Model 2, provides much higher explanatory power than zonal attributes. Of the different cost variables, distance along *quietest* routes is the cost variable that leads to the best fit, a result that is replicated in Model 3. An obvious limitation of Model 2 is that it lacks variables that might ultimately explain what is producing or attracting bicycle trips from each traffic zone. Our full model (Model 3) includes variables that might explain trips and cost variables, which ultimately provides the best fit of all models considered. As seen in Table 4, Model 3 with distance along inferred *quietest* routes provides a significantly better fit than any of the competing models, and the relative likelihood (calculated with respect to this model), indicates that the probability that any of the alternative models minimizes the information loss to the same extent is practically zero.

	Model 2		Model 3	
Cost Variable	AIC	Relative Likelihood	AIC	Relative Likelihood
Euclidean Distance	71514	<0.0001	63127	<0.0001
Fastest Distance	71839	<0.0001	63365	<0.0001
Fastest Time	71969	<0.0001	63521	<0.0001
Quietest Distance	71307	<0.0001	62973	1
Quietest Time	71589	<0.0001	63132	<0.0001
Balanced Distance	71647	<0.0001	63357	<0.0001
Balanced Time	71979	<0.0001	63541	<0.0001

Note:
Relative likelihood is calculated with respect to Model 3:Quietest Distance

Table 4: Comparison of model 2 (cost variables only) and model 3 (full model) using AIC and Relative Likelihood.

The results of all of the models are presented in Table 5. In addition to goodness of fit, each of the models was tested for network autocorrelation, using Jacqmin-Gadda's T statistic (Chun 2008; Jacqmin-Gadda, Commenges, et al. 1997; Metulini, Patuelli, and Griffith 2018). It is worth noting that the only model without residual network autocorrelation is model 3, which signifies that this model not only provides the best fit, it is also the only one that is free from network autocorrelation. As described above, testing for network autocorrelation in a spatial interaction model is a diagnostic tool. When no network autocorrelation is detected in the residuals of the model, this is a sign that all systematic variation has been accounted for with the variables included in the model. The model can be considered a *sufficient* explanation of the pattern observed. We discuss the results of the analysis next.

	Base Model		Model 1		Model 2		Model 3	
Variable	Estimate	p-value	Estimate	p-value	Estimate	p-value	Estimate	p-value
(Intercept)	0.2099	< 0.0001	0.0396	0.3735	2.4061	< 0.0001	1.9826	< 0.0001
Population.o			-0.0936	< 0.0001			-0.0273	0.0097
Points_of_Interest.o			-0.6827	< 0.0001			-0.7509	< 0.0001
Institutions.o			30.4358	< 0.0001			14.6119	< 0.0001
Commercial.o			5.5309	< 0.0001			-1.6004	0.0011
Industry.o			-5.8369	< 0.0001			1.6853	0.0125
Office.o			-11.2755	< 0.0001			-10.2228	< 0.0001
Residential.o			-0.7102	< 0.0001			-0.1558	< 0.0001
BusStops.o			1.6269	< 0.0001			1.7688	< 0.0001
BikeInfra.o			10.6592	< 0.0001			1.9312	0.0926
Population.d			-0.1667	< 0.0001			-0.0971	< 0.0001
Institutions.d			36.4256	< 0.0001			24.1953	< 0.0001
Commercial.d			1.5804	7e-04			-8.0098	< 0.0001
Industry.d			-6.0468	< 0.0001			5.3459	< 0.0001
Office.d			6.8574	< 0.0001			15.0947	< 0.0001
Residential.d			0.1398	< 0.0001			0.7039	< 0.0001
BusStops.d			-1.503	< 0.0001			-1.2592	< 0.0001
BikeInfra.d			2.3975	0.0442			-8.3041	< 0.0001
Full_time_jobs.d			0.1907	< 0.0001			0.0796	< 0.0001
Part_time_jobs.d			0.2368	< 0.0001			0.5414	< 0.0001
Topographylower city - rural					-2.53	< 0.0001	-2.4021	< 0.0001
Topographyrural					-0.6518	< 0.0001	-0.545	< 0.0001
quietest_distance					-0.3253	< 0.0001	-0.345	< 0.0001
Model diagnostics								
Jacqmin-Gadda z(T)	34.4011	p < 0.0001	26.5433	p < 0.0001	28.5666	p < 0.0001	0.1576	p = 0.4374
n =		9801		9801		9801		9801
log-likelihood =		-47902.9293		-41976.9929		-35649.4031		-31463.3543
AIC =		95807.8587		83993.9858		71306.8063		62972.7087
Relative likelihood =		< 0.0001		< 0.0001		< 0.0001		1

Note:
Jacqmin-Gadda T is converted to a z-score
Relative likelihood is calculated with respect to Model 3

Table 5. Results of the four spatial interaction models that were estimated, including model diagnostics. Base model = constant only; Model 1 = zonal attributes only; Model 2 = cost function only; Model 3 = full model.

Best Fit Model

Model 3 reveals that several built environment attributes at the zones of origin and destination produce or attract bicycle trips. Points of interest and commercial and office locations at the zone of origin had a negative influence on the number of expected bicycle trips. This is as expected: more destinations or amenities at the origin create more intervening opportunities that ultimately reduce the need to travel to other areas. Although population density has been found to influence cycling trips in several studies (e.g., Nielsen and Skov-Petersen 2018; Nordengen et al. 2019; Schneider and Stefanich 2015; Winters, Brauer, et al. 2010), in our analysis we find a negative effect of population density in terms of both producing and attracting trips by bicycle. Scott and Ciuro (2019) similarly found that population density around bike share hubs in Hamilton does not influence ridership. It is possible that this is due to the relatively low population density of Hamilton in general. In contrast, availability of jobs at the destination was a positive attractor of bicycle trips. The model also uncovered a positive relationship between number of trips and different land uses at the destination: institution, industry, office, residential locations. This reflects an abundance of amenities and diversity of jobs, as well as the reciprocal trip flow to return to one's residence. Geographical classification of the zones was found to have a negative relationship with the number of bicycle trips. This suggests relatively little interaction between the two broad regions in the city, namely lower city and escarpment/suburban/rural, and also lower interaction within the escarpment/suburban/rural compared to the lower city. The presence of the escarpment, in particular, echoes other studies that have found that elevation at the destination or changes in slope can deter travel by bicycle (e.g., Broach, Dill, and Gliebe 2012; Cole-Hunter et al. 2015).

Inferred Routes

The model reveals that the inferred *quietest* routes that allow bicyclists to minimize distance *and* interactions with other road users best explain the pattern of travel by bicycle in Hamilton. This suggests that people who travel by bicycle in Hamilton likely select routes that are less busy with car traffic by maximizing the use of local streets. This finding is consistent with previous research that used GPS data to reveal the route preferences of bicyclists in Hamilton (Lu, Scott, and Dalumpines 2018). After *quietest* distance, *quietest* time was the closest competitor. After the identified *quietest* routes, there was relatively little difference between using *balanced* distance and *fastest* distance as a measure of spatial separation in the model. Intuitively, it makes sense that these two measures would have similar goodness of fit since they both involve greater mixing with traffic. If traffic interactions cannot be avoided, then taking the fastest shortest path route would likely be the next best option for many.

Inferring the route travelled between zones of origins and destination using routing algorithms is an important method to account for route characteristics. It is also useful given that such data about routes is not available from travel surveys, including the *Transportation Tomorrow Survey*. Other studies have used GIS (Cole-Hunter et al. 2015; Winters, Brauer, et al. 2010), GPS data (Chen, Shen, and Childress 2018; Dill 2009; Lu, Scott, and Dalumpines 2018; Skov-Petersen, Barkow, et al. 2019), or new methods using crowd-sourced data (McArthur and Hong 2019; Sarjala 2019) to measure or approximate the built environment along routes travelled by bicyclists. However, GPS data are typically available only for small samples, or under limited conditions, such as bike share trips that may not cover the full geographical extent of travel by bicycle in a region (Lu, Scott, and Dalumpines 2018). To the best of our knowledge, this is the first North American study that uses *CycleStreets* in combination with travel survey data to infer routes in the analysis of trip flows by bicycle. The correlation of *quietest* routes with bicycle flows in Hamilton, however, leaves open the question whether routes inferred by *CycleStreets* have attributes that support cycling, such as infrastructure or enjoyable environments, in addition to less *busyness*. Despite this limitation, and the lack of transparency about certain aspects of the algorithm, in the experience of the authors the algorithm in R makes overall sensible recommendations for *quietest* routes. As shown in Table 2, the *quietest* distance routes and *quietest* time routes are longer than the *balanced* and *fastest* route counterparts, but not by much. This suggests that there are other factors at the micro-level of the routes that may influence cycling differently between these routes. Most of the *quietest* distance routes are also 50% longer than the Euclidean distance. While we cannot know with complete certainty which routes were actually travelled, by exploring different types of routes in our models we are able to provide statistical support for *quietest* routes that minimize distance - a finding in line with results reported by Lu et al. (2018) using Hamilton's bicycle share system data.

Analysis of Residuals

The best model minimized information loss conditional on the independent variables. Informed by the work of Moniruzzaman and Páez (2012) with walking trips in

Hamilton, we were curious to examine in more detail over- and under-estimated trip flows. There was a total of 6 over-estimated trip flows and 256 under-estimated trip flows. We hypothesize that discrepancies between the number of observed trips and the number of expected trips are due to the built environment, namely attributes along the *quietest* distance route that might influence bicycling but that we were not able to capture in the model. With respect to over-estimated trip flows, there may be barriers along the inferred cycle route between zone of origin and destination that deter bicyclists from travelling. The opposite may be true for under-estimated trip flows. It is worth noting first that the majority of trip flows were under-estimated which indicates, to some extent, that there is more bicycling in Hamilton than predicted by the model. This suggests that route characteristics that influence cycling may be influential. We provide a qualitative description of these trip flows next.

By plotting the negative residuals from the best model, after removing all origin-destination (OD) pairs with zero trips, bicycle trip flows that were over-estimated were visualized in Figure 3. There were only 4 trip flows, 3 of which represent travel in a westward direction. The zone of destination for 3 of the 4 trip flows includes the university, which is a major employment and educational institution, and thus acts as a strong push and pull factor for trips. This was identified with bike share trips in Hamilton as well (Scott and Ciruo 2019). Schneider et al. (2015) also found that neighbourhoods with high levels of commute trips by bicycle are located near to a university campus. This suggests that universities can attract lots of trips. Upon further investigation, the *Enhanced Points of Interest* dataset catalogues each different building and unit within the university, meaning that there are several hundred destinations within the traffic zone. The count may have skewed the relative influence of the university by indicating more potential destinations, instead of one institution, leading to over-estimation. The zone of destination for the other trip flow was also near the university, however the over-estimation was almost negligible. When analyzing the *quietest* distance routes for the O-D pairs that end at the traffic zone with the university, each route would require a cyclist to cross a major highway or travel along an arterial road. At the route level, road networks with fewer highways or arterial roads have been found to increase the likelihood of making a trip by bicycle (Winters, Brauer, et al. 2010; Zhao 2014]. Although we were able to provide statistical support for *quietest* routes that minimize distance, there are still roads and intersections in Hamilton that cannot be avoided and that still feature along routes that are less busy overall.

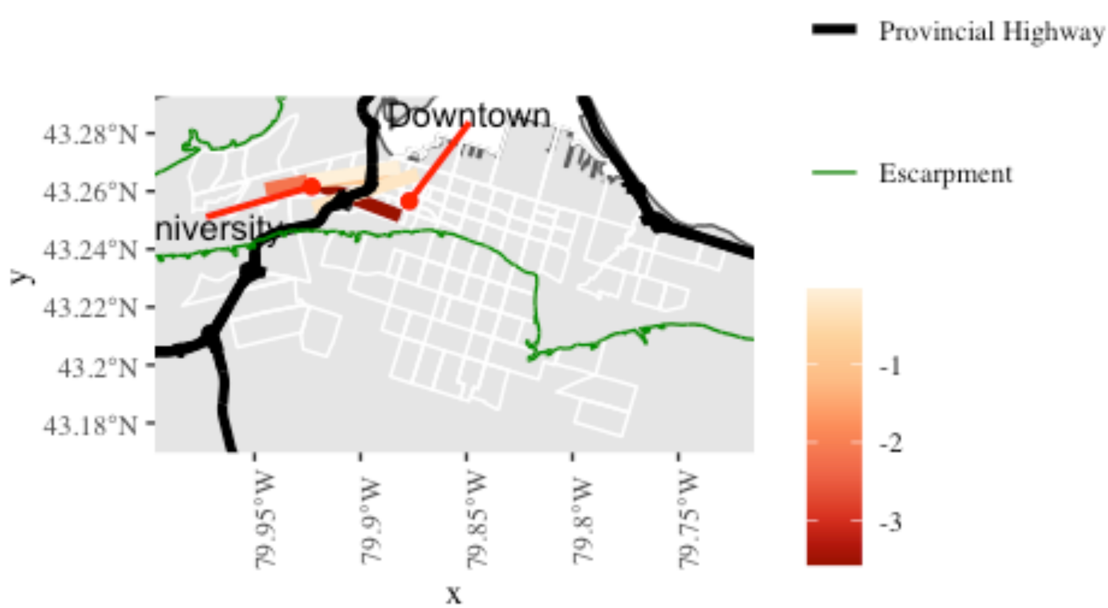

Figure 3. Map of Over-estimated bicycle trip flows (Black lines are provincial highways and green line is the Niagara Escarpment)

Similarly, by plotting the positive residuals, after removing all origin-destination pairs with zero trips, bicycle trip flows that were under-estimated were visualized in Figure 4. Given that the majority of trip flows were under-estimated, we visualized trip flows in different maps according to their characteristics. In addition, Figure 5 shows a map of trip flows over 5 km and Figure 6 shows trip flows under 5 km. One fifth of under-estimated trip flows, approximately 21%, had a *quietest* distance route between 5 and 25 kilometres. Less bicycling typically occurs if the distance to destinations is quite far (Cervero et al. 2019; Zhao et al. 2014; Pucher & Buehler 2008), at which point travelling by car is preferable. Distance between origin and destination could be the reason that these flows were under-estimated. Furthermore, approximately 17% of trip flows occurred within the suburban neighbourhoods on the Niagara Escarpment. This was also an expected result. Bicycle trips are also typically less likely in areas with low density (Pucher & Buehler 2008) that require bicyclists to travel greater distances to get to their destinations. It is also worth noting in this case that Hamilton's suburban areas have fewer cycling facilities compared to the lower city, which reinforces the car-centric design of these neighbourhoods. Finally, there is a noteworthy cluster of trip flows in the city's downtown core of 5 km or less. Nielsen and Skov-Petersen (2018) note that built environment attributes are effective at different spatial scales. They uncovered positive effects of cycling infrastructure within 1 km of the home on the probability of cycling, providing evidence that proximity to cycling facilities can influence transport mode choices. We hypothesize that this cluster was under-estimated because cycling infrastructure has been built more extensively in the downtown core and is likely normalizing travel by bicycle in this area. The connectivity of such infrastructure between zone of origin and zone of destination may not have been captured in the cost function, leading to under-estimation. Likewise, the downtown core features a higher density of destinations within a 1-5 km distance that Hamiltonians could comfortably travel to bicycle, compared to single use neighbourhoods.

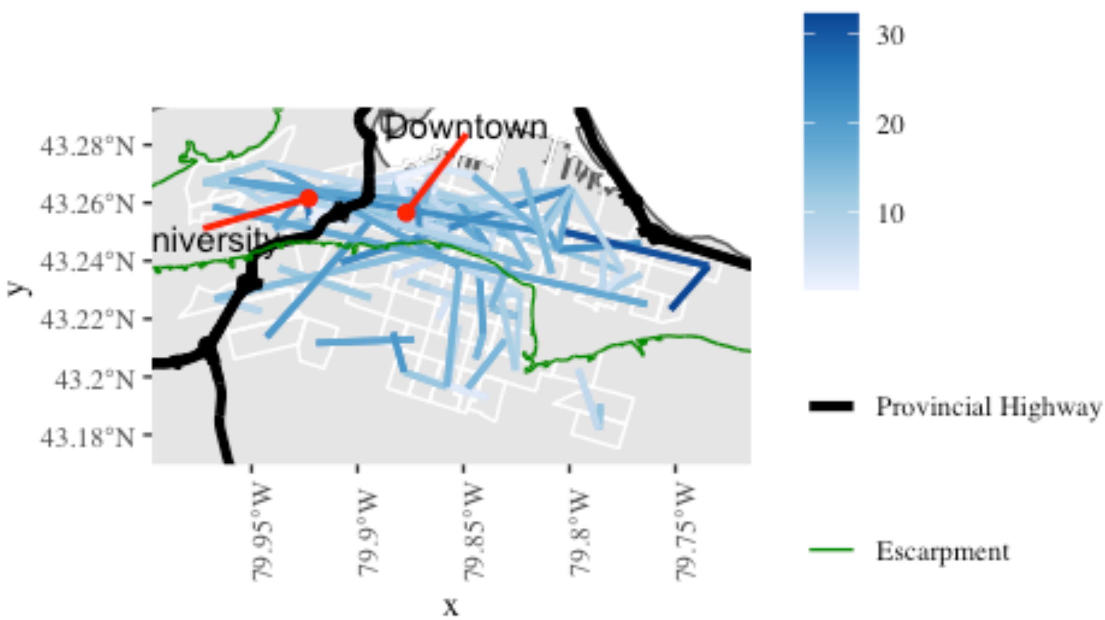

Figure 4. Map of under-estimated bicycle trip flows (Black lines are provincial highways and green line is the Niagara Escarpment)

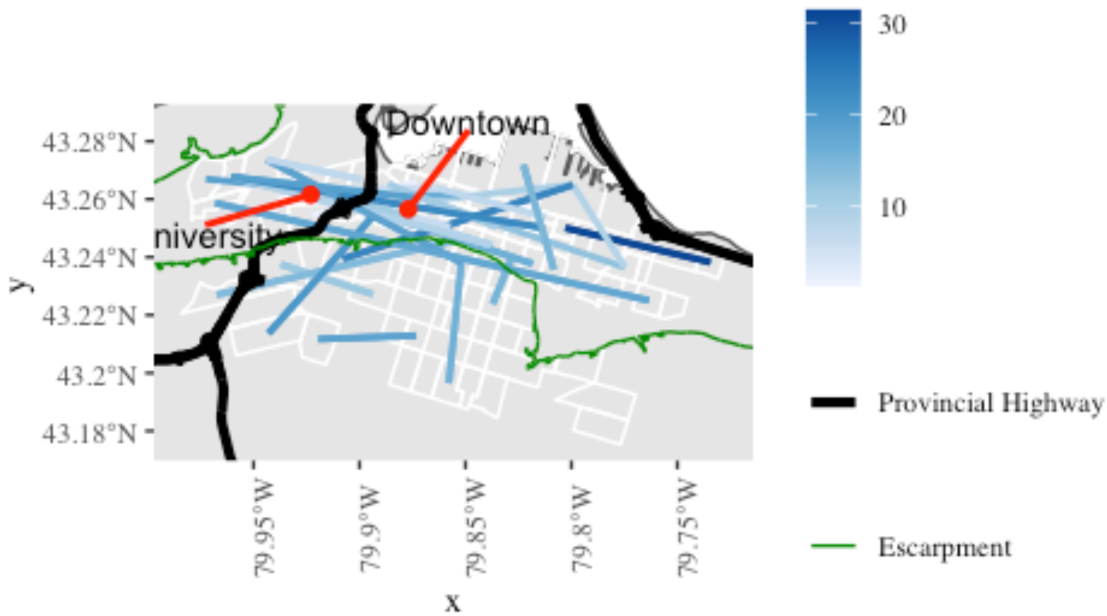

Figure 5. Map of under-estimated bicycle trip flows Over 5 km (Black lines are provincial highways and green line is the Niagara Escarpment)

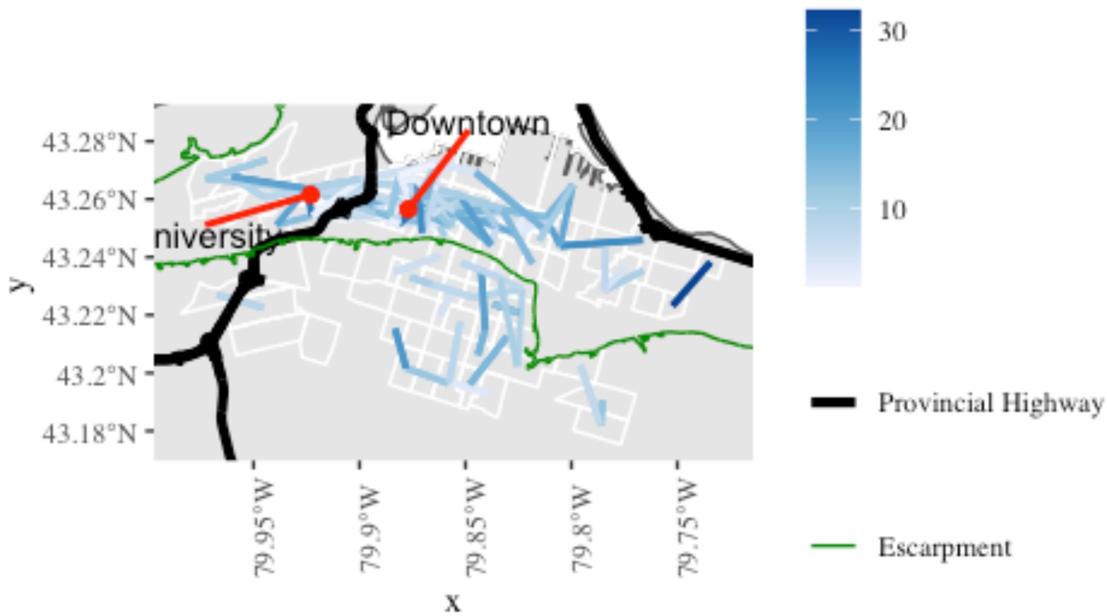

Figure 6. Map of under-estimated bicycle trip flows Less Than 5 km (Black lines are provincial highways and green line is the Niagara Escarpment)

Conclusion

The objective of this study was to address the following questions: 1) *Which built environment attributes at the zone of origin and destination influence cycling trip flows in Hamilton?* and 2) *Which type of route best explains the pattern of travel by bicycle in Hamilton?* The use of a spatial interaction model was methodologically more holistic than trip generation analysis, a more common approach in the cycling literature. Spatial interaction analysis captured two of the three components of the behavior model of the environment (zones of origin and destinations, and route characteristics). Use of a routing algorithm (i.e., *CycleStreets*) also constitutes a novel approach to overcome the limitation of travel surveys. The routing algorithm enabled us to experiment with different types of routes that cyclists may seek out. The model reveals that shortest-distance *quietest* routes that allow cyclists to avoid traffic best explain the pattern of travel by bicycle in Hamilton. In addition, the availability of jobs and different land uses and destinations at the end of the trip were positive attractors of bicycle trips. Commercial locations and other destinations at the zone of origin, as well as topography, had a negative influence on the number of expected bicycle trips. Other findings include that the misspecification in the analysis of bicycle flows is evident in the form of network autocorrelation - this has been known for other types of flows, but as far as we know, has never been reported in the cycling literature. By testing for network autocorrelation, we are confident in the final model, which not only accounts for various pull-push factors and cost measures, but also indicates that the model sufficiently describes the pattern observed. Finally, analysis of the model residuals to identify under- and over-estimated bicycle flows was also suggestive in terms of other information about potential cycling routes.

Broach et al. (2012) noted that the conventional travel demand model does not address cycling well for several reasons. Cycling is often combined with walking since they are both active modes and it is often excluded after the second step of the travel demand model, meaning that route choice and network assignment are not accounted for. Chen at al. (2018) touch upon this as well by suggesting that data about route choice is needed to overcome these limitations. However, common approaches of including only the shortest path route between origins and destinations when accounting for cycling in a travel demand model presents additional limitations because it excludes different built environment attributes that are known to influence route choice (Broach, Dill, and Gliebe 2012). Use of a routing algorithm helps to overcome the dearth of information on actual routes and can account for variability in route characteristics depending on the availability of data. However, there are advantages and limitations to using cycle routing algorithms. The ability to infer distance and time from different routes that a knowledgeable cyclist would take when modelling bicycle trips using data from travel surveys is particularly efficient when GPS data are not available. Thus, cycle routing algorithms can be more practical for transportation planners because they are less demanding and expensive than collecting route data in travel surveys or creating their own network dataset. A limitation, on the other hand, is the inability to capture the variety of routes that cyclists actually take. GPS data, when available, is more suited to capturing variations between dominant and shortest path routes (Lu, Scott, and Dalumpines 2018). However, despite some limitations, we offer that the approach outlined in this research can be replicated in other cities covered by *OpenStreetMap* and that strengthening publicly available data in this portal could be useful to measure the influence of route characteristics on travel by bicycle between different origins and destinations.

There is still much to learn about the quality and types of built environment along the inferred quietest routes in Hamilton, as well as bicyclists' perceptions and experiences with the built environment. The approach adopted in this research presents future opportunities to systematically investigate these routes. For instance, we hypothesize that shortest-path quietest routes may have attributes that promote travel by bicycle, such as bicycle facilities or lower speed limits, which leads to more bicycling than expected from the model. To test our assumptions, bikeability audits will be conducted along quietest routes for a selection of origin-destination pairs that were under-predicted in order to document the presence or absence of features that may influence bicycling [see Moniruzzaman and Páez 2012). There are many street audit tools available to assess bikeability, similar to tools for walkability, which can be used for this purpose. The documentation of built environment attributes would contribute to our understanding of what bicyclists experience as they travel through the city of Hamilton. This is the topic of ongoing research.

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Chapter 3: Environmental Audits

Background

Many Canadian cities have adopted pro-cycling policies and programs in recent years to support the uptake of cycling for transport (Assunçao-Denis and Tomalty 2019). Some of these mid-sized cities currently have low levels of cycling for transport, such as Halifax or Calgary, while other larger urban areas have more established cycling cultures like Montréal and Vancouver. Cities' efforts to increase cycling often involve a range of interventions from investments in infrastructure to educational programs or promotional events (Assunçao-Denis and Tomalty 2019). The successful transition to a bicycle-friendly city depends on the strategies adopted, with higher levels of cycling observed after implementing complementary interventions, policies, and programs that increase the utility and viability of this mode compared to others like driving (Pucher, Dill, and Handy 2010). Cycling experts from both the Netherlands and New Zealand agree on the "importance of providing a basic level of safe, high quality infrastructure as an essential starting point for inducing utility cycling mode share" (Adam, Jones, and te Brömmelstroet 2020, p. 8). This suggests that cycling infrastructure is a universal prerequisite in both countries with an established culture of cycling for transport and in countries with low levels of cycling. Likely for this reason, cities that have low levels of cycling due to the dominance of driving have started building infrastructure to encourage more people to cycle for different trip purposes. The case of Seville, Spain is a great example of the success that can be achieved by implementing a network of connected cycling facilities at a rapid pace (Marqués et al. 2015).

Revealed and stated preference studies have been informative about the types of environments that people who cycle prefer and have further supported the evidence that cycling infrastructure is fundamentally important. Using global positioning system (GPS) data, several studies have found that cyclists travel routes that have on-street and off-path cycling facilities and streets with low volumes of traffic (Broach, Dill, and Gliebe 2012; Dill 2009, Lu, Scott, and Dalumpines 2018; Misra and Watkins 2018). Stated preference studies indicate that cyclists dislike mixing with traffic and prefer dedicated infrastructure (*inter alia*, see Clark et al. 2019; Caulfield, Brick, and McCarthy 2012; Stinson and Bhat 2003; Veillette, Grisé, and El-Geneidy 2019; Winters et al. 2011). People who cycle are also willing to detour from the shortest path to access preferred cycling facilities or areas that are more pleasant to cycle (Krizek, Johnson, and Tilahun 2004; Winters, Teschke, et al. 2010). However, Buehler and Dill (2016) note that research from the United States and Canada, with a traditional transport culture of driving, reports that people who cycle often travel on shared roadways likely due in part to cities' fragmented cycling networks and more limited facilities. When they do have to share the road with other users, people who cycle prefer routes that have fewer cars such as residential areas with traffic calming (Winters and Teschke 2010) or bicycle boulevards (Broach, Dill, and Gliebe 2012). These findings suggest that streets that provide cyclists with their own space or that are more oriented to their unique travel needs are favoured. Other factors that influence where people choose to cycle include traffic volume and speed (Chen, Shen, and Childress 2018; Misra and Watkins 2018; Segadilha and Sanches 2014).

King and Krizek (2020) note that it may be more worthwhile in the short term for cities to focus on reorienting streets to increase human-powered modes and their accessibility to key destinations because this can, in theory, be accomplished more rapidly than changing the type and distribution of amenities in a given area. The COVID-19 pandemic has been seized as a window of opportunity to do just that: as a result of fewer motorized trips, cities worldwide have experimented with how they allocate street space by dedicating more space or facilities for active travel. "Pop-up" cycling facilities in Berlin, Germany (The Guardian 2020) and policies to close streets to cars in Toronto, Canada (City of Toronto 2020) are two examples of how streets can be reoriented with minimal resources in a short period. Changes to land use, either through new purposes to existing buildings or new development that brings mixed functions to a neighbourhood, can take decades and become less effectual as a lever for rapid change (King and Krizek 2020). The latter should, however, remain a long-term policy priority for cities who wish to encourage more cycling because land use mix is an important determinant of cycling behaviour (Cervero, Denman, and Jin 2019; Sallis et al. 2013; Winters, Brauer, et al. 2010) and where cyclists travel (Chen, Shen, and Childress 2018).

The quantitative nature of cycling research in general has traditionally focused more on the influence of objective environmental measures on cycling behaviour. But research has shown that perceptions of the built environment play a role as well. Ma et al. found that the objective environment influences cycling behaviour by altering perceptions but that "perceptions of the environment have a significant positive association with bicycling behavior" (2014, p. 1146). This suggests that environments that are perceived to be more bikeable will have higher levels of cycling. These findings are important for cities that alter the built environment in order to encourage more cycling. The perceptions and experiences of people who cycle are particularly valuable for understanding how they use and respond to street changes (King and Krizek 2020). It can be hypothesized that objective features that support cycling, such as the provision of infrastructure, and that are perceived positively by people who cycle will be used and those that are not will be avoided.

Qualitative methods that can examine the experience and perceptions of people who cycle in such settings, such as interviews (see Mayers and Glover 2019) or mapping exercises (see Manton et al. 2016), are one way to overcome these gaps (Liu, Krishnamurthy, and Wesemael 2018) and can complement objective assessments of the physical environment captured through methods like environmental audits. With more limited facilities or a cycling network under development, people who cycle in transitional cities can typically expect to travel routes from their origin to destination that include a mix of streets with and without infrastructure, or that may require them to negotiate space with other road users at one or more points along the way. It becomes important then to explore and understand perceptions of such routes that are designated for cyclists or routes that are more likely to be cycled over others. This can be also informative about the broader experience of cycling in a transitional city and capture how people who cycle perceive a wide range of attributes that may collectively support or hinder their ability to travel by bicycle.

In this paper, which is part of an explanatory sequential mixed methods study, we report on the findings from a series of environmental audits and semi-structured interviews with people who regularly cycle in Hamilton, Canada. This project explored the influence of the built environment on cycling for transport in a mid-sized city with low but growing cycling levels. This phase of the study builds upon our quantitative work [see Chapter 2] where we found that *quietest* distance routes between zones of origin and destination, inferred by the *CycleStreets* routing algorithm (Lovelace and Lucas-Smith 2018), best explained cyclist travel in Hamilton. Given that the routes were inferred, we did not know the quality of their built environment or how well they match routes that are actually travelled by people who cycle. To further explore the objective environment along the inferred routes, we audited 12 routes, of which we report on 6 here, to document micro-level factors that might influence cycling and explain why such routes best explain cyclist travel. We also conducted semi-structured interviews with 14 people who regularly cycle to examine their perceptions of the routes. Infrastructure and policy recommendations are made, informed by our findings, to improve the experience of cycling in Hamilton.

Methods

Context

Hamilton is a mid-sized city located in Canada with a population of roughly 540,000 according to the 2016 Census (Statistics Canada 2016). Similar to other Canadian cities, cycling levels have grown in recent years; the mode share of cycling for transport doubled from 0.6% in 2011 to 1.2% in 2016 according to the *Transportation*

Tomorrow Survey (Data Management Group 2018). This voluntary travel survey is conducted every 5 years to collect information about urban travel for commuting purposes in Southern Ontario (Data Management Group 2018). The final dataset for the 2016 survey includes 6,424 completed surveys in Hamilton out of a total of 162,708 from the entire Greater Toronto Hamilton Area. Between the 2011 and 2016 surveys, the City of Hamilton implemented a public bicycle share system and added 85 km of bicycle lanes (City of Hamilton 2018a). As of 2019, approximately 46% of the planned cycling facilities network has been built (City of Hamilton 2020), with the goal of implementing all proposed infrastructure by 2029 (City of Hamilton 2009). Therefore, it is suggested that Hamilton is in a state of transition at this mid-way point; infrastructure has been implemented and several interventions have been implemented to increase cycling, but the network is still fragmented and the City has not yet achieved its aspirational active travel mode share goal of 15% (City of Hamilton 2018b). Further analysis of the 2016 *Transportation Tomorrow Survey* revealed that 35% of all trips in Hamilton are 5 km or less, which means that these trips could be cycled (Mitra et al. 2016). Thus, there is the potential to incentivize modal shifts that specifically increase opportunities for physical activity. The city is relatively flat but is separated by the Niagara Escarpment which can be as high as 100m in many places. The rural and suburban parts of the city are on top of the Escarpment and the lower city and downtown core are below [see Figure 1 and 2 for reference]. This leads to less cycling between the lower city and areas on the Escarpment; most of the city's cycling trips occur in the west part of the city and downtown core [see

Chapter 2]. Part of the area above the Niagara Escarpment is referred to locally as 'the mountain' and will be used interchangeably with 'the Escarpment' throughout the paper.

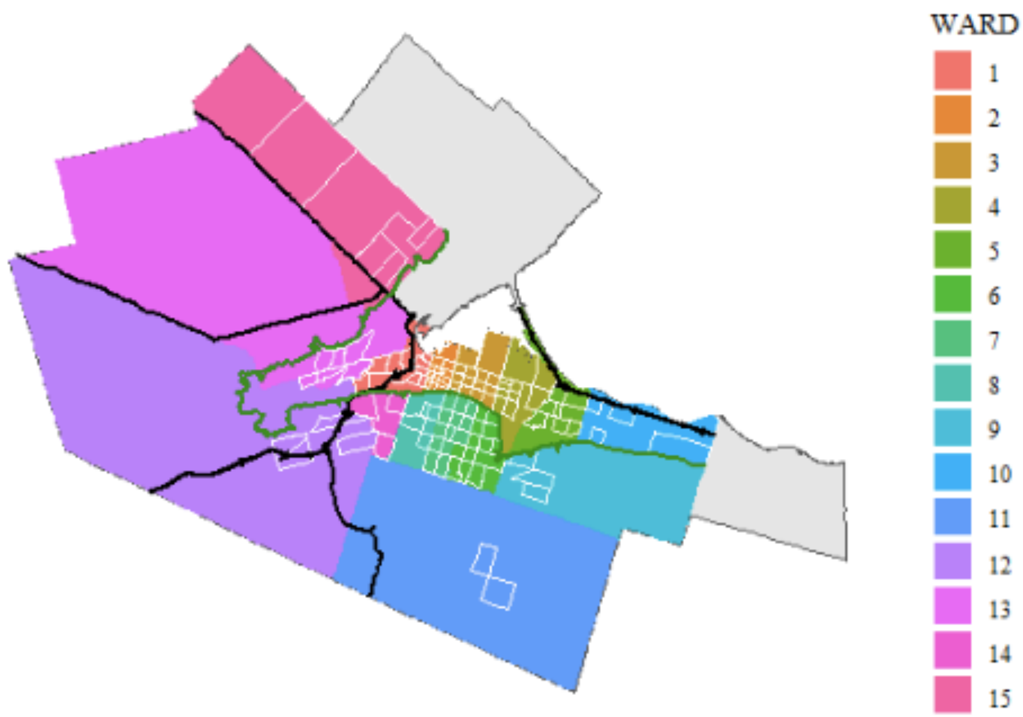

Figure 1. Traffic zones (in white) that produced or attracted cycling trips in Hamilton (The green line depicts the Niagara Escarpment and the black line depicts provincial highways).

Figure 2. Number of trips produced by or attracted to each traffic zone in Hamilton (Black lines are provincial highways and the green line is the Niagara Escarpment).

Previous Research

In the quantitative phase, we used bicycle trip records from the 2016 *Transportation Tomorrow Survey* to develop a spatial interaction model that investigated the correlates of cycling flows with a focus on various built environment attributes [See Chapter 2]. The survey was informative about the traffic zones[2] of origin and destination of cycling trips but did not reveal the route choice of people who cycle. A novel feature of this model was the use of a cycle routing algorithm, *CycleStreets* (Lovelace and Lucas-Smith 2018), to infer different types of cycle routes between zones of origins and destinations. The true origin and destination of each trip recorded in the *TTS* is not publicly available, so we used the centroid of each traffic zone as starting and ending

[2] The traffic zone is the smallest spatial unit at which data are aggregated in the *Transportation Tomorrow Survey*. It is a polygon which typically falls along the centre line of roads or geographic boundaries.

points for each inferred route. The distance and time of three different types of routes, characterized as *fastest*, *balanced*, or *quietest* by the *CycleStreets* algorithm, were used as measures of impedance in the spatial interaction model. The R package, which documents the use of the algorithm and was used for this analysis, states: "These represent routes taken to minimize time, avoid traffic, and compromise between the two, respectively" (Lovelace and Lucas-Smith 2018, p. 1). The routes differed primarily based on the amount of *busyness* along the route and the distance or time between origin and destination. The development, methodology for inferring the routes, and the findings of the model are described in Chapter 2.

The model revealed that inferred *quietest* routes that allow bicyclists to minimize distance *and* interactions with other road users best explain the pattern of travel by bicycle in Hamilton. This suggests that people who cycle are seeking out routes that enable them to avoid traffic while potentially maximizing the use of residential streets over arterial roads [see Chapter 2]. This finding aligns with a recent study using GPS data from Hamilton's public bicycle share system where researchers found that bike share users travel routes that are significantly longer than the shortest path distance and are more likely to use local streets with low traffic and bicycle facilities (Lu, Scott, and Dalumpines 2018). A further exploratory and descriptive analysis of the cycling flow residuals revealed the extent to which cycling flows were over- or under-estimated. The majority of the flows were under-estimated meaning that more cycling was occurring in Hamilton than predicted by the model. In other words, the positive values of the model residuals indicate that the actual number of bicycle trips was greater than the predicted value from the best model that was estimated. The use of *CycleStreets* was efficient for objectively inferring a large number of routes and estimating which type of route best explained the pattern of cyclist travel instead of subjectively identifying routes known to the researchers. However, the model did not capture any other attributes of the built environment beyond the data available through *Open Street Map* that was used by the algorithm to measure the level of *busyness*.

Without knowing more than the *busyness* rating of the route, our hypothesis is that there are micro-level attributes along the *quietest* distance routes that facilitate or hinder cycling between the zones of origin and destination but that were not captured by the model (see Moniruzzaman and Páez (2012) for a similar model-based approach for investigating walking shares). The model included many objectively measured environmental attributes at the traffic zone level that are known to influence cycling. The *CycleStreets* algorithm, however, was an approximate route that a knowledgeable cyclist could take. While there is no way of knowing which routes were actually travelled for the trip flows, we were able to provide statistical support for *quietest* routes that minimize distance by exploring different types of routes in our models. In theory, we could expect that more cycling will occur between zones of origin and destination when routes between these points are more bikeable due to the provision of infrastructure or other attributes that encourage people to cycle. Conversely, when routes between zones of origin and destination where the built environment are less supportive of cycling then other modes may be preferred and fewer cycling trips are made.

Environmental Audits

In cities where cycling is less mainstream, measuring the extent to which a neighbourhood or street is oriented for cycling can help to explain existing levels of travel but also identify opportunities to modify the urban design. An environmental audit, an instrument which systematically quantifies or "takes an inventory" of observable features along street segments that are thought to support active travel, is useful for this purpose (Moudon and Lee 2003). Most audit instruments collect data on physical attributes at the neighbourhood or street level, but perceptions of the built environment are measured less often and only by the auditor (Moudon and Lee 2003). To assess the micro-level attributes of the built environment that might influence cycling, we conducted environmental audits along the routes of 12 cycling flows that were strongly over-estimated (i.e., had a positive residual) or under-estimated (i.e., had a negative residual) by the spatial interaction model. Given that we were limited by the number of origin-destination pairs with negative residuals (i.e., there are only 4) [see Chapter 2] and that audits are known to be resource-intensive (Moudon and Lee 2003), we decided not to do case-control sites unlike Moniruzzaman and Páez (2012). This means that we did not audit pairs of routes that had similar deviations from the model (i.e., one that is over-estimated and one that is under-estimated). Instead, we chose to audit the largest negative residuals (i.e., out of a total of 4 routes), as well as a selection of the largest positive residuals that are above 20. It was hypothesized that this would be most informative because the trip flows that were most poorly predicted by the model, which are the negative and positive extremes, would be audited. There are 23 origin-destination pairs with large positive residuals above 20; of these, 8 pairs were too far apart, meaning that it would not be feasible in terms of time and distance to audit them. Many of the positive extreme pairs were reciprocal flows, meaning that trips in both directions between zones were over-estimated. This gave us a list of 10 under-estimated trip flows and 2 over-estimated flows to audit.

Moudon and Lee's (2003) review of audit instruments was consulted to compare different instruments and to select the most appropriate one for the study's objectives. The characteristics that are assessed by audit instruments typically fall within categories of urban design or transport planning that have been previously identified as associated with walking or cycling. The *Systematic Pedestrian and Cycling Environmental Scan* (*SPACES*) (Pikora et al. 2000a) documents the presence or absence of observable characteristics that are potential influences of walking and cycling. The framework describes four domains of the built environment that influence physical activity: functional, safety, aesthetic, and destination (Pikora et al. 2003). The instrument was developed for use along street segments within neighbourhoods around a residential location. However, the trips flows analyzed in the quantitative phase typically occur beyond the 400m neighbourhood range [see Chapter 2]. Our objective in auditing the routes was simply to conduct a descriptive analysis of observable attributes of the built environment at the street level along the inferred routes that might influence cycling so that we could explore and compare cyclists' perceptions of these characteristics and of the inferred routes. Our unit of analysis, namely a street segment, is the same as the *SPACES* instrument. The instrument also includes an extensive range of measurable features that have been identified in the literature. For these reasons, we determined that the *SPACES* audit instrument was suitable for our purposes. This instrument was also selected because it was developed for researchers and is relatively simple to use (Moudon and Lee 2003). The instrument comes from the field of health and the factors included in the audit were guided by stakeholder interviews and a Delphi study (Pikora et al. 2003). The inter- and intra-rater reliability of the instrument were found to be generally high (Pikora et al. 2002). Two studies have modified the instrument for research purposes in recent years: in Madrid, Spain (Gullón et al. 2015) and in Auckland, New Zealand (Badland et al. 2010). Unlike these studies, no virtual audits or statistical analysis of the attributes along the routes were performed for this study.

The audit instrument was adapted to the local context in Hamilton. Cycling was the primary focus of the assessment; accordingly, some factors that were less predictive of cycling, according to the literature, were removed for ease of data collection. The features that were removed from the SPACES instrument include: permanent path obstructions, pedestrian crossing aids, surveillance, building design, and driveway crossovers. Other features were combined: all types of maintenance instead of specific categories, and the types of paths. A broader range of cycling facilities and traffic calming measures that are found in Hamilton were also added. The modified *SPACES Audit Instrument* is shown in Appendix A and the added cycling guide to the *SPACES Observation Manual* is in Appendix B. ED and three research assistants conducted 12 physical audits during October and November 2019. ED was the only auditor who has cycling experience in Hamilton. Each auditor participated in a training exercise to become familiar with the instrument and the *SPACES Observation Manual* (Pikora et al. 2000b), and to standardize the way in which the audits were carried out. The training exercise was also useful to improve the clarity of the additional sections specific to Hamilton that were added to the instrument. ED prepared the packages of printed audit instruments which were delivered to the research assistants before each audit. The package included the correct number of audits (i.e., one page per segment of the route) and a map of the route with each segment labelled. The majority of routes (n = 10/12) were audited by a pair of research assistants who filled out the instrument together. Two routes (n = 2/12) were audited by ED alone due to a scheduling conflict with the other research assistants. The auditors were instructed to discuss any disagreements and reach consensus before filling out the instrument. Once the audits were completed, the features of each route segment were manually recorded in an Excel sheet by ED. Any perceived errors in data collection were reviewed using Google Street View and were corrected. A descriptive analysis of each route was performed in R to determine the presence and frequency of features along each route.

Ethics

This study was approved by McMaster University's Research Ethics Board in September 2019. In accordance with the requirements of the Research Ethics Board, each participant was provided with a letter of information to describe the study and had to sign a consent form prior to beginning the interview. In appreciation of their time, each participant received a $20 gift card to a coffee chain.

Semi-Structured Interviews with Cyclists

In addition to documenting objective measures of the built environment that might explain why the inferred routes were over- or under-estimated, we wished to explore how well the routes matched where cyclists travel or would travel in Hamilton. We also wanted to examine how people who cycle perceive these routes, knowing from the literature that the perceived environment influences cycling behaviour (Ma, Dill, and Mohr 2014), and to further understand which built environment attributes are perceived to influence where people do and do not cycle. Following the audits, 14 people who regularly cycle in Hamilton were recruited to participate in a 90-minute semi-structured interview (see Table 1 for demographics of participants). We employed a convenience sampling strategy to recruit participants using posters in local bike stores and coffee shops in Hamilton and a social media post on Twitter. Members of the City of Hamilton's Cycling Advisory Committee were also invited to participate. A total of 28 people responded to the recruitment notice, and the first 14 who met the inclusion criteria were recruited to the study. Inclusion criteria were as follows: age (18 years of age or older) and regular travel by bicycle for transport. The latter was defined as cycling for transport at least once per week. Cyclists who ride for recreational purposes only or who did not meet the age criteria were excluded. The first author (ED) conducted semi-structured one-to-one interviews with 14 participants, ranging in time from 60 to 90 minutes. The interviews were conducted between November 2019 and January 2020 at either McMaster University, a local coffee shop, or local library. The interview was separated in two parts: i) general questions about the participant's bicycling behaviour and perceptions of the built environment in Hamilton; and ii) an activity where the participant was asked to look at pictures of different cycling routes that were inferred in the quantitative phase and share their perceptions of the route. The interviews were audio recorded and later transcribed using Temi, an online AI-based transcription software. ED then reviewed and proofread each transcript.

Participant	Pseudonym	Age	Gender	Frequency of Cycling	Confidence Level
1	Gary	18-24	Male	Every day	Excellent
2	Sven	25-44	Male	Multiple times a week	Excellent
3	Annie	25-44	Female	Multiple times a week	Excellent
4	Steve	25-44	Male	Multiple times a week	Excellent
5	Stewart	45-64	Male	Multiple times a week	Good
6	Tanner	45-64	Male	Every day	Excellent
7	Adam	45-64	Male	Multiple times a week	Excellent
8	Doug	45-64	Male	Multiple times a week	Good
9	Tessa	25-44	Female	Multiple times a week	Excellent
10	Daniel	25-44	Male	Every day	Excellent
11	Sally	25-44	Female	Multiple times a week	Good
12	Martha	25-44	Female	Every day	Excellent
13	Kyle	25-44	Male	Every day	Excellent
14	Nicole	25-44	Female	Multiple times a week	Excellent

Table 1. Demographics of participants (pseudonym, age, gender, self-reported frequency of cycling, self-reported confidence level).

Thematic analysis was conducted using the qualitative software NVivo. ED coded all of the interviews. Themes were determined by the prevalence of codes (Braun and Clarke 2006), meaning the number of different participants who expressed a similar like, dislike, or perception for each route. Unlike Chapter 4, analysis was conducted in a more quantitative manner to align with the specific questions that participants answered after looking at route (i.e., *What do you like about the route? What do you dislike about the route?*). In this way, themes were identified for each individual route and not for the collective of six routes.

This paper describes only the findings from the second half of the interviews where participants were asked to review photos of 6 audited routes. The findings from the first part of the interview, respecting participants' general perceptions of the built environment factors in Hamilton that affect their route choice or travel by bicycle, are presented in Chapter 4. Due to time constraints of a typical semi-structured interview, participants only reviewed half of the routes that were audited (see Table 2 for a description of the routes). The routes included in the photo activity were chosen by the authors because they were considered to be potentially the most informative about the influence of the built environment on cycling. More specifically, we were most curious about cyclists' perceptions of these particular routes. The photos of the audits were taken from Google Street View.

Participants were presented with three packages of photos that each contained two routes (i.e., the first package contained routes labelled *1A* and *1B*; the second package contained routes *2A* and *2B*; and the third package contained routes *3A* and *3B*). The residuals of the routes in each package are shown in Table 1. The first two packages each had one route where cycling was over-estimated (i.e., route *1A* and *2A*) between the zone of origin and destination, and one route where cycling was under-estimated (i.e., route *1B* and *2B*). The final package had two routes where cycling was under-estimated (i.e., route *3A* and *3B*) between the zones of origin and destination. The routes in each package were paired according to their length and number of segments. Participants did not know which routes were over- and under-estimated. The photos for each route were numbered to make it easier to transcribe and ensure that participants' comments could be attributed to the appropriate part of the route. Segments that were long or that had changing attributes (i.e., land use was different at multiple points in the same segment) were given multiple photos. Participants were asked to look through the photos from start to finish and then to comment on what they liked and disliked about the route. However, some participants preferred to make comments as they looked through the photos. The amount of time taken to look through the photos of each route varied; some participants went through them quickly and provided a small amount of feedback whereas others spent more time looking at the photos and shared in-depth descriptions of their perceptions or recounted their own experiences travelling along the route. After commenting on both routes in one package, participants were asked which route they preferred (i.e., did they prefer route *1A* or route *1B*?). Because the routes were inferred, there were additional questions asked if a participant reported having cycled part of a route or if they described taking a different route than the one inferred. Other follow-up and off-script questions were asked to better understand participants' preferred routes and behaviour navigating the city.

Findings

A total of 6 routes were reviewed by 14 people who regularly cycle in the second half of the interviews [see Table 2]. For each route, we present first specific objective features of segments to give the reader a sense of the quality of the route before describing participants' perceptions which are subjective. This section is structured as follows: the findings from audits using the *SPACES instrument* are documented (e.g., on-road features, destination features, green space, and subjectively rated attractiveness, comfortability, and wayfinding) followed by a description of the perceptions of people who cycle (i.e., their likes and dislikes of the routes). The characteristics documented from the *SPACES* instrument are presented only for the side of the street where cyclists would be travelling, which is typically the outer right lane of the roadway, unless travelling on a one-way street with infrastructure in the outer left lane. Each route is accompanied by a map of the street network from origin to destination and by two or more photos to illustrate segments that were particularly noteworthy or that elicited a significant number of comments from many participants. Several features measured by the audit are not included in this paper due to space constraints, but the full results of the audits will be publicly available in an online repository.

Package	Route	Origin	Destination	Distance	Number of Segments	Residual
1	1A	Dundas	West Hamilton	2.3km	13	**-2.275**
	1B	East Mountain	East Mountain	1.3km	10	**22.874**
2	2A	Downtown core	West Hamilton	5.3km	27	**-3.63**

	2B	East Hamilton	East Hamilton	4.7km	31	**21.851**
3	3A	Stoney Creek	Stoney Creek	3.6km	19	**29.343**
	3B	Downtown core	Downtown core	2.5km	20	**24.728**

Table 2. Description of inferred routes that were audited using the SPACES instrument.

Package 1

***Route 1A: Dundas to West Hamilton*[3]**

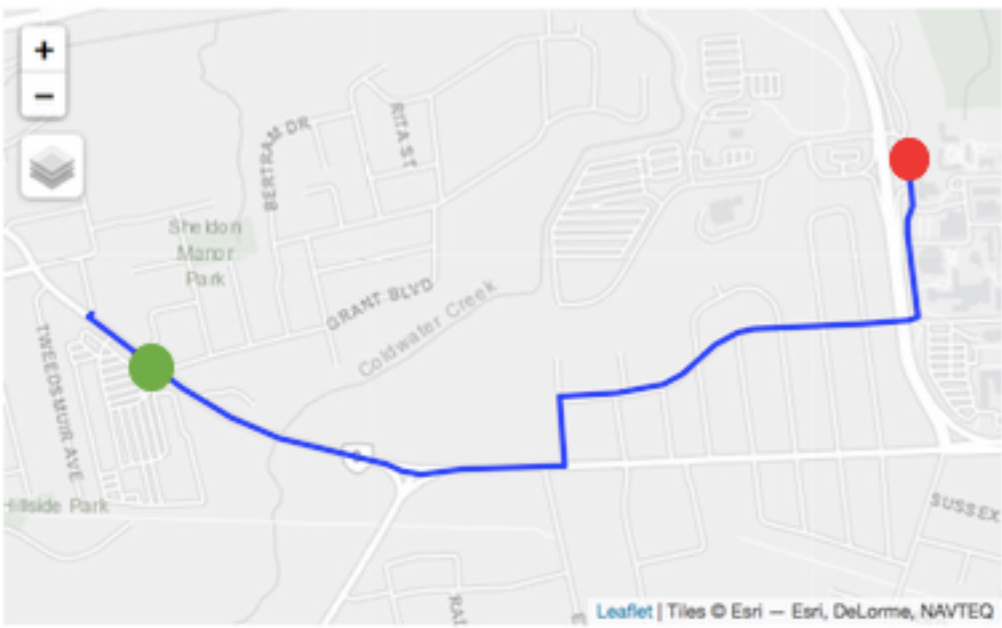

Figure 3. Map of route 1A.

<u>Observable Route Attributes Measured using the SPACES Instrument</u>

This route has 13 segments and connects a commercial plaza in Dundas to the city's university in west Hamilton. The first three segments (n = 3/13) have a mix of functions including housing as well as services and food locations in two different

[3] This route was slightly adjusted for the audit. Rather than starting midblock, the audit started one block south at the commercial plaza. Recall that the origin of each inferred route is the centroid of the traffic zone, so this is not the true origin of this cycling flow.

shopping places. These segments have two or three lanes in each direction and had a traffic signal at two intersections (n = 2/13). These segments lacked cycling facilities but had one or more bus stops per block. One of these segments has a steep uphill slope, but the rest of the route was flat. The route requires a cyclist to make a left turn at an unsignalized intersection on a street with two or three lanes in direction. There are also wayfinding signs from the City's signed route that advise cyclists to turn left. After this turn, the majority of route segments (n = 9/13) that follow are located on a residential street and have a marked on-street bicycle lane (n = 7/9). This street has one lane in each direction (n = 7/7). From start to end, more than half of the route (n = 7/13) features cycling facilities. The entire route (n = 13/13) was subjectively rated as maintained well (i.e., the street verge looked trim, clean, and the grass was kept up). There were no traffic calming measures along the route. All segments had streetlights (n = 13/13) which covered the path area where one would cycle. All segments have tree canopy where the majority of trees range in height from small to medium. More than half of the segments (n = 7/13) are subjectively rated as *very attractive* for cycling. These segments correspond with those that have an on-street marked bicycle lane. Segments at the beginning of the route (n = 3/13) that were in the commercial area with two or more lanes in each direction were rated as *not attractive* for cycling. The route's subjectively rated *comfortability* varied according to the presence or absence of a cycling facility. The segments that had an on-road marked bicycle lane (n = 9/13) or were on less busy segments were rated *easy* to cycle, while those with a signed route (n = 1/13) and no facilities (n = 3/13) were rated as *moderately difficult* and *very difficult*, respectively. There are many destinations along the route that a cyclist could access. The majority of segments (n = 11/13) had good road condition. This route also featured 3 public bicycle share system hubs. Overall, wayfinding was subjectively rated as *easy* because the route followed a direct path and there were destinations or wayfinding signs to help orient someone who cycles.

Cyclists' Perceptions of the Route

Most participants reported being familiar with this route; they had previously cycled at least part of the route or in this general area. The majority of participants strongly disliked the first 3 segments (n = 13/14) and more than half stated that they would not cycle this part of the route. Those who disliked these segments perceived them to be "*terrible*", "*terrifying*", or "*scary*". Other factors that made them dislike these segments include the lack of cycling facilities or "*cyclist space*" (n = 7/13), number of traffic lanes (n = 2/13), the width of the lanes (n = 3/13), and the uphill section (n = 4/13) (see Figures 4 and 5). Most participants (n = 9/13) expected car traffic to be moving faster on these segments. However, one participant perceived this part of the route differently: "*It's never super busy that you need two lanes of car traffic. While it's not built for cycling safety, with that in mind, most cars very easily and safely move out of the way and around you. So it's not super scary to bike through.*"

Figure 4. Segment 2 of route 1A depicting two or three lanes in each direction and no cycling facilities on the roadway. Lighting and natural views are present (Source: Google Street View).

Figure 5. Segment 2 of route 1A depicting the uphill section on a two lane arterial road with no on-street cycling infrastructure (Source: Google Street View).

A few participants (n = 3/14) who were familiar with the area reported that they would have chosen to cycle the Hamilton-Brantford Rail Trail, an off-street multi-use trail parallel to the first 3 segments, to avoid travelling on the arterial road. The lack of lateral space to move out of the way in the event of conflict with other road users and the poor condition of the road were also reasons that some participants disliked these segments (see Figure 4). Many cyclists (n = 5/14) noted that there was no sidewalk or shoulder on the right side of the roadway where they would be cycling, with some describing that it would make them feel "*uncomfortable*" or "*anxious*" to cycle without that space. In general, the first 3 segments were perceived to be too busy and not designed for cycling. The left turn from segment 3 to 4 was noted as difficult by a few participants (n = 4/14) or led to "*vulnerability*" because, as two participants described it, "*it's not the safest*" and "*you're a sitting duck in the middle of a turning intersection with two lanes of traffic whizzing by*" (see Figure 6).

Figure 6. Segment 4 of route 1A depicting the urban design of the street when making a left turn to follow the City's signed bicycle route (Source: Google Street View).

However, the route was generally perceived positively from segment 4 onwards once it entered a residential area. The majority of participants (n = 12/14) specifically reported liking or had positive comments of the segments that had an on-street marked bicycle lane (see Figure 7). Most participants (n = 9/14) also liked these segments because they were perceived to be "*residential*" or "*quiet*", which was described by several participants as meaning less busy with traffic and lower speeds or wide enough that cars and bicycles could safely have their separate space. Based on experience or perceptions, many cyclists (n = 6/14) liked that these segments would were not as busy in terms of car volume. A few participants reported feeling comfortable (n = 4/14) cycling on these segments with infrastructure, compared to the first four that lacked cycling facilities. One said that he felt more relaxed, and participant reported feeling calmer. One cyclist said that she could "*feel her pulse dropping*" after making the left turn and entering the residential area. Along the segments with the on-street marked bicycle lane, four participants (n = 4/14) reported liking the green space and nature. The only feature noted by two participants that could improve the residential segments was added protection to the on-street marked bicycle lane.

Figure 7. Segment 9 of route 1A depicting the on-street marked bicycle lane in a residential neighbourhood (Source: Google Street View).

In addition, half of the participants (n = 7/14) stated that they liked the pedestrian-activated signal because it enabled them to cross the arterial road promptly and safely [see Figure 8].

Figure 8. Segment 13 of route 1A depicting a pedestrian-activated signal to cross a an arterial road (Source: Google Street View).

Route 1B: East Mountain

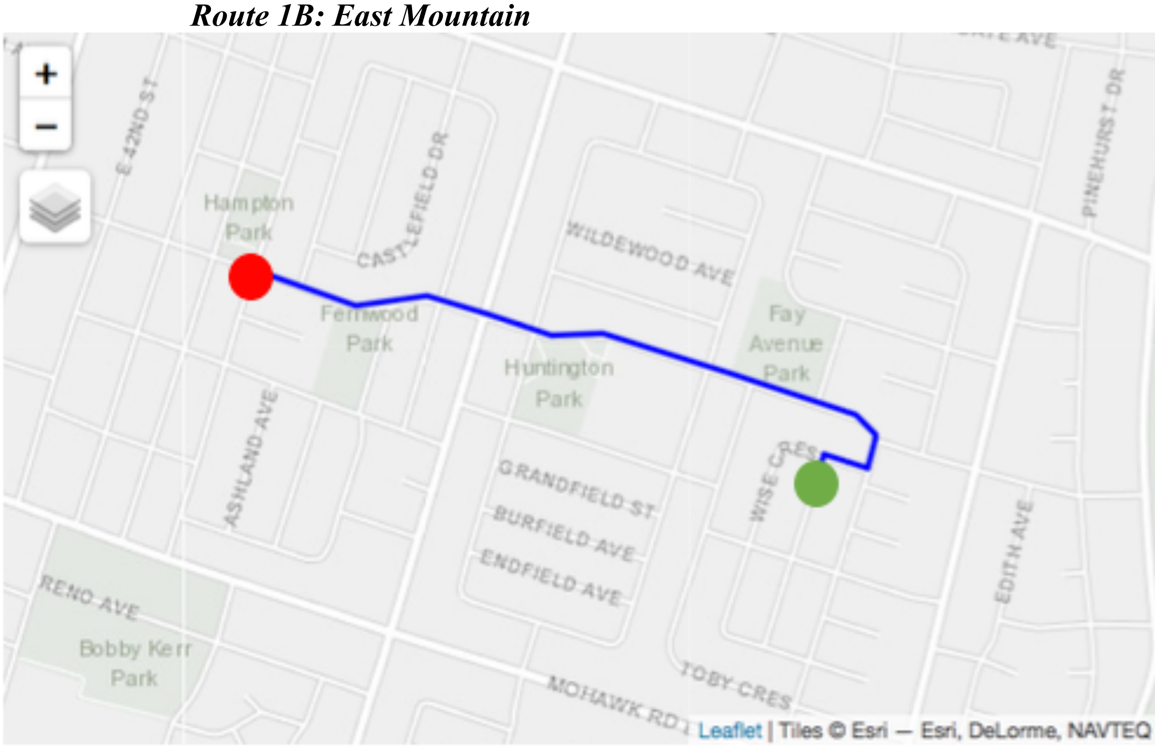

Figure 9. Map of route 1B.

Observable Route Attributes Measured using the SPACES Instrument

This route connects two neighbourhoods in the east mountain area and has 10 segments. The entire route is located in a residential area (n = 10/10). The majority of segments (n = 8/10) feature a signed route, indicating that people who cycle are directed with signs from the City of Hamilton to use this route. These segments are on a street that appears to be a direct route in and out of the neighbourhood. All segments (n = 10/10) had one lane in each direction. The first five segments predominantly feature housing (n = 5/10) and one segment had a park (n = 1/5). This is followed by a segment with a school, a park, and more housing (n = 1/10). There is one (n = 1/10) signalized intersection that would require a cyclist to cross an arterial road. The second half of the route (n = 5/10) predominantly features housing. One segment has a park with recreational facilities (n = 1/5). The entire route was subjectively rated as well maintained (n = 10/10). There were no traffic calming measures along the route. Most segments had streetlights (n = 8/10) which covered the path area where one would cycle. Overall, the route is subjectively rated by the auditor as *attractive* (n = 7/10) for cycling meaning that it was mostly aesthetically pleasing. The auditor rated most segments to be *moderately difficult* (n = 7/10) to cycle because there are no separated facilities, and this would require cyclists to mix with traffic along a route with a school and several parks that might have parked cars. This could pose some difficulties depending on the skill of the person cycling. However, the speed limit was observed to be 40 km/h, therefore the route is not expected to have fast traffic. The street pavement on all segments (n = 10/10) is in good condition (i.e., few bumps) and most had a flat slope (n = 9/10) except for one that had a moderate slope (n =

1/10). There were no bus stops along the route. All segments have tree canopy where the majority of trees range in height from small to medium. Wayfinding was rated as *not easy at all* for most segments (n = 6/10) because the signed route was not consistently displayed, and it might have been easy to get confused because all segments looked fairly similar.

Cyclists' Perceptions of the Route

None of the participants were familiar with this route likely because they did not report cycling often on the mountain (see Chapter 4). This route received overall positive comments from participants (n = 14/14). Cyclists primarily liked the route because it was perceived to have low traffic (n = 5/14), fewer cars (n = 9/14), and was quiet or residential (n = 11/14). Some descriptions of the route include "*nice*", "*residential*", "*lots of trees*", and "*not busy*" (see Figure 10). The lack of infrastructure was noted by several participants (n = 5/14) but only two reported that they disliked this aspect of the route. Only one participant noticed that it was a signed route, but participants reported that they would generally feel comfortable cycling this route. Finally, a few participants (n = 3/14) commented on the good quality of the pavement. Although the route was perceived to be low traffic and residential, some cyclists (n = 4/14) would still have preferred if the route had some type of dedicated cycling facility. Four participants noticed or liked the 40 kilometres/hour speed limit on the route. A few participants (n = 3/14) disliked that the route was not direct; one participant perceived it to be "*disjointed*" and another described it as "*for recreational cycling*". Two participants (n = 2/14) commented that it did not appear to pass by any key destinations other than the school.

Figure 10. Segment 4 of route 1B depicting the streetscape on a signed route in a residential area (Source: Google Street View).

Package 2

***Route 2A: Downtown to West Hamilton*[4]**

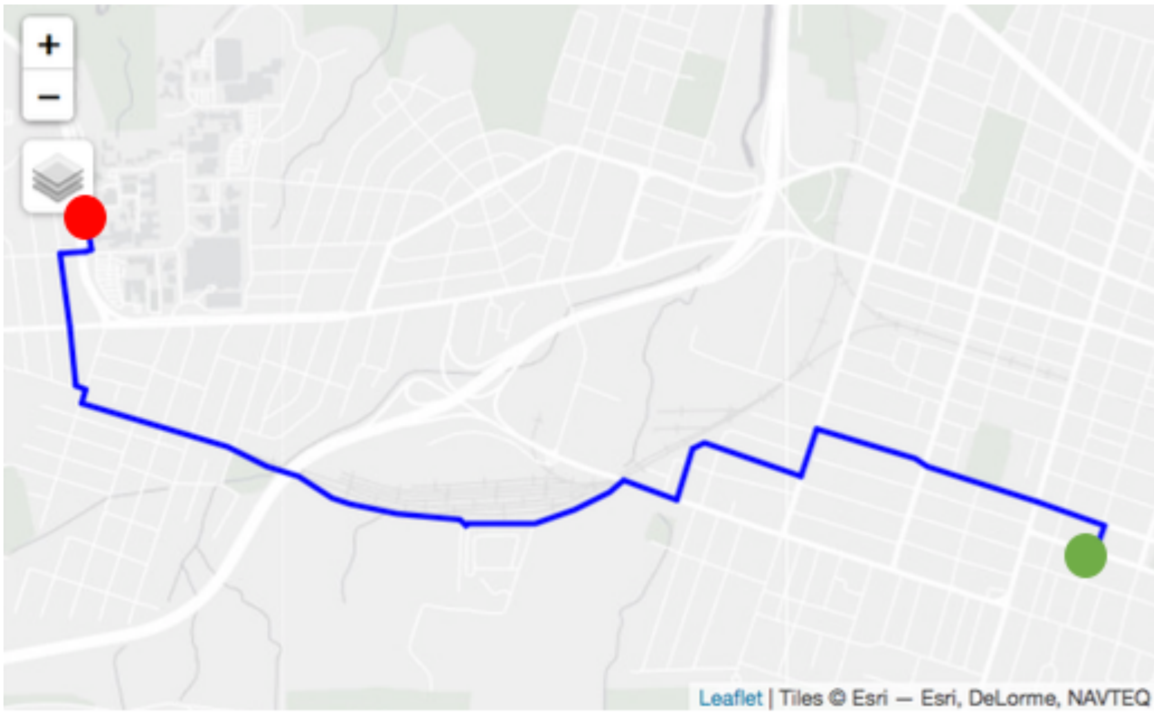

Figure 11. Map of route 2A.

Observable Route Attributes Measured using the SPACES Instrument

This route connects the Durand neighbourhood in the downtown core to the city's university in west Hamilton and had 27 segments. More than half of this route had cycling infrastructure (n = 15/27) but there was a lot of variability in the type of cycling facility present. Many segments lacked cycling facilities (n = 12/27). The route begins with several segments in a mixed use residential area that has services, educational, and food locations (n = 7/27). Most of these segments (n = 6/7) have an on-street marked (n =

[4] This route was slightly adjusted for the audit. CycleStreets inferred that cyclists would cross midblock at an unsignalized intersection towards the end of the route. Cyclists have been found to be sensitive to intersections (Broach, Dill, and Gliebe 2012). Therefore, the audited route was adjusted to a parallel street one block east that would enable a cyclist to cross at a signalized intersection.

5/7) or buffered bicycle lane (n = 1/7). These segments are located on a one-way street that has one lane in a westward direction and cycling facilities on the right side of the roadway (n = 7/7). The buffered bicycle lane ends, and the route requires a cyclist to make a left turn at an unsignalized intersection from a one-way residential street to a segment with one lane of traffic in each direction. These segments (n = 2/27) have an on-street marked bicycle lane and a variety of retail, service, and food locations. The route then takes a right turn to enter another residential area and travels along 5 segments with no cycling facilities (n = 5/27). Next, the route turns right on to an arterial road with two lanes in each direction that lack cycling facilities for two segments. The cyclist then makes a left turn at a signalized intersection on to a segment that had sharrows and a steep slope. The segment that followed is located in a residential area and leads to the Hamilton-Brantford Rail-Trail. There are four segments with an off-street multi-use path. After getting off the trail, most of the segments for the rest of the route (n = 6/7) had one lane in each direction except for the final segment which had two or three lanes (n = 1/7). There is one signalized intersection at the second last segment. The segments that had some type of cycling facility were all in good condition (n = 13/15) and all except for one were flat (n = 14/15). Nearly all segments (n = 24/27) had well-maintained verges that were clean and kept up, and more than half had one lane of traffic in each direction (n = 18/27). Two segments (n = 2/27) were undergoing road repairs at the time of the audit. Two segments had speedhumps (n = 2/27), one near the start of the route and one towards the end. Overall, the majority of the route (n = 24/27) had a good amount of tree coverage where the majority of trees ranged from small to tall. Most of the segments (n = 17/27) were subjectively rated as *attractive* or *very attractive* to cycle and these segments typically corresponded with those that had some type of cycling facility or were a residential street. Similarly, the segments (n = 10/27) that were subjectively rated as *easy* to cycle either had an on-street marked or buffered bicycle lane or an off-street multi-use path. The segments that were rated as *moderately difficult* (n = 13/27) had dedicated infrastructure on a busier street or had no infrastructure on a residential street. Segments that were subjectively rated as very difficult to cycle (n = 4/27) were located on streets that had more than 2 lanes of traffic or no facilities. Finally, wayfinding was mostly subjectively rated as *fairly easy* because there were signs at various points that indicated the different directions that a cyclist could travel and destinations to help orient.

Cyclists' Perceptions of the Route

The participants were familiar with this route and had previously cycled the entire route or parts of it. Cyclists reported liking the cycling infrastructure (n = 14/14), particularly the on-street marked bicycle on segments 2 to 7 and the Hamilton-Brantford Rail Trail on segments 17 to 20 (see Figure 12 and Figure 13). The Rail Trail was perceived to be ideal for cycling: one participant called it a "*superhighway for bicycles*", another described it as a fundamental "*arterial route*" for cyclists in Hamilton. One participant said, "*this is where I want to bike*", and someone else commented that it reminded him of infrastructure in The Netherlands. Most participants (n = 9/14) also liked that many sections of the route that did not have dedicated on-street infrastructure were on residential streets that were perceived to be "*quiet*" and "*calm*". Several cyclists liked or noticed (n = 4/14) that the route connected them to or passed by key destinations. One participant remarked that this route was more direct than other routes in the city because the on-street marked bicycle lanes were located on arterial roads.

Figure 12. Segment 5 on route 2A depicting an on-street marked bicycle lane on a one-way street with one lane going westward (Source: Google Street View).

Figure 13. Segment 18 of route 2A depicting the off-street multi-use path called the Hamilton Brantford Rail Trail (Source: Google Street View).

There were four areas or features along the route that participants disliked or that were more poorly perceived. First, several participants (n = 6/14) disliked or expressed concern about turning left at an intersection without a signal after the bike lane ends. For instance, it was described as "*a little tricky*" and "*problematic*". The bike lane ending shortly before the intersection requires a cyclist to transition from the right lane to the far left lane of the roadway to turn left. Cyclists who disliked this feature reported often waiting a while to turn left, but it was more challenging for them that people who drive did not always anticipate their need to transition lanes like other road users or that they were not given enough space (see Figure 14).

Figure 14. Segment 8 of route 2A depicting the buffered bicycle lane ending and the transition that a cyclist would have to make to get into the left-turn lane (Source: Google Street View).

Second, the short stretch along an arterial road with two lanes in each direction and no dedicated cycling infrastructure (see Figure 15) was strongly disliked by most participants (n = 9/14). Others had mixed perceptions or experiences or reported being fine cycling on a short stretch of this road. Those who strongly disliked the arterial road reported avoiding this street as much as possible or preferred to cycle on the sidewalk instead. For example, the arterial road was perceived to be a "*speedway*" leading to the highway and an area that had "*a lot of car entitlement*". Third, the left turn at a signalized intersection from the arterial road to a street with sharrows was disliked or concerning for some participants (see Figure 16). Three participants (n = 3/14) shared that they knew or had heard of someone who had been hit from behind when waiting to turn left. A few cyclists try to avoid this area, and one reported that he would have crossed like a pedestrian on the sidewalk instead. Many participants (n = 6/14) noted that they used a similar alternate route to get to the Rail Trail by taking an off-street path through a nearby golf course that helps them avoid this arterial road and intersection entirely.

Figure 15. Segment 14 of route 2A depicting an arterial road without on-street cycling infrastructure (Source: Google Street View).

Figure 16. Segment 14 of route 2A depicting a signalized intersection where a cyclist would turn left on to a street with sharrows to travel to the Hamilton-Brantford Rail Trail (Source: Google Street View).

Finally, most cyclists (n = 9/14) stated that they disliked an intersection at the end of the route that would require them to transition from a residential to arterial road (see Figure 17). There was also a lane of traffic merging to the shared roadway after the intersection. The area was viewed as very busy, confusing, and "*not fluid*" by participants because there was an off-street multi-use path parallel to the road on the left side of the roadway that could not be accessed swiftly from the right side. One participant who was familiar with this intersection described this alternative to staying on the road: "*The confusing intersection of impending doom. If you don't know what you're doing, you just sort of come up to this and go, "I have no idea what to do." If I was new to the city, I* *would just... hit the panic button, get off my bike, and then just do what the pedestrians do - which unfortunately would mean doing two crosswalks. If I knew that I was coming [to this intersection] - if I go back [a segment] - right about here after the stop sign, there's a little entrance to the gas station. I'd go up onto the sidewalk so that I can go through this crosswalk and then, making sure there's no traffic coming this way off of Cootes, I'd get onto the bike path there. And then safety. Again, it's an intersection that just doesn't make sense. Not designed by a cyclist. Or someone who just [said], 'Let's just make this work with what we've got.' Poorly planned.*" After looking at this intersection, another participant said: "*I find that a lot with cycling - you can get* ***almost*** *to where you need to go and then you have to do one risky thing before you reach your final destination. And I think that's a problem with a lot of the cycle routes in the city, but especially this one.*" However, several participants (n = 5/14) reported that they would have taken an alternate route after leaving the Rail Trail and would have accessed the university campus from another entrance.

Figure 17. Segment 29 of route 2A depicting the intersection of a residential road and two arterial roads (Source: Google Street View).

Route 2B: East Hamilton

Figure 18. Map of Route 2B.

Observable Route Attributes Measured using the SPACES Instrument

This route is located in the city's east end and connects a neighbourhood to a commercial and industrial area. The route has 31 segments. The majority of the route was a signed route (n = 17/31) and the rest had no facilities (n = 13/31) except for one segment (n = 1/31) on the bridge over the Red Hill Valley Parkway that had a separated and protected multi-use trail on the right side of the roadway. There are many destinations along the route that a cyclist could access. The first eight segments were in a predominantly residential area (n = 8/31) on a street with one to three lanes in each direction that had no cycling infrastructure. There was one segment (n = 1/8) in this stretch that had services and natural features. After this part, the cyclist turned right and the segments that followed were a signed route (n = 17/31). These segments had two or three lanes in each direction with a mix of housing and food, retail, and service locations. After the signed route ended, there was one segment on a residential street then the cyclist turned right on to an arterial road with two or three lanes in each direction. This segment had a separated and protected multi-use path. Once the path ended over the Red Hill Valley Parkway, the segment that followed required a cyclist to quickly merge across two or three lanes of traffic to make a left turn at a signalized intersection. The last two segments of the route (n = 2/31) were located in a commercial and industrial area. Several segments had one or more bus stops (n = 9/31). Tree coverage was sparser, with nearly half of segments having no trees at all (n = 14/31). Streetlights were located on the left side of the roadway for most of the route, meaning that there were limited segments (n = 5/31) that had light cover on the right side of the roadway where a cyclist would travel in the direction of the route. There were no traffic calming measures along the route. The majority of segments along the route were well-maintained (n = 23/31), but there were some segments that were undergoing construction (n = 5/31) at the time of the audits or less maintained (n = 2/31). Overall, the route is subjectively rated as *not attractive at all* for cycling (n = 19/31), but there are some segments rated as *attractive* (n = 11/31) or *very attractive* (n = 1/21). There is no discernible pattern corresponding to other features; routes that are both rated as *not attractive at all* or as *attractive* are a mix of residential and commercial areas and also a mix of segments with signed route and no facilities. All segments, but one, were subjectively rated as *moderately difficult* (n = 19/31) or *very difficult* to cycle (n = 11/31). This is likely due to the lack of dedicated facilities or the number of lanes being two or more which would require a fair amount of mixing with traffic. The road condition along the segments with a signed route ranged from moderate with some bumps and holes (n = 8/17) to good with few bumps or holes (n = 9/17). Finally, the route was entirely flat and subjectively rated as *fairly easy* for wayfinding likely because it had a lot of segments along arterial roads that made the route more direct.

Cyclists' Perceptions of the Route

Some cyclists (n = 4/14) reported that they were familiar with this route or that they had previously cycled part of the route. The participants commented that there was a mix of features of the route that they liked and disliked, although generally there were more dislikes. The segments along the route that were perceived to be "*quiet*" or "*residential*" were liked by most participants because car volume and speed were perceived to be lower (see Figure 19). The protected off-street multi-use trail over the Red Hill Valley Parkway was also a feature that most participants liked or that elicited positive comments (n = 9/14), particularly the separation from traffic on a busy arterial road (see Figure 20). In general, the route or segments that were perceived to not be busy were liked or participants reported feeling comfortable cycling there, but the segments where car volume or speed was perceived to be higher were disliked. One participant said, "*The fact that it has a lot of residential streets through the beginning and middle. Those are nice and safe. No problem with that. [But] there's a lot of shared two lane traffic roads and avoiding parked cars, and people getting out of parked cars. So, I'm not going to have a comfortable ride. I'm always going to have to be on my game and looking through car windows to see if someone's in the driver's seat.*"

Figure 19. Segment 11 of route 2B depicting a residential area (Source: Google Street View).

Figure 20. Segment 30 of route 2B depicting the protected multi-use trail on the right side of the roadway on an arterial road over the Red Hill Valley Parkway (Source: Google Street View).

Some cyclists had mixed perceptions about the width of some of the segments. A few participants commented that at times there appeared to be enough space for people who drive to safely pass cyclists, while others perceived the wide streets to invite people who drive to speeding or to be less comfortable to cyclists. One participant said, "*I think it makes people feel empowered*", implying that wider streets might encourage people to drive faster. Another participant noted, "*[I dislike] the busy streets. Where there's obviously nothing in place to accommodate cyclists. You would have to act as a vehicle, I guess. There is nothing resembling a bike lane.*" Anticipated car volume and the presence of on-street parking along these segments seemed to influence these views, meaning that the photos of wider segments were generally perceived better than photos of wider segments with on-street parking or more traffic volume (see Figure 21 and Figure 22). This suggests that comfort with lane width is influenced by the perceived busyness, with cyclists preferring to have space away from cars when the road is busier. Some participants (n = 3/14) commented that many segments looked wide enough to incorporate cycling infrastructure, suggesting an upgrade from a signed route to a route with some type of on- or off-street facility would be preferred. Most participants noticed or disliked the poor condition of the road along part of the route (n = 9/14). Finally, most participants (n = 10/14) reported that they disliked the end of the multi-use trail or having to cycle on an arterial road and cross four lanes to make a left turn [see Figure 23].

Figure 21. Segment 14 on Route 2B depicting a two-lane arterial road with on-street parking (Source: Google Street View).

Figure 22. Segment 20 on Route 2B depicting a two-lane arterial road with no on-street parking and a wide grassy verge on the right side of the roadway (Source: Google Street View).

Figure 23. Segment 31 of Route 2B depicting a lane change from the far right side of the roadway to the left-turn lane on a four-lane arterial road (Source: Google Street View).

Package 3

Route 3A: Stoney Creek[5]

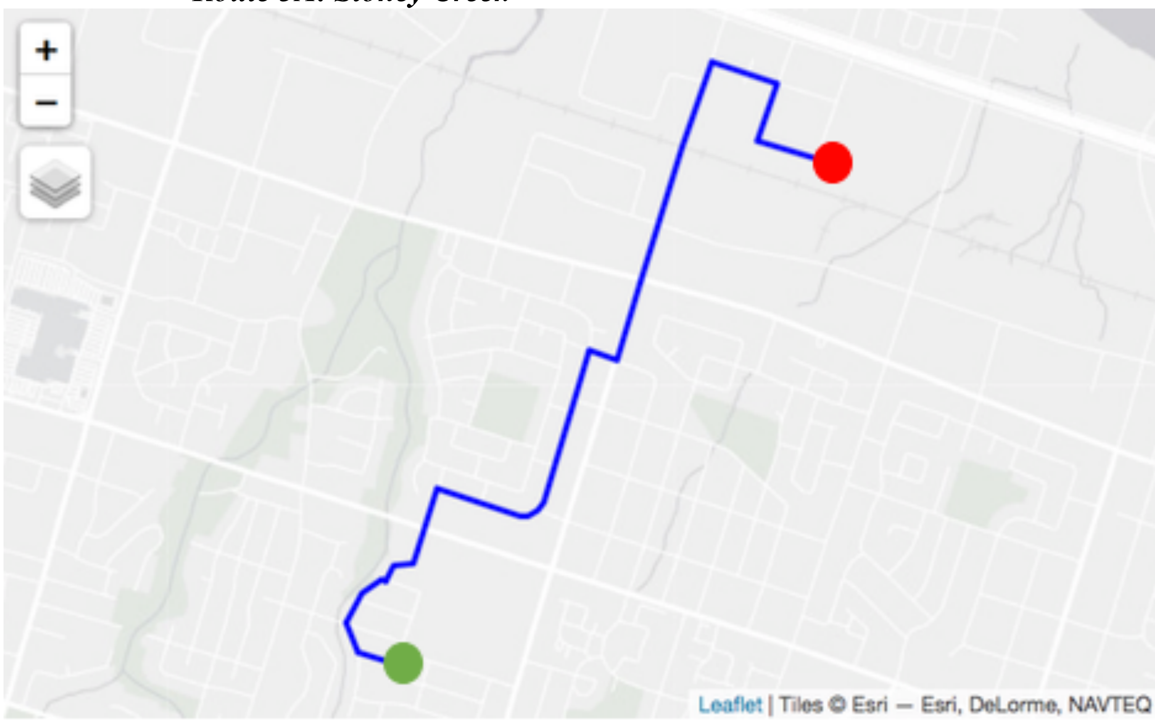

Figure 24. Map of route 3A.

Observable Route Attributes Measured using the SPACES Instrument

This route is located in Stoney Creek and connects a neighbourhood to an industrial area. The route had 19 segments. There were no segments with cycling infrastructure (n = 19/19). The route starts in a residential area; more than half of the route is residential (n = 13/19) and these segments typically had one lane in each direction (n = 11/13). These segments had one or more trees per block, ranging in height from small to medium. To leave the residential area, the route requires that a cyclist turn left on

[5] This route was slightly adjusted for the audit. The starting point was midblock on a residential street. The audit started instead at the nearest intersection along the route.

to an arterial road with two or three lanes in each direction. This intersection is not signalized. The rest of the continues on the arterial road (n = 6/19). The first two segments on this stretch are mixed use; there is housing, services, food, and retail locations. The cyclist then crosses another arterial road, but this intersection has a traffic signal. The route then enters a more industrial area with car and construction services or offices. The last five segments of the route have signs that designate it a truck route and have two or three lanes (n = 3/5) or one lane in each direction (n = 2/5). A few of these segments have one tree approximately every few blocks (n = 3/5) while the other two had one or more per block (n = 2/5). There were no traffic calming measures along the route. Two segments on the arterial road before entering the industrial area had one or more bus stops (n = 2/19). The entire route is rated as *moderately difficult* or *very difficult* to cycle because it lacks cycling facilities. While many segments are residential (n = 13/19), it would require a cyclist to mix with traffic and negotiate both moving and parked cars. The other segments (n = 6/19) are on an arterial road where traffic volume and speed are expected to be higher. Overall, the residential segments are rated as *attractive* to cycle (n = 11/13), but the segments on the arterial road and in the industrial area are rated as *not attractive at all* cycle (n = 6/19). There are many destinations along the route that a cyclist could access. The area around the end point of the route likely has many employment opportunities.

Cyclists' Perceptions of the Route

None of the participants had cycled in this area or were familiar with this route. The opposite to route 1A, the participants liked the first half of the route and generally disliked features of the second half. The beginning of the route was in a residential area; most cyclists (n = 13/14) reported that they liked the quiet and nicely paved streets (See Figure 25). The lower speed limit of 40 km/h was noticed by several participants (n = 5/14) and some commented that they like travelling on streets with this speed limit (n = 3/14). Once the route left the residential area about mid-way, most participants (n = 10/14) disliked making a left turn to a two-lane arterial road. The segments leading towards the industrial area destination were perceived by some cyclists to be "*uncomfortable*", "*terrifying*", and "*busy in terms of traffic*" (see Figure 26). The lack of infrastructure along the arterial roads in the second half of the route suggested to a few cyclists (n = 3/14) that this area was designed for cars [see Figure 27]. One participant described this as, "*you're just out on a bike in the middle of the highway*". The route ended in an industrial area which received mixed perceptions; some cyclists commented that traffic volume did not appear to be too heavy in the photos (n = 5/14) while others reported feeling less comfortable cycling in an area where they could expect to see a lot of trucks (n = 7/14). Another participant commented "*it doesn't look like a cyclist would belong*" in the industrial area.

Figure 25. Segment 2 of route 3A depicting a residential street (Source: Google Street View).

Figure 26. Segment 13 of route 3A depicting a two-lane arterial road without cycling facilities in a residential area (Source: Google Street View).

Figure 27. Segment 15 of route 3A depicting a two-lane arterial road without cycling facilities or a sidewalk leading to a more industrial area (Source: Google Street View).

***Route 3B: Downtown Core*[6]**

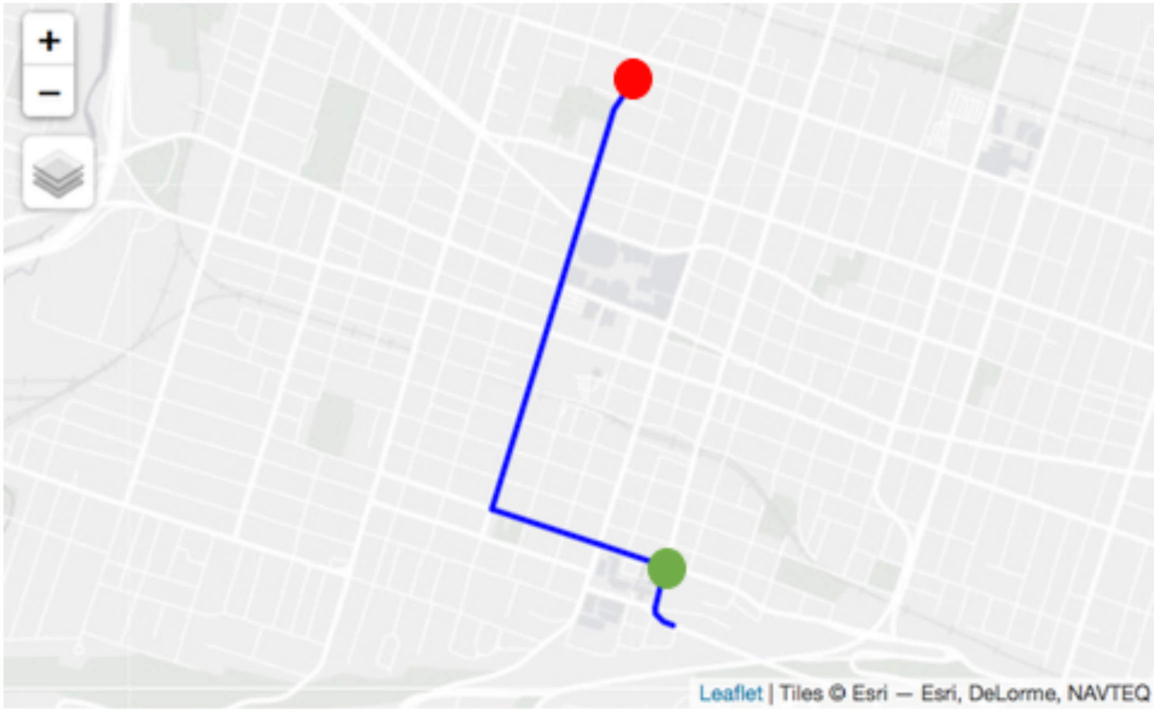

Figure 28. *Map of route 3B.*

Observable Route Attributes Measured using the SPACES Instrument

This route connects two neighbourhoods in the downtown core and had 20 segments. This route has cycling facilities for the majority of segments (n = 19/20). The route begins in front of a hospital - the first segment has no facilities and the two segments that follow are signed route (n = 2/20). These segments predominantly have health services (n = 3/20) and one to three lanes in each direction. The route requires a cyclist to cross a signalized intersection and then the on-street cycling facilities begin on a one-way street with one lane of traffic in a westward direction. This route differs slightly

[6] This route was slightly adjusted for the audit. Rather than starting midblock on an uphill access to the escarpment, which would be an unlikely origin, the audit started two blocks south. Recall that the origin of each inferred route is the centroid of the traffic analysis zone, so this is not the true origin of this cycling flow.

from the others in that the cycling facilities are on the right side of the roadway for the next three segments where there is an on-street buffered bicycle lane (n = 1/20) followed by a parking protected bicycle lane (n = 2/20). After this, a cyclist would turn right, and the cycling facilities switch to the left side of the roadway on a one-way street where there is a two-way cycle track (n = 12/20). These segments (n = 12/20) have two or three lanes in a northbound direction, with a parking lane on the right side of the roadway. There are five segments with intersections that have either a traffic signal (n = 2/5), bike signal (n = 1/5), or bike box (n = 2/5). At the end of the route, the two-way cycle track ends because the street becomes two-way. At this point, there is a bike box at the signalized intersection and the two-way cycle track becomes an on-street buffered bicycle lane (n = 1/20) on the right side of the roadway and an on-street marked bicycle lane (n = 1/20) on the left side of the roadway. The route varies in terms of land use; segments at the beginning are predominantly residential (n = 6/20) and the segments with the two-way cycle track are mixed use (n = 12/20) with housing, services, and educational, office, and food locations. The route is mostly flat with the exception of a few segments (n = 2/20) along the two-way cycle track that have a moderate or steep uphill slope. The route had some segments with one or more bus stops (n = 7/20). There were no traffic calming measures along the route. The majority of segments (n = 17/20) had one or more trees per block that ranged in height from small to tall. All segments were well-maintained (n = 20/20) and most of the route was subjectively rated as *attractive* or *very attractive* for cycling (n = 15/20). The majority of segments (n = 11/20) were rated as *easy* to cycle and these segments typically corresponded with those that had on street cycling facilities. The segments that had either no facilities or a signed route (n = 3/20) were rated as *very difficult* to cycle. Due to its location in the downtown core, wayfinding was primarily rated as *fairly easy* and *very easy* because of known landmarks on the route like a hospital and the city hall. The entire route was maintained well (n = 20/20).

Cyclists' Perceptions of the Route

This route was familiar to the participants and the majority had cycled at least part of it (n = 13/14). The start of the route near the hospital was perceived to be busy by many participants. Cyclists (n = 14/14) liked that the majority of the route had cycling infrastructure (see Figure 29 and 30). The first few segments at the beginning of the route were perceived to be busy in terms of traffic by several participants, but many noted that people drive slower near the hospital. Several participants noted that they would be fine mixing with traffic in this area.

Figure 29. Segment 4 on route 3B with a buffered on-street bicycle lane on a one-way street (Source: Google Street View).

The two-way cycle track was generally perceived well and elicited a lot of comments from participants, likely because they reported using it. However, participants expressed a mix of appreciation and frustration about this "*major cycling infrastructure*". One participant described the two-way cycle track as "*some of it is taking up space*" on an arterial roadway that was previously designed without accommodation for cyclists (see Figure 30). A few other participants noted that the cycle track was important to increase awareness of cycling. Another commented that the route was "*central*". It would be comparable, if not the same, as a route for someone driving from the origin to the destination, which suggests that it is relatively direct. While the separation of the on-street infrastructure throughout the route was noticed by most participants, many (n = 9/14) expressed a desire to have enhanced protection along these facilities and disliked the plastic barriers. This was influenced by their experiences cycling in the area. Several participants (n = 6/14) reported that they had witnessed people drive or park in the lanes, as well as drift into them to avoid passing closely to the parked cars. Three participants, one travelling with a young child, reporting being hit by a motorist who was turning left across the cycle track. Many participants reported being vigilant when using this infrastructure because it is a two-way facility on a one-way street. One participant who was hit by a motorist suggested that visual cues should be added to remind people who drive to check their left blind spot before turning. Despite it being a relatively new and important North-South route in the city's cycling network, cyclists described that it needed full protection and improvements to particular areas that were conflict points with other road users.

Figure 30. Segment 8 on route 3B depicting a two-way cycle track on a one-way arterial road (Source: Google Street View).

There were also mixed comments about a few intersections along the route. In each of these cases, the city had installed bike boxes which are a type of infrastructure that is meant to show people who cycle, using green paint on the road, how to position themselves to safely make left or right turns to perpendicular streets that also have cycling facilities. Most cyclists (n = 8/14) reported that the bike boxes were confusing or somewhat confusing, both for them and for people who drive, and that sometimes these were not respected spaces (see Figure 31). They reported that people who drive may park in them if the light was red which prevented cyclists from safely accessing this space to make a turn or transition to another cycling facility. However, other participants (n = 4/14) reported that they really liked the bike boxes and find them useful for those transition points. Finally, several participants (n = 3/14) disliked a few segments on the route where the bike lane passed parking lots in the downtown core. They reported that it was a busy area where people who drive would often cross the bike lane suddenly or without looking for people who are cycling. The route was also perceived to be disconnected or disjointed by some participants (n = 5/14); these comments were in reference to the different or inconsistent types of infrastructure along the route and because the infrastructure ends at certain spots.

Figure 31. Segment 20 of route 3B depicting the bike box at the intersection of two cycling facilities. After the intersection, the two-way cycle track on the left side of the roadway because on-street bicycle lanes on both sides of the road (Source: Google Street View).

Preferred Routes

After reviewing each of the three packages of photos, participants were asked to select which of the two routes in each package they preferred. All participants consistently selected the same routes: *1B* was preferred over *1A*, *2A* over *2B*, and *3B* over

3A. In the first package, *1A* was an over-estimated route, meaning that there was less cycling than expected by the spatial interaction model, and *1B* was under-estimated. Cyclists preferred route *1B* because they strongly disliked the first few segments of *1A*; they would rather cycle on a route through a residential area with quiet streets than negotiate shared space on a busy four-lane arterial road even though there are dedicated cycling facilities later in the route. It is worth noting that a few participants commented that they most preferred the second half of *1A* because it had an on-street marked bicycle lane, but that *1B* was a better route overall. Our hypothesis is that *1A* may have been over-estimated by the model because the cycle routing algorithm included busy segments on a four-lane arterial road and failed to account for the parallel Hamilton-Brantford Rail Trail which was preferred by many participants. The fastest and balanced routes inferred for this cycling flow also includes the busy segments. The findings from the interviews suggest that the first half of *1A* is poor enough to deter a cyclist from travelling this route. In the second package, *2A* was over-estimated and *2B* was under-estimated. Participants preferred *2A* because it had cycling infrastructure throughout compared to *2B* which had a signed route only for part of it. *2A* was also a familiar route to most participants. In this case, we hypothesize that *2A* was also over-estimated by the model because of the segments on the busy arterial road. It may also have been over-estimated because it had only 6 recorded trips in the *TTS* for this trip flow despite starting and ending in mixed use areas of the city. Finally, *3B* was preferred for similar reasons that *2A* was preferred; there were on-street cycling facilities for most of the route and it was familiar to most participants. It is hypothesized that this route may have been under-estimated because there were no cycling facilities along part of the inferred *quietest* distance route until late 2017, which was not captured by the algorithm. The relatively new two-way cycle track along this route is now a popular North-South corridor for cyclists in the downtown core. It is worth noting that one of the participants who was cycling with her child when she was hit by a motorist said that she still preferred *3B* over *3A*: "*I don't know if that's because I bike it. I actually bike this route. Or it's because the city is trying. Whereas here [3A], there's nothing and it just happens to be conveniently quiet streets. Whereas if the Bay Street bike lane didn't exist, with all its problems, it would be much harder to get downtown.*"

Discussion

The environmental audits revealed that the *quietest* distance routes inferred by *CycleStreets* had a mix of micro-level attributes that support or hinder cycling. This helped to explain why certain trip flows were over- and under-estimated in the spatial interaction model. The use of *CycleStreets* to infer different types of routes was practical because the travel survey used in the quantitative phase was not informative about routes travelled by respondents. All inferred routes included streets in residential areas with lower volumes of cars or cycling infrastructure, which studies have shown are attributes that are preferred by people who cycle in cities where cycling is less mainstream (Caulfield, Brick, and McCarthy 2012; Clark et al. 2019). With respect to the routes that were over-estimated (i.e., *1A* and *2A*), the presence of multi-lane arterial roads that lacked infrastructure can help to explain their negative residuals. As the photo activity revealed, both routes had several segments that would never by cycled as reported by participants.

With respect to the routes that were under-estimated (i.e., *1B*, *2B*, *3A*, and *3B*), there were many features that might influence cycling. For instance, two of the four (i.e., *2B* and *3B*) had some type of separated cycling facility. Three of the four routes (i.e., *1B*, *2B*, and *3A*) included residential streets with lower volumes of traffic. Based on the routes audited, we observed that the algorithm makes sensible recommendations that a knowledgeable cyclist could take. Three of the six routes, *1A*, *2A*, and *3B*, were familiar or partly familiar to many participants which suggests that the inferred routes do match where cyclists actually travel in Hamilton.

The findings from the photo activity aligned with previous literature and did not differ significantly from the first half of the interviews [see Chapter 4]. We were also able to provide further support to the finding from the quantitative phase that the *quietest* distance routes best explain cyclist travel in Hamilton. When asked to select which route they preferred in each photo package, participants chose routes that had cycling facilities and lower levels of traffic. This has been found in many other studies (*inter alia*, see Buehler and Dill 2016; Clark et al. 2019; Winters et al. 2011). Participants were sensitive to travelling through intersections (see Broach, Dill, and Gliebe 2012), particularly those that are unsignalized or that require a left turn, and enjoyed routes that had natural features (see Marquart et al. 2020). Car volume was also a factor that participants commented on as they reviewed photos, likely because cyclists are known to be sensitive to busy traffic (Segadilha and Sanches 2014). Participants preferred routes that are visibly oriented to cycling and consider a range of factors to determine whether a street has been accommodated sufficiently for their needs.

In addition to the built environment attributes identified by participants in Chapter 4, the photo activity helped to reveal other factors that are perceived to be important for cycling but that were previously mentioned less often in the first half of the interviews. For instance, more participants commented on the quality of the road pavement along the routes and many reported that they like to cycle on roads with smooth or good conditions during the photo activity compared to the first half of the interviews. Other studies have reported similar findings (Stinson and Bhat 2003; van Miltenburg 2016). Participants also noticed the availability of lateral space to their right on the routes. Some cyclists reported disliking segments on busy roads that lacked a sidewalk or some other "escape zone" in the event that they needed to quickly move out of the way to avoid a person driving too closely or a collision. In the absence of a paved shoulder or grassy verge, a few participants reported that they would hop onto the sidewalk and ride there instead. This emphasizes how the lack of dedicated road space for people who cycle can put them in precarious situations both on and off-street, and reinforced that their urban design needs are indeed different from both pedestrians and motorists (Forsyth and Krizek 2011). Cycling on the sidewalk is not permitted for adults in Hamilton, presumably to prevent potential collisions with pedestrians, but this space may be perceived to be a more viable option on streets that are not accommodated for cycling. People who cycle do not currently seem to fit in either the pedestrian or car zone (Liu, Krishnamurthy, and Wesemael 2018) which highlights how the built environment needs to be more explicitly oriented for people who cycle. The emergence of additional route preferences in the second half of the interviews suggests that, in addition to a hierarchy of infrastructure preferences (Buehler and Dill 2016), there may also be a hierarchy of preferred route attributes. What came to mind first for participants in the first half of the interviews were more obvious features that might improve safety or impact their experience of cycling, such as the presence of infrastructure, the aesthetics of the street, and the volume or speed of cars along the route. However, other more subtle factors that also affect cycling appear to be secondary. Some preferences may not ultimately deter cyclists from a route, such as the quality of the pavement, but others may be more detrimental like the absence of space to move off the roadway. These attributes may be overlooked by transport planners but should be considered when planning cycling networks and routes. Liu et al. (2018) were correct in identifying that qualitative methods are informative for uncovering the influence of micro-level characteristics on cycling, which can complement other methods like travel surveys or diaries.

Furthermore, the photo activity revealed that there is a threshold of unpleasantness that people who cycle are willing to tolerate along a route. Even though there were attributes along part of the inferred routes that support cycling, such as infrastructure, there were other segments with attributes that ultimately discourage people from cycling there. In the case of route *1A*, the first 4 segments were such strong deterrents that cyclists chose the other unfamiliar and residential route as their preferred option between the two. Although route *1A* was an inferred route and not one that participants reported using, someone who is new to cycling but unfamiliar with other routes could likely consider this to be the most direct route. The photo activity underscored that the fragmented nature of the cycling network in a transitional city can create barriers for accessing bikeable streets.

More importantly, these streets are not separate from the rest of the transport system and the ability to reach this infrastructure matters. If getting to on-street cycling facilities is perceived to be challenging or too dangerous, then regular and even potential cyclists may be unwilling to use the infrastructure or avoid routes that incorporate these streets altogether. Then it is no longer failure by design of the infrastructure, but failure by design of the cycling network. Street attributes in the broader transport system are just as important and also need to be more adapted for cycling during a transitional stage. Planning for cycling in Hamilton should focus beyond infrastructure and seek to better integrate these individual links within a transport system that is designed with pro-cycling policies in mind. It also implies that the fluidity and efficiency of travel by bicycle, which is reported by cyclists in highly bikeable cities as important (van Duppen and Spierings 2013), has not yet been achieved in Hamilton. If cyclists have to continuously navigate less bikeable areas as part of their travelled routes, then this may deter the uptake of cycling for more people.

Policy Implications

There are three important implications of this study: i) the perceptions of people who cycle should be regularly explored by transport planners and incorporated in route design; ii) efforts to encourage cycling in a transitional city should focus on more than infrastructure; and iii) the timing of incorporating cyclists' feedback is important for ensuring that infrastructure is functional and adapted as it grows.

Ma et al.'s research (2014) indicates that perceptions of the built environment should be considered more explicitly in planning. The photo activity was particularly illuminating because it helped participants recall their own experiences while cycling some of the inferred routes. This revealed rich insights that could not have been derived from a travel survey or cycle routing algorithm. The adaptations and detours that people who have cycle have learned over time as they navigate the city, as well as the conditions that they perceive to make cycling safe or challenging, were often described in detail as they looked through the photos. This is valuable information about cycling behaviour for transport planners in Hamilton that can be used to improve how the city is experienced and travelled by bicycle. For example, the two-way cycle track on a one-way arterial road in route *3B* indicates that this street accommodates cycling to some extent. However, participants reported that it should be more protected to ensure greater separation from cars, and some felt uncomfortable cycling in the one opposite direction on a one-way street. Two participants also reported being hit along this cycle track by people who drive which suggests that the desire for more protection is strongly warranted.

Inviting people who cycle to have a more participatory role in route design and planning can be achieved by creating more engagement opportunities to explore and listen to their preferences. Planners should take advantage of cyclists' expertise and their regular close contact with different environments on a bicycle. van Miltenburg (2016) previously reported that cyclists in Hamilton are valuable experts at critically evaluating their environment. Likewise, Marquart et al.'s (2020) interviews with cyclists and experts in politics and planning demonstrate that qualitative approaches are useful for exploring perceptions that are otherwise less known or perceived differently by planners. The authors highlight that planners "are determining the characteristics of routes in urban areas" (Marquart et al. 2020), which supports the recommendation that people who cycle need to share their perceptions and preferences to ensure that transport planning efforts align with their needs. These early adopters who choose to cycle when it is not yet mainstream can provide recommendations for enhancing street design to improve their experience or reveal how people who cycle negotiate shared roadways in response to other users. Participants' comments in the photo activity about the quality and functionality of bike boxes, a relatively new cycling intervention in Hamilton, is one example of how their feedback can be informative for transport planners. Likewise, people who are new to cycling or willing to cycle have specific preferences (see Clark et al. 2019 and Winters et al. 2011) that also need to be fulsomely explored to ensure that efforts to grow ridership have a positive influence.

The provision of cycling facilities is highly important, but our findings also suggest that additional changes are needed to more explicitly accommodate cycling on direct routes and major roads. Infrastructure alone may not be enough to encourage more cycling if other street level attributes are not adapted for people who cycle. It is for this reason that cities that are transitioning to being more bicycle-friendly, like Hamilton, should pay attention to a broader range of factors that influence cycling. Pucher, Dill, and Handy's (2010) review provides evidence that cities that are most successful in increasing their cycling trips and levels have implemented a suite of interventions to change behaviour and the built environment. These efforts include, among many others, additional traffic calming, intersection modifications, promotional or day campaigns, restrictions on motor vehicles and free parking, and cycling education for children

(Pucher, Dill, and Handy 2010). Our findings support the recommendation that the City of Hamilton explore and implement bolder policies identified in the literature to encourage modal shifts; this can include increasing the cost of or removing parking in dense areas, adopting regular open streets events that encourage people to explore their city on a bicycle, and car-free zones across the city in local business and tourist areas. In mid 2020, the City of Hamilton lowered the speed limit in many residential areas to 40 km/h which is an important change given that participants report that they rely on quiet streets that have slower traffic. However, Pucher, Dill, and Handy's review (2010) highlights that successful cycling cities have traffic calmed residential areas to 30 km/h or less, which suggests that further lowering the speed limit from 40 km/h may be needed.

As a matter of policy, clear goals provide a strong direction. By 2031, the City of Hamilton aims to achieve its aspirational mode share target of 15% walk/cycle trips (City of Hamilton 2018a). A breakdown per mode is not articulated in the Transportation Master Plan, but assuming that it is split evenly, this means that the city has just over 10 years to increase cycling levels from 1.2% to 7.5%. This significant increase cannot be accomplished without bolder policies and stronger political will. The next *Transportation Tomorrow Survey* in 2021 will reveal what changes, if any, to the cycling mode share were achieved in the past 5 years. At present, there is a window of opportunity over the next decade to more boldly make the city bicycle-friendly. There is strong incentive for taking this path: 35% of all current trips in Hamilton are 5 km or less, which means that these trips could be cycled (Mitra et al. 2016) and more people could benefit from increased physical activity. Therefore, a clear goal for the cycling mode share is needed.

This research supports the recommendation that the City of Hamilton adopt a unique mode share target for cycling instead of combining this mode with walking. Otherwise, the target may be met only as a result of increasing walking shares, which says little about the city's success in becoming a true cycling.

Furthermore, tailing to understand and integrate cyclists' perceptions and preferences in planning efforts early on in a city's cycling development can negatively impact efforts to increase cycling; resources could be spent on facilities that are fundamentally unappealing to cyclists or other aspects of the travel experience that act as barriers can be ignored. Marquart et al.'s (2020) research illuminated the mismatch that between the perceptions of people who plan cities and those who travel it by bicycle. In this stage of transition, it is recommended that developing cycling cities collect and examine more qualitative data on a routine basis to inform and adapt their interventions. In addition to our methods in this study, other mapping techniques (see Manton et al. 2016 and Marquart et al. 2020) or ride-along activities (see Duppen and Spierings 2013) may be further informative for understanding how people who cycle navigate the city. Frequent environmental audits with planners and cyclists, particularly before or after new infrastructure is built, can reveal how streets are experienced and whether investments in cycling are useable. With 46% of the cycling network completed, participants still report that the design of existing infrastructure does not fully meet their needs and preferences. It is therefore also recommended that the City of Hamilton explore new frameworks for determining infrastructure design that align more with cyclists' preferences and adopt an all ages and abilities lens for the city's cycling network and interventions. For instance, the Cycling Master Plan notes that the City of Hamilton uses the *Desirable Bicycle Facility Pre-Selection Nomograph* from the Ontario Traffic Manual (City of Hamilton 2018, p. 8) to determine the type of cycling facility that is "deemed suitable for the roadway" (City of Hamilton 2018b). However, there is no stated objective to consider the needs of people of all ages and abilities. The photo activity highlights that cyclists dislike shared roadways and prefer infrastructure even where traffic levels are low. Using this nomograph in practice suggests that the needs of people who cycle are given lower priority than people who drive and leads to areas of the city that lack infrastructure because the car volume and speeds do not necessitate it. Our findings recommend that local policymakers and planners consider a different framework for determining cycling facilities, one that more readily incorporates evidence from the literature and preferences of local cyclists. At a critical stage in Hamilton's transition to a cycling city, exploring and considering the perceptions and preferences of cyclists while planning is crucial for avoiding a cycling city that fails by design.

Study Limitations

While the algorithm made sensible recommendations for *quietest* distance routes that did indeed include attributes that influence cycling, like on-street marked bicycle lanes or two-way cycle tracks, there are some instances where it failed to include some of the city's off-street infrastructure (i.e., Hamilton-Brantford Rail Trail and signed routes) as part of the routes. Some participants noted these situations. They also described some alternate detours that are more locally known to people who cycle which highlights that a routing algorithm like *CycleStreets* may not reflect the extent of behaviours of people who cycle. The fact that these routes were inferred means that we don't know where cyclists actually travel, but as reported by cyclists, they were familiar with many of the routes. It would be worth exploring in further research how the inferred *quietest* distance routes compare to routes travelled by bike share users. Several cyclists noted that the routes they preferred were familiar to them, which suggests that familiarity played a role. This makes sense because it affords them more intimate knowledge of the route. Therefore, our findings could have been different if the participants were familiar with all of the routes or if they were familiar with none. However, their familiarity offered insightful information about how these road spaces are actually experienced and how cyclists might adapt or respond in specific situations. This rich data is particularly useful for transport planners in Hamilton which is a strength of local research. Our findings would also likely have been different if the participants were new or occasional cyclists. People who have less experience with cycling are likely to have even stronger preferences for protected infrastructure and be more averse to mixing with traffic. Finally, some of the routes had photos that were darker or cloudier than others. This was noticed by two participants, suggesting that it may have subconsciously influenced participants' perceptions as well. However, there was a lot of homogeneity in participants' stated preferences and they all selected the same preferred routes. This suggests that the weather depicted in the photos likely had less of an influence on individual perceptions and preferences, and that other attributes of the routes were more important.

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Chapter 4: Cyclists' Perceptions of the Built Environment

Background

Research in recent years has largely been dedicated to the role of the built environment because of its strong influence on cycling for transport (Heinen, Wee, and Maat 2010). Quantitative approaches have been primarily used to gain insights of this relationship, and in general are most common in travel behaviour studies (Mars, Arroyo, and Ruiz 2016). Travel surveys are often used for individual-level or aggregate studies to infer basic information about cycling trips: how often people cycle, for which trip purposes, and where cycling trips start and end (Handy, Wee, and Kroesen 2014). However, travel surveys often lack data about *where* cyclists travel from origin to destination. Global positioning system (GPS) devices or crowdsourced data from phone applications have helped to fill this gap by revealing which routes are actually travelled by cyclists (Pritchard 2018). Cyclists can also be presented with different infrastructure options in a survey or in an interview and asked to state their preferences (*inter alia*, see Stinson and Bhat 2003; Veillette, Grisé, and El-Geneidy 2019; Winters et al. 2011). This type of data can inform changes to the built environment or the development of new policies that might attract new cyclists or those who ride infrequently (Clark et al. 2019).

From both revealed and stated preference studies we know that cyclists, both current and potential, prefer routes that feature separated on-street infrastructure or off-street paths (*inter alia*, see Broach, Dill, and Gliebe 2012; Chen, Shen, and Childress 2018; Dill 2009; Lu, Scott, and Dalumpines 2018; Misra and Watkins 2018; Winters et al. 2011). Cyclists are also sensitive to traffic which influences the routes that they travel (*inter alia*, see Segadilha and Sanches 2014; Stinson and Bhat 2003; Misra and Watkins 2018; Winters et al. 2011). Routes that have beautiful scenery are preferred by current and potential cyclists (Chen, Shen, and Childress 2018; Winters et al. 2011). In Quebec City, Canada, researchers found that cyclists are most likely to use off-street recreational paths followed by a separated bicycle lane (Veillette, Grisé, and El-Geneidy 2019). Chen et al. (2018) examined the route choice of cyclists in Seattle and found that they prefer routes with facilities and slow traffic, but that there is some variability in other built environment attributes such as nature or land use along the route. Preferences among cyclists also differ by gender – female cyclists report a stronger preference than male cyclists for greater separation from motor vehicle traffic (Aldred et al. 2017; Heesch, Sahlqvist, and Garrard 2012), but both men and women are willing to travel for a longer time to use infrastructure that they prefer (Krizek, Johnson, and Tilahun 2004). Cyclists also report being willing to make detours to maximize their travel experience by using preferred facilities (Krizek, Johnson, and Tilahun 2004; Winters et al. 2010).

Quantitative-based research provides necessary evidence for researchers and transport planners about where cyclists do or would travel. Illuminating as they are, these studies are relatively silent about *why* cyclists prefer certain routes over others, *how* they perceive or experience different environments or infrastructure, and *how* they make decisions about where they travel. However, these kinds of questions are ideally suited to be answered by qualitative methods (Clifton and Handy 2003; Mars, Arroyo, and Ruiz 2016). Qualitative work in cycling research is increasingly common and has been used to identify barriers and facilitators to bike share use in Australia (Fishman, Washington, and

Haworth 2012) and to explore what is supporting cycling growth in Canadian communities from the perspective of cycling experts (Assunçao-Denis and Tomalty 2019). In Leipzig, Germany, researchers used qualitative data to better understand how cyclists perceive their city differently than planners and identified areas that needed to be improved (Marquart, Schlink, and Ueberham 2020). Mayers and Glover (2019) interviewed cyclists in Waterloo, Canada and found that cycling in a car-centric city leads to positive and negative experiences with infrastructure. Therefore, qualitative research can be very useful to explore and examine a diversity of subjective factors that influence cycling behaviour. Qualitative data may be the missing key to make quantitative data more useful in practice.

Knowing what factors ought to be modified to facilitate cycling for transport is particularly important in cities that wish to grow their currently low levels. These cities are arguably those most in need of evidence that can inform the creation of more bikeable spaces that are appealing and useable to a large population (see Caulfield 2014; Mayers and Glover 2019; Muñoz, Monzon, and López 2016). Perceptions of the built environment do influence cycling behaviour, as Ma et al. (2014) have found in Portland, which highlights that this subjective factor needs to be explored and understood when trying to increase cycling levels. For instance, the provision of infrastructure may be insufficient alone in cities with low cycling levels where other cultural factors may also act to impede cycling for transport (Aldred et al. 2017). Therefore, exploring how the built environment is perceived from the view of those choose to cycle despite low levels in their city can inform researchers and planners' understanding of their experiences navigating the built environment. This information can also help to gauge the current cycling culture, if there is one emerging and evaluate the limited cycling facilities that currently exist to inform future interventions. Cycling practices tend to be less established in cities with fewer cyclists, and as the research of Aldred and Jungnickel (2014) demonstrates, it is precisely during this transformative stage that cycling practices can become mainstream or remain as a niche choice. As cities transition from lower to higher levels of cycling for transport, cyclists in such cities can be viewed as an asset; their familiarity with different environments can help a city become more bicycle-friendly by revealing existing facilitators and barriers to adopting the bicycle as a mode of transport and areas most in need of improvement. Indeed, van Miltenburg's (2016) research highlights that "practiced cyclists" are capable of critically evaluating the urban spaces in cities through which they travel which reinforces that their perspectives should be leveraged at a critical stage of cycling development.

In this paper we contribute to this body of knowledge by reporting on the qualitative findings from an explanatory mixed methods study conducted in Hamilton, Ontario. Hamilton is a mid-sized city in Canada where cycling represents 1.2% of all trips and 46% of the planned cycling facilities network has been built as of 2019 (City of Hamilton 2020). We previously analyzed bicycle trip records in Hamilton from the 2016 *Transportation Tomorrow Survey* (Data Management Group 2018) to develop a spatial interaction model using a cycle routing algorithm that investigated the built environment correlates of cycling flows [see Chapter 2] and conducted environmental audits of some inferred routes [see Chapter 3]. To further explain what we learned from the spatial interaction model, and to develop a more comprehensive understanding of how the built environment influences travel behaviour, we conducted semi-structured interviews with 14 people who regularly cycle in Hamilton. Therefore, this paper adds to the understanding of how the built environment is perceived and influences route choice from the unique perspective of people who cycle in a city with low cycling levels but that currently is transitioning to becoming more bicycle-friendly. This qualitative descriptive study aims to answer the following research question: *What are cyclists' perceptions of the factors in the built environment in Hamilton that influence their route choice?*

Methods

Study Setting

Hamilton is a mid-sized city in Ontario located approximately 50km from Toronto with over 650,000 residents. Cycling represents 1.2% of all commuting trips in the city according to the most recent regional travel survey conducted in 2016 which is a twofold increase from 2011 (Data Management Group 2018). Cycling levels are growing but still much lower than other urban Canadian cities like Vancouver, Montréal, and Toronto (Verlinden et al. 2019). The City of Hamilton's current Cycling Master Plan was drafted in 2009, and revised in 2018, with the goal of completing the planned cycling facilities network within 20 years (City of Hamilton 2009). According to the province of Ontario's *Highway Traffic Act*, a bicycle is considered a vehicle, and people who cycle are expected to share the road with other users. For this reason, they have the same rights and responsibilities as people who drive. The City currently spends approximately $1-2 million per year on cycling facilities, compared to a typical an annual budget of over $70 million towards roads, bridges, traffic, and sidewalks. Around 15 to 20 km of new facilities are typically built each year (City of Hamilton 2020). In addition, the City has adopted other policy interventions such as *Bike Month*, a month dedicated annually to promoting cycling, and a public bicycle share system. The City also has a Cycling Committee made up of local representatives who cycle. The Committee advises City Council on matters relating to cycling, including promotion, safety, infrastructure design, and tourism. With almost half of the planned cycling facilities have been built, it is suggested that Hamilton is currently in a phase of transition. The city has implemented several interventions similar to other Canadian cities (see Assunçao-Denis and Tomalty 2019) but there is still a lot of progress to be made towards completing the network and growing the cycling culture to reach the city's aspirational goal of 15% mode share of walking and cycling by 2031. Geographically, the city is relatively flat, but it is divided by the Niagara Escarpment which separates the lower city and downtown core from the suburban and rural parts of the city on top of the Escarpment. The Escarpment is approximately 100m tall in many places, and previous research has found that this generally results in two separate zones of cycling with little cycling occurring between them [see Chapter 2]. Most areas of the city did generate or attract cycling trips, but the majority of trips were concentrated in west and central Hamilton. For reference, Figure 1 depicts west and central Hamilton's cycling facilities, arterial roads, street grid, and the Niagara Escarpment. Part of the area above the Niagara Escarpment is referred to locally as 'the mountain' and will be used interchangeably with 'the Escarpment' throughout the paper.

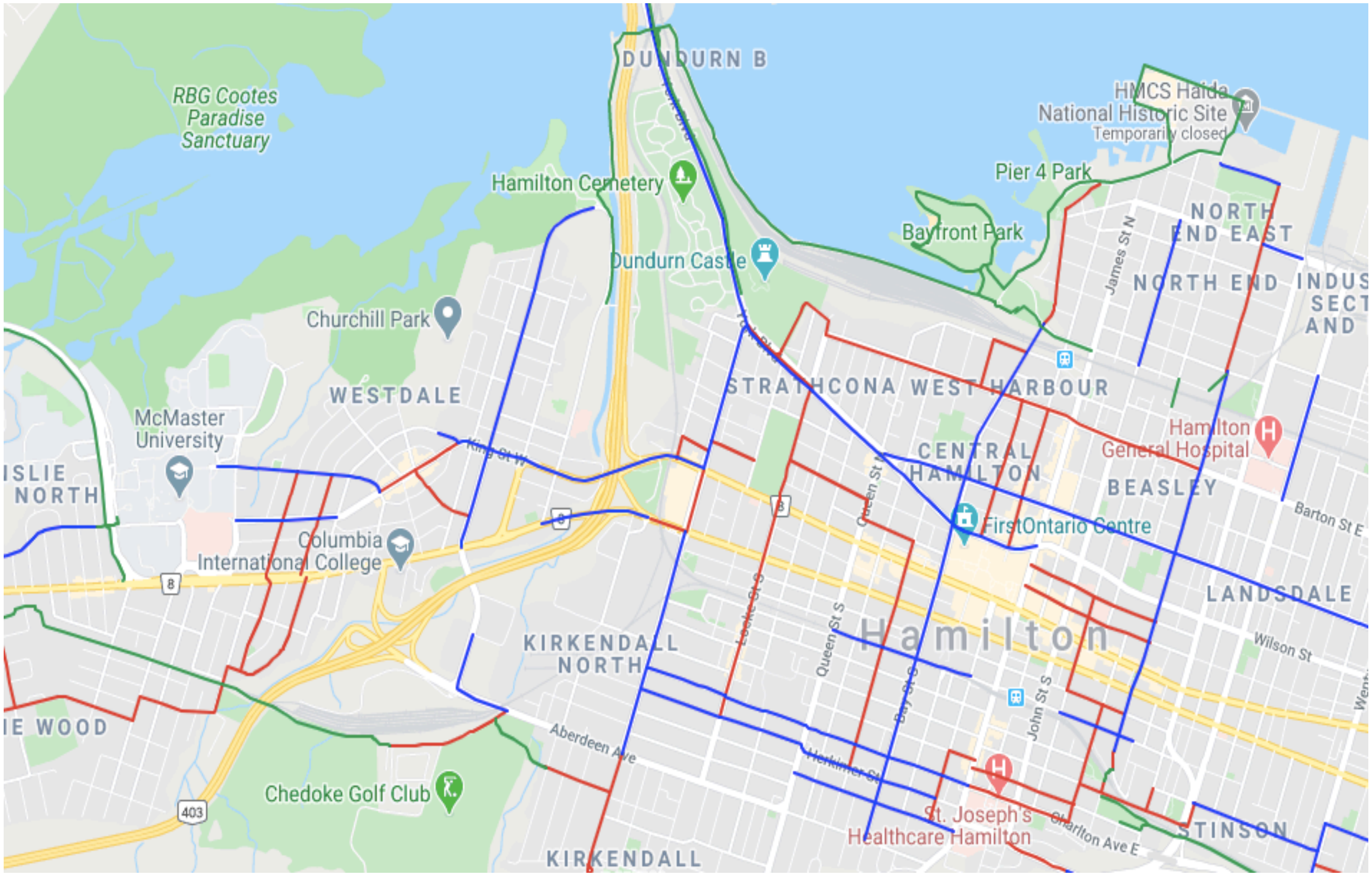

Figure 1. Road network and cycling facilities in the lower city in Hamilton. ***Legend****: blue lines indicate designated on-street bicycle lanes; red lines indicate signed on-street bike routes on streets with mostly low traffic volume; green lines indicate off-street paved multi-use trails that are shared with pedestrians; yellow lines represent highways;* *<u>white</u> lines represent arterial, collector, and residential roads.*

Study Design

A mixed methods approach was selected by the authors to develop a comprehensive understanding of the influence of the built environment on travel by bicycle in Hamilton. A mixed methods study design is well suited for topics that explore the interactions between health or health outcomes and the built environment (Steinmetz-Wood, Pluye, and Ross 2019). This design allows for the integration of data with the goal of using qualitative findings to build upon quantitative results in a way that provides a more comprehensive and contextual understanding of what is being studied (Steinmetz-Wood, Pluye, and Ross 2019). Qualitative research has been identified as a useful approach in transportation research in general to fill gaps from quantitative methods (Clifton and Handy 2003), but also in travel behaviour studies to illuminate decision-making processes that would otherwise be challenging to capture with other methods (Mars, Arroyo, and Ruiz 2016). With respect to cycling and our study's objective, Pritchard (2018, p.12) notes that interviews are an effective method "to gather richer open answers regarding variables that may have influenced route choice". Considering the fact that cycling research provides evidence that can be used by cities to make decisions about resources and investments that support cycling (Handy, Wee, and Kroesen 2014), stories and descriptions of cycling experiences can ultimately complement quantitative data by illuminating how attributes of the built environment influence cycling behaviour and to what degree. This is particularly important as any city aims to transition to be more bicycle-friendly.

The quantitative phase of this project identified that availability of jobs at the destination and different land use mixes were statistically significant built environment attributes that produced or attracted cycling trips in Hamilton [see Chapter 2]. A novel feature of this analysis was the use of *CycleStreets* (Lovelace and Lucas-Smith 2018) to infer the distance and time of different routes as a measure of impedance in the model. The *quietest* shortest path route, compared to the *fastest* and *balanced* routes, between the zone of origin and zone of destination was found to best predict cycling flows, suggesting that people who cycle select routes that enable them to avoid traffic. The development of the spatial interaction model and the methodology for inferring the routes are described in detail in Chapter 2. We hypothesized that the over- or under-estimation of trip flows is due to micro-level attributes at the route level that we were not able to capture in the model. To document the built environment along the inferred routes, we conducted several environmental audits and also involved regular cyclists in our research to examine what they liked and disliked about the routes [see Chapter 3]. We also wished to understand how the built environment in a transitional city was viewed more broadly, whether the current stage influenced their travel, and which attributes they consider as they select routes. Therefore, we explored these topics more in-depth during the same semi-structured interview.

Recruitment

The data from the 2016 *Transportation Tomorrow Survey*, which was used in the quantitative phase, is anonymized so there is no information about survey respondents and no opportunity for them to be contacted to participate in any follow-up research for other purposes. To then build upon the quantitative findings by exploring how the built environment was perceived and influenced where cyclists travel, participants were instead recruited from a sub-set of Hamilton's general population, namely those who regularly cycle for transport.

We employed a convenience sampling strategy given the low cost and short period of time available to recruit (Miles & Huberman 1996, as reprinted in Creswell 2007). Participants were recruited through several channels: posters were put up in local bike stores and coffee shops in Hamilton and a post was shared online through Twitter (see Appendix C). In addition, an invitation to participate in the study was sent to the City of Hamilton's Cycling Advisory Committee. The majority of participants responded after the post was shared on Twitter. A total of 28 people responded to the recruitment notice, and the first 14 who met the inclusion criteria were recruited to the study. When conducting interviews for a qualitative description study, where richness is emphasized over generalizability and the topic is clear, the inclusion of 10 to 15 participants is often deemed to be sufficient for graduate research. However, Hennick et al. (2017) note that code saturation, when researchers have "heard it all" is typically met after 9 participants whereas meaning saturation to "understand it all" is typically achieved after 16 to 24 participants. The first author (ED), who conducted the interviews, and the co-supervisors

(EA and AP) were in agreement after discussing the 14 interviews that this number of participants struck balance between the two and produced a sufficient and manageable amount of data to analyze. Inclusion criteria were as follows: age (18 years of age or older) and regular travel by bicycle for transport. The latter was defined as cycling for transport at least once per week. Cyclists who ride for recreational purposes only or who did not meet the age criteria were excluded. See Appendix D for the Letter of Information provided to participants.

Data Collection

A pilot interview was conducted with a local cyclist to practice interviewing styles and avoid common mistakes that might influence data collection (Banner 2010). The first author (ED) then conducted semi-structured one-to-one interviews with 14 participants, ranging in time from 60 to 90 minutes. The interviews were conducted between November 2019 and January 2020 at either McMaster University, a local coffee shop, or local library. The interview was separated in two parts: i) general questions about the participant's cycling behaviour and perceptions of the built environment in Hamilton; and ii) an activity where the participant was asked to look at pictures of different cycling routes that were inferred in the quantitative phase and share their perceptions of the route. This paper focuses on the qualitative data from the first part of the interviews. The findings from the photo activity are described in Chapter 3. The interview guide was developed in consultation with cycling stakeholders from the Hamilton community (e.g., local government and non-profit organizations) to ensure that the data collected could also be useful for decision-making or to inform future policy and infrastructure changes.

The complete interview guide is provided in Appendix E. In addition to these questions, participants were probed for further details and other non-scripted questions were asked based on what participants shared about their experiences with cycling for transport. The interviews were audio recorded and later transcribed using Temi, an online AI-based transcription software. ED then reviewed and proofread each transcript. This increased ED's familiarity with the data. Final and complete interview transcripts were exported as Microsoft Word documents and are available in an online repository.

Thematic Analysis

The qualitative software NVivo was used to analyze the data. Thematic analysis was selected as a method because it provides a rich description of participants' perceptions and experiences (Braun and Clarke 2006). It is also flexible to allow for the detailed interpretation of various themes across the entire data set (Braun and Clarke 2006). Themes within the data were identified inductively, meaning that they were derived from the data and not in reference to an existing theoretical framework or coding frame. Using the semantic level analysis approach, "themes are identified within the explicit or surface meanings of the data" (Braun and Clarke 2006). Therefore, the analysis does not get at the underlying ideologies or assumptions that may have informed the content of the data, but the authors still interpret the patterns and the broader implications of the findings. It is important to note that the authors determined 'key' themes by their prevalence (i.e., occurred frequently throughout the data set), and that interesting but less prevalent concepts that are relevant to the research questions identified above were also interpreted to inform the themes (Braun and Clarke 2006). For example, several participants reported cycling with children or other less experienced riders and described how this influenced their route choice which was interesting to ED but not a common theme for all participants. The approach to analysis was iterative in nature – there was frequent returning to the data to deepen familiarization while writing and revising the analysis (Braun and Clarke 2006).

The following steps outlined by Nowell et al. (2017) guided the analysis:

1. Data familiarization: ED reviewed and corrected the transcripts of all interviews and documented thoughts and ideas of potential codes and themes. ED also made analytic notes to document reflexivity.

2. Generating initial codes: ED developed a codebook, based on the data, which was shared with and reviewed by the second author (EA) and the third author (SDR). At this stage, researcher triangulation and peer debriefing began. ED subsequently revised the initial codes.

3. Searching for themes: ED established connections between codes through diagrams, post-it notes representations, and drawings to document concepts and themes.

4. Reviewing themes: The codebook was again shared with and reviewed by the EA and SDR. ED returned to the interview transcripts to test for adequacy.

5. Defining and naming themes: Through ongoing researcher triangulation and peer debriefing, the themes were refined and consensus between ED and EA was achieved.

6. Producing the report: The coding framework and analysis were finally shared with the entire research group, who confirmed that the identified themes made sense based on the data and that the process of coding and analysis was methodologically sound.

Ethics

This study was approved by McMaster University's Research Ethics Board in September 2019. In accordance with the requirements of the Research Ethics Board, each participant was provided with a letter of information to describe the study and had to sign a consent form prior to beginning the interview. In appreciation of their time, each participant received a $20 gift card to a coffee chain.

Findings

Participant Characteristics

Participants were asked to self-report their age range, gender, frequency of cycling, and perceived confidence level with cycling [see Table 1]. Of the 14 participants recruited, 9 were male (64%) and 5 were female (36%). Despite using a convenience sampling strategy and without selecting participants based on gender, we were able to achieve a similar gender split as is typically observed naturally among people who cycle in Canada. Only about one third of females reported cycling in 2014 (Ramage-Morin

2017). The majority of participants (n = 9/12) were aged between 25 and 44 years. The requirement to participate in the study was to cycle for transport at least once per week, but participants either cycled multiple times per week (n = 9/12) or every day (n = 5/12). 79% of participants (n = 11/14) reported that their perceived confidence level while cycling was excellent and 21% (n = 3/14) reported that their confidence level was good. Based on the self-reported frequency of cycling, all participants fit within the category of regular cyclist.

Participant	Pseudonym	Age	Gender	Frequency of Cycling	Confidence Level
1	Gary	18-24	Male	Every day	Excellent
2	Sven	25-44	Male	Multiple times a week	Excellent
3	Annie	25-44	Female	Multiple times a week	Excellent
4	Steve	25-44	Male	Multiple times a week	Excellent
5	Stewart	45-64	Male	Multiple times a week	Good
6	Tanner	45-64	Male	Every day	Excellent
7	Adam	45-64	Male	Multiple times a week	Excellent
8	Doug	45-64	Male	Multiple times a week	Good
9	Tessa	25-44	Female	Multiple times a week	Excellent
10	Daniel	25-44	Male	Every day	Excellent
11	Sally	25-44	Female	Multiple times a week	Good
12	Martha	25-44	Female	Every day	Excellent
13	Kyle	25-44	Male	Every day	Excellent
14	Nicole	25-44	Female	Multiple times a week	Excellent

Table 1. Descriptions of participants (pseudonym, age, gender, self-reported frequency of cycling, self-reported confidence level).

The interviews opened with three general questions that were not included in the analysis but that are described briefly here to introduce participants and their reported cycling habits. Cyclists cited health, financial, or environmental motivations for cycling. They reported that they cycle for transport for different trip purposes - to work, for errands or appointments (e.g., groceries, bank, doctor's visits), to visit friends and family, to get to recreational activities (e.g., sports, singing groups, etc.), and to bring their children to school or daycare. Five participants reported cycling with children, and eight had previously cycled in other Canadian cities or in European countries. Finally, as a collective, participants cycled in many areas of the city both above and below the Niagara Escarpment, and have been cycling in Hamilton for at least two years. However, the geographic range for cycling tended to be more localized for each individual participant with most trips occurring in west or central Hamilton.

Major Themes

The major themes identified from the interviews are reported below. All participants agreed or strongly agreed that the built environment influences the routes they choose to travel. There was more variation with respect to whether the built environment influences where they cycle to; some participants reported that it does, while others stated that they would cycle to destinations regardless of the built environment. However, there was further contextualization needed to understand their decisions. We elaborate on this further below. Three themes that relate to participants' perceptions of the built environment and the factors that influence their route choice are explored and discussed: (1) the built environment is not yet bicycle-oriented; as a result (2) infrastructure influences mobility and (3) seek routes that invite cycling.

1. The built environment is not yet bicycle-oriented

Participants frequently made reference to car volume as a factor that influences where they cycle in Hamilton or that they consider when selecting routes. This suggests that cars currently have a significant presence on the city's streets and that cyclists are noticeably a minority of road users. As such, participants reported a preference for routes with fewer cars and disliked mixing with traffic. They would typically only cycle on a busier road if there was dedicated infrastructure. Similar to sidewalks being dedicated space for pedestrians, the presence of cycling facilities, or lack thereof, was perceived as a sign that the street accommodates cycling. However, arterial roads with designated bicycle lanes are limited in the city [see Figure 1]. They also have other qualities like higher speed limits or multiple lanes that were also cited as factors that cyclists try to avoid. Many participants explicitly acknowledged streets that prioritized the movement of motor vehicles and that did not integrate cycling.

"There's nowhere to bike on Main and King [the city's two main arterial roads]. I sometimes see people going downhill on Main [Street] and think that's very brave of them. Even if people were respecting the 50-kilometre limit, it is a literal freeway through the city and the lanes are narrow for a car driver. There's nowhere for people to go and people are really impatient. So even though it is obviously the direct route in Hamilton for cars, cyclists have to find creative ways around it." ***(Daniel, 25-44 years)***

"There's certain roads, I have realized, that are just not meant for bikes. Which is why I would say, yeah, I more or less agree that the built environment does play a factor. I'm not going to bike down Queen Street. I'm not going to bike down Aberdeen Street [...] There is nothing telling a driver on Queen Street not to drive at 80 kilometres an hour. The same with Aberdeen. It [Aberdeen] does have the friction of oncoming traffic and they do have more parked cars on it. But just the total volume of cars along there..."

(Gary, 18-24 years)

Many participants described some of the city's major arterial roads as "*highways*", "*freeways*", "*superhighways*", "*throughfares*", or "*thruways*". These words typically designate roads that are exclusively for motor vehicles, which suggests that some arterial roads in Hamilton are perceived to be designed for and used by people who drive only. The quotes illustrate how Tessa and Tanner perceived the design of the built environment in Hamilton as a person who cycles, and link to the perception of less access to road space compared to other modes as described above.

"The civic design of Hamilton is... abominable when it comes to bicycle transportation. I have many feelings about the way that the Main and King superhighways end up prioritizing cars to the detriment of every other person who might try to move around the city."[7] ***(Tessa, 25-44 years)***

"The eight lane roads that are essentially highways in Hamilton, they're not treated like roads. Like theoretically I'm allowed to take a lane. There's no way of doing that. No one's expecting me to be out there. If I'm out there, I'm kind of deemed as useless and I might actually get some bad behaviour on

[7] Although not specific to cycling, this quote is reminiscent of a bus-only lane that was piloted on King Street but ultimately removed after opposition.

purpose from drivers. Any of those major roads in Hamilton that are like throughfares, like that just take you from A to B, I avoid.” ***(Tanner, 45-64 years)***

Participants reported avoiding busier roads that lacked infrastructure or that had qualities that discouraged cycling. As a result, the preferred routes of people who cycle may not be the direct route that a person who drives would travel. Cycling on arterial roads would offer an equivalent travel experience to people who drive because it would be more direct and take less time, but it was often perceived to be unsafe or uncomfortable if there was no infrastructure. Moreover, many participants provided detailed descriptions of how they selected or found routes to cycle. This emphasized that when the built environment is not bicycle-oriented, effort is required to find streets or spaces that feel safe and comfortable to cycle. Some participants used words like “*jiggle*”, “*shimmy*”, “*squiggle*”, or “*zigzag*” to describe how they cycle. One participant said that it took several years to find an ideal route. This suggests to some extent that cycling in a transitional city with a cycling network under development is not intuitive or fluid.

"I still haven't figured out how to get from A to B without going on some squiggly kind of all over the place thing... But it always felt kind of, you know, just like all over the place and kinda took me a while to figure it out." ***(Adam, 45-64 years)***

"Over the four years I was at that job, [I] honed my route to find all these little spots where cars don't go, so that I can have the most car-free route." ***(Annie, 25-44 years)***

One participant described how he began the process of finding a route to cycle to bring his child to daycare. He described that the more direct route would have been comfortable if he was cycling alone, but he chose to explore different routes that were less direct but perceived to be safer when cycling with a child.

*"I've been gearing up for a while to do the daycare drop off ... And for me, it was like, I know I can do this, and I've got the time, resources, and energy. But I need to plan it out because life is too nuts right now to not do it well. Also, it really needs to be safe … I was doing some test runs … so I was testing out some different things … I was trying to think about the most direct route, like I have my ways of … getting around that I'm very comfortable with. But this is a little bit different. And I want to really maximize it and try to do this well cause it's going to be a big part of my life. I was thinking about some other shortcuts that I can take that would get me off some different routes and get me in better shape." (**Daniel, 25-44 years**)*

Being acutely aware of how other road users travel or interact with people who cycle also sometimes necessitated or helped cyclists adjust or adapt their routes. For example, one participant described being more cautious at a specific intersection downtown where people run the red light, while others expected aggressive behaviours from people in certain areas of the city. One participant reported trying the most direct route to get to work but then changed his route altogether as a result of negative experiences.

*"When I first started riding from my house, it's a time factor. I started off just going straight down Sherman. Cause that's the most direct route. But it's super crazy in the mornings at rush hour specifically between Main and Cannon... Drivers are crazy, like going across four lanes and going at 80 kilometres an hour. Really fast. I just realized cycling in that area is going to kill me. It was either ride on the sidewalk or find a different route. I actually just went on Google Maps and looked for the longest stretch of continuous road that didn't involve shimmying around." (**Steve, 25-44 years**)*

It is worth noting that one participant perceived that the city's transition to a more bicycle-friendly city created a source of tension with other road users. The established car-centric design of the city is familiar to residents and making changes to the built environment so that it is more bicycle-oriented could be a challenging adjustment.

"I guess it has been changing a lot just recently. The infrastructure has grown leaps and bounds, and that's been positive. My perception of it is that I think we're going through a little bit of growing pains right now. Because we were very car-centric, there was no bike infrastructure and then all of a sudden, I think it happened quite quickly, and it might be rubbing people the wrong way. They're not used to it; they feel like what they've been used to having as a right is now being taken away. And I think there's a little bit of friction there between, you know, cars and bikes because of that." ***(Tanner, 45-64 years)***

Some cyclists acknowledged that cycling facilities are more limited in the suburban parts of Hamilton or on the mountain relative to the lower city, but that there were some good infrastructure links in the city's downtown core, like the cycle tracks on Cannon (East-West) or Bay (North-South) Streets and the bicycle lanes on Charlton Avenue and Herkimer Street (both North-South). Three participants suggested that the presence of cycling infrastructure in the lower city had the positive outcome of serving to increase awareness of cyclists as road users, and that this was important for its legitimacy as a mode.

"I find it way easier, way more comfortable for my psychology to ride a bike down here than I do up on the mountain. I just feel like at least the people who drive or live down here tend to know that cyclists exist and tend to pay more attention." ***(Sally, 25-44 years)***

Our findings highlight that participants are aware of streets that do not accommodate cycling and perceive cycling to be excluded from many of the city's arterial roads. These are streets where policy and design favour the movement of cars. People who cycle are sensitive to car volume and speed, and without dedicated infrastructure, they report avoiding such roads where cars are prioritized. The lack of infrastructure for cycling on direct routes had impacts on mobility options. With dedicated infrastructure, cyclists have their own space on a direct route and can travel with fewer interactions with other road users. But when infrastructure ends or is lacking, cyclists either have to navigate interactions and potential conflict points with other road users or find an alternate route. The latter was often preferable, and participants reported that they travelled routes that were less direct. This emphasizes that it currently requires a lot of effort to navigate the city by bicycle. However, there is also a perception that new infrastructure has contributed to increased awareness of cyclists as road users in the city's downtown core. This is a promising sign that facility interventions can have positive outcomes.

2. Infrastructure influences mobility

Participants reported a preference for cycling infrastructure, and this was a primary determinant of their route choice. This means that it either supported or hindered their ability to travel by bicycle in Hamilton. Infrastructure along the route and, to a lesser extent, bike parking at the destination were perceived to be very important factors that influenced how participants navigated the city and, for some, where they travelled.

Cyclists reported including many on-street designated bicycle lanes and off-street multi-use paths as part of their frequent or preferred routes. The participants both stated and revealed a preference for dedicated infrastructure.

*"I prefer to ride in areas where there are protected bike lanes or just designated bike lanes. The fact that Bay [Street] has been sort of turned into a bike-friendly 'space', that is very appealing. Herkimer is basically bike-laned, with the way cars are parked along and the way they've designed the street. That's really helpful. I really like doing that. The rail trail, things like that. Those are all reasons I would choose to cycle somewhere. Because it's actually convenient for some things and it just makes it a more enjoyable ride. You don't have to sort of battle cars." (**Sally, 25-44 years**)*

"I would choose a street that had a bike lane as opposed to one that didn't have a bike lane pretty much every time. I liken a bike lane to being like... In your cutlery drawer, you have that thing where your forks go in here and your big spoons go here. Little spoons here, knives here. To me that's what a bike lane does. You know, the cars go here, then the fast cars go here, the slower cars go here, and the buses go here, and the bikes go here, and everyone's happy. The people walking on the sidewalk there, everyone's happy. Everyone has a space. I just like it." ***(Annie, 25-44 years)***

However, a perceived deficit of infrastructure or lack of cycling routes impacted where some participants cycled. For example, Doug (25-44 years) reported that he would only cycle to the downtown core using the Waterfront Trail, which enabled him to avoid busier but more direct roads; when the Waterfront Trail was under construction, he did not cycle and used public transit instead to get downtown. Three other participants reported that there were destinations or areas of the city that they did not travel to because there were either no cycling routes or the current route options were not ideal. Many participants described that they would also be willing to find a route to get to destinations that they needed to visit. This highlights that these decisions were dependent on context: personal levels of tolerance, willingness, and importance of the destination. The decision to cycle to specific destinations also depended on whether the participant was cycling with a less experienced rider, like a child, or another adult's level of comfort. Three participants who cycled with their children stated that there were areas where they did not bring their children, suggesting that families with children are more limited in where they can cycle. However, one of these participants said that she would find a way to travel to those destinations on her own. Although some participants reported being willing to cycle to a destination even if they didn't like the route or wouldn't choose it if they didn't have to, the interviews revealed that specific areas are not accessible for some people who cycle and that lack of infrastructure plays a role.

Two participants describe that they spend less or no time at destinations that are perceived to be inaccessible by bike and spend more time instead in areas of the city that are accessible. Martha (25-44 years) illustrates how a parent who cycles with her children weighs her options about which destinations to take them to, and Gary (18-24 years) evaluates the different routes he could take to a local business district on the mountain.

> *"… anything we do, we're trying to do [it at] a destination that is bikeable. We love going to the Royal Botanical Gardens, but it's not super accessible by bike in the state of life that we are in right now. In a couple of years, it [RBG] will be, but right now it's not. To get to the Royal Botanical Gardens, the speed limit on the road is 70. Which is... horrific even though there are bike lanes with the white piece of paint, that keep you safe. But it's not an accessible destination for us really. Whereas the rail trail and the Dundas Valley Conservation Area are super accessible by bike. In the summer we spend a lot more time going that way."* ***(Martha, 25-44 years)***

*"Every time I go up to Concession [Street], I'm reminded of how the streets, you know besides the fact that there's a lot of cars, it's kind of cozy. There are lots of nice places to go. I never bike there. How am I supposed to get there? My options to get up the mountain are: take my chance on a paved shoulder on the Jolly Cut, which is incredibly steep; walk my bike up the Chedoke stairs and bike all the way over the mountain; or take the rail trail all the way to upper Stoney Creek and bike back. Concession is a place I would like to go to more, but it's really not accessible by bike." (**Gary, 18-24 years**)*

Two other participants identified similar challenges to cycling between the lower city and the mountain area, with few ideal options. But Adam (45-64 years) reported regularly using the Chedoke Stairs to push his bike up the Escarpment on his route from the lower city to his workplace on the mountain. This suggests that there is infrastructure available to help to overcome the topographical barrier.

Moreover, the functionality of existing infrastructure, meaning its design quality and connectivity, were important attributes that drew comments from cyclists. If cycling facilities were protected or perceived to be safe, cyclists would report using and liking them. Other existing infrastructure was not perceived to be ideal by many cyclists for a variety of reasons. This may include: the infrastructure was narrow, unprotected or not sufficiently protected, bi-directional on a one-way street, ended abruptly, or located on a heavily travelled route with lots of cars or trucks. Some participants reported that they avoid cycling facilities if the functionality was perceived to be poor. But at other times, as described below, many cyclists described using infrastructure despite the fact that it does not fully meet their needs or preferences.

"I guess it depends on how you define a bike lane and infrastructure. So, for me, a bit of paint is not very useful. On Dundurn [Street], there's a few stretches where there's a painted bike lane but it's right in the door zone[8]. Sometimes I end up just cycling in the car lane despite the occasional honk. There are so many lanes in Hamilton that really don't feel usable to me because of that. And the fact that they're kind of disconnected and they just stop randomly and then you have to figure out which way and so on."

(Adam, 45-64 years)

"I love the Bay Street bike lane and I do ride it when it's not busy, or when it is extremely busy and everybody's really slow. But otherwise I try to stay on the sidewalk if I can. Unless there's a barrier. I don't want to be that close to vehicles that can crush me. I like what they did on Herkimer. I wish they would use more vehicles as buffers because it doesn't cost anything. They're going to park there anyway. I think that would be a really easy win. I don't see how it can be that expensive to convert all bike lanes like that. Some people don't like them. I don't understand where they're coming from... but that doesn't matter to me. There's got to be some separation... I'm happy that there are bike lanes at the same time. Because it just brings an awareness that they're supposed to be there. They just aren't there as often as they could be, had it been more thoughtfully designed." ***(Kyle, 25-44 years)***

One participant suggested that the gaps in the cycling network or the busy areas that lack infrastructure were at such key locations that they could not be avoided. In these instances, infrastructure was used despite it not being perceived to be ideal or entirely functional. For example, the area described below is on a major arterial road that separates the west Hamilton from the downtown core and acts as a “gate” between these areas. This area was also mentioned by five other participants.

[8] This refers to situations where the bike lane is located to the left of a parked car, which can lead to a sudden door opening and the cyclist swerving into the traffic lane to avoid collision. This can inadvertently lead to collisions with cars in the traffic lane who do not expect a cyclist to swerve out of the bike lane.

"I think if you're a cyclist, it's almost impossible to avoid the ones [infrastructure or conflict areas] you don't like. I really don't enjoy going North on Dundurn. And I almost exclusively have to, to get home, because the bike lane ends. And it's like an insane two-lane thing where people are going to the grocery store and people are trying to get the advanced green. You have to make this giant leap across to the bike lane. Things like that I hate but there's really no avoiding it." ***(Sven, 25-44 years)***

The provision of bike parking at the destination was also a built environment factor that cyclists paid attention to in Hamilton (n = 6/14). While two participants indicated that they would not cycle to a restaurant or coffee shop that lacked bike parking, four others disagreed but still perceived it to be important.

"I don't really take this into account when selecting a bike route... Well I guess I sort of do. There's just… bike parking. Sometimes there's not a bike rack near where I'm going and I'm walking a block away to find a bike rack. I'm baffled as to why there's a block with no bike rack on it. I wouldn't say that would stop me from biking there because I wouldn't realize until I got somewhere. Yeah, that makes a difference."

(Nicole, 25-44 years)

It is worth noting that one participant said that he made a point of using the city's bicycle lanes or going out of his way to use them to show that they are being used. This suggests that cycling facilities can be contentious in a transitional city and that using infrastructure can be perceived to necessary to justify the investment in building them.

"I like to ride the bike lanes as much as possible. I don't know if it adds that much safety for me, but it does a little bit. They built them, so I want to use them. Because I kind of hate that attitude or that perception that, 'Oh, we built these things and no one's using them'. I try to make a point of using them

regularly. I'll go out of my way a little bit to use them… Every time they would add something, I would incorporate that into my route… I want to be one of them. I don't want to be the person where they said we built it and you're not using it. I make a point of being visible, like I ride every day, pretty much every day, all year round… I'm always out there and I want to be one of those people that they say, 'Yeah, that's why we built it.' There are people using it." ***(Tanner, 45-64 years)***

Participants reported that they seek out and incorporate streets with infrastructure as part of their routes. The provision, quality, and connectivity of infrastructure were important for cyclists' mobility: where cycling infrastructure was available and perceived to be well-designed, cyclists would use it; but if infrastructure was lacking or not perceived to be sufficiently protected, then cyclists may avoid it or have to use it despite it being less than ideal. Many participants also revealed that specific destinations or areas of the city are not accessible for people who cycle, especially those who cycle with their children, and suggested that further efforts to make cycling safer for less experienced riders, like women and children, are needed.

3. Seek out routes that invite cycling

The prioritization of motor vehicles on arterial roads and direct routes led participants to seek out streets and routes that explicitly accommodate or invite cycling. As identified in the themes above, people who cycle often oriented their riding around or in response to people who drive and the availability of infrastructure. But participants also reported selecting routes that have characteristics that are perceived to be friendly or attractive to cycling. Routes that are perceived to be safe, comfortable, or preferable to cycle allow cyclists to minimize interactions with motorists. These types of routes typically include separated or protected infrastructure, quiet residential streets with low volumes of cars, or spaces where cars cannot go. The latter might include parks, schools, alleys, church parking lots, streets or areas closed to cars, or off-street multi-use paths. A desire to use infrastructure and minimize interactions with cars appeared to be due in part to, or to avoid, close calls, unpleasant experiences, or collisions with motorists. But travelling on streets that invite cycling also increased the enjoyment or safety of the travel experience.

The participant below describes how he travelled through a park on his daily route, and when this was not available, would take quiet streets away from his neighbourhood's commercial area where there was more traffic.

"Prior to them putting the trails through Churchill Park, which was closed for a while, I would take that route a lot. But now my preference is to take a right-hand turn for bikes onto Cline. I'll take Cline and go through the back streets. But the fastest route would be for me to take King to Sterling."

(Doug, 45-64 years)

Most participants stated that their preferred routes included separated or protected infrastructure and that they tried to incorporate existing cycling facilities that were perceived to be functional as much as possible when they ride. Protected infrastructure, in particular, felt safer and participants described their routes as a mix of streets with and without cycling infrastructure and off-street paths. Participants strongly liked the city's off-street paths like the Waterfront Trail, the Escarpment Trail, and the Hamilton-Brantford Rail Trail.

Participants reported that they rely on and incorporate residential streets as part of their routes. This is likely due to the limited cycling facilities available in the city. Although these spaces typically lack infrastructure, participants preferred to cycle there. People who cycle often used "quiet" to describe streets that had fewer cars and that had a different atmosphere compared to busier roads with more or faster traffic.

"I try to avoid anything which is just a strip of paint. Coming from maybe McMaster University to the rail trail or Chedoke, and then from Chedoke staircase to my workplace, I tend to squiggle around through kinda quiet streets where it's a pleasanter cycle. People are driving slower. There's less drivers. It's quieter. It's just more chilled out." ***(Adam, 45-64 years)***

"I'm thinking [about the] built environment where I am right now and the routes I take from [my home or neighbourhood]. The bike lane comes up our street and then ends. It kicks you out into a traffic lane, two lanes merging into one, and parking, and a bus. So, I do not continue up that way. I often cut through the park and then take quieter streets that don't have traffic [to my workplace]."

(Martha, 25-44 years)

In addition to selected routes or streets would help them to avoid cars, some participants reported seeking out nature or aesthetically pleasing streets when they ride. For instance, many participants reported that they use Waterfront Trail to get to or from downtown in order to avoid other direct routes that would take them on busier streets. Some participants, like Annie (25-44 years) even reported lengthening her daily commute route so that she could cycle the Waterfront Trail which was more enjoyable than the direct route. This appeared to be one positive impact of adjusting their routes to minimize interactions with cars – people who cycle do have the ability to take a longer, preferred route with a more enjoyable environment. However, other participants did not specifically report going out of their way for routes that had more aesthetic qualities.

> *"Especially on Bayfront [the Waterfront Trail] cause there's so much nature. The birds and the ducks out there... Like I said, you get to see nature changing and I probably wouldn't get to see as much on foot and certainly not using a car or bus."* ***(Kyle, 25-44 years)***

> *"I consider routes that are a little bit slower paced. Getting away from all the cars, it's nice, and trucks... The streets [that are quiet] definitely have more trees… It just seems like it's a more pleasant ride. There are more birds out, there's more people walking… Just changes the attitude of the ride."*
>
> ***(Stewart, 45-64 years)***

Although participants primarily discussed their experiences when cycling alone, several reported cycling with children or adults who are less experienced riders. There were generally no major differences between the routes travelled with children or less experienced riders and the routes travelled alone since participants reported that their routes typically included infrastructure and quiet streets. However, when travelling alone, a few of these participants shared that they were willing to take more risks and described being more comfortable travelling on busier roads that did not have dedicated infrastructure if they needed to. For instance, Daniel (25-44 years) perceived some intersections along Dundurn Street to be "*poorly designed*" which increased his sense of vulnerability when cycling with his child. Two parents described a sense of responsibility and accountability for "*managing risks*" or exposing their children to appropriate traffic environments. Martha (25-44 years), who only reported cycling with her children in a highly bikeable area of the city, reported a positive and enjoyable experience but acknowledged that she couldn't speak to what it would be like to cycle in busier areas: "*I haven't been in that experience. Where I felt like I'm trying to stake my claim or, or what not. I haven't done that kind of cycling with the kids.*" Children's inability to react to traffic or changes in infrastructure was also cited as a reason to be cautious when cycling with them. Two participants who cycled with significant others who are sensitive to traffic also expressed a desire to have safer infrastructure so that their partners would feel comfortable cycling with them.

> *"I have dreams of going places with my kids. I'm only going to take them [my children] to places that involve the rail trail or places that don't involve much interaction with cars. Even just getting to the rail trail, I've been scared having the kids on my bike. Even on slow streets there's just some people that... Just inattentive or don't think that we should be on the road." (**Kyle, 25-44 years**)*

> *"It makes me nervous. I would say [the experience is] good, but it's stressful to figure out what is safe for a kid. We let my daughter, who is four, bike on our street. It's a dead-end residential street. When we're right there. But we're often on Dundurn which has a bike lane, but it's not separated in any way. She can't bike there. Sometimes I bike in the bike lane and she'll be on the sidewalk." (**Nicole, 25-44 years**)*

> *"[Biking with my son], it's me managing the risks on the road while we're cycling. That can get tricky in some of the parts where it goes from a dedicated bike lane and then all of a sudden, you're in traffic. The transition there relies on a consistency of cycling. Kids wobble and it's just very difficult to arrange that." (**Steve, 25-44 years**)*

Our findings illustrate how certain streets in Hamilton have been designed to accommodate cycling or have inherent qualities that attract people who cycle. The environments where participants report cycling are starkly different from those they report avoiding, suggesting that there are fundamental elements that motivate people to choose certain streets or routes over others, like fewer cars and a more relaxing pace of travel. The interviews also revealed that some participants do not perceive the built environment to be designed for less experienced riders who are unable or may have difficulty negotiating different traffic situations. As a result, parents are selective about the types of routes that are safe for children to cycle since they must assume the role of negotiating their children's mobility. This suggests that the built environment in Hamilton, as it currently is, is perceived to be geared towards supporting cyclists who have the confidence or skill to navigate a city that is not oriented to cycling. As such, cycling may not be a viable mode for all ages or abilities, or for less experienced or confident cyclists.

Discussion

Our study demonstrates that the built environment in Hamilton strongly influences route choice for people who regularly cycle, and that various attributes are considered when deciding where to cycle. During this stage of the city's transition, participants highly value and use cycling facilities and are primarily motivated to travel routes with fewer cars. They seek out routes that have dedicated infrastructure, are safer for less experienced riders when travelling with them, and that have pleasant environments. People who cycle are very sensitive to car volume. Participants are also conscious of how streets in Hamilton are used by other road users and whether they have been adapted to accommodate cycling. The interviews provide additional support to the findings from the study's quantitative phase – that people who cycle in Hamilton usually select routes that allow them to avoid traffic while using residential or "quiet" streets. The interviews increased our understanding of the attributes that cyclists consider when they select routes and why they might choose such routes. The themes from the interviews broadly align with what is reported in the literature. Specifically, cyclists' route preferences: the provision of dedicated and protected infrastructure (*inter alia*, see Aldred et al. 2017; Broach, Dill, and Gliebe 2012; Clark et al. 2019; Chen, Shen, and Childress 2018; Dill 2009; Winters and Teschke 2010), quiet or residential streets with lower volumes of traffic (Chen, Shen, and Childress 2018; Winters and Teschke 2010), and pleasant or natural environments (Chen, Shen, and Childress 2018; Marquart et al. 2020; Winters et al. 2011). Residential streets were reported to be the preferred road environment for participants who cycle with children, another finding mirrored in the literature (Aldred 2015). Our findings are also consistent with van Miltenburg's (2016) research on cycling deterrents in Hamilton. Among others, lack of infrastructure, lack of connectivity within the cycling network, and major arterial roads that prioritize cars were cited as challenges for people who cycle (van Miltenburg 2016). Our study reveals that these challenges remain in the built environment after 4 years, but we now have a deeper understanding of how these factors influence where cyclists travel and the route adaptations they make in a city with a cycling network under development.

Our qualitative approach was particularly useful for exploring and describing cyclists' perceptions of the built environment in a transitional city. In particular, the participants gave detailed examples of the range of factors that they consider when selecting a route and determining where they travel by bicycle. For instance, the provision of infrastructure and the traffic volume along a route. This confirms the value of qualitative methods in illuminating these considerations (Mars, Arroyo, and Ruiz 2016); travel surveys and even stated preference surveys could likely not have captured this amount of detail or reported on the diversity of experiences described by participants. While our findings with respect to the environments and routes that cyclists prefer align with the literature, we learned much more about the experience of cycling in a transitional city. This information may be particularly important for transport planners or public health professionals who wish to support more cycling in their communities.

Similar to Mayers and Glover's (2019) study of cyclists in Waterloo, Canada, another city with low cycling levels, participants had both positive and negative experiences with the city's infrastructure. Participants reported using dedicated cycling facilities, but some were avoided by participants if they were perceived to be poorly designed, unsafe, or disconnected from the cycling network. However, infrastructure that was not perceived to be ideal was still used. This reveals that when infrastructure is limited, or a cycling network is under development, people who cycle will use what they can even if it does not match their needs. In the case of Hamilton, this finding also suggests that cyclists' preferences have not been sufficiently considered in the design of the current facilities. Marquart et al.'s (2020) interviews with cyclists and experts in politics and planning demonstrate that qualitative approaches are useful for exploring perceptions that are otherwise less known or perceived differently by planners. The authors highlight that planners "are determining the characteristics of routes in urban areas" (Marquart et al. 2020), which supports the recommendation that people who cycle need to share their perceptions and preferences to ensure that transport planning efforts align with their needs.

Furthermore, the perceived inability to access some local business or tourist areas by bicycle can limit the viability of this mode for those who currently cycle and for the population more broadly. With one participant pointing out that gaps in infrastructure can be at critical locations, this suggests that someone who currently chooses to cycle in Hamilton has to be willing, or can expect, to navigate sub-optimal routes. Given its relative importance and frequency of use, cycling facilities in Hamilton appear to warrant improvements to increase their quality and connectivity. These investments should better reflect the preferences of people who cycle, as well as support them in feeling safe as they travel and in reaching key destinations like other road users.

Our findings also suggest that despite having built nearly half of the planned cycling network, the built environment more broadly in Hamilton is still not oriented to cycling. While cycling levels have grown over the past five years, participants' perceptions and experiences of the built environment reveal that other aspects of the transport system have not been addressed. For instance, the volume of motor vehicles strongly influences where cyclists travel likely because they are a minority of road users. Furthermore, the interviews also highlighted that cycling is not yet accommodated in the transport system to the same extent as other modes. While cyclists are technically allowed to travel on any road, lack of infrastructure, which is a factor that cyclists consider when they select routes, can be perceived as a visual indication to avoid a particular street if other attributes also act as strong deterrents. Most of the city's arterial roads do not have infrastructure and the number of streets adapted specifically for cyclists' needs is more limited. On busier streets that lack infrastructure, factors such as higher speed limits or the number of traffic lanes support other modes to a greater degree and discourage cycling. As such, cyclists have more limited route options. This was reinforced by our finding that many cyclists try different routes to find one that is preferred, and that the most direct route may not be perceived to be safe for cycling and will be avoided. The City, through policy and design, is able to direct cyclists to streets that accommodate their needs and away from those that do not. Unequal access to road space is the consequence of decades of marginalizing cycling in transport planning in favour of focusing on motorized traffic, as well as a sign of "power relations in urban traffic spaces" (Koglin and Rye 2014). If people who cycle are acutely aware of where they can and cannot travel, and how they must orient their travel around motorized traffic, it suggests that cycling is still given low priority in transport planning in Hamilton which can help to explain why the built environment is not yet bicycle-oriented. Infrastructure matters to people who cycle, but their mobility is also hindered by the broader transport system and culture, as Aldred and Jungnickel (2014) have shown. This raises an important question: can the existing policies that guide the rest of the transport system be shifted enough in the final half of the City's Cycling Master Plan implementation to become a truly bicycle-friendly city? If cycling is not more prioritized during this transitional phase, and if factors beyond infrastructure that influence cycling behaviour are not addressed, then other intervention efforts to make cycling a larger part of the mode share may fail.

In Lisbon, Portugal, another city with low cycling levels, Félix et al. found that both cyclists and non-cyclists perceived a lack of safe routes as a barrier to cycling (Félix, Moura, and Clifton 2019). These insights underscore that in a growing cycling city there should be alignment between building infrastructure that obviously connects to key destinations, and other road conditions that are suitable for cycling. Furthermore, participants in our study displayed a strong awareness of how different users interact in road space which ultimately influenced where and how some travelled. The difference in size and speed between people who cycle and people who drive may necessitate this awareness. The mobility experience of cyclists is then co-produced with and influenced by other road users, but they do not hold equal status on the road as described above. Although researchers have found that cyclists report being motivated to cycle as a result of its convenience, efficiency, and flexibility (Fernández-Heredia, Monzón, and Jara-Díaz 2014), these benefits of cycling can be hindered in a city that is not yet fully bicycle-oriented. Their direct contact with the built environment affords them a greater degree of sensitivity to certain attributes that impact where they travel which makes them unique to other road users. A parent who drives their child to daycare may using routing services, like Google Maps, to find a route that takes the least amount of time, but a parent who cycles with their child to daycare in a transitional city has a larger number of considerations beyond timing that may reduce the convenience and efficacy of travel by bicycle.

Policy Recommendations

There are many cities in Canada, and elsewhere in North America, that have low levels of cycling but that have implemented interventions to encourage more cycling. Hamilton is not alone or unique in its challenge to become more bicycle-friendly. What we have learned about Hamilton through this study can be informative for other cities in a similar stage of transition. Based on our findings, we identify several policy recommendations, informed by the perceptions and experiences of regular cyclists, to further improve the experience of cycling in transitional cities like Hamilton. When policies that support cycling and investment in infrastructure or programs are lower or just being started, there tends to be a homogeneous and less diverse segment of the population that chooses to cycle (Garrard, Rose, and Lo 2008). As policies take hold, there is plausibly the greatest potential for change before practices become established. It is at this stage that there is a window of opportunity to make cycling appealing to a more diverse population, like women or older adults who generally cycle less than younger males (Garrard, Rose, and Lo 2008; Ramage-Morin 2017), and for people of all ages and abilities. Conversely, we can shape how the built environment can be adapted to new practices and cultures as they are emerging.

The provision of infrastructure is important as a city transitions to be more bicycle-friendly, but other policies that accommodate cycling more explicitly and put it on par with other modes also matter. Our findings suggest a broader range of factors at the street level, such as the speed limit or number of lanes, need to be adapted alongside infrastructure development to create more spaces that include cycling. Regular cyclists are not alone in wanting to minimize interactions with traffic; streets that are busy with traffic or that have high speed limits are a stronger deterrent to cycling for potential cyclists than those who cycle regularly (Winters et al. 2011). If at the mid-way point, as our findings reveal, people who currently cycle still experience challenges with negotiating streets that have been designed for people who drive, and the quality of cycling facilities does not match their preferences, then this may create barriers for the uptake of cycling in the broader population. Potential cyclists or cyclists with less experience who prefer protected infrastructure may ultimately be discouraged from travelling by bicycle. This may keep cycling as a niche mode only accessible to more confident riders. One positive finding of our study is that the presence of infrastructure in the downtown core was perceived to have increased awareness of cyclists as road users. The presence of infrastructure has also been found to be associated with perceptions of cycling safety (Branion-Calles et al. 2019). This suggests that continuing efforts to increase access to road space is an important policy priority alongside other changes to road conditions and transport culture. Furthermore, increasing connectivity in the cycling network and accessibility to a range of destinations is another policy recommendation for the city. Qualitative methods, like semi-structured interviews or focus groups can help to identify the locations that people want to reach by bicycle and explore current challenges that may currently hinder cycling. The purpose of planning for the automobile was to afford people the ability to reach a larger number of destinations (Brown, Morris, and AICP 2009). But the utility of other modes, like cycling, were decreased and marginalized in the process (Koglin and Rye 2014). With respect to Hamilton, our findings reveal a few key business and tourist areas that are good candidates for additional infrastructure connectivity.

Our findings also highlight that transitional cities should pay attention to *who* is cycling at this critical stage of development and what preferences cyclists have to support their mobility. In the case of Hamilton, several participants reported that their partners who are less experienced cyclists or their children could not safely cycle beyond residential areas without a network of protected infrastructure. As a matter of policy, cities that wish to become more bicycle-friendly ought to be designed for people of all ages and abilities. This can ensure that sustainable and healthy transport habits are adopted from a young age and incorporated daily throughout the life course. The present research reveals a strong preference for dedicated infrastructure and that facilities may be avoided by people who cycle if they are perceived to not be useable. Therefore, for a city to effectively grow its cycling levels, the design of the cycling network should ultimately reflect what will encourage people to use it. It is suggested that the City of Hamilton revise and condense the diversity of facility types that are built (see City of Hamilton 2018) to align with cyclists' preferences, as well as explicitly adopt an all ages and abilities framework to guide the design and implementation of the cycling network. Other research has shown that most types of cyclists prefer dedicated infrastructure, especially new or potential riders (Clark et al. 2019; Winters and Teschke 2010) and parents who cycle with their children (Aldred 2015). This is further incentive for the city to commit to only building facilities that are perceived favourably by cyclists because it leads to opportunity that other people who may currently be deterred from cycling to adopt this mode. If the City of Hamilton's vision is to be *the best place to raise a child and age successfully* then a healthy transport mode like cycling should be appealing, made available to everyone, and given more priority in transport planning to reap the health and environmental benefits.

Study Limitations

Though the findings presented are not representative due to the sampling strategy and number of participants, this research aligns with other studies which suggests that they are generalizable to other North American cities to some extent. Furthermore, the participants in this study reported living and working in west or central Hamilton where most of the city's cycling infrastructure is built. Their perceptions and experiences may be dissimilar to people who cycle in other areas of the city where there are fewer facilities and even less cycling than the overall mode share of Hamilton. The study included only people who regularly cycle, so it is unclear if the findings are similar or different for occasional or new cyclists. Recent research in a city with an emerging cycling culture does suggest that there is a lot in common between different groups of cyclists in terms infrastructure preferences (Clark et al. 2019), which is encouraging for the generalizability of our results. However, occasional or new cyclists may be more sensitive to certain attributes, like traffic, as a result of less experience. Nevertheless, within growing cycling cities, qualitative research can be a starting point for unearthing current cycling behaviours and practices, and for identifying points of intervention in the built environment to make cycling more mainstream (Aldred 2019). In order to increase uptake of cycling beyond those who are already committed, cities looking to grow their cycling levels should engage more with people who are interested in cycling. Interviews with people who are thinking about taking up cycling is an area of research that needs more attention to understand their perceptions and potential motivators and barriers. The policy recommendations from our findings are based on the perceptions and experiences of regular cyclists, so there is more evidence needed to determine what else should change within transitional cities so that people of all ages and abilities feel comfortable cycling. Finally, it remains unknown to what extent perceptions of cycling as a transport mode might influence adoption. In cities that are traditionally car-centric, it should be explored whether attitudes towards cycling or representations of cyclists play a role in mode choice.

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Chapter 5: Conclusion

Cycling in a Mid-Sized Transitional City

This mixed methods explanatory sequential study explored cycling for transport in a mid-sized Canadian city where cycling levels are growing, and the cycling facilities network is still under development. This research extends our understanding of the built environment correlates of cycling trips in Hamilton, Ontario and offers key insights about the route choice of people who cycle in this city. This research also joins the growing list of recent studies that explore cycling in cities without an established culture of cycling (*inter alia*, see Clark et al. 2019; Félix et al. 2020; Mayers & Glover 2019) from a Canadian perspective. By drawing on the complementary strengths of quantitative and qualitative methods, this project has contributed a more holistic understanding of the influence of the built environment on cycling in Hamilton and has produced evidence that will be useful to transport planners to inform infrastructure changes.

In the quantitative phase, the model uncovered a positive correlation between the number of cycling trips and different land uses at the destination (i.e., institution, industry, office, residential locations) which reflects an abundance of amenities. Geographical classification of the zones was found to have a negative correlation with the number of bicycle trips. Jobs at the zone of destination were also a positive attractor for cycling trips. The use of a novel cycling routing algorithm, *CycleStreets*, to infer different routes between traffic zones also revealed that *quietest* routes that minimize interactions with road users and distance best explain travel by bicycle in Hamilton. This finding suggests that people who travel by bicycle select routes that are less busy with car traffic by maximizing the use of residential streets.

Using environmental audits, qualitative evidence was collected and analyzed to build upon and interpret the findings described above. Inferred routes by *CycleStreets* possessed a range of built environment attributes that can help to explain cyclist travel, including the presence of cycling infrastructure and residential streets. Although only a limited number of inferred routes were audited using the *SPACES Instrument* (Pikora et al. 2002), the algorithm appears to make sensible recommendations for routes that a knowledgeable cyclist could travel. The audits revealed that most routes have a mixture of objectively measured and perceived factors, according to semi-structured interviews with people who cycle, that may support and hinder cycling for transport. This suggests that additional changes to the built environment may be warranted to remove factors that discourage cycling in order to facilitate the widespread adoption of this mode. Participants in this study described their perceptions of the inferred routes which was informative about the range of factors that people who cycle consider when they evaluate routes, and offered valuable feedback on locations that are need of improvement.

The semi-structured interviews explored how the built environment in Hamilton is viewed more broadly, and the characteristics that people who cycle consider when they select routes to travel. This also helped to support the finding that *quietest* distance routes best explain cyclist travel. Despite completing 46% of the planned cycling facilities network and implementing a range of pro-cycling programs and events, our findings indicate that the built environment in Hamilton is not yet oriented to cycling. Participants' stories reveal that cycling is not yet explicitly accommodated on every street in Hamilton, as a result of policy or design, which can limit the routes that are perceived to be available to them. Many arterial roads in Hamilton are perceived to prioritize the movement of cars and attributes of these roads, including car volume and speed, deter people who cycle from taking them. The provision of infrastructure can be perceived as access to road space, which in turn is suggested to increase awareness of cyclists as road users in Hamilton. Therefore, the availability, connectivity, and quality of the infrastructure strongly influences where participants travel by bicycle both in terms of routes and destinations. People who cycle report that they seek out routes that invite cycling. These routes typically have infrastructure, enable them to minimize interactions with cars, have an enjoyable environment, and are safer for less experienced riders. These findings reveal that people do indeed cycle on routes that are perceived to be quiet, and that micro-level attributes beyond the origin and destination of a trip are important.

This study makes several contributions to cycling and transport research. First, the use of *CycleStreets* to infer different types of routes has been found to be practical because aggregate travel surveys, while useful for describing broad travel patterns within a geographic area, are not informative about route choice. It enabled the experimentation with different types of routes that knowledgeable cyclists may travel and to explore which route best explains the pattern of travel observed. Use of a cycling routing algorithm helps to overcome the dearth of information on actual routes and can account for variability in route characteristics depending on the availability of data. A limitation, on the other hand, is the inability to capture the variety of routes that cyclists actually take.

GPS data, when available, is more suited to capturing variations, but is typically available only for small samples or under limited conditions. By strengthening publicly available data through *Open Street Map*, the approach outlined in Chapter 2 can be used by transport planners to better understand travel patterns in developing cycling cities using large, representative travel surveys. This approach is also less demanding and expensive than collecting route data or creating their own network dataset.

Second, our qualitative approach was particularly useful for exploring and describing cyclists' perceptions of the built environment in a developing cycling city and the experience of navigating a city by bicycle under these conditions. To ensure that investments in cycling infrastructure will ultimately increase the number of people who choose to cycle for transport, facilities ought to be perceived positively and useable by their intended users. Semi-structured interviews accompanied by a photo activity was a useful method for collecting rich descriptions of perceptions and experiences that could not have been derived from a travel survey or cycle routing algorithm. The adaptations and detours that people who cycle have learned over time as they navigate the city, as well as the conditions that they perceive to make cycling safe or challenging, were described in detail. This yields valuable information about cycling behaviour for transport planners that can be used to improve how a city is experienced and travelled by bicycle. Likewise, Marquart et al.'s (2020) interviews with cyclists and experts in politics and planning demonstrate that qualitative approaches are useful for exploring perceptions that are otherwise less known or perceived differently by planners. The authors highlight that planners "are determining the characteristics of routes in urban areas" (Marquart et al.

2020), which supports the recommendation that people who cycle need to share their perceptions and preferences to ensure that transport planning efforts align with their needs.

This study also provides direction for new transport priorities and policies in Hamilton order to more explicit accommodate cycling in the built environment and put it on par with other modes. The findings reveal that the infrastructure preferences of people who cycle, and their perceptions of the city's transport system gained by travelling by bicycle, should be more regularly explored and used to inform transport planning in Hamilton. These early adopters who choose to cycle when it is not yet mainstream can provide important perspectives and recommendations for enhancing street design to improve their experience. The provision of protected infrastructure is extremely important as a city transitions to be more bicycle-friendly. Our findings suggest that decision-makers with the City of Hamilton need to pay attention to a broader range of attributes at the street level, such as the speed limit or number of traffic lanes, which need to be adapted alongside infrastructure development to create more spaces that include cycling. If cycling is not more prioritized during this transitional phase, and if factors beyond infrastructure that influence cycling behaviour are not addressed in a timely manner, then other intervention efforts to make cycling a larger part of the mode share may fail. For instance, it was found that many of the challenges for the participants in van Miltenburg's research from 2016 remain in 2020. This suggests that major transport policies identified as barriers, such as the car-centric orientation of the city, continue to marginalize cycling as a viable mode of transport. By failing to address these broader issues, people who cycle may remain a minority of road users despite the City's efforts to encourage more people to cycle.

During the transitional stage, there is also a window of opportunity to make cycling appealing to a more diverse population and for all ages and abilities. The City of Hamilton should pay attention to *who* is cycling at this critical stage of development and what preferences other underrepresented groups of people have in order to support their ability to travel by bicycle. It is recommended that the City of Hamilton explicitly adopt an all ages and abilities framework to guide the future planning and implementation of cycling infrastructure in order to ensure that it meets the needs of a wider segment of the population. Otherwise cycling practices may become established, whereby people who currently tolerate the cycling conditions and are able to navigate the city by bicycle are the only users to benefit from the investment in cycling infrastructure, while cycling remains unappealing and impractical for most people.

Reflection on Qualitative Research

This was a more ambitious but rewarding project than I initially anticipated. My aim was to produce evidence that could improve cycling in Hamilton and potentially lead to changes that might encourage more people to adopt this mode. This aim was motivated by my experience with cycling advocacy and a desire to use evidence and data to inform policy or infrastructure solutions. Planning and doing mixed methods research requires a range of skills and a certain degree of flexibility and comfort with switching between these approaches. I am thankful for the opportunity to have gained expertise in different methods throughout this project, which will help me as I pursue further graduate studies.

Qualitative research seeks to understand and describe a phenomenon but recognizes that what is produced is influenced by the subjectivity of the participants and the researcher (Bradshaw, Atkinson, and Doody 2017). As such, I acknowledge an epistemological position of subjectivism. When adopting this approach, it is recognized that "qualitative description research is socially constructed not only by the participants obviously but also by the researchers, and it is therefore recognized that an objective reality cannot be discovered or replicated by others" (Bradshaw, Atkinson, and Doody 2017, p. 2). The researcher is an active participant in the research process. For this reason, Hammersley and Atkinson (2007) have noted that the "researcher is the instrument" in qualitative data collection and analysis. As an active participant, the qualitative researcher creates space where others feel comfortable sharing their stories and experiences. As a cyclist conducting research on cycling in the community where I live and am intimately familiar with, I can be considered an "insider researcher" because I belong to the population that I am studying (Kanuha 2000, as cited in Dwyer and Buckle 2009). This leads to certain considerations that a researcher must be mindful of to ensure that interpretation remains true to the stories of the participants and not based on personal experiences.

First, I recognize that my connections to the cycling community in Hamilton have afforded me access to participants that might not have been possible for someone who does not share the same identity. Dwyer and Buckle note that one of the benefits of being a member of the population that you are studying is that "one’s membership automatically provides a level of trust and openness in your participants that would likely not have been present otherwise" (2009, p. 58). If or when asked by participants whether I cycle in Hamilton or why I am conducting this research, I would openly share that I am a cyclist and that my aim was to produce evidence that could improve the experience of cycling in Hamilton. The perceptions and experiences that participants shared with me were intimate and honest, including frustrations with infrastructure or their negative experiences with people who drive, which might not have been disclosed if there was no perceived or explicit commonality between us. As Jootun et al. state, "Outsiders unfamiliar with this can experience difficulties in understanding the true meaning" (2009, p. 44). It is important to acknowledge that while I shared moments of frustration with participants if I had experienced similar situations there were also many situations that I did not relate to or had not experienced by virtue of how and where I cycle in the city. Furthermore, though the interview questions were developed to build upon the quantitative analysis, the semi-structured nature of the interview also gave me the opportunity to ask questions that were informed by my own experiences as a cyclist in the city or by interesting comments made by participants to further understand the research phenomenon.

Qualitative researchers engage in reflexivity as "the continuous process of reflection on his or her values, preconceptions, behaviour or presence and those of the participants, which can affect the interpretation of responses" (Parahoo 2006, as cited in Jootun, McGhee, and Marland 2009, p. 42). Researchers are encouraged to "bracket" in order to increase rigour and avoid interpreting the research phenomenon from their own perspectives and experiences (Jootun, McGhee, and Marland 2009). Throughout the qualitative data collection phase, I approached each interview without any pre-conceived ideas of what a participant might share. I also kept a research diary - I would immediately jot down notes after finishing each interview, and I regularly reflected on staying true to the data by questioning my own assumptions. My regular meetings with Dr. Apatu were useful to discuss the emergence of codes and themes, to articulate patterns that I observed, and to ensure that I sufficiently bracketed my own experiences from the interpretation of the research phenomenon. In this process, several concepts that were personally interesting to me but not central to the research question were removed from the interpretation. For instance, several participants briefly described their experiences cycling in other Canadian or European cities and how this differed from cycling in Hamilton or shaped their behaviours as people who cycle. While this was interesting, it was not central to the research questions and was not explored in depth during the interviews. This process added rigour and credibility to the findings presented in Chapters 3 and 4. But, as Jootun et al. note, "Ultimately, the reflexive researcher acknowledges that any finding is the product of the researcher's interpretation" (2009, p. 45).

Implications for Public Health and Future Research

In recent years, public health officials in Ontario have turned their attention to the built environment and active transportation and have taken a more proactive approach to support the design of healthy communities. The field undoubtedly has a range of skills and research strengths that support the recommendation for public health officials to play a stronger role in active travel planning and contribute to efforts to increase cycling. First, as several studies have noted (see Aldred 2019 and Yang et al. 2010), there is a need for more evidence on the effects of interventions to encourage cycling. Sallis et al. emphasize that "the health and behavioural studies have strengths in physical activity measurement and behaviour change models" (2006, p. 314). This expertise could fill research gaps that remain with respect to the strengths of the evidence and the causality between interventions and changes in behaviour. Aldred also suggests that "we still need more natural experiments and other high quality studies, particularly covering subgroup differences and impacts on walking" (2019, p. 313). While there are differences in metrics, methods for monitoring and evaluation, and evidence standards between the fields of public health and transport planning (Aldred 2019), there are opportunities for public health to help with intervention studies by examining whether and how a range of interventions to make active travel safer in cities (for example, see Pucher & Buehler 2010) can change behaviour or improve health.

There are several topics that emerged during the interviews that were not explored, or not sufficiently, in this study that could be of interest to public health officials and qualitative researchers. The influence of the built environment on children's mobility was raised by several participants during the interviews. While some aspects of this phenomenon were explored further within the context of the identified research questions, namely with respect to where people who cycle travel and the routes that they prefer to take, there is a great deal more to learn. It would be of interest to the field of public health to examine levels of active travel to school or other child-friendly areas in Hamilton, and whether and how the built environment at the neighbourhood level surrounding these destinations might influence this behaviour. Public health officials and researchers could also support longitudinal studies within one or more schools to assess how active travel to school contributes to physical activity levels under different built environment designs. Children's perceptions of the built environment along routes that they walk or cycle to school could be informative. Furthermore, this research project investigated an important intrapersonal factor, perception of the built environment, but further exploration of cyclists' perceptions of safety, comfort, and stress with different types of infrastructure is suggested. To further lend support for drastic transport policy changes, additional evidence of the impact of cycling facilities on physical activity levels and potential associations with health outcomes, like cardiovascular health, diabetes, or obesity, could also encourage greater funding for cycling infrastructure in Hamilton. There is likely a sufficiently large group of people who regularly cycle who might be motivated to participate in such research.

There is also opportunity for natural experiments to evaluate the impact of built environment interventions. Over 2020, the City of Hamilton is building a key link in the cycling network, the Keddy Access Trail, which is a protected two-way cycle track on the Claremont Access to connect the lower city and suburban neighbourhoods on the Niagara Escarpment. There are also plans to pilot bicycle boulevards in select lower city neighbourhoods. Both of these interventions present opportunity to study the effect of these facilities on increasing cycling or physical activity levels. For instance, Dill et al. (2014) conducted a natural experiment after the installation of bicycle boulevards in Portland, USA but did not find conclusive evidence that it led to more physical activity or active travel. Pucher, Dill, and Handy (2010) note that before-and-after counts of cyclists in some Canadian cities, like Vancouver and Toronto, have shown increases after cycling facilities are built, but that other studies have shown that this increase is not due to new riders but to shifting existing riders from other routes. Therefore, additional research could be conducted to measure whether these new cycling facilities lead to the desired effect of increasing cycling among new riders, and whether perceptions of connectivity in infrastructure or the built environment change after these new interventions.

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Appendix A

Systematic Pedestrian and Cycling Environmental Scan (SPACES) – Hamilton, Ontario

Auditor Name ____________ Date ____________
Traffic Zone ____________ Street ____________
Segment ID ____________ Time ____________

Buildings

1a. Type of buildings/features *(check all applicable)*:

	Side 1	Side 2
Transport infrastructure		
Housing		
Office		
Convenience stores		
Other retail		
Industrial		
Educational		
Service		
Natural features		

1b. Predominant buildings/features *(check ONE per side only)*:

	Side 1	Side 2
Transport infrastructure		
Housing		
Office		
Convenience stores		
Other retail		
Industrial		
Educational		
Service		
Natural features		

1c. Are the predominant buildings/features the same for both side?

Yes	
No	

On-Road Features

2. Type of cycling facility *(only if a path is present)*:

	Side 1	Side 2
Go to section C ← No facilities		
Sharrows		
Signed route		
Bicycle lane - marked		
Buffered bicycle lane		
Protected bicycle lane		
Two-way cycle track		
Multi-use trail		
Bike path		

3. Facility location:

	Side 1	Side 2
On-road		
Off-road		

4. Slope:

	Side 1	Side 2
Flat or gentle		
Moderate slope		
Steep slope		

5. Facility condition & smoothness *(only assess road if bicycle facilities are present)*:

	Side 1	Side 2
Poor (a lot of bumps/holes)		
Moderate (some bumps/holes		
Good (few bumps/holes)		
Under repair		
Not applicable		

6. Condition of road:

	Side 1	Side 2
Poor (a lot of bumps/holes)		
Moderate (some bumps/holes		
Good (few bumps/holes)		
Under repair		
Not applicable		

7. Number of lanes on road *(in total)*:

	Side 1	Side 2
1 lane		
2 or 3 lanes		
4 or 5 lanes		
6 or more lanes		

8. Vehicle parking restriction signs present:

	Side 1	Side 2
Yes		
No		

9. Curb type:

	Side 1	Side 2
Curb cut present		
No curb cut		
No curb		

10. Traffic calming devices *(check all applicable)*:

	Side 1	Side 2
Roundabouts		
Speed humps		
Chicanes or narrowed lanes		
Two-way traffic		
Traffic islands		

11. Other routes available:

	Side 1	Side 2
Lane		
Path through park		
None		

12. Type of crossing:

	Side 1	Side 2
Traffic signal		
Bike signal		
Bike box		
Bridge/overpass		
Underpass		
None		

13. Streetlights present?

	Side 1	Side 2
Yes		
Go to Q15 ← No		

14. Does lighting cover path area?

	Side 1	Side 2
Yes		
No		

15. Are destinations present in segment?

	Side 1	Side 2
Yes		
Go to Q18 ← No		

Destination Features & Green Space

16. Number of car parking facilities at destinations *(approx.)*:

	0	1-20	21-50	51-70	71-100	101+
Shops						
School						
Other						

17. Bike parking facilities:

	Side 1	Side 2
Bike locker or enclosure		
On-street rack or stand		
None		

18. Street Maintenance: *(well maintained = looks clean & kept)*

	Side 1	Side 2
Over 75%		
Between 50-74%		
Less than 50%		
Currently undergoing work		
Not applicable		

19. Number of trees on street:

	Side 1	Side 2
1 or more per block		
Approx. 1 tree for every 2 blocks		
Approx. 1 tree for every 3 or more block		
No trees at all		

20. Average height of trees:

	Side 1	Side 2
Majority are small		
Majority are medium		
Majority are tall		
None		

21. Cleanliness of street: *(can you see any litter, graffiti, broken glass, discarded items)*

	Side 1	Side 2
Yes lots		
Yes some		
None or almost none		

Transit

22. Number of bus transit stops on street:

	Side 1	Side 2
1 or more per block		
Approx. 1 for every 2 blocks		
None		

Public Bicycle-Sharing System

23. Are there public bicycle-sharing hubs present?

	Side 1	Side 2
Yes		
No		
Not available in this area		

Attractiveness			Comfortability		
24. How attractive would you rate this segment for cycling?			**25. How physically difficult would you rate this segment for cycling?**		
	Side 1	Side 2		Side 1	Side 2
Very attractive			Easy		
Attractive			Moderately difficult		
Not attractive at all			Very difficult		

Land Use Mix			Neighbourhood Wayfinding		
26. Type of views (*check all applicable*):	Side 1	Side 2	**27. Ease of finding your way around the neighbourhood on a bike:**	Side 1	Side 2
Urban (tall buildings, etc.)			Very easy		
Residential (houses, gardens, etc.)			Fairly easy		
Commercial (shops, offices, schools)			Not easy at all		
Water (river, stream, lake)					
Parks, community gardens					
Other nature (trails, escarpment)					

Additional Notes *Please include any noteworthy observations in the section below.*

Appendix B

Adapted *SPACES Observation Manual*

SECTION. ON-ROAD FEATURES

Q2. Facility type – *if there is no path on either side, or if the path is under construction, tick first box and go to Q6.*

Sharrows – a road marking in the form of a bicycle symbol with two arrows above it. The marking is usually painted in white directly in a traffic lane to indicate that the lane should be shared between cyclists and car drivers, and that the middle of the lane is the safest space on the road for them to ride.

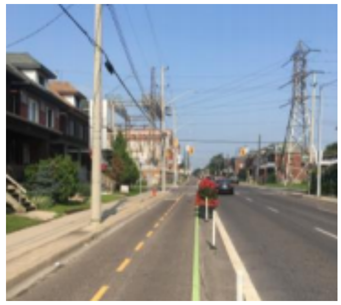
Signed route – a green sign with a white bicycle symbol is attached to posts along the route. On-street pavement markings or bicycle lanes are typically not present.

Bicycle lane - marked – an on-street bicycle lane that is only marked by a white painted line and sign.

Buffered bicycle lane – an on-street bicycle lane that is marked by a white painted line and visual barriers.

Protected bicycle lane – an on-street bicycle lane that is marked by a white painted line and physical barriers (parked cars, rubber curbing, knock-down sticks, etc.).

Two-way cycle track – an on-street, bi-directional bicycle lane that is marked by a white painted line with both visual and physical barriers.



Multi-use trail – a paved or packed loose-material trail that is physically separated from vehicular traffic by an open space or barrier.

Bike path – visually similar to a multi-use trail, but for the exclusive use of bicyclists.

Appendix C

McMaster University

PARTICIPANTS NEEDED FOR
RESEARCH ON BICYCLING IN HAMILTON

We are looking for volunteers to take part in a study of how the built environment influences bicycling behaviour and route choice.

We are looking for adults, aged 18 years or older, **who regularly bicycle for transport (at least once per week, NOT recreation)** in Hamilton, Ontario.

You would be asked to participate in 1 semi-structured interview, which will be about 90 minutes long. You will be asked to describe how you experience the local built environment as a bicyclist and which factors in the built environment influence the routes you choose to bike.

In appreciation for your time, you will receive a $20 gift card to Tim Hortons.

For more information about this study, or to volunteer for this study, please contact:

Elise Desjardins
Department of Health Research Methods, Evidence, & Impact

Email: desjae@mcmaster.ca

This study has been reviewed by, and received ethics clearance by the McMaster Research Ethics Board (MREB #2333).

Email Elise Desjardins
Email:
desjae@mcmaster.ca

Email Elise Desjardins
Email:
desjae@mcmaster.ca

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Email:
desjae@mcmaster.ca

Email Elise Desjardins
Email:
desjae@mcmaster.ca

Appendix D

DATE: ______________

LETTER OF INFORMATION / CONSENT

A Study of Built Environment Influences on Bicycling Behaviour and Route Choice in Hamilton, Ontario

Principal Investigator:
Dr. Antonio Paez, PhD
School of Geography & Earth Sciences
Faculty of Science
McMaster University
Hamilton, Ontario, Canada
(905) 525-9140 ext. 26099
E-mail: paezha@mcmaster.ca

Student Investigator:
Elise Desjardins, BSc.
Department of Health Research Methods
Evidence & Impact
Faculty of Health Sciences
McMaster University
Hamilton, Ontario, Canada
E-mail: desjae@mcmaster.ca

Purpose of the Study:

You are invited to take part in this study about how the built environment in Hamilton influences bicycling for transport.

I want to understand and describe how adults who regularly travel by bicycle experience the built environment in Hamilton, Ontario. I am hoping to learn about the attributes of the local built environment that promote or hinder your choice/experience/ability to bicycle for transport and how these factors influence which routes you choose to take. I also hope to find out what changes in the built environment could improve your experience.

I am doing this research for a thesis in the Master of Public Health program in the Faculty of Health Sciences at McMaster University.

Procedures involved in the Research:

You will be invited to participate in a one-to-one 90-minute semi-structured interview facilitated by the student investigator. The interview will take place at a convenient time and place of your choice. With your permission, I will take handwritten notes supplemented by audio recording. I will be asking you questions about your experience bicycling in Hamilton with a focus on the built environment. I will ask you to describe how this experience influences which routes you choose to take. Finally, I will also share some photos from bikeability audits that were conducted and ask you to comment on the cycling routes that were audited.

Potential Harms, Risks or Discomforts:
The risks involved in participating in this study are minimal. It is possible that you may feel uncomfortable, anxious, or uneasy about describing or sharing a previous unpleasant experience as a bicyclist. However, you do not need to answer questions that you do not want to answer or that make you feel uncomfortable. I also describe below the steps I am taking to protect your privacy to minimize any risks.

Potential Benefits:

Participants may not benefit from the research. However, for some, the research may provide an opportunity to share your experience as a bicyclist in Hamilton and to contribute to local research that may have the potential to lead to change in the built environment. I hope that what is learned as a result of this study will help us to fill a gap in our current understanding of how bicyclists experience the built environment in Hamilton. This study could help to support other initiatives currently underway in Hamilton that are aiming to make Hamilton safer and more enjoyable for bicycling.

Compensation:

In appreciation for your time, you will receive a $20 gift card to Tim Hortons.

Confidentiality:

You are participating in this study confidentially. I will not use your name or any information that would allow you to be identified. No one but me will know whether you were in the study unless you choose to tell them. Every effort will be made to protect (guarantee) your confidentiality and privacy. I will ask you to choose a pseudonym so that any direct quotations that are used in the dissemination of results are not identifiable to you. However, we are often identifiable through the stories we tell. Since the cycling community in Hamilton is small, others may be able to identify you on the basis of references you make. Please keep this in mind in deciding what to tell me during the interview.

Handwritten notes that include any information/data you provide will be kept in a locked desk/cabinet where only I will have access to it. Information and audio recordings are kept on a computer that will be protected by a password and only accessible to me. **All data will be kept for a minimum of two years and may be used for further analysis and publication.** After that, data (e.g., interview transcripts) will be available for public use (without any personal information of participants). Audio recordings will not be made available to the public, but will be kept in a secure location in the event of future publications. This is according to the new research data archiving policy of Canada's three federal research funding agencies, which suggests that "All research data must be preserved and made available for use by others within a reasonable period of time. SSHRC considers "a reasonable period" to be within two years of the completion of the research project for which the data was collected". More information can be found at "http://www.sshrc-crsh.gc.ca/about-au_sujet/policies-politiques/statements-enonces/edata-donnees_electroniques-eng.aspx".

Participation and Withdrawal:

Your participation in this study is voluntary. If you decide to be part of the study, you can stop the interview for whatever reason, even after signing the consent form or part-way through the study. You can withdraw up until **January 31, 2020**. At that point, data will be aggregated and it will not be possible to remove your responses from the analysis. If you decide to withdraw, there will be no consequences to you. In cases of withdrawal, any data you have provided will be destroyed unless you indicate otherwise. If you do not want to answer some of the questions you do not have to, but you can still be in the study.

Information about the Study Results:

I expect to have this study completed by approximately May 2020. A summary of the results will be published in academic journals and shared in a final report. If you would like to receive the summary personally, please let me know how you would like me to send it to you.

Questions about the Study: If you have questions or need more information about the study itself, please contact me at:

Elise Desjardins
Email: desjae@mcmaster.ca

This study has been reviewed by the McMaster University Research Ethics Board and received ethics clearance. If you have concerns or questions about your rights as a participant or about the way the study is conducted, please contact:

McMaster Research Ethics Secretariat
Telephone: (905) 525-9140 ext. 23142
C/o Research Office for Administrative Development and Support
E-mail: ethicsoffice@mcmaster.ca

CONSENT

- I have read the information presented in the information letter about a study being conducted by Elise Desjardins (BSc.) of McMaster University.
- I have had the opportunity to ask questions about my involvement in this study and to receive additional details I requested.
- I understand that if I agree to participate in this study, I may withdraw from the study at any time or up until **January 31, 2020**
- I have been given a copy of this form.
- I agree to participate in the study.

1. I agree that the interview can be audio recorded.
   [ ] Yes
   [ ] No

2. I would like to receive a summary of the study's results.
   [ ] Yes
   If yes, please send them to me at this email address: ______________________________
   [ ] No, I do not want to receive a summary of the study's results.

3. I have received my $20 gift certificate to Tim Hortons as compensation.
   [ ] Yes
   [ ] No

Signature: ____ Date: _________________________

Name of Participant (Printed) _____________________________________

Appendix E

Interview Guide

BUILT ENVIRONMENT INFLUENCES ON BICYCLING IN HAMILTON, ON

Elise Desjardins, BSc. (Master of Public Health student)
Department of Health Research Methods, Evidence, & Impact – McMaster University

Dr. Antonio Páez, PhD
School of Geography and Earth Sciences – McMaster University

Introduction

You are invited to take part in this study about how the built environment in Hamilton influences bicycling for transport. In particular, I want to understand how adults who regularly travel by bicycle experience the built environment in Hamilton. I am hoping to learn about the attributes of the built environment that promote or hinder your choice/experience/ability to bicycle for transport and how these factors influence which routes you choose to take. I also hope to find out what changes in the built environment could improve your experience when cycling in Hamilton.

For the purpose of this interview, I'll be defining the built environment as follows:

> The ***built environment*** includes the human-design and layout of the communities in which people live, work, and play. The ***built environment*** is made up of neighbourhoods, homes, workplaces, schools, shops and services, sidewalks and bike paths, streets and transit networks, green spaces, parks, and playgrounds, buildings and other infrastructure, and food systems.

Individual Factors

Cycling Background

1) How long have you been bicycling for transport in Hamilton?

2) What prompted you to start bicycling for transport in Hamilton?

3) Why do you bicycle for transport?

Cycling Experience

4) Where do you cycle in Hamilton?

5) Does the built environment in Hamilton influence the routes that you generally you take when cycling for transport? Please rate your level of agreement according to the Likert scale.

Strongly agree	Agree	More or less agree	Undecided	More or less disagree	Disagree	Strongly disagree
(1)	(2)	(3)	(4)	(5)	(6)	(7)

Please tell me more about why you think that.

6) Does the built environment in Hamilton influence where you travel to by bike? Please rate your level of agreement according to the Likert scale.

Strongly agree	Agree	More or less agree	Undecided	More or less disagree	Disagree	Strongly disagree
(1)	(2)	(3)	(4)	(5)	(6)	(7)

Please tell me more about why you think that.

Environmental Factors

7) What characteristics of the built environment in Hamilton [e.g., bicycle lanes, volume of traffic, speed of traffic, types of views, etc.] do you consider when you select cycle routes?

8) What, if any, are the built environment features (e.g., intersections, crossings, bridges, etc.) in Hamilton that you avoid as a bicyclist?

9) To observe and document the built environment, we conducted bikeability audits along select routes in Hamilton. We took photos of the built environment along each of the routes. Here is a package of photos along two different routes.

   What do you like about these routes? What do you dislike?
   Of the two, which route do you prefer?

10) Here is another package of photos along two different routes.

   What do you like about these routes? What do you dislike?
   Of the two, which route do you prefer?

11) Here is a final package of photos along two different routes.

    What do you like about these routes? What do you dislike?
    Of the two, which route do you prefer?

12) What changes would you prioritize in the built environment in Hamilton to improve your experience as a bicyclist?

End of Interview

13) We are collecting the demographics and bicycling habits of each participant in order to include these individual characteristics in future publications. This will also be useful to generalize any findings from the study.

    a. Age:
        i. 18-24 years
        ii. 25 to 44 years
        iii. 45 to 64 years
        iv. 65+ years
        v. Prefer not to say

    b. Sex:
        i. Male
        ii. Female
        iii. Other
        iv. Prefer not to say

    c. Frequency of bicycling:
        i. Once a week
        ii. Multiple times a week
        iii. Every day

    d. Level of confidence in bicycling:
        i. New to bicycling
        ii. Moderate
        iii. Good
        iv. Excellent

14) Is there something important that I forgot to ask? Is there anything else that you think I need to know?