Analyzing Network Connectivity by Cyclist Comfort: An Empirical Reappraisal of the Four Types of Cyclists Typology and Level of Traffic Stress Framework

by

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ABSTRACT

North America is seeing a resurgence of interest in cycling both for recreation and as a transportation mode. Cycling is touted as a means to reduce traffic congestion and its GHG emissions and pollution, increase livability, and provide a remedy to inactivity and its related health problems. Building a network of safe and connected infrastructure has been recognized as an important step for cities seeking to increase the share of cycling as a transportation mode. Developing methods to assess bicycle network connectivity and accessibility has been the focus of a large body of research. In particular, the Level of Traffic Stress (LTS) framework was developed to classify network links according to the stress they might represent for cyclists. The level of stress is roughly mapped to accommodate cyclists with varying cycling confidence, known in the literature as the Four Types of Cyclists: No Way No How, Interested but Concerned, Enthused and Confident, and Strong and Fearless. In this work, we first adapt the LTS framework to a Canadian context and apply it to Edmonton's network to understand the connectivity improvements stemming from the implementation of a network of physically protected bike lanes in the city's core in 2017. Our metrics show an important increase in network integration and an almost four-fold increase in connected origin-destination pairs. We then ask whether the LTS framework adequately captures the comfort of the Four Types of Cyclists, and whether the Four Types of Cyclists adequately represents the distribution of cyclist types in Edmonton. To answer these questions, we developed a survey where we presented respondents with cycling environment descriptions and video clips, and asked them to rate their perceived comfort. We also asked about their intent to cycle more often than they do now, their cycling habits, and demographic information. We analyzed survey results to test the existing cyclist typology and determine whether a new one is warranted, using variables as similar as possible to the Four Types of Cyclists. Our results show a three-level typology better describes survey respondents and uncovers some limitations of the Four Types of Cyclists as applied to an Edmonton population. Our three types of cyclists are Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable

Cyclists. We then apply binary logistic regression to understand environmental and infrastructure characteristics that make each cyclist type most comfortable. We pair this data with the comfort ratings and route descriptions from a subset of survey respondents to develop an updated LTS framework called Level of Cycling Comfort (LCC). The levels of the LCC framework map onto the three types of cyclists to reflect their perceived comfort on different types of infrastructure. Overall, dedicated cyclist/pedestrian paths and certain protected lanes are suitable for the Uncomfortable or Uninterested; protected lanes and very calm residential streets are adequate for the Cautious Majority; most other cycling conditions with up to two lanes of traffic per direction and 60 kph motorized traffic speeds are suitable for Very Comfortable Cyclists. Finally, we use the LCC framework to reassess network connectivity and compare results with those obtained using the LTS framework. The LCC framework generally shows a less optimistic, but more realistic assessment of network connectivity compared to the LTS framework.

PREFACE

Some of the research included in this thesis has been published or is currently submitted for publication. Much of Chapter 3 was published as *L. Cabral, A. M. Kim and M. Shirgaokar (2019). "Low-stress bicycling connectivity: Assessment of the network build-out in Edmonton, Canada."* Case Studies on Transport Policy ***7****(2): 230-238*. Chapter 1 and Chapter 2 also contain excerpts from this publication. I was involved in all aspects of the research from design to writing. Professor Amy Kim participated in data collection and manuscript writing, and Professor Manish Shirgaokar helped with the study conception and participated in manuscript writing.

Chapter 4 and Chapter 5 are an extended version of a paper entitled "*An Empirical Reappraisal of the Four Types of Cyclists*" which was submitted to a peer-reviewed journal and co-authored by Laura Cabral and Professor Amy Kim; this paper is currently under review. I was involved in all aspects of the research. Professor Kim participated in the design and data collection, provided analysis guidance, and participated in manuscript writing. Again, Chapter 1 and Chapter 2 contain excerpts from this publication.

Finally, Chapter 6 has not been submitted for publication yet, but will be adapted for consideration in a peer-reviewed journal under the title "*An Empirical Reappraisal of the Level of Traffic Stress Framework*". I was involved in all aspects of the research. Professor Amy Kim's contribution included data collection, analysis guidance, and participation in manuscript writing.

Although the content of the paper published as *L. Cabral, A. M. Kim and J. R. Parkins (2018). "Bicycle ridership and intention in a northern, low-cycling city."* Travel Behaviour and Society ***13****: 165-173* is not included in this thesis as it is out of the scope of the subject being discussed, it is in part responsible for the research question being explored. Elements of the paper's introduction and literature review are also included in the thesis. I was involved in all aspects of the research for this paper. Professor Amy Kim participated in manuscript writing and Professor John R. Parkins helped with design and analysis.

Part of this research project, namely the survey presented in Chapter 4, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Bicycle Ridership and Traffic Stress Tolerance", No. Pro00081782, 2018-2019.

Note that given large sections of this research were or will be co-authored in published works and that, in these publications, the personal pronoun 'we' and possessive pronoun 'our' were used as a means to demonstrate ownership, responsibility, and accountability for the work, the entire thesis is also written in this manner. The purpose of using the first person plural writing style in the thesis is to maintain the accountability initially sought out in the publications while also recognizing the contributions of co-authors and of others who contributed to the research (see Acknowledgements).

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I am grateful for the financial support of the National Sciences and Engineering Research Council, the Government of Alberta, and the University of Alberta Faculty of Graduate Studies and Research, who have enabled me to fully dedicate my time and energy to my work. This research was also funded by the Office of Traffic Safety at the City of Edmonton, and supported by various groups within the City of Edmonton. In particular, I would like to thank Stevanus Tjandra, Thareesh Kariyawasam, and Ariel Luo for providing mapping data and other inputs, and Curtis Rollins for his support with distributing our survey on the City's online platform. From the City of Edmonton, I would also like to thank the Institute of Transportation Engineers - Northern Alberta section past president Dallas Karhut, who acted as a mentor to both me personally and for the ITE student chapter, of which I was an executive member.

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I would like to thank my husband, Roland Lee, whose love, support, and experience of graduate life have been invaluable throughout my studies and for the last seven years. To my parents, Alexandre Cabral and Martine Lafortune, and sister, Éloïse Cabral, who have always been there for me: merci infiniment.

Finally, I would like to acknowledge that this research was conducted at the University of Alberta, which is located on Treaty 6 territory, traditional meeting ground and home for many Indigenous Peoples, including Cree, Saulteaux, Niisitapi (Blackfoot), Métis, and Nakota Sioux.

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CHAPTER 1 INTRODUCTION

1.1 Background and Motivation

Despite Canada's employed population growing 1.2 million between 2006 and 2016 (to 15.9 million as of 2016) (Statistics Canada, 2009, 2017a), the proportion of those that commute by bicycle has remained steady at 1.4%. Over the same decade, larger jurisdictions such as Toronto, Montreal, and Vancouver have steadily invested in bicycling infrastructure (Vijayakumar & Burda, 2015). However, mid-size metropolitan regions such as Edmonton (pop. 1.3 million (Statistics Canada, 2017a)) have only started to make significant investments in bicycling infrastructure over the last few years.

Edmonton is a post-war city largely designed for car travel. In 2016, 82% of Edmonton's workers relied on an automobile for their commute, while only one percent of all commuters mainly bicycled to work (Statistics Canada, 2017a). The consideration of cycling infrastructure investments by city policymakers is usually accompanied by vigorous debate about the efficacy of such spending. Supporters contend that capital investments are a tiny fraction of annual budgets spent on other modes, but have an outsized impact on urban livability and sustainability. They also argue that once the infrastructure is built, it will attract more users. Critics, however, maintain that given the small number of current active transportation users, it is an inefficient use of resources.

Nonetheless, city planners, health officials, and academics alike largely agree that greater levels of cycling can contribute to mitigating ever-increasing congestion in urban environments, reduce transportation-related greenhouse gas emissions and pollution, and offer a remedy to inactivity-related health problems (Guttenplan et al., 2003; Lindsay et al., 2011; Oja et al., 2011). Recognizing this, the City of Edmonton made a bold investment in urban bicycling in 2017 by building a traffic-separated downtown bike grid of 7.8 kilometers, at a cost of C$ 7.5 million (City of Edmonton, 2016). The network of protected bike lanes consists of two-way cycle lanes with extensive signage and green paint indicating conflict areas. The bike lanes are protected from the motor vehicle travelling lanes by raised curbs and flexible bollards. In some locations, a buffer of parked cars or planters is also present. This downtown network was the central piece of a larger project, which resulted in the construction of about 20 kilometers of protected bike lanes in central city neighborhoods that year. More physically separated lanes have been built since then and are planned as mature central neighbourhoods go through the neighbourhood renewal process.

In a car-centric city, this new infrastructure has sparked heated debate and polarized opinions. An independent assessment of the effectiveness (or lack thereof) of the protected bike lane network can help support the discussion. One facet of a network's effectiveness is its connectivity: more connected and direct networks are associated with higher levels of bicycle commuting (Schoner & Levinson, 2014). Assessing bicycle network connectivity requires the recognition that the level of connectivity will be perceived and experienced differently by different cyclists. Indeed, it is well recognized that cyclists are a heterogeneous group (Damant-Sirois et al., 2014; Kroesen & Handy, 2014); their route and infrastructure preferences, and their comfort, varies for different types of cyclists (Larsen & El-Geneidy, 2011; Stinson & Bhat, 2005; Veillette et al., 2019). The Level of Traffic Stress (LTS) framework (Mekuria et al., 2012) fulfills this requirement by defining four levels of traffic stress based on infrastructure characteristics. Each LTS level is meant to cater to cyclists of increasing confidence, defined by the Four Types of Cyclists typology comprised of the No Way No How, Interested but Concerned, Enthused and Confident, and Strong and Fearless (Dill & McNeil, 2013, 2016; Geller, 2006). Network connectivity for a particular cyclist type can be assessed by considering only the network of links of a given LTS level.

The general objective of this research is to measure network connectivity while integrating different cyclists' perception of comfort on different types of cycling infrastructure, including protected bike lanes. We initially seek to quantify any expansion of low-stress connectivity stemming from the construction of the downtown bicycle grid. We adapt the LTS framework to a Canadian context and develop connectivity measures inspired from existing literature to obtain an initial assessment of Edmonton's connectivity improvements. We then ask, does the LTS framework adequately capture the level of comfort of cyclists, and do the Four Types Cyclists reflect the cyclist types that exist in Edmonton? We develop and implement a survey to answer these questions. We then empirically assess the Four Types of Cyclists and propose a new data-driven typology. Finally, we adjust the LTS framework to reflect the newly defined cyclist types and compare connectivity results with those obtained from the LTS framework.

1.2 Objectives and Tasks

The central objective in this work is to quantify bicycle network connectivity based on the perception of different types of cyclists. We also aim to evaluate changes in low-stress connectivity stemming from the implementation of protected bike lanes in Edmonton. The research evolved over time and new objectives and tasks arose throughout the project. Two main chronological phases can be identified, each with their specific objective and tasks.

Phase I Objective: Assess network connectivity improvements using the LTS framework, adapted to the Canadian and local context. This phase contains three main tasks:

1. Creation of a complete network dataset including streets, alleys, trails, breezeways, park paths, and shared-use paths in Edmonton.

2. Translation of the LTS framework to the metric system and adaptation to local data availability.
3. Development of connectivity metrics inspired from existing literature and comparison of connectivity before and after bike lane implementation.

The conclusion of Phase I brought some answers to the network connectivity question, but also generated new questions. Our own use of the LTS framework as well as results from previous work (not included in this thesis (Cabral et al., 2018)) and the acknowledgement of several known limitations to the Four Types of Cyclists (Damant-Sirois et al., 2014; Dill & McNeil, 2016; Félix et al., 2017; Geller, 2006), which form the basis for the LTS framework, prompted a second phase of research.

Phase II Objective: Adjust the LTS framework to better represent the comfort of Edmonton cyclists and re-evaluate network connectivity. This second phase is divided in four main tasks:

1. Design and distribution of a survey to understand infrastructure characteristics that make Edmontonians perceive cycling environments as more or less comfortable.
2. Development of a new, empirically-derived cyclist segmentation to understand types of cyclists in Edmonton and their comfort level.
3. Realignment of the LTS framework to reflect the new cyclist typology.
4. Reassessment of network connectivity using the metrics developed in Phase I.

In the first phase we created a network geodatabase, including streets, alleys, trails, breezeways, park paths, and shared-use paths in Edmonton. The network was constructed in a collaborative effort with the City of Edmonton using their existing data. The City maintains separate databases for these different types of infrastructure representations; hence, extensive manual corrections are required. The resulting network contains attributes required to classify all segments using the LTS framework. We used geo-spatial tools to evaluate the connectivity impacts of the bicycle grid implementation.

In the second phase, we designed a survey and distributed it in collaboration with the City of Edmonton using their existing survey platform and the Insight Community, a panel of Edmonton citizens who sign up to answer surveys on a regular basis. The survey measures respondents' comfort on several types of cycling facilities using both infrastructure descriptions and video clips we prepared for the survey. Respondents were also asked about their cycling habits and intent as well as their demographic information. In addition, one hundred respondents completed an optional mapping module by meeting us in person to describe their most common utility or commute cycling route. We used the survey data to conduct a Cluster Correspondence Analysis, with the aim to empirically segment respondents into relatively homogeneous groups of cyclists. We then compared the results to the Four Types of Cyclists and derived a new empirical cyclist segmentation that better reflects the comfort of local cyclists or potential cyclists. Finally, we used logistic regressions and revealed preferences from the survey's mapping module to aid in realigning the LTS framework with the new cyclist segmentation, in the process creating a new network assessment framework we name Level of Cycling Comfort (LCC). We used this updated framework to reproduce the connectivity assessment carried out in the first phase and compare connectivity results obtained from the LTS and LCC frameworks.

The main contribution of our work is to critically and empirically assess the suitability of the Four Types of Cyclists and the Level of Traffic Stress – two well-known and widely used cycling frameworks. Our evaluation confirms and uncovers flaws from these methods and provides data-driven updates to both while also retaining their positive characteristics, such as intuitiveness and ease of use. Because Edmonton is our research setting, our work also provides valuable information about this city's network connectivity taking into account recent bicycle infrastructure improvements.

1.3 Thesis Outline

Chapter 2 contains the core literature review, presenting elements which are relevant to all subsequent chapters. Further literature reviews specific to particular parts of the research are presented within the relevant chapter. Chapter 3 reveals the initial assessment of Edmonton's low-stress connectivity improvements using the LTS framework. Chapter 4 explains the rationale for developing a survey, describes the survey instrument designed for this work and the collection method, and presents a select number of summary descriptive statistics. Chapter 5 introduces the empirical assessment of the Four Types of Cyclists typology and proposes a set of new cyclist segmentations of which one is recommended as the basis for the realignment of the LTS framework to better represent cyclists' comfort. Chapter 6 provides supporting evidence to adjust the LTS framework and shows the result of the reassessment of Edmonton's low-stress connectivity using the newly developed LCC framework. A conclusion outlining scientific contributions, limitations, and future work is offered in Chapter 7.

CHAPTER 2 CORE LITERATURE REVIEW

The Four Types of Cyclists and the LTS framework are two classification systems central to our work; we therefore review both in turn. We then discuss important determinants of cycling that are relevant for the two classifications. More detailed literature review is provided in the following chapters where topics are relevant to each chapter individually.

2.1 Cyclist Typologies and the Four Types of Cyclists

It is well recognized that cyclists are a heterogeneous group; policies impact cyclists differently depending on their particular characteristics (Damant-Sirois et al., 2014; Kroesen & Handy, 2014), and their route and infrastructure preferences vary accordingly (Larsen & El-Geneidy, 2011; Stinson & Bhat, 2005; Veillette et al., 2019). This explains the relative abundance of segmentations found in the literature attempting to categorize cyclists. Félix et al. (2017) offer an excellent review of different cyclist segmentations from peer-reviewed and grey literature published between 1994 and 2014. Common reasons to create cyclist typologies are planning infrastructure and cycling policies, understanding sociodemographic profiles of different types of cyclists, and for the sake of segmenting *per se* (Félix et al., 2017). Variables used often include frequency and purpose of cycling and variations on the theme of comfort, cycling confidence, risk perception, and experience. A few typologies also include socio-demographic variables.

Two broad methodological categories are identified by Félix et al. (2017): bottom-up and top-down. The first category refers to empirical segmentations, usually found in the academic literature and involving the use of factor analysis, clustering methods, or a combination of both to derive cyclist types from data. The second is more commonly found in the grey literature (although not exclusively) and relies on expert knowledge to define cyclist types. This is the case for the Four Types of Cyclists, which are an important focus of this work.

The Four Types of Cyclists typology is a popular cyclist classification developed by Portland's Bicycle Coordinator, Roger Geller, in 2006 (Geller, 2006). Comprised of No Way No How, Interested but Concerned, Enthused and Confident, and Strong and Fearless, it has become a widely adopted, and adapted, method for classifying cyclists and potential cyclists, both in research and in practice (Dill & McNeil, 2013; Félix et al., 2017). The objective was to understand Portland's market for cycling based on existing surveys and expert knowledge (Geller, 2006).

Dill and McNeil (2013) later formalized a method to classify a population into the Four Types of Cyclists and reaffirmed the typology using a wide sample of American cities (Dill & McNeil, 2016). The variables used to derive cyclist types include stated comfort on different types of infrastructure, the intent (or lack thereof) to cycle more often, and use of a bicycle in the last 30 days. The methodology uses a rule-based approach to determine the cyclist type; it is summarized in Figure 2.1. The typology's ease of application and intuitiveness have led to its adoption for other important applications, including the Level of Traffic Stress Framework discussed in the following section.

Despite its popularity, the typology is not without flaws. First, the segmentation was subjectively developed based on expert knowledge; thus, the categories are imposed on the population, rather than being empirically developed from it. Second, unanticipated contradictions emerge from its application. For example, the expected relationship of higher cycling frequency with higher comfort is not held; in particular many Strong and Fearless respondents are not, in fact, cyclists, as pointed out by Damant-Sirois and El-Geneidy (2015). This may be linked to the subjective development of the typology or could also be an artefact of the rule-based method developed by Dill and McNeil (2013).

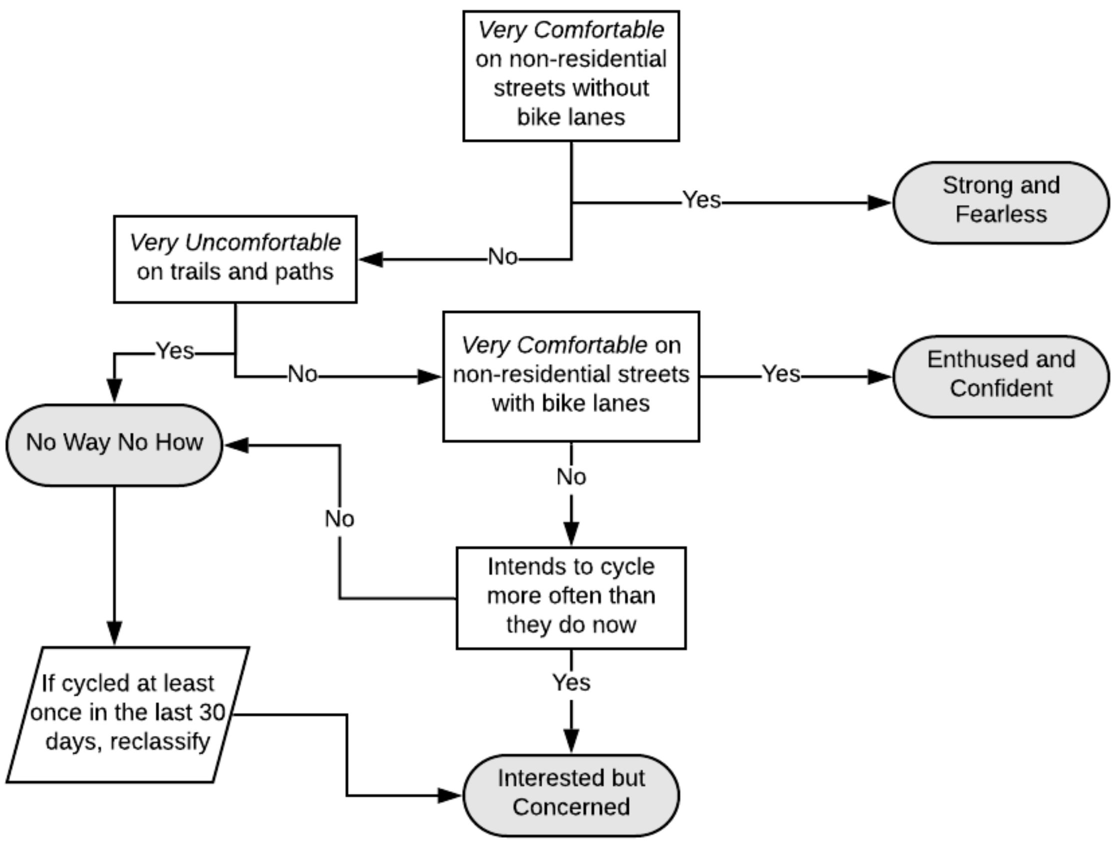


Figure 2.1 Summary of Rule-Based Classification of the Four Types of Cyclists
Based on Dill and McNeil (2013)

2.2 The Level of Traffic Stress Framework

The Four Types of Cyclists typology has been translated to an infrastructure classification scheme which allows the assessment of low-stress connectivity (Mekuria et al., 2012). The classification has been used extensively by academics in various locales to assess connectivity, prioritize future projects, analyze collisions, etc. (Chen et al., 2017; Kent & Karner, 2018; Moran et al., 2018; Semler et al., 2018). Four levels of traffic stress (LTS) are defined, as shown in Table 2.1. Levels 2, 3, and 4 are designed to identify cycling environments suitable to the last three types of cyclists (Interested but Concerned, Enthused and Confident, and Strong and Fearless, respectively). The first level is added to identify cycling environments appropriate for safety-aware children. The levels are cumulative, e.g., LTS 2 contains LTS 1. Our research adopts the above LTS classification scheme, but we note that other ways to quantify roadway stress have been proposed, notably through the calculation of marginal rates of substitution (Lowry et al., 2016).

Table 2.1 Level of Traffic Stress: Summary Description and Criteria for Street Segments
Adapted from Table 2, p.18 and Table 4, p.21 in Mekuria et al. (2012)

LTS Level		**LTS 1**	**LTS 2**	**LTS 3**	**LTS 4**
Target population		Safety-aware children	Most of the adult population	Confident cyclists	Fearless cyclists
Example facilities		Trails, shared-use paths, low-traffic and low speed limit residential streets	Lower traffic streets or moderate traffic streets with bicycle lanes; lower speed limits	Streets with moderate traffic or higher traffic streets with bicycle lanes	Any cycling situation
Criteria for mixed traffic		Street width: 2-3 lanes AND speed limit up to 40 kph[a]	Street width: 2-3 lanes AND speed limit up to 50 kph[a]	Street width: 4-5 lanes AND speed limit up to 40 kph	Any street width if speed limit 60 + kph OR Any speed limit if 6 + lanes OR Street width: 4-5 lanes AND speed limit 50 + kph
Criteria for streets with bicycle facilities[b]	Number of lanes per direction	1	(no effect)	2 or more	(no effect)
	Speed limit	40 kph or less	50 kph	60 kph	70 kph or more
	Bike lane blockage	rare	(no effect)	frequent	(no effect)

[a] One LTS level higher if not a local-residential street
[b] Assumes parking lane presence. See Section 3.3.1 for details.

Once a network is classified using the LTS framework, various metrics can be applied to measure connectivity. By isolating the network links of a particular LTS level, it is possible to measure how connectivity changes for groups of different stress tolerance. Typically, to measure "low-stress" connectivity, LTS 2 and LTS 1 links are kept in the network representation. The next chapter discusses connectivity metrics in more detail.

2.3 Determinants of Cycling

There is a rich body of knowledge exploring why people do or do not choose to cycle. From the perspective of the commuter, factors like physical ability, gender, cost, risk aversion, inclination to bicycle in inclement weather, and snow clearing policies have been studied and found to influence the decision to cycle in general and on any given day (Heinen et al., 2010; Shirgaokar & Gillespie, 2016). Because of their particular relevance in our research, in the next paragraphs we explore the importance and correlates of comfort, intent, cycling frequency, and network connectivity.

2.3.1 Comfort

A lack of perceived and actual comfort and safety is associated with lower levels of cycling (Dill & Voros, 2007; Winters et al., 2011) and is a known, major deterrent to cycling (Heinen et al., 2010; Lois et al., 2015; Manaugh et al., 2017; Sanders, 2015). Comfort is affected by many aspects of the cycling environment, including the type of bicycle facility, the width of the bicycle facility or of the shoulder in the case of mixed-traffic riding, the presence of physical separation from traffic, the presence and occupancy of parking, the land use type, etc. (Blanc & Figliozzi, 2016; Heinen et al., 2010; Li et al., 2012). Bicycle-specific infrastructure such as traffic separated bike lanes, signalized intersections with bicycle priority, and bike boxes for turning against traffic have been widely found to encourage bicycling (Buehler & Dill, 2016; Heinen et al., 2010; Pucher et al., 2010). Amongst other demographics, gender influences the perception of safety, with women more likely to perceive their cycling environment as more dangerous or less comfortable than men (Sener et al., 2009).

2.3.2 Intent

Intent quantifies the pool of potential future cyclists as it is a predictor of actual behaviour (Ajzen, 1991), although an intention-behaviour gap is often observed (Sheeran, 2002). Intent to cycle can be influenced by social and self-identity (Heinen, 2016; Lois et al., 2015), subjective norms (i.e. how cycling is perceived by the respondent's peers) and descriptive norms (i.e. whether others in the respondent's circle cycle) (Eriksson & Forward, 2011). Self-efficacy (the knowledge and skills required to ride and maintain a bicycle) and current cycling frequency are also found to influence intent (Lois et al., 2015). Finally, our own study found no statistically significant difference in cycling intent between respondents of different genders (Cabral et al., 2018).

2.3.3 Frequency

Damant-Sirois and El-Geneidy (2015) found that perceived safety throughout the network, the low cost of cycling, and its perceived convenience are associated with higher cycling frequency. It is also associated with cycling for multiple purposes in addition to commuting (e.g. recreation, running errands, etc.) (Stinson & Bhat, 2004) –trips that seem to be a gateway to bicycle commuting (Sener et al., 2009). As was the case for comfort, gender influences cycling frequency with males generally cycling more than females (Cabral et al., 2018; Heinen et al., 2010; Sener et al., 2009).

2.3.4 Connectivity

Another major consideration when contemplating cycling as a transportation mode is the directness and connectivity of a route (Schoner & Levinson, 2014; Shirgaokar & Gillespie, 2016; Titze et al., 2008). Greenways and recreational bicycle paths offer a high level of safety, but often fail to connect homes to important destinations such as schools, workplaces, shopping areas, and recreational facilities. If such paths do connect, they often require long detours compared to using the street network with its (often) higher stress links. Therefore, to encourage utility cycling, not only is high-quality infrastructure needed, but it must also be well-connected and direct.

2.4 Conclusion

In this short literature review, we provided background information that is central to understanding our work. We reviewed the Four Types of Cyclists and the LTS framework, and provided detailed descriptions of the determinants of cycling with a particular emphasis on the importance of comfort, intent, cycling frequency, and network connectivity. We provide more detailed literature reviews regarding connectivity metrics, segmentation methods, and updates to the LTS framework in Chapter 3, Chapter 5, and Chapter 6, respectively.

CHAPTER 3 ASSESSING EDMONTON'S LOW-STRESS NETWORK CONNECTIVITY

This chapter presents our initial assessment of Edmonton's low-stress connectivity improvements using the LTS framework. All subsequent sections are extracted from our work published in *Case Studies on Transport Policy* (Cabral et al., 2019). We first present a short literature review of connectivity metrics, then provide a description of the data used for the analysis as well as the geospatial analytical approach. Our findings describe the improvements in network connectivity gained from the new cycling infrastructure. The chapter closes with a brief discussion of policy implications, the strengths and limitations of this research, and concluding remarks.

3.1 Literature Review: Connectivity Metrics

Dill (2004) was among the first to apply connectivity measures specifically to cycling. The connectivity measures tested in this early publication were almost exclusively confined to topology: street network density, connected node ratio, intersection density, and link-node ratio. Over time, researchers developed new connectivity measures which are more appropriate for cycling or active travel in general, and more useful in providing policy or planning guidance.

One such measure, explored specifically in pedestrian connectivity research, is the "pedshed," defined as "the area that can be reached from a given origin by walking along the network for a specified distance as a percentage of the area of a circle with a radius of the same distance" (Tal & Handy, 2012, p. 49). In Section 3.3 we propose a slightly modified "bikeshed" measure. Boisjoly and El-Geneidy (2016) tested a composite connectivity measure specifically for cycling, using Montreal as a case study. Based on two travel surveys, they measured diversion (additional length of detour as a percentage of the shortest path) as well as the proportion of bicycle facilities along a route. The final connectivity measure integrated their two indicators: trips made on routes consisting of at least 50% bicycle facilities and 12% detour or less were considered connected.

A different approach was adopted by Mekuria et al. (2012). Based on their LTS framework, they consider that two nodes are connected if they can be reached using only links of a given stress level while limiting the detour to less than 25% beyond the shortest path. Two connectivity measures are developed from this: percent trip connected, which requires a trip table, and percent nodes connected, which is a coarser method if a trip table is not available.

Although our work is not focused on accessibility, it must be recognized that connectivity is an integral component in many accessibility assessment frameworks (Vale et al., 2016). Both cycling accessibility

(Houde et al., 2018; Kent & Karner, 2018; Saghapour et al., 2016; Tal & Handy, 2012) and the related field of bikeability (Lowry et al., 2012; McNeil, 2011; Winters et al., 2013) have been studied extensively, with some work focusing specifically on low-stress accessibility (Imani et al., 2018; Kent & Karner, 2018; Lowry et al., 2016).

3.2 Data

We assembled a complete network geodatabase for Edmonton from shapefiles provided by the City and in collaboration with its GIS division. The integration of streets, alleys, trails, breezeways, park paths, and shared-use paths is critical to this work as cyclists are likely to travel on any of these facilities. As noted in Chapter 1, we did extensive manual corrections to integrate the different databases and update outdated information. The resulting integrated network (Figure 3.1) contains 57,756 segments with the minimum attribute information required to assess the LTS level on each link, including segment type (street, trail, etc.), street functional class, bicycle infrastructure type, and speed limit. Despite the weeks dedicated to manual corrections, there are still known missing or disconnected links in the network. We have concentrated our efforts in the core areas of the city to minimize any impacts on analysis, but acknowledge that results on the outskirts of the core area are impacted by remaining map errors.

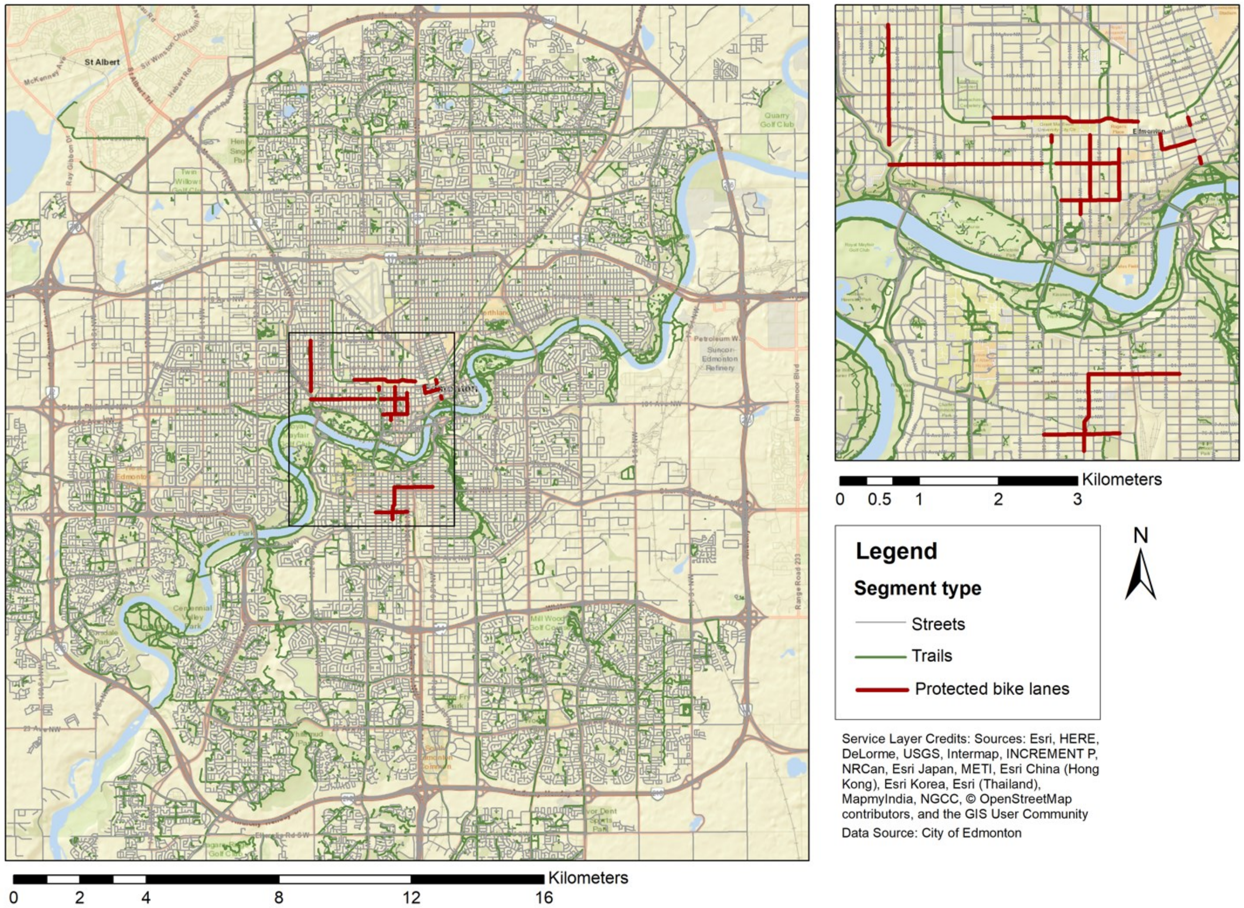


Figure 3.1 Edmonton Street and Trail Network and Protected Bike Lane Network

To conduct the analyses, we chose seven significant destinations of interest in the city's central core (see Figure 3.2). These destinations were selected because of their high trip generation potential. Edmonton's central core, where we are more likely to observe utility cyclists, has traditionally been anchored in government, as Edmonton is Alberta's capital city, and education, notably through the University of Alberta, the province's flagship institution. The selection thus includes three major academic institutions (University of Alberta, MacEwan University and the Northern Alberta Institute of Technology (NAIT)), two government centers (the Alberta Legislature Building, which is also surrounded by other government offices, and Churchill Square, the public space in front of Edmonton City Hall), and two social centers (Rogers Place Arena and the Old Strathcona Farmer's Market). Note that both Churchill Square and the Alberta Legislature grounds are also entertainment centers as several festivals and public activities are held in these locations throughout the year. Four destinations (the Legislature grounds, MacEwan University, Rogers Place, and Churchill Square) border the central business district where the protected bike network was built in 2017.

Finally, we generated potential origin points from the centroids of Traffic Analysis Zones. Figure 3.2 displays the 298 origins. Points in the central region of the city between major arterial roads or highways were retained (Yellowhead Trail to the north, Whitemud Drive, 61 Avenue and 63 Avenue to the south, 170 Street to the west, and 50 Street and up to Rundle Park in the east).

3.3 Analytical Approach

In order to assess potential changes in low-stress connectivity afforded by the protected bicycle lanes, each link in the Edmonton network was assigned a LTS rating. Low-stress was defined as the LTS 2 network (inclusive of LTS 1 by definition). Links designated with this level of stress are assumed suitable for most of the adult population (see Table 2.1) and we deem this level adequate for a city-wide network. Three network analyses were then performed, each comparing results with and without the new cycling infrastructure included. First, we conducted a "bikeshed" analysis, where a "bikeshed" is defined as the area reachable via exclusively low-stress routes around important destinations (Figure 3.2). Second, we identified potential origin points and computed the number of origin-destination pairs connected. Finally, shortest paths before and after build-out were compared for each connected origin-destination pair. The analyses are proposed as straightforward indicator tools, which together can inform decision-making for transportation planners and engineers. All analyses were performed using ESRI's ArcGIS software ArcMap 10.6 and open source programming software R (R Core Team, 2019).

3.3.1 Level of Traffic Stress Assignment

A segment's LTS is determined mainly by its physical characteristics and speed limit, as outlined in Table 2.1 (Mekuria et al., 2012). The table shows an adaptation of the LTS framework for the metric system, using commonly found thresholds in Canada. This results in a slight rounding up of threshold values compared to the imperial system. We assigned each link, with its combination of segment type, functional class, bike infrastructure characteristics, and speed limit, a LTS rating. Some information normally required for the classification, such as the number of lanes or the presence of on-street parking, was not available. Informed assumptions regarding the number of lanes and parking presence were made based on the functional class, design standards (City of Edmonton, 2015), and spot checks using Google Street View. For example, arterials are normally found to have four travel lanes (two each way) and parking is generally allowed on all streets except arterials located outside the core neighbourhoods. Mekuria et al. (2012), use different tables and criteria depending on parking presence. Table 2.1 considers that the bicycle lanes are along a parking lane since information regarding parking could not be provided by the City. This assumption was used because it best distinguishes the effect of traffic speed, which is the most accurate information provided by the City.

Alleys were removed from the dataset as they are not part of the primary network and are generally used, at most, as an access point to the main network and to detour around construction. In the LTS framework, alleys are considered very low stress (LTS 1). However, alleys in Edmonton generally exhibit severe pavement degradation and their use as access points for motor vehicles makes them undesirable for cyclists. Retaining alleys in the network representation would erroneously increase low-stress connectivity.

3.3.2 Network Analyses

Common preliminary steps were required for all network analyses. Since this work focuses on low-stress connectivity, a low-stress network comprising exclusively of LTS 2 and LTS 1 links was extracted from the full network. Two base maps were generated: one with the protected bicycle lanes, and the other without.

Bikeshed Analysis

The service area tool in the ArcGIS Network Analyst module was used to create “bikesheds” – a representation of the area within which one can reach each of the seven destinations of interest using only the low-stress (LTS 2 or LTS 1) network. A break value of 12 km (network distance) was established based on mean bicycle commuting distance reported in other research (Larsen & El-Geneidy, 2011; Moritz, 1997). This analysis is useful to visually identify improvements in connectivity, as well as barriers. The bikeshed area can also be used to measure accessible area changes.

Origin-destination Connectivity

Using the origin and destination points described in Section 3.2, we calculated the number of connected origin-destination pairs before and after construction of the protected bicycle lanes. To carry out this analysis, we used Esri ArcMap’s Origin Destination Cost Matrix.

Shortest Path and Detour Factor

The output of the Origin Destination Cost Matrix analysis also includes the shortest path length between connected pairs. We calculated the detour needed to remain exclusively on a low-stress network by dividing the low-stress trip lengths by the shortest path lengths when using the full network of streets and trails. Finally, for origin-destination pairs connected both with and without the bike lanes, we compared shortest path lengths to quantify potential improvements to consider in reducing travel distances (see Table 3.1).

3.4 Findings

Figure 3.2 shows the result of the LTS classification. Edmonton's main system of arterials is immediately evident (LTS 4–highest stress, in red), as is the network of trails in the River Valley and along the ravine system (LTS 1–lowest stress, in green). Some neighborhoods just southeast and northwest of the central area (shown in Figure 3.2b and Figure 3.2c) stand out as all the streets are rated LTS 1, whereas most residential neighborhood streets are assessed as LTS 2. The CBD also stands out as all streets are rated LTS 3 or LTS 4, at least before implementation of the protected bike lanes (Figure 2b).

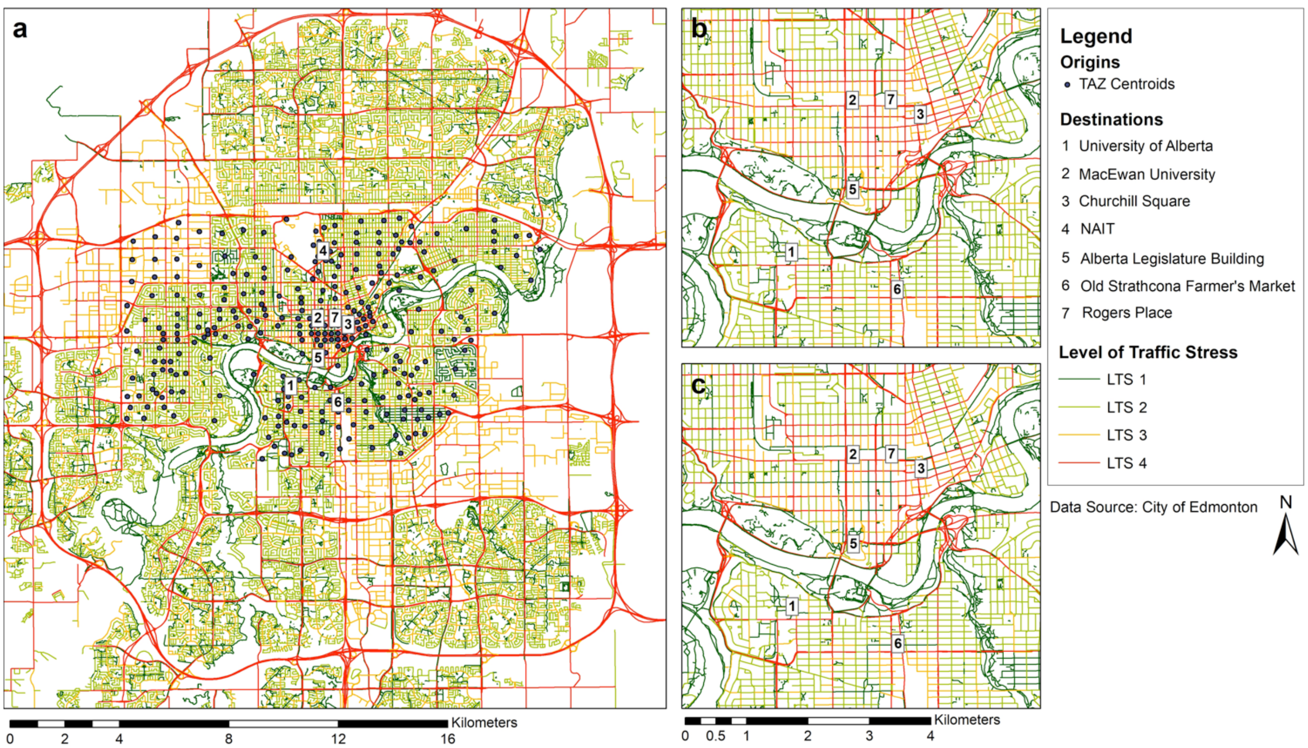


Figure 3.2 LTS Rating, Origins And Destinations. (a) Full Network (b) Core Area Before Implementation of Protected Bike Lanes (c) Core Area After Implementation of Protected Bike Lanes

3.4.1 Bikeshed Analysis

Figure 3.3 and Figure 3.4 show bikeshed maps for each destination individually and all destinations combined, respectively. At low traffic stress levels (LTS 2 and LTS 1), a notable result is that MacEwan University and Churchill Square were not reachable using low-stress paths before the Downtown bike grid was installed. Indeed, they were both located more than 150 m away from any street or biking facility suitable for low-stress cycling. This 150 m threshold represents a 1.5 to 2-minute walk, which is short enough to be reasonable for cyclists to walk their bike from their origin point to the network or from the network to their destination.

Figure 3.3 Bikeshed Area for Each Destination Before and After Protected Bike Network Construction

Churchill Square and MacEwan University have greatly benefited from the addition of bike lanes; they are now connected to the low-stress network, and their bikeshed areas have increased from null to 41.1 km^2 and 56.2 km^2, respectively. Northern Alberta Institute of Technology (NAIT) has experienced no increase in its bikeshed (see Table 3.1). This result was expected since no new infrastructure was constructed in the immediate vicinity of the campus. Of the remaining four destinations, the Old Strathcona Farmer's Market and Rogers Place have seen the most important increases in bikeshed area, both exceeding 400%. Finally, the University of Alberta and the Legislature Building have the largest bikesheds overall, both before and after bike lane implementation.

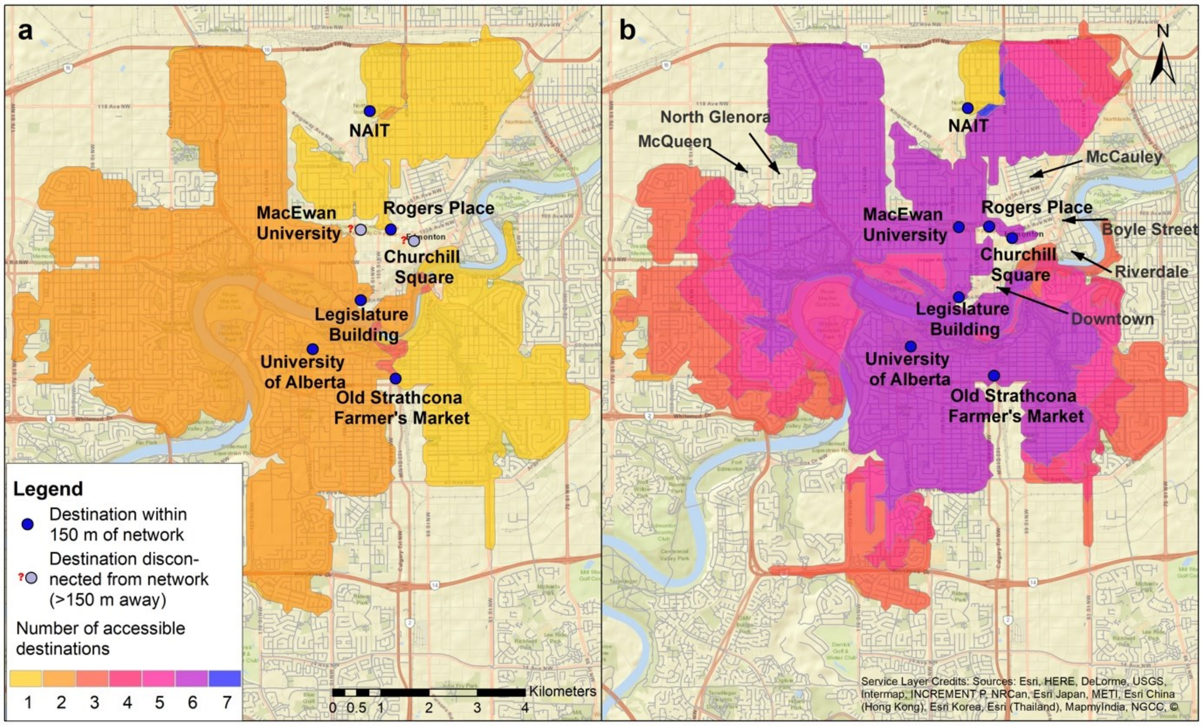


Figure 3.4 Bikeshed Area for All Destinations Combined, (a) Before and (b) After Protected Bike Network Construction

Beyond bikeshed size, Figure 3.4 illustrates an improved integration of accessible destinations. Before bike network build-out, NAIT, Rogers Place, and the Farmer's Market each had their own separate bikeshed, and the University of Alberta and Legislature Building shared a common bikeshed (see Figure 3.3). A cyclist leaving from the west side of the city could therefore access the University of Alberta and the Legislature, but no other destination. Similarly, a cyclist leaving from the southeast could only reach the Farmer's Market. In contrast, with the new bike lanes in place, many areas of the city (illustrated in purple in panel b of Figure 3.4) can access six of the seven destinations; NAIT remains isolated. Table 3.1 also emphasizes this improved integration, showing that all six destinations increased their number of connected origins to 177. The remaining 121 possible origin points are either disconnected from the network (i.e., 33 points are more than 150 meters away from any low-stress link), or are on a small island of connectivity isolated from the central network of connected low-stress links where the destinations are located (88 points).

As shown in Figure 3.4a, the Rogers Place bikeshed is isolated from the CBD (due to lack of low-stress connections) before the bike network implementation. The network allowed for connection of the northern areas with the CBD and the other bikesheds. Despite all the improvements, some neighborhoods are still unreachable using the low-stress network, including McQueen, North Glenora, Riverdale, Downtown, Boyle Street, and McCauley, as illustrated in Figure 3.4b. Notably, the latter three neighborhoods are among the poorest in the city (Statistics Canada, 2017a). Some of the connectivity issues in these neighborhoods will likely be resolved once the Downtown portion of a new light rail transit line is finalized and the protected bike lanes currently absent because of construction are completed.

3.4.2 Origin-destination Connectivity, Shortest Path, and Detour Factor

In addition to bikeshed areas, Table 3.1 presents other results from the origin-destination shortest path analysis. The number of connected origin-destination pairs increases after bike lane construction for all destinations with the exception of NAIT. Overall, the number of connected pairs more than triples. Increases in average trip length and detour factor can be attributed to the greater number of distant locations accessible with the new lanes.

We also considered the average trip lengths that were possible before and after bike lane construction. Churchill Square and NAIT are excluded since no trips were originally possible on the low-stress network. Of the remaining five locations, only some trips to the University of Alberta, the Legislature Building and Old Strathcona Farmers Market are shortened through the addition of the bike lanes. The average change in trip length for these destinations is minimal (between 81-322 m), but still statistically significant ($p < 0.05$). The maximum reduction in individual trip length was 1.5 km, although the majority of trip length reductions were much smaller.

The detour factor increased for trips to all but two destinations. NAIT experienced no change, while the Old Strathcona Farmer's Market has a slightly smaller detour factor on average after construction. Most importantly, even with the most recent build-out, detour lengths and the corresponding detour factors are higher than the observed thresholds of a few hundred meters or 25% longer than the shortest route as reported in the literature (Boisjoly & El-Geneidy, 2016; Larsen & El-Geneidy, 2011; Mekuria et al., 2012; Winters et al., 2010). The average detour for all destinations is 2.8 km, which is substantial given the average trip length is only 5.8 km. These values are driven up by the detours necessary to reach MacEwan University, Churchill Square, and Rogers Place (3.5 km, 4.5 km, and 3.8 km on average, respectively). These destinations remain accessible only through the new protected bike lane network, as the surrounding streets are classified as high-stress. This limits the possible paths to these destinations compared to a full network usage and is reflected in the high detour factors.

Table 3.1 Comparison of Various Metrics Before and After Network Build Out

		University of Alberta	MacEwan University	Churchill Square	NAIT	Legislature Building	Old Strathcona Farmer's Market	Rogers Place	Total
Bikeshed area (km^2)	Before	46.5	0.0	0.0	1.3	46.5	12.8	8.8	68.9
	After	67.9	56.2	41.1	1.3	69.0	65.5	50.6	70.5
	Abs. change	21.3	56.2	41.1	0.0	22.5	52.7	41.8	1.6
	Pct. change (%)	46	-	-	0	48	410	477	2
Connected origins	Before	94	0	0	4	94	35	32	259
	After	177	177	177	4	177	177	177	1,066
	Abs. change	83	177	177	0	83	142	145	807
	Pct. change (%)	88	-	-	0	88	406	453	312
Avg. trip length (all trips) (km)	Before	5.2	0.0	0.0	0.9	5.4	3.9	3.6	4.8
	After	6.3	7.7	8.9	0.9	6.3	6.9	8.1	7.3
	Abs. change	1.1	7.7	8.9	0.0	0.9	3.0	4.5	2.5
	Pct. change (%)	21	-	-	0	16	77	125	52
Num. of shorter trips	Absolute value	18	0	0	0	18	20	0	56
	Prop. of possible trips	0.2	-	-	-	0.5	0.6	-	0.2
Avg. trip length (shorter[a]) (km)	Before	7.0	-	-	-	5.9	4.6	-	5.8
	After	6.7	-	-	-	5.6	4.5	-	5.5
	Abs. change*	0.3	-	-	-	0.3	0.1	-	0.2
	Pct. change (%)	-5	-	-	-	-5	-2	-	-4
Avg. detour length (km)	Before	0.7	-	-	0.2	0.9	1.2	0.9	0.8
	After	1.4	3.5	4.5	0.2	1.9	1.8	3.8	2.8
	Abs. change	0.7	-	-	0.0	1.1	0.6	2.9	2.0
	Pct. change (%)	110	-	-	0	128	48	325	240
Avg. detour factor	Before	1.2	-	-	1.3	1.2	1.4	1.3	1.2
	After	1.3	2.0	2.3	1.3	1.6	1.3	2.0	1.7
	Abs. change	0.1	-	-	0.0	0.4	0.0	0.6	0.5
	Pct. change (%)	11	-	-	0	30	-3	48	41

[a] Trips possible both before and after the bike network construction and that are shorter on average after bike lanes.
* Statistical significance of the difference in length was tested through a paired t-test for each location. All were found to be significantly different ($p > 0.05$).

3.5 Discussion

We can apply bikeshed analysis to identify islands of connectivity around important destinations. Our results show that the protected bike lane build-out allowed a better integration of the network, with six of the seven bikesheds now connected. Furthermore, we can also easily identify neighborhoods with remaining high-stress barriers. By targeting infrastructure improvements at these locations, the city could greatly increase connectivity, not only for trips to downtown, but also (and most importantly) across adjacent neighborhoods where short car trips could more easily be replaced by bicycle trips. We noted some improvements in trip length (Table 3.1) in an analysis of equivalent LTS networks after the implementation of the protected bike lanes. Most bicycle trips at lower stress levels remain considerably longer than similar trips using the full network of streets and trails. Cyclists value directness and are averse to anything but the most minor detours when making utilitarian trips (Winters et al., 2010). Our research highlights that despite significant overall improvements, in order to reduce detour lengths, we must be able to identify and target specific links. Centrality measures, as proposed in other works (Lowry et al., 2016), could be used to target the next stages of improvements.

We presented the results of the research to several representatives from stakeholder organizations, specifically a local cycling advocacy group and the City of Edmonton. Some stakeholders verified our findings to be true, specifically mentioning the continuing isolation of NAIT, and the lack of connection to Churchill Square before the bike lanes were constructed. Advocates also noted that a greater number of destinations are available for cycling with children with the bike grid in place. This corroborates our finding that it provides increased low-stress connectivity. City employees indicated anecdotal evidence that more women and families are cycling and that winter riding has increased, likely associated to increased access to, and connectivity of, protected routes; these observations have yet to be confirmed quantitatively. Another stakeholder commented that ease of cycling on the grid is impeded by the numerous intersections. This observation highlights that the low-stress connectivity framework does not account for ease of flow. If this aspect is desired in the analysis, adding a measure of impedance to intersections when calculating shortest paths or connected origin-destinations pairs could be used in combination with the LTS framework. Finally, all stakeholders indicated our findings can be leveraged to build support for cycling infrastructure, by providing a tool to communicate the value of targeted infrastructure improvements for the network as a whole.

The analysis methodology we present requires low-cost geo-spatial tools typically available in urban jurisdictions. It is technically straightforward to implement and easily leveraged to study the impact of infrastructure investments. In particular, we demonstrate that lessons from other studied locations can be adapted to various levels of data availability.

A secondary contribution of this research is the translation of the speed criteria from miles per hour to kilometers per hour, taking into account speed limits normally found in Canada. This makes the framework more applicable to other jurisdictions that use the metric system. In our study, a number of assumptions were required since parking and lane information were not available (Section 3.3.1). Moreover, intersection information was not available to implement the LTS framework fully. As such, the results represent an optimistic assessment of the connectivity of the network. Future work may include these more detailed infrastructure variables, in addition to location information on trip starts and ends, and even origin-destination matrices.

3.6 Conclusions

We have presented a method to assess Edmonton's cycling connectivity before and after the construction of several kilometres of protected bicycle lanes. Our analysis considered network infrastructure suitable for cyclists, or potential cyclists, of different abilities and comfort levels. The study shows notable connectivity improvements, as revealed by the increase in bikeshed areas (Figure 3.3), greater bikeshed overlap (Figure 3.4) and number of connected origin-destination pairs (Table 3.1). Improvements in connectivity are notable, but detours remain high when comparing exclusively low-stress journeys with the shortest path regardless of stress level. Finally, our study identified central neighborhoods that remain disconnected from the low-stress network, and the corresponding high-stress barriers (links) that would benefit from infrastructure investments.

In this chapter, we have demonstrated that a relatively straightforward analysis can be used to evaluate existing and new infrastructure, quantify the connectivity effects post network build-out, and identify geographic areas and network links for improvement. This methodology is adaptable to various levels of data availability. Our contribution is aimed at mid-size to smaller urban jurisdictions that are in the initial phases of bicycle network development and that have limited resources for network analysis. Planners and engineers can apply our methodology to produce knowledge that helps policymakers evaluate cycling projects and ultimately make informed infrastructure investments decisions.

CHAPTER 4 SURVEY INSTRUMENT AND SUMMARY STATISTICS

This chapter first discusses the rationale for creating a survey of Edmonton cyclists. We then describe the survey design and provide select summary statistics from the survey.

4.1 Background

As noted in the introduction, the conclusion of the connectivity assessment presented in the previous chapter provides a foundation to understand Edmonton's network connectivity. However, two questions arose from this work and from further research into the LTS framework and the Four Types of Cyclists:

1. *Does the LTS classification adequately capture the comfort of different types of (potential) cyclists?*
   LTS levels 2, 3, and 4 are meant to cater to Interested but Concerned, Enthused and Confident, and Strong and Fearless cyclists, respectively. However, there has been no empirical validation, to our knowledge, of the correspondence between LTS levels and each cyclist types' perception of the environments that are meant to be comfortable to them.
2. *Does the Four Types of Cyclists typology adequately represent the distribution of (potential) cyclist characteristics in the cycling and non-cycling population?*
   The typology was subjectively developed based on expert knowledge (Geller, 2006) rather than using a data-driven approach. We also know the typology contains certain contradictions noted in the literature review. Finally, our own research showed cyclists in Edmonton seemed to naturally form three categories rather than four based on comfort alone (Cabral et al., 2018).

If the Four Types of Cyclists typology does not adequately represent the (potential) cycling population (Question 2), then a lack of correspondence between LTS levels and the cyclist types mentioned above (Question 1) becomes irrelevant. A new version of LTS would need to be developed to align with the preferences of the types of cyclists actually found in the population. These considerations prompted a second phase of research, starting with the development of a survey designed to gather insights regarding Edmonton's cycling population and that would be helpful in answering the questions above.

In the next sections, we describe our development and distribution of the Bicycle Ridership and Traffic Stress Tolerance survey and discuss several summary statistics obtained from the survey.

4.2 Survey Design

We designed the Bicycle Ridership and Traffic Stress Tolerance survey such that we could use it to explore various research questions and interests, some beyond the scope of this thesis. Classifying respondents into the Four Types of Cyclists was a central aim of the survey and therefore we included and adapted questionnaire elements from Dill and McNeil (2013) in our own design. We also decided to use video clips as a more immersive tool to assess comfort. In this section, we describe the video data collection method, the online survey design, and the optional mapping module design.

4.2.1 Video Data Collection

Previous research has shown that respondents are able to discern most roadway environment conditions as accurately with videos as if they were in the field (Harkey et al., 1998). Thus, videos are effective assessment tools (Harkey et al., 1998; Jensen, 2007; Landis et al., 1997; Lehtonen et al., 2016; Parkin et al., 2007), while also minimizing risk and allowing extensive data collection, including from participants who do not cycle.

We collected video footage by riding bicycles with a helmet-mounted camera at different locations throughout Edmonton. We used a GoPro Hero 6 camera, which allowed smooth recording that did not require post-processing to stabilize images. Of the 26 locations initially filmed, we retained and presented 16 to respondents, because of video quality issues and to avoid survey fatigue. The 16 locations are shown in Figure 4.1, and a representative frame from each video clip (8-12 s long each) is presented Table 4.1 (Cabral & Kim, 2019). Eight videos were shot in locations that were as similar as possible to the eight infrastructure descriptions used in the Four Types of Cyclists typology (discussed in the next section), within the constraints of available infrastructure in Edmonton, and traffic conditions at the time of recording. The other eight videos were added to the survey to capture a wider variety of cycling environments, including different types of protected bike lanes (PBL), a contra-flow bike lane (CF), painted bike lanes (BL), and several mixed-traffic environments (MT). For each video, we recorded a series of roadway conditions and other relevant characteristics of the cycling environment, with the intent of using those variables to understand what characteristics make each cycling environment more or less comfortable. In particular, we measured all the variables that form the input to the LTS framework (see Table 2.1) and assigned the appropriate LTS level to each video. We also recorded other information such as the land use type, the presence of vegetation, the horizontal alignment of the street, etc. A selection of the most important variables for the present research is available in Table 4.2.

Although videos have become ubiquitous in survey research, the specific study of differences in survey responses between audiovisual stimuli and written descriptions has only been explored in a handful of studies (Shaw et al., 1992; Sleed et al., 2002); none pertain to the transportation field at large. Generally, videos have complete contextual information, while written descriptions focus on a limited set of variables. With videos, respondents have the same contextual cues, and unspecified aspects are not left to the imagination (Sleed et al., 2002) while also limiting influence from lack of prior knowledge about the subject (Shaw et al., 1992). On the other hand, the rich context does not allow for control of which variables the respondents focus on, contrary to the written descriptions. While more research is needed, videos are found to portray the given situation in a more realistic way than the written equivalent (Smith & Sokolowski, 2008).

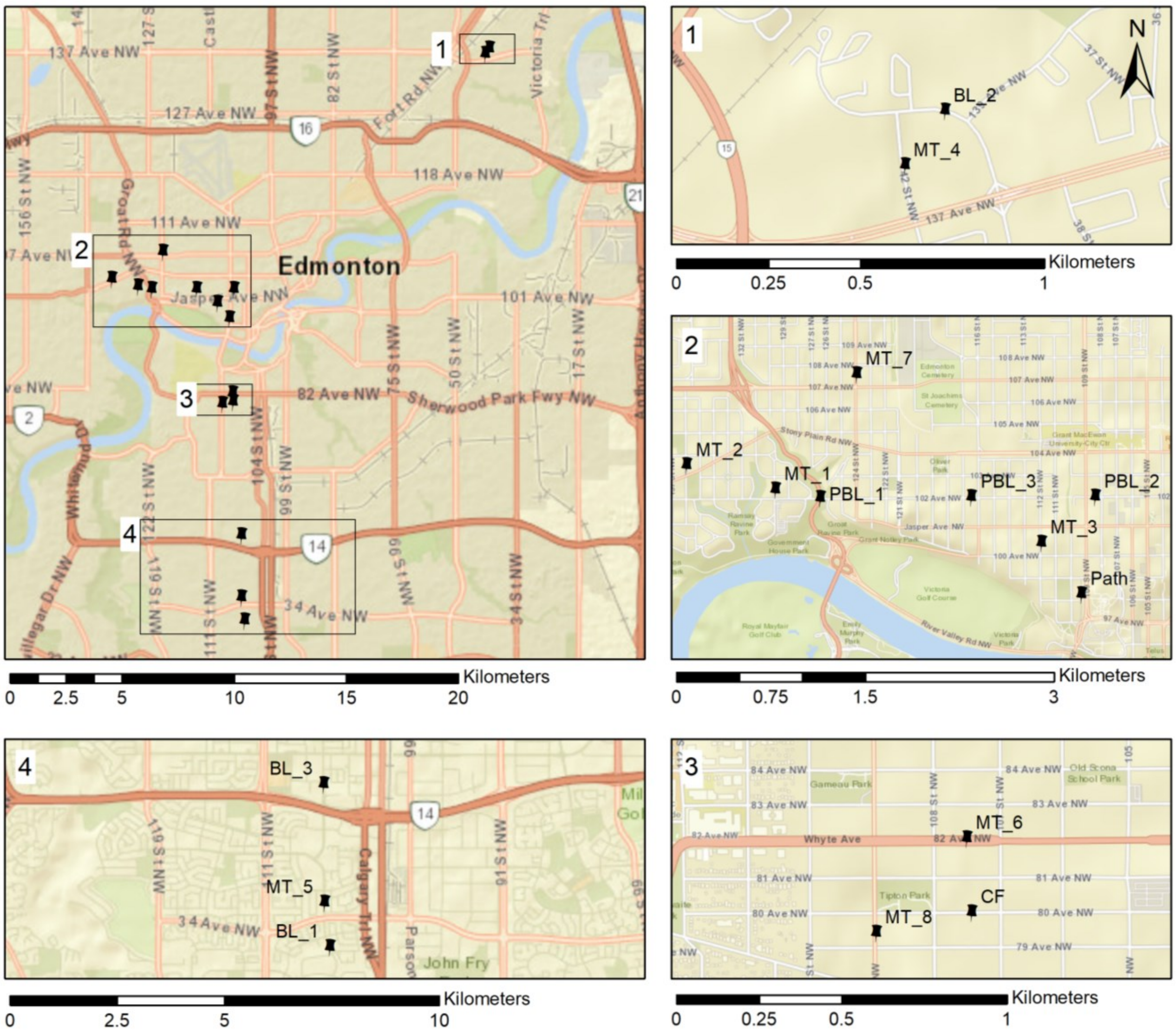
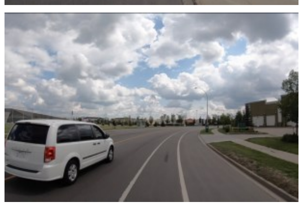
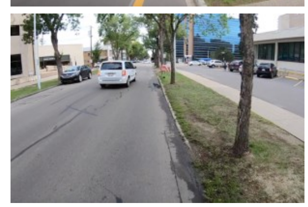
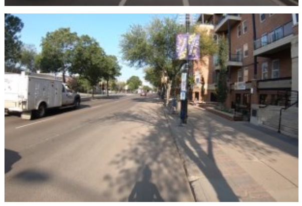
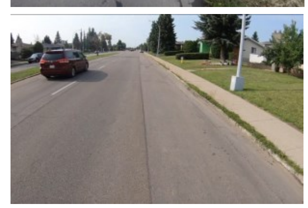
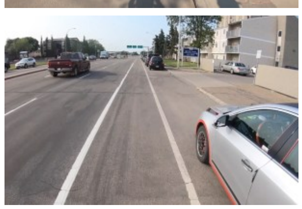
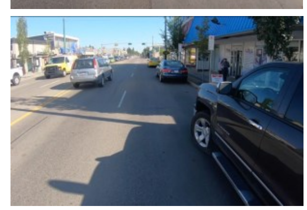
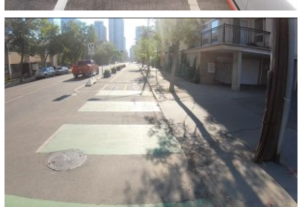
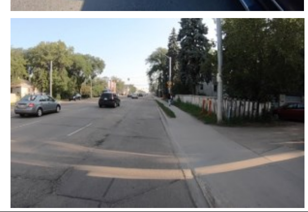


Figure 4.1 Video Recording Locations

Table 4.1 Representative Frame for Each Video Clip

Equivalent Video Clips*		Other Video Clips	
Path *= Facility_1*		**PBL_1** *Protected bike lane on bridge. 60 kph limit, two lanes per direction*	
MT_1 *= Facility_2*		**PBL_3** *Conflict section of protected bike lane. Residential one-lane, one-way street.*	
MT_2 *= Facility_3*		**BL_1** *Narrow painted bike lane. Two lanes per direction, residential collector.*	
MT_4 *= Facility_4*		**CF** *Contra-flow bike lane on one-way residential street.*	
BL_2 *= Facility_5*		**MT_3** *Mixed-traffic cycling. Downtown environment with institutional land use.*	
MT_6 *= Facility_6*		**MT_5** *Mixed-traffic, residential arterial, two lanes per direction with wide shoulder and median.*	
BL_3 *= Facility_7*		**MT_7** *Mixed-traffic, commercial arterial, two lanes per direction.*	
PBL_2 *= Facility_8*		**MT_8** *Mixed-traffic, major arterial, three lanes per direction, no median.*	

* Equivalent to the eight facility descriptions presented in Table 4.3.

Table 4.2 Selected Video Characteristics

Location	Facility Type	Prevailing Speed (kph)	Speed Limit (kph)	Lanes Per Direction	Centerline	Intersection Visible	Horizontal Alignment	Width of Bike & Parking Lane (m)	Parking Occupation	Land Use	Vegetation	Surface	LTS
Path	Shared-Use Path	-	-	-	-	No	Straight	-	-	Green Space	Plenty	Good	1
PBL_1	Protected Lane	52	60	2	Yes	No	Straight	2.77	No Parking Lane	Other	None	Good	1
PBL_2	Protected Lane	50	50	2	No	Yes	Straight	3.07	No Parking Lane	Commercial or Institutional*	Some	Good	1
PBL_3	Bike Lane	30	50	1	No	Yes	Straight	2.74	No Parking Lane	Residential	Plenty	Good	1
CF	Contra-flow	35	50	1	No	No	Straight	1.24	No Parking Lane	Residential	Plenty	Good	2
BL_1	Bike Lane	44	50	2	Yes	No	Curve	1.17	No Parking Lane	Residential	Some	Bad	2
BL_2	Bike Lane	40	50	1	Yes	Yes	Curve	3.56	Not Occupied	Commercial or Institutional	None	Good	3
BL_3	Bike Lane	48	50	2	Yes	No	Straight	4.21	Occupied	Residential	None	Good	3
MT_1	Mixed Traffic	-	50	1	No	No	Straight	-	Occupied	Residential	Plenty	Good	1
MT_2	Mixed Traffic	25	50	1	No	Yes	Straight	-	Occupied	Residential	Plenty	Good	1
MT_3	Mixed Traffic	46	50	1	No	Yes	Straight	-	No Parking Lane	Commercial or Institutional	Plenty	Bad	2
MT_4	Mixed Traffic	49	50	1	No	Yes	Straight	-	No Parking Lane	Commercial or Institutional	Some	Good	3
MT_5	Mixed Traffic	47	50	2	Yes	Yes	Straight	-	Not Occupied	Residential	None	Good	3
MT_6	Mixed Traffic	50	50	2	Yes	No	Straight	-	Not Occupied	Commercial or Institutional	Some	Good	4
MT_7	Mixed Traffic	40	50	2	Yes	Yes	Straight	-	Occupied	Commercial or Institutional	Some	Good	3
MT_8	Mixed Traffic	55	50	3	Yes	Yes	Straight	-	No Parking Lane	Commercial or Institutional	Plenty	Bad	4

* *Institutional* refers to hospitals, schools, etc.

4.2.2 Online Survey Design

As noted above, one of our first aims was to reproduce the Four Types of Cyclists segmentation based on the established methodology (Dill & McNeil, 2013, 2016). The minimum data required includes comfort ratings for different types of facilities, a measure of respondents' intent to cycle more often than they currently do, and a measure of recent cycling frequency; these variables and other important variables are listed in Table 4.3. We adapted the list of infrastructure descriptions (*Facility* variables, Table 4.3) to our local Canadian context and edited it for conciseness. For example, speeds were converted to kilometers per hour (kph), using commonly found thresholds rather than an exact conversion. We also eliminated some redundant or underutilized descriptions. Note that the comfort of videos is rated on the same four-point scale as the facility descriptions from Table 4.3. Our criteria to define recent cycling frequency also differed slightly: rather than biking at least once in the last month, our method counted those who cycled at least once a month in the previous season (summer 2018); we recorded cycling frequency by season to fulfill other survey objectives.

Finally, in addition to these core survey elements, respondents were asked about their general cycling behaviour (purpose, when they last biked, etc.) and demographic information. The full survey questionnaire is presented in Appendix 1.

Table 4.3 Core Survey Variables (excluding videos, see Table 4.1)

Variable	Question	Possible Responses
Comfort	How comfortable would you feel riding in these different environments?	Very Uncomfortable Somewhat Uncomfortable Somewhat Comfortable Very Comfortable
Facility_1	A path or trail separated from the street.	
Facility_2	A quiet residential street with low traffic speeds.	
Facility_3	A quiet residential street with bike route signs and shared-use lane or sharrow markings.	
Facility_4	A neighborhood commercial shopping street with one lane in each direction, traffic speeds of 40 to 50 kphour, on-street car parking, and no reserved (painted) bike lane.	
Facility_5	A neighborhood commercial shopping street with one lane in each direction, traffic speeds of 40 to 50 kphour, on-street car parking, and a reserved (painted) bike lane.	
Facility_6	A major street with two lanes in each direction, on-street parking, traffic speeds of 50 to 60 kphour and no reserved (painted) bike lane.	
Facility_7	A major street with two lanes in each direction, on-street parking, traffic speeds of 50 to 60 kphour and a reserved (painted) bike lane.	
Facility_8	A major street with two lanes in each direction, on-street parking, traffic speeds of 50 to 60 kphour and a bike lane physically protected from traffic by bollards or planters.	
Intent	Please indicate your level of agreement or disagreement with the following statement: I would like to travel by bike more than I do now.	Strongly Disagree Somewhat Disagree Neither Agree nor Disagree Somewhat Agree Strongly Agree
Frequency *Freq_F16* *Freq_W17* *Freq_P17* *Freq_S17* *Freq_F17* *Freq_W18* *Freq_P18* *Freq_S18*	In the last year (Sept. 2017 to August 2018) how often did you ride a bike during each season? Please indicate your cycling frequency only if you lived in Edmonton during each period. Think back to the previous year (Sept. 2016 to August 2017). How often did you ride a bike during each season? Please indicate your cycling frequency only if you lived in Edmonton during each period.	Daily 4 or more times per week 2 to 3 times per week Once per week Once per month Never
Biked_S18	Binary variable created from *Freq_S18*. Indicates if respondent biked at least once a month or not in Summer 2018.	Yes No
Purpose	In the last year (Sept. 2017 to August 2018), for which reasons did you ride your bike? Select all that apply.	Recreation Fitness Utility Commute

4.2.3 Optional Mapping Module Design

The objective of the mapping module was to obtain a detailed description of the cycling route taken by respondents who volunteered at the end of the survey questionnaire to come to the University of Alberta in person. The option was only offered to cyclists who biked in the previous year and to those who indicated they cycle for utility or commuting. For time management and budget reasons, the number of mapping module respondents was capped at 100. Each meeting with respondents lasted approximately 10 to 30 minutes depending on route length and ease of recall from participants. We rewarded respondents with a $15 gift card from Mountain Equipment Coop and entered them in a draw for two additional $50 gift cards.

We recorded the routes using Esri's ArcMap software and created a new shapefile for each respondent with a unique ID number to allow response-matching to the rest of the survey. We started the route mapping from the closest intersection to the respondent's home and moved along segments to their destination. Priority was given to the commute route to work or school. For those who did not regularly commute, the destination could be any other utility-type destination (e.g. shopping). The geometry of segments used by respondents were copied from the base map used in Chapter 3 to their personal shapefile. For each segment, we asked respondents to indicate if they usually ride on the road, on the sidewalk, in a bike lane, etc. Where needed, we added segments (e.g. if the respondent used a significant shortcut) and infrastructure descriptions (e.g. the funicular newly built in Edmonton was not originally envisioned as a potential facility).

4.3 Survey Distribution and Data Collection

The online survey was distributed from August 27 to September 17, 2018, in collaboration with the City of Edmonton. We were generously offered the opportunity to use the City's in-house survey platform and the Insight Community, the panel of Edmontonians who agree to receive and answer surveys from the City, usually once a month. In addition, an open link to the survey was distributed through multiple channels, including university mailing lists, local active transportation advocacy groups, community league emails, and media outlets. Both cyclists and non-cyclists were encouraged to participate. After data cleaning, 3208 valid responses remained, with 2193 responses from Insight Community members (24% response rate) and 1015 from other Edmonton residents. To obtain the 100 respondents sought out for the in-person mapping module, we contacted 161 respondents who indicated their interest in the survey. We conducted the in-person interviews between September 20 and October 13, 2018.

4.4 Summary Statistics

Table 4.4 shows the demographic characteristics of the study respondents as well as their cycling purpose and cycling history. Non-male respondents compose 46.2% of respondents. The *Not Male* label encompasses those who identify as female or otherwise. Those who did not answer the gender question (2.4% of respondents) are not included in the stated proportion since we cannot be certain that they do not identify as male. The sample is mostly young (under 45 years old), and skews towards high income and educational achievement. Recreation is the most cited reason for cycling and approximately three quarters of respondents cycled in the last summer and in the last year.

Compared to 2016 census data for the City of Edmonton, our sample has less young respondents (15 to 24 years old), a similar proportion of older adults (65 and over), and a higher proportion of 25 to 64 years old respondents. The sample is highly skewed towards higher-income earners and high educational attainment (Statistics Canada, 2017b). This was expected based on previous use of Insight Community responses (Cabral et al., 2018).

Table 4.5 shows the mode and proportion in mode for the intent, frequency, and comfort variables, the three core variables used to divide cyclists in the Four Types. Summary statistics for cycling intent show that over one third of respondents would strongly like to travel by bicycle more than they do now. When adding both those who strongly and somewhat agree, 64.8% of respondents say they would like to cycle more than they currently do. During the last two years, the most common cycling frequency was two to three times per week. Notable exceptions are winters, where about 70% of active cyclists (those who declared they cycled in the past year) say they do not cycle. Despite this significant drop in the cold season, 17.3% and 19.9% of active cyclists bicycled at least once a week in winter 2017 and winter 2018, respectively. Summer 2018 was the only season in the two years surveyed where the dominant cycling frequency was four or more times per week, with about one quarter of active cyclists choosing this response category.

The comfort ratings of both facility descriptions and videos indicate paths, protected bike lanes, and quiet residential streets are generally assessed as *very comfortable* whereas painted bike lanes are most often rated *somewhat comfortable*. Non-residential mixed-traffic environments are most often rated *somewhat uncomfortable* or *very uncomfortable*.

Table 4.4 Demographic Breakdown, Cycling Purpose, and Cycling History

Variable	Proportion of Respondents (n = 3208)
Gender	
Not male	46.2
Age	
15 – 24	4.1
25 – 44	47.0
45 – 64	35.9
65 – 98	12.2
Prefer not to answer	0.8
Income	
< 50,000	9.9
50,000 to 99,999	26.3
100,000 or more	47.4
Prefer not to answer	16.4
Education	
High school or less	9.6
Technical school	22.4
University degree	65.7
Prefer not to answer	3.3
Purpose	
Recreation	67.5
Fitness	41.9
Utility	47.7
Commute	39.7
Last Biked	
Never	1.2
In my childhood	3.9
Several years ago	13.1
1-2 years ago	5.3
Within the last year	76.6

Table 4.5 Summary Statistics: Intent, Frequency, and Comfort

Variable	Mode	% Respondents (n = 3208)	Variable	Mode	% Respondents (n = 3208)
Intent	Strongly Agree	35.5	**Comfort (Videos)**		
Frequency[a]			*Path*	Very Comfortable	84.2
Fall 2016	2 to 3 times per week	19.7	*PBL_1*	Very Comfortable	71.6
Winter 2017	Never	72.8	*PBL_2*	Very Comfortable	59.6
Spring 2017	2 to 3 times per week	23.2	*PBL_3*	Very Comfortable	39.7
Summer 2017	2 to 3 times per week	24.3	*CF*	Somewhat Comfortable	38.5
Fall 2017	2 to 3 times per week	20.2	*BL_1*	Somewhat Comfortable	32.4
Winter 2018	Never	70.3	*BL_2*	Somewhat Comfortable	37.4
Spring 2018	2 to 3 times per week	22.9	*BL_3*	Somewhat Comfortable	32.4
Summer 2018	4 or more times per week	25.4	*MT_1*	Very Comfortable	52.3
Biked in Summer 2018	Yes	73.8	*MT_2*	Very Comfortable	48.8
Comfort (Descriptions)			*MT_3*	Somewhat Uncomfortable	34.9
Facility_1	Very Comfortable	84.8	*MT_4*	Somewhat Uncomfortable	32.1
Facility_2	Very Comfortable	64.1	*MT_5*	Somewhat Comfortable	35.0
Facility_3	Very Comfortable	58.1	*MT_6*	Very Uncomfortable	38.4
Facility_4	Somewhat Uncomfortable	34.4	*MT_7*	Very Uncomfortable	56.3
Facility_5	Somewhat Comfortable	39.6	*MT_8*	Very Uncomfortable	45.0
Facility_6	Very Uncomfortable	56.2			
Facility_7	Somewhat Comfortable	34.8			
Facility_8	Very Comfortable	52.5			

[a] Values based on those who declared cycling at least once in the past year (active cyclists, n = 2456).

Figure 4.2 provides an overview of the routes used by the 100 respondents who participated in the optional mapping module. About one fifth of respondents described a utility route since they did not commute by bike regularly; the rest described their commute route. As would be expected, most routes are concentrated in central neighbourhoods where infrastructure, population, and destination densities are highest. The busiest link is the High Level Bridge, which is used by 24 of the respondents. Of the six centrally-located bridges available to cyclists to cross the North Saskatchewan River, the High Level Bridge is the only one that offers an almost at-grade crossing between the two banks, making it an essential cycling connection, particularly for commuting purposes.

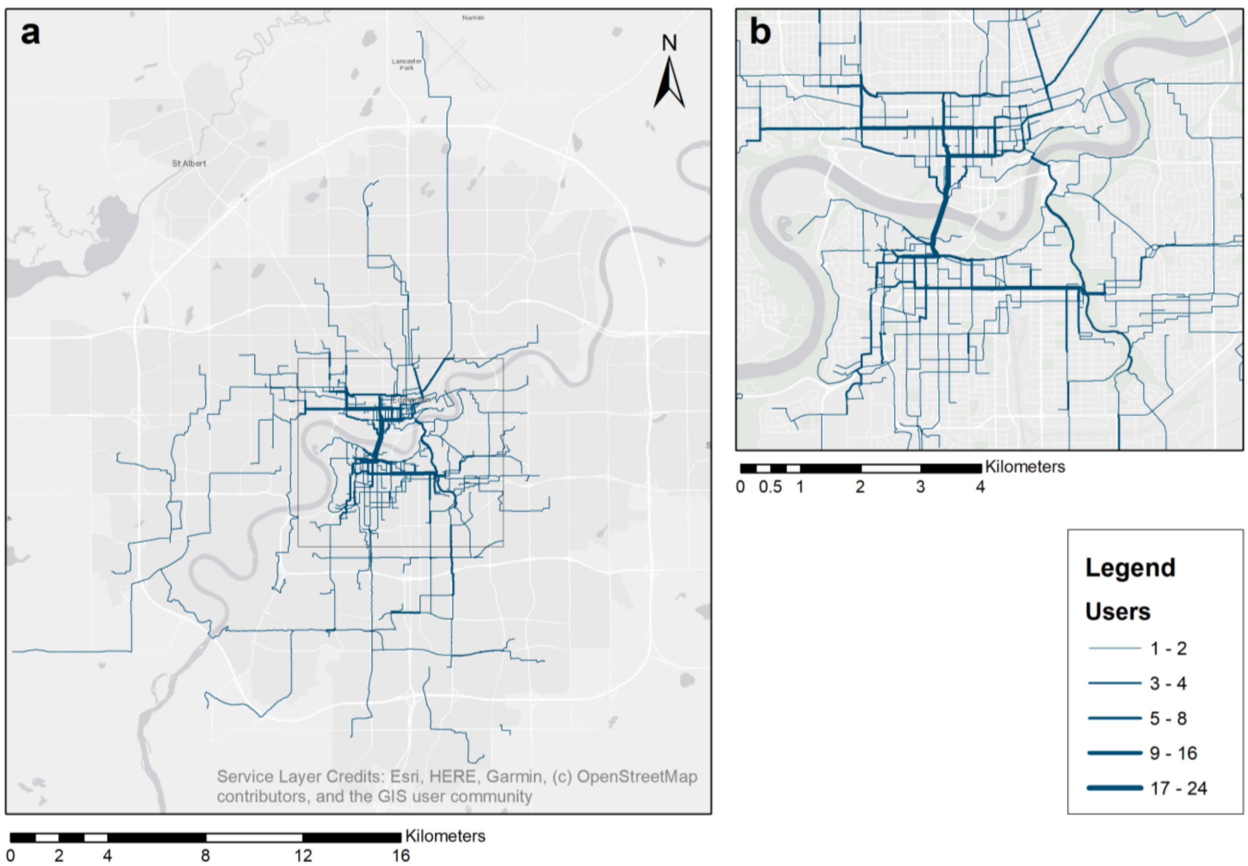


Figure 4.2 Mapping Module Route Overview: (a) All Routes (b) Central Routes

Table 4.6 displays summary statistics on the proportion of different types of facilities used by respondents on their route as well as the total route distance statistics. Note that the range, median and mean include null values to account for the respondents who do not use a particular type of facility on their route; the number of null values is also reported in Table 4.6. The median is reported alongside the mean since values are not normally distributed; the median may therefore be a better measure of central tendency. Riding on the road in mixed-traffic ("Street" in Table 4.6) represents the highest proportion of respondents' routes by far. This is followed by shared-use paths, and to a much lesser extent, protected bike lanes. This was expected as these types of infrastructure are the most common in Edmonton's network (in the case of shared use paths and streets) and the most centrally located and comfortable (in the case of protected bike lanes). All other facility types represent a fairly minor proportion of respondents' routes, overall.

The range of distances travelled is large, with a minimum of ~850 m (a parent riding with their young child to school) up to a 21-km commute.

Table 4.6 Proportion of Route Travelled on Different Types of Infrastructure and Total Route Length

Facility Type	# Null Values	Range	Median	Mean
Alley	43	0.0 – 20.7	1.3	2.9
Protected Bike Lane	35	0.0 – 81.5	7.7	15.4
Painted Bike Lane	64	0.0 – 40.0	0.0	4.1
Shared-Use Path	15	0.0 – 88.9	25.0	27.2
Street	2	0.0 – 100.0	32.2	37.2
Sidewalk	32	0.0 – 50.0	2.3	7.5
Stairs or Funicular	92	0.0 – 4.7	0.0	0.2
Other Path	76	0.0 – 19.0	0.0	1.0
Other	48	0.0 – 50.3	1.2	4.6
Total Distance (km)	0	0.85 – 21.0	5.25	6.61

4.5 Conclusion and Limitations

In this chapter we presented the research questions that prompted our development of the Bicycle Ridership and Traffic Stress Tolerance Survey. We then discussed the data collection effort and survey design, and presented summary statistics for the most important variables for this thesis.

The survey has several limitations, the first of which is the non-random sampling method used to obtain responses. Using the Insight Community and the City of Edmonton's online platform allowed us to conduct the survey at no cost, while benefitting from a well-designed interface, a large pool of respondents, and expert knowledge from City of Edmonton professionals. However, using this platform also has several drawbacks: the survey was administered online and in English only, which limited *de facto* the ability of certain populations of Edmontonians to answer, in particular lower-income groups, non-English speakers, visually impaired Edmontonians, those with limited access to the Internet, and those who do not have the required computer or reading literacy.

CHAPTER 5 AN EMPIRICAL REAPPRAISAL OF THE FOUR TYPES OF CYCLISTS

The research we present in this chapter grew from previously discussed issues with the Four Types of Cyclists typology (subjective development, inconsistencies in cycling frequency), as well as previous research results where we found cyclists to naturally form three categories rather than four when assessed using comfort variables (Cabral et al., 2018). Although and because the typology has been so widely adopted, more empirical testing and validation is warranted. Our hypothesis is that the Four Types of Cyclists do not adequately reflect the distribution of cyclist types. We propose a reappraisal of the Four Types of Cyclists based on an empirical segmentation method developed with the data collected in our survey. Our approach is to use variables as similar as possible to the original typology, such that any new segmentation that results can serve the same purpose as the Four Types of Cyclists. In particular, we aim to make our typology amenable to an LTS-like connectivity assessment framework with the objective of forming groups of cyclists of similar comfort level in a more consistent way, thus creating a solid basis for a more exact network assessment framework.

5.1 Literature Review: Cyclist Segmentation Methods

As noted in Chapter 2, there are multiple methods to develop cyclist typologies; Félix et al. (2017) divided two broad categories: top-down and bottom-up, which could be rephrased as expert knowledge-driven or data-driven. Of the latter category, a method borrowed from market segmentation research has been adopted in several empirical cyclist typology development papers: principal component analysis (PCA) followed by clustering (usually k-means). The PCA is first carried out using a series of variables of interest for the segmentation. This allows a reduction from a large set of variables to a limited number of underlying factors. Clustering is then applied to the reduced set of factors to yield a given number of cyclist types with similar characteristics. Using this method, different typologies can be derived based on the characteristics of interest for the researchers. For example, Damant-Sirois et al. (2014) defined four types of cyclists and then used the classification to measure the importance of different factors in determining the cycling frequency for each type (Damant-Sirois & El-Geneidy, 2015). The same segmentation methodology was used by Gatersleben and Haddad (2010) to define cyclist stereotypes. Their aim was not to segment cyclists *per se*, but rather to understand how cyclists are perceived by both cyclists and non-cyclists.

Two segmentations published more recently are noteworthy since their aim is in line with ours (defining cyclist types to uncover infrastructure preferences). Veillette et al. (2019) used the tandem PCA and k-means clustering method to define six types of cyclists. Using 29 variables grouped into nine factors by

PCA, their final typology after k-means clustering of factors includes urban, benefit-seeking, happy, picky-efficiency, childhood-influenced and indifferent cyclists. Their objective was to understand how the use of three types of facilities (recreational paths, bidirectional protected bike lanes, and painted lanes) was influenced by membership in each of the six categories. The purpose was to provide nuanced infrastructure preference information for each cyclist type to inform future infrastructure planning.

Griswold et al. (2018) sought to develop a new quantitative bicycle LOS measure, using latent class choice models to segment cyclists and uncover their infrastructure preferences in one integrated framework. The latent class model defined three types of cyclists based on demographics, experience, and cycling preferences: neighborhood, urban, and fitness cyclists. The class-specific models identify the specific infrastructure preferences for each cyclist type. The results were obtained from convenience sampling of a limited number of respondents (221 online and 14 in person); this means the three types defined should be considered with caution. Nonetheless, their work highlights that the three types are not on an ordinal scale of comfort, contrarily to the Four Types of Cyclists, and the authors argue that cyclist typologies developed specifically to help with infrastructure choice do not necessarily have to follow an ordinal pattern.

Overall, tandem PCA and k-means clustering is a well-recognized empirical method to segment cyclists. It requires at least a five-point Likert-type scale such that responses can be assimilated to continuous data (Markos et al., 2018). However, our video (Table 4.1) and facility description (Table 4.3) comfort ratings emulate Dill and McNeil's (2013) who required respondents to rate infrastructure descriptions on a four-point scale. These responses can hardly be assimilated to continuous data and should be treated as categorical. An equivalent PCA method for categorical variables is Multiple Component Analysis (MCA), which can be followed by k-means clustering to obtain similar segmentation results (Markos et al., 2018). However, it has been shown that this tandem approach, despite its popularity, does not yield the best possible results as the PCA/MCA and k-means clustering optimize different functions and the original dimension reduction can mask crucial variables to identify niche segments (Dolnicar & Grün, 2008; van de Velden et al., 2017). van de Velden et al. (2017) proposed Cluster Correspondence Analysis (CCA), a method that simultaneously reduces and clusters categorical data to create the segmentation. This method identifies cluster membership and category weights such that between cluster and between category variances are simultaneously maximized. Cluster membership and variable categories are cross-tabulated to this effect, allowing a single objective function to be maximized, thus eliminating the main drawback of the tandem approach. The mathematical details of the method are presented in (van de Velden et al., 2017).

CCA has been used to segment different populations into categories with similar characteristics. For example, in their demonstration of the R package *clustrd* (Markos et al., 2019), which implements CCA, Markos et al. (2018) identified groups of similar Indonesian women with respect to socio-economic factors and choice of contraceptive method. CCA results have also been used to make policy recommendations. This was the case in a study of student profiles (Papageorgiou et al., 2016), which aided in the identification of potential gaps in teaching instruments used to discuss the atom, and in the formulation of recommendations to address those gaps.

5.2 Methodology

We use CCA to derive the empirical segmentations using variables as close as possible to those used to determine membership in each of the Four Types of Cyclists. We also explore segmentations using other variables to better understand the characteristics of different types of cyclists (or non-cyclists) in Edmonton, resulting in four different segmentations that help answer the research question and shed light on different cyclist types.

1. 'Geller' Segmentation
   This segmentation is meant to be as close as possible to the Four Types of Cyclists as it includes the same input variables: the eight Facility variables, Intent, and Biked_S18.
2. 'Video Equivalent' Segmentation
   This segmentation is the same as the 'Geller' segmentation, but the eight Facility variables are replaced by the eight equivalent video clips listed in Table 4.1. We expect this segmentation to yield a more representative classification given video clips offer a more immersive experience, producing environments that can be more consistently perceived from person to person since respondents do not have to imagine the environments described.
3. 'All Videos' Segmentation
   All sixteen videos are included in this segmentation to capture comfort from a wider variety of cycling environments. The Intent variable is included again, but Biked_S18 is removed because exploratory segmentations showed it to be insignificant to cluster definition.
4. 'Frequency and Purpose' Segmentation
   This segmentation includes all sixteen videos and the Intent variable as well as the eight Frequency variables and the Purpose variable. As noted in the literature review, frequency and cycling purpose are often considered when defining cyclist typologies. We therefore added

these variables to our core segmentation variables and evaluated their influence on the typology. Our choice to include cycling frequency is also supported by the critique, mentioned in the literature review, that comfort relates poorly to cycling frequency in the Four Types of Cyclists typology.

For each set of potential variables, we used several diagnostic tools to determine the most appropriate number of clusters and dimensions. To compare different combinations, the *tuneclus* function in the *clustrd* package assesses average silhouette width (ASW, Rousseeuw (1987)), with higher values indicating better separation and more compact clusters (see Appendix 2 for computation). We also employed bootstrapping methods to assess cluster stability. The *global_bootclus* function iterates through numbers of clusters and returns adjusted Rand index (ARI) values; again, higher values indicate higher stability, with ARI > 0.8 considered an indication of good stability (Steinley, 2004). Finally, the *local_bootclus* function also uses a bootstrapping method to assess the stability of each cluster within a given solution with *m* clusters. The Jaccard index is returned and a cluster can be considered stable when the index is above 0.75 (Hennig, 2007). An appropriate number of clusters for each set of variables was determined using these diagnostic tools as well as considering the interpretability of the resulting clusters. For each set of variables, we evaluated solutions with three to eight clusters. The number of dimensions can range from 1 to *m*–1, where *m* is the number of clusters.

To understand the distinctive attributes of each cluster, we examine variable-categories (e.g. Intent = Strongly Disagree) with high standardized residuals. High values indicate a significantly higher observed frequency for a given variable-category in the cluster, compared with the observed frequency for all survey respondents. For large samples such as ours, the standardized residual values can be interpreted in a similar way to z-scores. Values of two and above are considered significant at the 95% level, and three and above, at the 99.9% level. Sample code to obtain ASW, ARI, and Jaccard Index values as well as the variable-categories and respective standardized residuals is provided in Appendix 3.

5.3 Findings

5.3.1 Four Types of Cyclists: Results from the Classic Cyclist Classification

We first classify survey respondents into the four types using Dill and McNeil's methodology (Dill & McNeil, 2013). Our sample is composed of 13.4% No Way No How, 70.3% Interested but Concerned, 11.1% Enthused and Confident, and 5.2% Strong and Fearless. Compared to results reported for 50 U.S. metropolitan areas (Dill & McNeil, 2016), our sample has a lower proportion of No Way No How and a higher proportion of Interested but Concerned. These differences can likely be attributed to our survey design, which did not use random sampling and thus, increased the likelihood of self-selection bias. In particular, respondents who accessed the survey through the open link rather than the Insight Community likely chose to participate because of an underlying interest in the subject of cycling. Other factors may also contribute to differences in cyclist type distribution. Edmonton has an extensive network of paved recreational trails along the River Valley and connected ravines. The lower proportion of No Way No How cyclists may in part be explained by the high use of these trails, resulting in fewer respondents considering trails as 'Very Uncomfortable' cycling environments. Finally, cycling culture is becoming more mainstream and interest may have increased in the years since Dill and McNeil (2016) collected their data. This may be particularly true for Edmonton, where significant active transportation investments (including bicycle infrastructure improvements and education campaigns) have taken place since 2017.

Table 5.1 shows some of the demographic and cycling characteristics for each of the four cyclist types, while Figure 5.1 shows the comfort ratings of the eight facility descriptions and the sixteen video clips, and Figure 5.2, the cycling frequency for each type of cyclist. These tables and figures serve as comparison points for the empirical segmentations. Some notable observations include the gender and age disparity, particularly between the No Way No How and Strong and Fearless groups (Table 5.1). The proportions of non-males and older adults are much higher in the No Way No How group.

As expected, Figure 5.1 shows that mixed traffic cycling environments on non-residential streets (Facility_4, Facility_6, and MT_3 to MT_8) are least comfortable for all groups, except the Strong and Fearless. Generally, separated trails (Facility_1, Path) are considered *very comfortable* by more respondents than the protected bike lanes (Facility_8, PBL_1 to PBL_3). Note that there is an interesting discrepancy in the Strong and Fearless group, who proportionally have more respondents who rate the above-mentioned separated paths and protected bike lanes as *somewhat uncomfortable* or *very uncomfortable* compared to the Interested but Concerned and Enthused and Confident. We hypothesize that is a reflection of the Strong and Fearless' likely preference for speed and directness. Members of this group likely engage in vehicular cycling; the windiness of paths and frequent stops/crowdedness of protected lanes may reduce their perception of comfort on these infrastructures. Finally, in line with observations from the original investigations in the Four Types of Cyclists (Dill & McNeil, 2013, 2016), Figure 5.2 shows that higher comfort does not necessarily correlate to higher cycling frequency, excluding the No Way No How group.

Table 5.1 Demographic and Cycling Characteristics for Classic 'Four Types of Cyclists' (Percent in Category)

Variable	No Way No How	Interested but Concerned	Enthused and Confident	Strong and Fearless
Gender				
Not male	57.0[a]	46.5[b]	40.2[c]	27.4[d]
Age†				
15 – 24	2.5[a]	4.3[a]	4.5[a]	5.4[a]
25 – 44	25.1[a]	52.6[b]	46.3[c]	29.8[a]
45 – 64	41.4[a]	33.1[b]	39.6[a]	51.8[c]
65 – 98	29.4[a]	9.4[b]	9.3[b]	10.7[b]
Income				
< 50,000	12.0[a]	8.8[a]	12.4[a]	12.5[a]
50,000 to 99,999	29.7[a]	27.3[a]	20.5[b]	17.3[b]
100,000 or more	32.6[a]	49.2[b]	52.5[b]	50.6[b]
Prefer not to answer	25.7[a]	14.7[b]	14.6[b]	19.6[ab]
Education†				
High school or less	16.3[a]	9.0[b]	9.8[b]	11.9[ab]
Technical school	33.6[a]	19.5[b]	21.6[b]	38.7[a]
University degree	49.4[a]	70.9[b]	67.4[b]	47.0[a]
Intent				
Somewhat or strongly agree	0.5[a]	79.0[b]	68.0[c]	35.1[d]
Purpose				
Recreation	5.5[a]	78.2[b]	77.2[b]	64.9[c]
Fitness	1.6[a]	46.9[b]	57.6[c]	45.8[b]
Utility	1.4[a]	55.9[b]	57.3[b]	37.5[c]
Commute	1.1[a]	46.8[b]	48.9[b]	24.4[c]
Biked in Summer 2018				
Yes	0.0[a]	86.2[b]	83.4[b]	77.4[c]
Last Biked				
*Never**	4.8[a]	0.4[b]	1.1[bc]	2.4[ac]
*In my childhood**	20.0[a]	1.3[b]	2.0[b]	0.6[b]
Several years ago	53.3[a]	6.0[b]	8.1[b]	14.9[c]
1-2 years ago	15.2[a]	4.0[b]	2.2[b]	3.0[b]
Within the last year	6.7[a]	88.3[b]	86.5[bc]	79.2[c]

Note: All variables are statistically significantly different (Chi-square, $p < 0.05$)

[a, b, c, d] Pairwise significant differences ($p < 0.05$). Cyclist types sharing the same letter for a given variable are not statistically different.

* Low-count cells: statistical significance must be considered with caution.

† *Prefer not to answer* category is negligible.

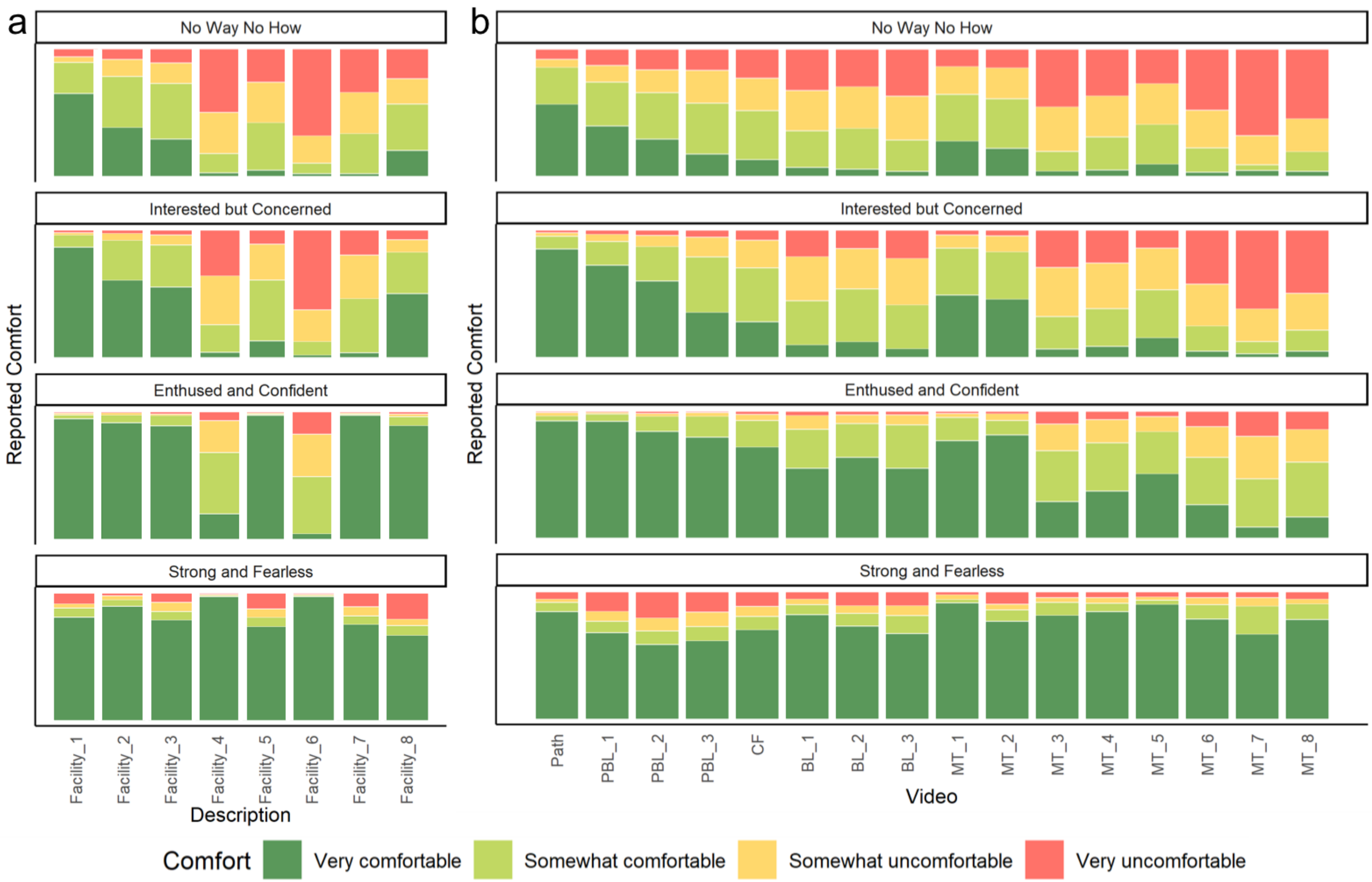


Figure 5.1 Stated Comfort for (a) Facility Descriptions and (b) Video Clips – Four Types of Cyclists

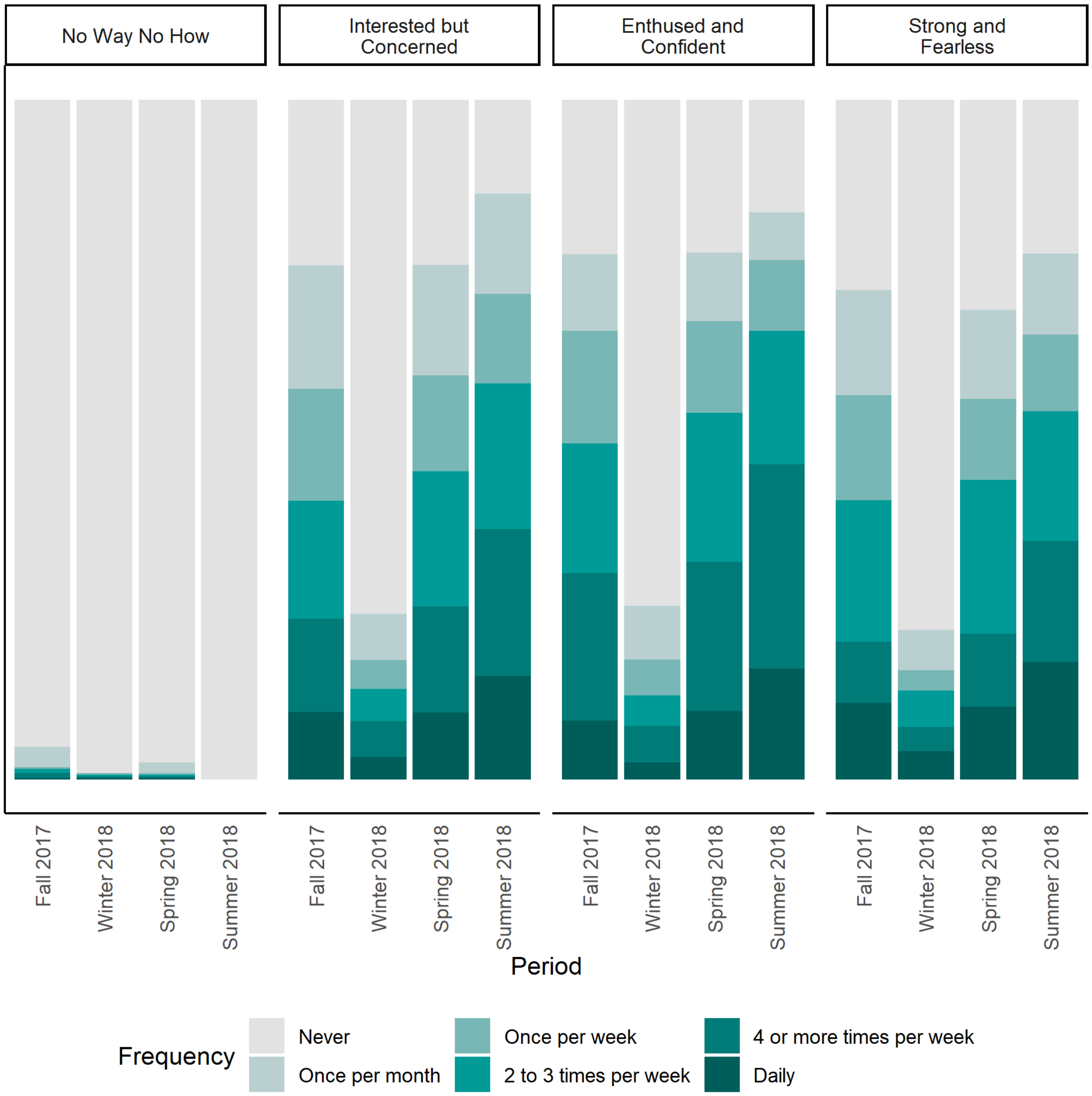


Figure 5.2 Proportion of the Stated Cycling Frequency per Season in the Previous Year for Each Cyclist Type – Four Types Of Cyclists

5.3.2 Empirical Segmentation through Cluster Correspondence Analysis

Table 5.2 shows test results on the clusters and sets of variable combinations considered. Although three to eight clusters were initially evaluated for all combinations, the solutions with five to eight clusters were systematically of lower quality. In the interest of space, Table 5.2 only reports results for solutions with three or four clusters. In all cases, the ideal number of dimensions to maximize the ASW (average silhouette width) value was *m* -1.

Table 5.2 Cluster Selection Statistics

Seg. Name	# of Clusters (*m*)	ASW[a]	ARI[b]				Jaccard Index (median)			
			Min	*Max*	*Mean*	*Median*	*Clus. 1*	*Clus. 2*	*Clus. 3*	*Clus. 4*
Geller	3	0.199	0.282	0.963	0.888	0.919	0.898	0.889	0.762	-
	4	0.161	0.424	0.953	0.878	0.909	0.846	0.789	0.826	0.520
Video Eq.	3	0.215	0.604	0.973	0.873	0.900	0.885	0.830	0.817	-
	4	0.181	0.659	0.960	0.867	0.884	0.881	0.800	0.911	0.609
All Videos	3	0.220	0.406	0.962	0.795	0.812	0.878	0.815	0.861	-
	4	0.177	0.600	0.967	0.851	0.858	0.886	0.902	0.888	0.769
Freq. Purpose	3	0.171	0.183	0.979	0.818	0.880	0.835	0.796	0.999	-
	4	0.166	0.598	0.957	0.844	0.867	0.862	0.849	0.997	0.908

[a] Average Silhouette Width (see p. 38 and Appendix) 3
[b] Adjusted Rand Index (see p. 38)

5.3.2.1 'Geller' and 'Video Equivalent' Segmentations

From Table 5.2, we observe that the best solution contains three clusters for both the 'Geller' and 'Video Equivalent' segmentations. Indeed, the highest ASW values are achieved with the three cluster solutions, which also have mean and median ARI values above 0.8, indicating good stability. Each of the three clusters in these solutions are also suitably stable. In contrast, the solutions with four clusters result in a fourth cluster below the 0.75 threshold in both cases. (Jaccard = 0.520 and 0.614, respectively).

Table 5.3 shows the significant variable-categories for each cluster created in the 'Geller' segmentation. The Facility_X label numbers refer to the facility descriptions stated in Table 4.3. Based on the variable-categories that define each cluster and on examination of the characteristics shown in Table 5.6 and Figure 5.3, a proposed descriptive name is also offered for each cluster. Recall that a variable-category deemed significant means the condition is over-represented in the cluster compared to the full surveyed population.

For the 'Geller' segmentation, the first cluster (n = 1979) can be identified as the Cautious Majority. Cyclists or potential cyclists in this group are likely to be *somewhat comfortable* or *somewhat uncomfortable* on non-residential streets with and without painted bike lanes. The description of a protected bike lane (*Facility_8*) is more likely to be rated as *somewhat comfortable* by this group than by the sample overall. The second largest cluster (n = 803) can be identified as Comfortable Cyclists, as they are more likely than the overall survey population to find all cycling environments comfortable. However, observing Figure 5.3a, we find that only 35% and 20% of respondents in this group rate *Facility_4* and

Facility_6 –non-residential streets without bike lanes– as *very comfortable*, respectively. Indeed, this group is also more likely to rate these two cycling environments as *somewhat comfortable*, according to Table 5.3. Hence, this group's label does not include a qualifier such as 'very comfortable' like the video equivalent segmentation does. Finally, the least comfortable cyclists or non-cyclists dominate in the third cluster (n = 426). This segment is most likely to find all descriptions uncomfortable. Residential streets and trails are more likely to be rated as *somewhat uncomfortable* by the respondents in this group. Intent and cycling in the previous summer are significant variable-categories only for this group: respondents are more likely to strongly disagree with the statement about wanting to travel by bike more often and are more likely not to have cycled in the past summer; this group is therefore labeled Uncomfortable or Uninterested.

Table 5.3 Significant Variable-Categories – 'Geller' Segmentation

Cluster # 1 (61.7%) *Description: Cautious Majority*		
Variable		*Category*
Facility_4, Facility_5*, Facility_7*	=	Somewhat Uncomfortable
Facility_2, Facility_3, Facility_5*, Facility_7, Facility_8	=	Somewhat Comfortable
Cluster #2 (25.0%) *Description: Comfortable Cyclists*		
Variable		*Category*
Facility_4*, Facility_6*	=	Somewhat Comfortable
Facility_2*, Facility_3*, Facility_4*, Facility_5*, Facility_6*, Facility_7*, Facility_8*	=	Very Comfortable
Cluster #3 (13.3%) *Description: Uncomfortable or Uninterested*		
Variable		*Category*
Facility_1*, Facility_2*, Facility_3*, Facility_4*, Facility_5*, Facility_6, Facility_7*, Facility_8*	=	Very Uncomfortable
Facility_1, Facility_2*, Facility_3*	=	Somewhat Uncomfortable
Facility_1	=	Somewhat Comfortable
Intent*	=	Strongly Disagree
Biked_S18*	=	Never

Note: All variable categories have at least standardized residuals > 2
* Standardized residuals > 3.

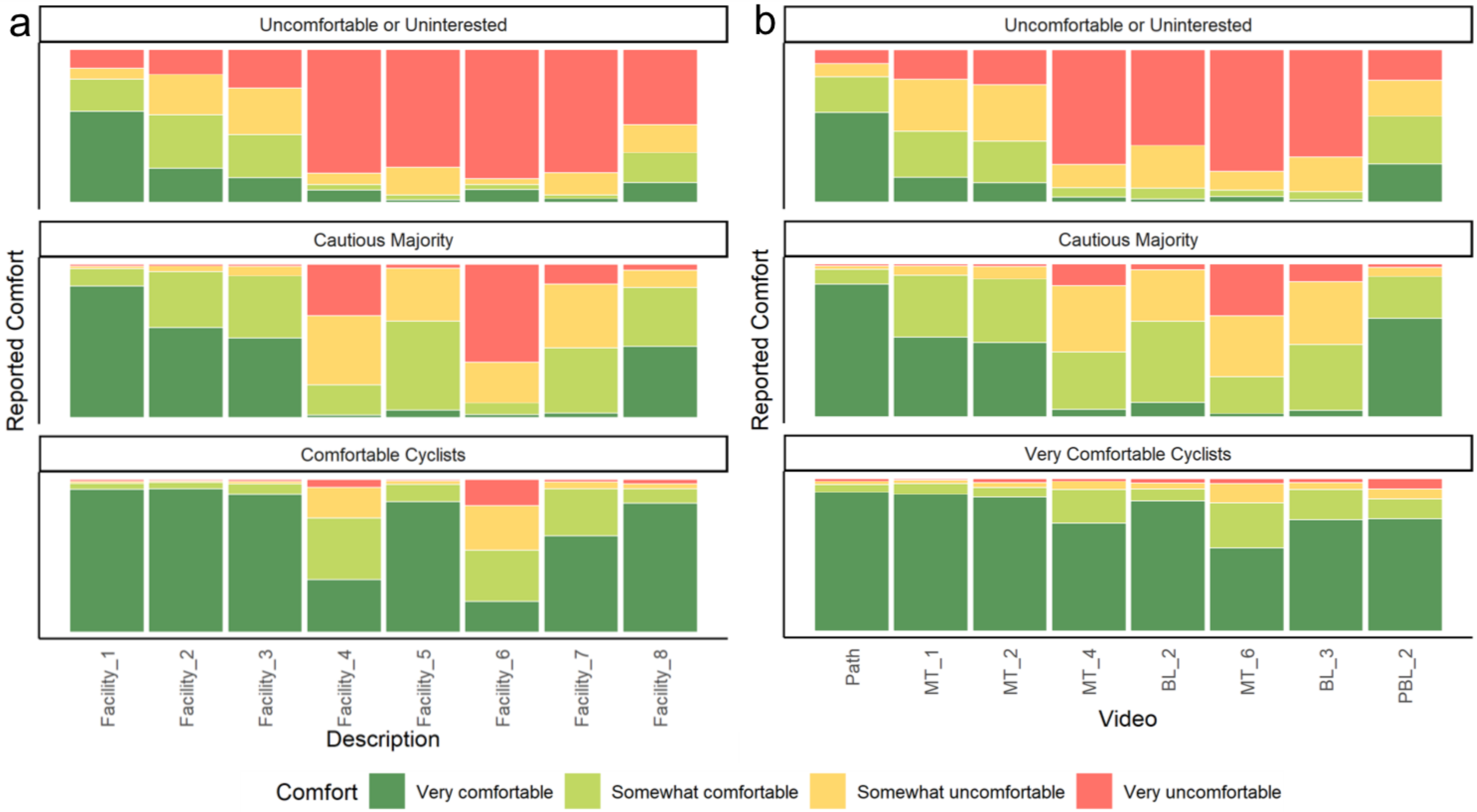


Figure 5.3 Stated Comfort for (a) Facility Descriptions for the 'Geller' Segmentation and (b) Video Clips for the 'Video Equivalent' Segmentation

Table 5.4 shows the significant variable-categories for the three clusters in the 'Video Equivalent' segmentation. Overall, the characteristics of the three clusters are similar to the one obtained in the 'Geller' segmentation. The same observations about the roles of intent and cycling in the previous summer hold. The examination of comfort ratings, presented in Figure 5.3, also shows the majority of respondents in the most comfortable group rate the least cyclist-friendly videos (MT_4 and MT_6) as *very comfortable*. These contrasts between the two segmentations prompted a change in nomenclature for the most comfortable group; they are named Very Comfortable Cyclists in the 'Video Equivalent' segmentation.

Compared to the 'Geller' segmentation, the proportion of respondents in each cluster of the 'Video Equivalent' segmentation changes: the Cautious Majority cluster (n = 2075) gains membership, and the Uncomfortable or Uninterested cluster (n = 618) becomes larger than the Very Comfortable Cyclists (n = 515). Consistent with the changes in proportions, a cross-classification between the two segmentations (not shown) indicates a reclassification of some Comfortable Cyclists as Cautious Majority, and of some in the Cautious Majority group as Uncomfortable or Uninterested in 'Video Equivalent'. The most comfortable cluster shrinks in size from 25% to 16% of respondents.

Table 5.4 Significant Variable-Categories – 'Video Equivalent' Segmentation

Cluster # 1 (64.7%) *Description: Cautious Majority*		
Variable		*Category*
BL_3, MT_4*, MT_6	=	Somewhat Uncomfortable
BL_2*, BL_3, MT_2, MT_4	=	Somewhat Comfortable
Cluster #2 (19.3%) *Description: Uncomfortable or Uninterested*		
Variable		*Category*
Path*, PBL_2*, BL_2*, BL_3*, MT_1*, MT_2*, MT_4*, MT_6*	=	Very Uncomfortable
Path, PBL_2*, MT_1*, MT_2*	=	Somewhat Uncomfortable
Path	=	Somewhat Comfortable
Intent	=	Strongly Disagree
Biked_S18	=	Never
Cluster #3 (16.0%) *Description: Very Comfortable Cyclists*		
Variable		*Category*
BL_2*, BL_3*, MT_1*, MT_2*, MT_4*, MT_6*	=	Very Comfortable

Note: All variable-categories have at least standardized residuals > 2
* Standardized residuals > 3.

The typologies obtained using cluster correspondence analysis differ in several ways from the Four Types of Cyclists. The most obvious distinction is the presence of three classes rather than four. This finding is consistent with results shared in previous work by the authors, where a factor analysis on facility descriptions resulted in three groups being defined (Cabral et al., 2018). A cross-classification of the membership in the Four Types of Cyclists against the two empirical segmentations presented thus far (Table 5.5) shows two important redistributions of the class membership. First, only 27%/50% (‘Geller’/‘Video Equivalent’, respectively) of No Way No How are classified as Uncomfortable or Uninterested (first cell of Table 5.5 for each segmentation divided by row sum). Second, the Uncomfortable or Uninterested cluster is composed of 36%/35% No Way No How and 58%/61% Interested but Concerned (first cell of Table 5.5 for each segmentation divided by column sum). The redistribution is also present for the next level of cyclists, although in a less pronounced way: about 76% (both ‘Geller’/‘Video Equivalent’) of the Interested but Concerned are reclassified as Cautious Majority, while the Cautious Majority cluster is composed at 86%/83% of respondents categorized as Interested but Concerned. Most of the Enthused and Confident and Strong and Fearless fall in the third cluster.

Another major difference is the role of the Intent variable. As noted before, Intent is only a significant variable-category for the Uncomfortable or Uninterested group, where respondents are more likely to strongly disagree they would like to travel by bicycle more often than they do now compared to the full sample of respondents. The proportion of those who would like to cycle more often is similar for the two more comfortable groups, and it does not significantly contribute to defining these cluster memberships.

Table 5.5 Cross-classification between Four Types of Cyclists and Empirical ‘Geller’ and ‘Video Equivalent’ Segmentations

	‘Geller’ Segmentation			**‘Video Equivalent’ Segmentation**		
	Uncomf. or Unint.	*Cautious Majority*	*Comf. Cyclists*	*Uncomf. or Unint.*	*Cautious Majority*	*Very Comf. Cyclists*
No Way No How	152	273	10	216	205	14
Interested but Concerned	249	1704	296	376	1722	151
Enthused and Confident	1	1	354	10	139	207
Strong and Fearless	24	1	143	16	9	143

Table 5.6 and Figure 5.4 display demographic and cycling characteristics for each of the three cyclist types defined in our empirical ‘Geller’ and ‘Video Equivalent’ segmentations. Table 5.6 shows the gender

disparity between groups, with non-male respondents in significantly higher proportion in the Uncomfortable or Uninterested compared to Comfortable Cyclists. The disparity is also significant between Uncomfortable or Uninterested and the Cautious Majority in the 'Video Equivalent' segmentation, but not for the 'Geller' segmentation. Again, the immersive nature of the videos may explain some of those differences by limiting the part imagination may play in assessing comfort. The observed trend for gender is in line with the literature (Heinen et al., 2010; Sener et al., 2009), but not as important as observed in the Four Types of Cyclists typology (Table 5.1). The age disparity also holds in the empirical segmentations, with a significantly higher proportion of older adults as part of the Uncomfortable or Uninterested group. Lower income and university education attainment are also significant traits for this group.

Table 5.6 also shows that, as expected, the Uncomfortable or Uninterested have the lowest proportion of respondents who agree with the statement of intent to cycle more often. The highest proportion is found in the Cautious Majority. The comparatively lower proportion of (Very) Comfortable Cyclists who agree with the statement could be attributed to the already higher cycling frequency observed in this group (Figure 5.4); these respondents may be content with their current cycling levels.

The empirical segmentations yield more homogeneous groups when it comes to the comfort ratings compared to the classic Four Types of Cyclists. This is particularly noticeable for the Uncomfortable or Uninterested groups in Figure 5.3; as compared to the No Way No How (Figure 5.1), the empirical clusters for both segmentations group cyclists who are mostly *very uncomfortable* on a majority of facilities, which is not the case in the Four Types classification.

A critique of the Four Types concerns class membership, which is not correlated to cycling frequency; this is also confirmed by Figure 5.2, where the Interested but Concerned and Enthused and Confident generally cycle more often than the Strong and Fearless. One hypothesis is that some cyclists who fall in the Strong and Fearless category are likely to be weekend road cyclists who use highways and rural roads, and thus have a high tolerance for roadways without cycling-specific infrastructure. In our segmentation, the highest comfort group includes more cyclists than the stereotypical Strong and Fearless; the particularities of these Strong and Fearless cyclists are therefore likely to be masked by characteristics of the rest of the (Very) Comfortable Cyclist groups.

Table 5.6 Demographic and Cycling Characteristics for 'Geller' and 'Video Equivalent' Empirical Segmentations (Percent in Category)

Variable	'Geller' Segmentation			'Video Equivalent' Segmentation		
	Uncomf. or Unint.	*Cautious Majority*	*Comf. Cyclists*	*Uncomf. or Unint.*	*Cautious Majority*	*Very Comf. Cyclists*
Gender						
Not male	50.0[a]	48.9[a]	37.6[b]	53.6[x]	47.5[y]	32.4[z]
Age†						
15 – 24	3.3[a]	3.9[a]	5.0[a]	2.8[a]	4.5[a]	4.3[a]
25 – 44	39.2[a]	49.4[b]	45.2[c]	40.0[a]	51.3[b]	38.3[a]
45 – 64	35.9[a]	34.6[a]	39.2[a]	37.2[a]	32.8[b]	47.2[c]
65 – 98	19.7[a]	11.4[b]	10.0[b]	18.8[a]	10.8[b]	9.5[b]
Income						
< 50,000	10.6[a]	9.3[a]	10.8[a]	10.0[a]	9.3[a]	11.7[a]
50,000 to 99,999	25.1[ab]	28.1[a]	22.4[b]	25.6[ab]	27.6[a]	21.9[b]
100,000 or more	40.1[a]	47.1[b]	51.9[c]	40.8[a]	48.6[b]	50.5[b]
Prefer not to answer	24.2[a]	15.4[b]	14.8[b]	23.6[a]	14.4[b]	15.9[b]
Education†						
High school or less	10.8[a]	10.0[a]	10.5[a]	11.7[a]	9.5[a]	11.5[a]
Technical school	31.5[a]	21.0[b]	22.2[b]	26.5[a]	21.2[b]	23.9[ab]
University degree	56.6[a]	68.4[b]	66.6[b]	60.5[a]	68.9[b]	63.3[a]
Intent						
Somewhat or strongly agree	37.8[a]	70.1[b]	66.0[c]	43.4[x]	73.1[y]	57.3[z]
Purpose						
Recreation	44.1[a]	68.4[b]	77.8[c]	42.6[x]	73.4[y]	73.6[y]
Fitness	22.3[a]	40.2[b]	56.3[c]	20.6[x]	44.6[y]	56.5[z]
Utility	20.4[a]	48.8[b]	59.4[c]	21.2[x]	54.5[y]	52.2[y]
Commute	16.9[a]	41.8[b]	46.5[c]	16.8[x]	45.7[y]	42.7[y]
Biked in Summer 18						
Yes	48.4[a]	73.7[b]	87.3[c]	45.8[x]	79.9[y]	82.7[y]
Last Biked						
*Never**	3.3[a]	1.0[b]	0.6[b]	2.8[x]	0.8[y]	1.0[xy]
In my childhood	10.8[a]	3.6[b]	0.9[c]	10.5[x]	2.6[y]	1.2[y]
Several years ago	26.3[a]	12.4[b]	7.8[c]	28.3[x]	9.0[y]	11.3[y]
1-2 years ago	7.7[a]	6.3[a]	1.5[b]	8.3[x]	5.1[y]	2.3[z]
Within the last year	51.9[a]	76.8[b]	89.2[c]	50.2[x]	82.5[y]	84.3[y]

Note: All variables are statistically significantly different (Chi-square, $p < 0.05$)

[a, b, c,] Pairwise significant differences ($p < 0.05$) for 'Geller' segmentation. Cyclist types sharing the same letter for a given variable are not statistically different.

[x, y, z] Pairwise significant differences ($p < 0.05$) for 'Video Equivalent' segmentation.

* Low-count cells: statistical significance must be considered with caution.

† *Prefer not to answer* category is negligible.

From Figure 5.4, we can see that although cycling frequency is not a variable included in the empirical segmentations presented thus far, frequency does increase with greater comfort. This does not mean that Uncomfortable or Uninterested cyclists never cycle; on the contrary, we can find daily cyclists in all categories. However, the proportion of daily or frequent cyclists grows, as expected, with increased cycling comfort. We can hypothesize that the uncomfortable cyclists who cycle frequently may do so recreationally, or may live in a neighborhood with an adequate supply of infrastructure that is considered highly comfortable across the entire population, enabling them to reach their main destinations.

Finally, another interesting observation from Figure 5.4 is the winter cycling rate. While cycling frequency largely drops in winter for all cyclist types, relatively high cycling frequency (once a week or more) follows a pronounced progression with comfort level. Based on the 'Video Equivalent' segmentation, 7.4% (n = 46) of Uncomfortable or Uninterested, 15.9% (n = 330) of the Cautious Majority, and 21.9% (n = 113) of Very Comfortable Cyclists continue to cycle at least once a week in winter. Cycling in winter requires a few additional skills to adjust to slippery and dark conditions. Higher comfort as measured through our survey instrument may be correlated with higher comfort in these winter conditions, which would explain the progression observed.

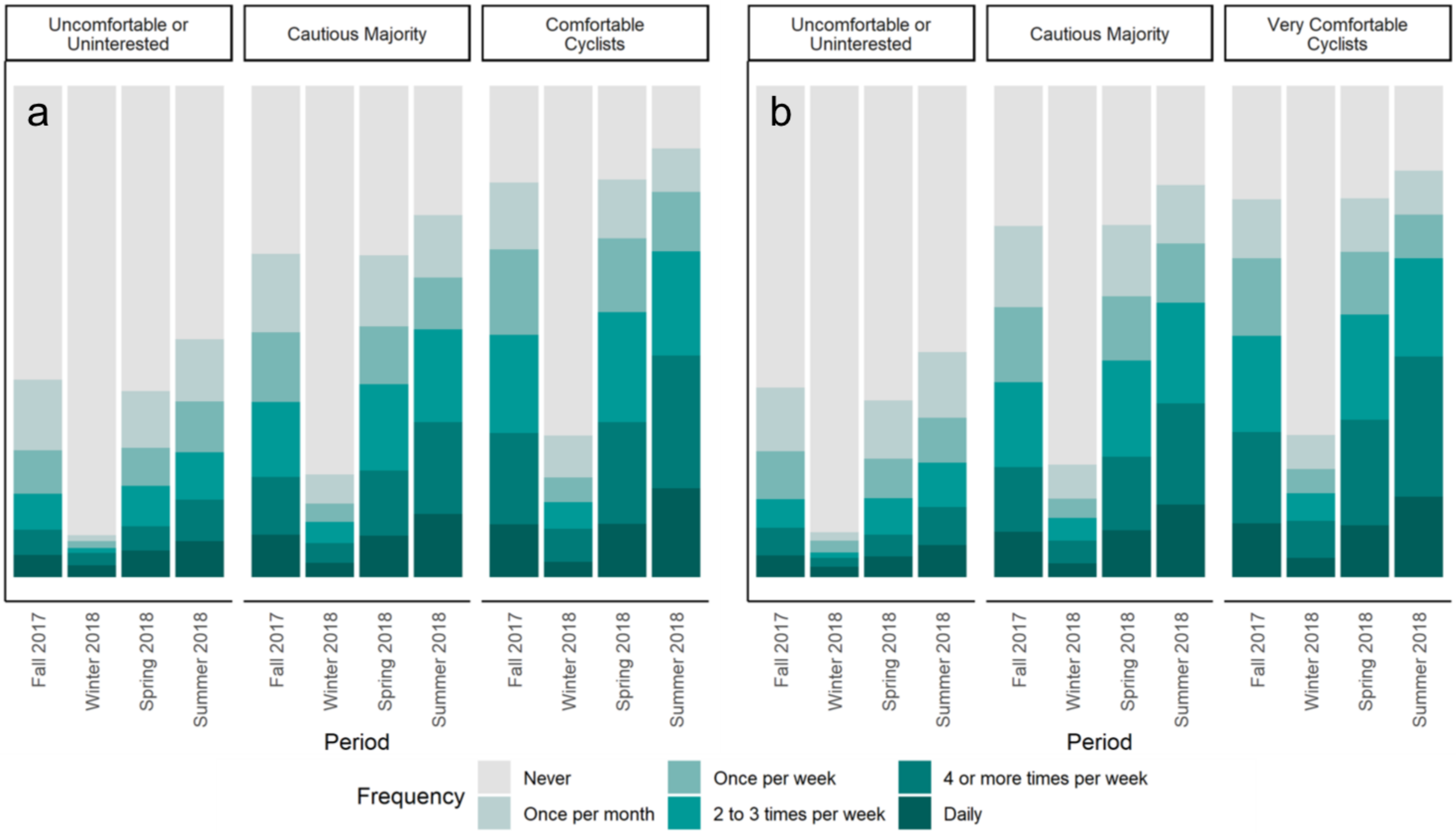


Figure 5.4 Proportion of the Stated Cycling Frequency per Season in the Previous Year for Each Cyclist tyTe – (a) 'Geller' Segmentation and (b) 'Video Equivalent' Segmentation

5.3.2.2 'All Videos' Segmentation

Including all videos in this segmentation allows a wider array of cycling environments to be considered in determining a cyclist type. Notably, the cycling environments depicted in the videos include different types of protected bike lanes, a contra-flow bike lane, and a variety of land use types and densities.

Table 5.2 suggests both the three-cluster and four-cluster solutions would be reasonable choices; while the three-cluster solution has a higher ASW value, the global (ARI) and local (Jaccard Index) stability of the four-cluster solution is superior. A quick assessment of the three-cluster solution showed the results were very similar to those obtained from the 'Video Equivalent' segmentation, with the same three types of cyclists represented in comparable proportions. This supports our hypothesis that the (potential) cyclist population is best described by three groups rather than four. However, in the interest of gaining a more detailed understanding, we examine the four-cluster solution in this section. Again, this solution delivers a high quality and stable segmentation. The significant variable-categories and proposed cluster names for this typology are presented in Table 5.7.

Once again, the intent variable is only significant for the most uncomfortable cluster (Uncomfortable or Uninterested), with this group more likely to strongly disagree that they would like to cycle more often compared with the entire surveyed population. When we observe the detailed comfort ratings for each video, presented in Figure 5.5, we can see that only the Path video clip is considered *very comfortable* by a majority of respondents in this group, certainly justifying the "Uncomfortable" part of the Uncomfortable or Uninterested characterization.

The next cluster is largely defined by respondents who are *somewhat uncomfortable* on major streets with bike lanes, and *very uncomfortable* without bike lanes. Residential streets without bike lanes (MT_1 and MT_2) are considered only *somewhat comfortable* by a large proportion of respondents in this cluster (Figure 5.5). The group, Protection Seekers, look for as much physical separation from motorized vehicles as possible, and are *very comfortable* in locations with common traits: the Path and two protected bike lanes with at least a concrete median (PBL_1) or bollards (PBL_2). Note that the third location that features a 'protected' bike lane, PBL_3, is not considered as favorably by this group; the particular section of the protected network shown in the video clip only has stencil markings since it is an area with many residential driveways.

Table 5.7 Significant Variable-Categories – 'All Videos' Segmentation

Cluster # 1 (39.6%) *Description: Protection Seekers*		
Variable		*Category*
MT_3, MT_4, MT_6*, MT_7*, MT_8*	=	Very Uncomfortable
CF, BL_1*, BL_2*, BL_3*, MT_4, MT_5*	=	Somewhat Uncomfortable
PBL_3, MT_1, MT_2	=	Somewhat Comfortable
Cluster #2 (38.0%) *Description: Cautious Cyclists*		
Variable		*Category*
MT_7*, MT_8	=	Somewhat Uncomfortable
BL_1*, BL_2*, BL_3*, MT_3*, MT_4*, MT_5*, MT_6*, MT_8*	=	Somewhat Comfortable
PBL_3, CF, MT_2	=	Very Comfortable
Cluster #3 (12.6%) *Description: Very Comfortable Cyclists*		
Variable		*Category*
PBL_3, CF*, BL_1*, BL_2*, BL_3*, MT_1, MT_2, MT_3*, MT_4*, MT_5*, MT_6*, MT_7*, MT_8*	=	Very Comfortable
MT_7*	=	Somewhat Comfortable
Cluster #4 (12.9%) *Description: Uncomfortable or Uninterested*		
Variable		*Category*
All videos†	=	Very Uncomfortable
Path, PBL_1*, PBL_2, PBL_3, MT_1, MT_2	=	Somewhat Uncomfortable
Intent*	=	Strongly Disagree

Note: All variable-categories have at least standardized residuals > 2
* Standardized residuals > 3
† Standardized residuals > 3 for all, except MT_7, with std. res. > 2.

Cautious Cyclists are generally *somewhat comfortable* on major streets with bike lanes, and even on some without bike lanes. Some of the videos rated as least comfortable by the surveyed respondents (MT_6, MT_7, and MT_8) can be *somewhat uncomfortable* for the Cautious Cyclists (Figure 5.5). This group is also characterized by high comfort on residential streets and protected lanes.

Finally, the last group is Very Comfortable Cyclists. Most locations shown in the video clips are very comfortable for respondents in this group. The three video clips rated as least comfortable by the entire surveyed population do have a smaller proportion of *very comfortable* ratings, although only MT_7 has less than 50% *very comfortable* ratings. Nonetheless, we decided to forgo the 'Fearless' terminology, as truly fearless cyclists are likely only a fraction of this group. Informal discussions with members of the Edmonton cycling community highlighted that many cyclists who are very comfortable in high stress environments feel this way because they have extensive experience, know what to look out for, and how to behave to be predictable and be seen. Having no fears has little to do with their comfort; rather they master fears by taking control of the situation as much as possible.

Figure 5.5 Stated comfort for video clips – 'All Videos' segmentation

Our segmentation and nomenclature seem to uncover quite a steep step in comfort between the Cautious Cyclists and the Very Comfortable Cyclists. It is difficult to ascertain whether this is an artefact of the survey instrument, which uses a four-point scale and therefore has little nuance, or if there is truly a stark contrast in cyclist comfort, potentially related to experience or frequency of riding. This will need to be investigated further in future work. Cycling frequency is indeed higher than in other groups for the Very Comfortable Cyclists – the progression observed in the previous segmentations is also valid here – although the differences are not as pronounced.

Contrasting with the classic Four Types of Cyclists, this version of the empirical segmentation suggests there are two 'extreme' groups that are highly uncomfortable or highly comfortable, and that the majority of cyclists are divided between two levels of cautiousness. A cross-classification of the two typologies is presented in Table 5.8; had the two corresponded perfectly, the matrix would have been diagonal. However, this is not the case and we can see Interested but Concerned are largely redistributed between Protection Seekers and Cautious Cyclists, whereas Enthused and Confident and Strong and Fearless are largely collapsed into the Very Comfortable Cyclists group. We conclude that the 'All Videos' empirical segmentation removes focus from the more confident cyclists (Strong and Fearless and Enthused and Confident) and rather uncovers differences in the large group of cyclists who are neither generally *very comfortable* nor *very uncomfortable* in most cycling environments. This results in the definition of two cautious groups: Protection Seekers and Cautious Cyclists.

Table 5.8 contains 18 surprising reclassifications: 10 No Way No How are considered Very Comfortable Cyclists in this segmentation, and 8 Strong and Fearless, as Uncomfortable or Uninterested. A closer look at the first ten cases indicates the respondents did not rate Facility_4 to Facility_7 as *very comfortable*, which means they were automatically considered either No Way No How or Interested but Concerned. Because none had cycled in the last two years and all but one strongly or somewhat disagreed they would like to cycle more often, they were classified as No Way No How. The ratings for the videos equivalent to those four descriptions (MT_4, BL_2, MT_6, and BL_3) were much more positive, which explains why the 'All Videos' segmentation classified those respondents as Very Comfortable Cyclists. It could very well be argued that these respondents belong more intuitively in the Uncomfortable or Uninterested group since they do not cycle and have no intention of cycling in the future. On the other hand, the second set of eight cases contains respondents who rated Facility_4 and Facility_6 as *very comfortable*, automatically classifying them as Strong and Fearless. However, their ratings of the equivalent videos (MT_4 and MT_6) were on the uncomfortable side, as were many other video ratings. All eight also strongly disagreed they would like to cycle more often. Arguably, they are best classified as Uncomfortable or Uninterested rather than as Strong and Fearless. These discrepancies point to the difficulties inherent in creating summary categories to describe a wide variety of different cyclists and non-cyclists in one unified framework. No typology is able to fully capture the variety of cyclist comfort, intent, and cycling frequency. However, our methodology defines within-group comfort rating patterns that are more homogeneous than that of the Four Types of Cyclists.

Despite being very comfortable, Very Comfortable Cyclists do appreciate at least minimal cycling infrastructure on major arterials, as demonstrated by the lower proportion of *very comfortable* ratings attributed to the MT_6, MT_7, and MT_8 videos (Figure 5.5), which depict high-stress arterials without bike lanes. As opposed to Strong and Fearless, for which we usually plan no specific infrastructure, Very Comfortable Cyclists may still appreciate and benefit from some accommodations in particular parts of an urban transportation network.

Table 5.8 Cross-classification Between Four Types of Cyclists and Empirical 'All Videos' Segmentation

	Uncomf. or Uninterested	Protection Seekers	Cautious Cyclists	Very Comf. Cyclists
No Way No How	121	189	115	10
Interested but Concerned	184	1048	917	100
Enthused and Confident	2	31	176	147
Strong and Fearless	8	3	10	147

Finally, Table 5.9 presents the same demographic and cycling characteristics discussed for the other segmentations. The gender disparity is observed again, although the proportion of non-male respondents is not significantly different between the Uncomfortable or Uninterested and the Protection Seekers. Age, income, and education seem to follow a relatively similar pattern to the Four Types of Cyclists typology. The general trend for the Intent variable is also similar to that observed in the other segmentations, although values are more contrasted. As with other segmentations, there is a small percentage of respondents in each group who have never cycled or last cycled in their childhood; the highest frequency is, not surprisingly, found in the Uncomfortable or Uninterested group.

Table 5.9 Demographic and Cycling Characteristics for 'All Videos' Empirical Segmentation (Percent in Category)

Variable	Uncomfortable or Uninterested	Protection-Seekers	Cautious Cyclists	Very Comfortable Cyclists
Gender				
Not male	52.4[a]	53.7[a]	42.2[b]	30.2[c]
Age†				
15 – 24	2.9[a]	4.4[a]	4.1[a]	4.2[a]
25 – 44	37.5[a]	52.4[b]	46.6[c]	38.9[a]
45 – 64	38.4[a]	30.7[b]	37.0[a]	47.3[c]
65 – 98	19.4[a]	11.9[b]	11.7[b]	8.7[b]
Income				
< 50,000	11.4[a]	10.1[a]	8.6[a]	11.4[a]
50,000 to 99,999	23.8[a]	28.2[a]	26.4[a]	22.0[a]
100,000 or more	37.5[a]	47.0[b]	50.3[b]	47.8[b]
Prefer not to answer	27.3[a]	14.6[b]	14.7[b]	18.8[b]
Education†				
High school or less	13.0[a]	9.8[a]	9.5[a]	11.4[a]
Technical school	30.8[a]	20.0[b]	22.0[bc]	26.7[ac]
University degree	55.2[a]	69.7[b]	68.0[b]	59.7[a]
Intent				
Somewhat or strongly agree	33.7[a]	71.9[b]	70.0[b]	51.2[c]
Purpose				
Recreation	43.2[a]	64.7[b]	74.8[c]	73.5[c]
Fitness	19.0[a]	38.6[b]	46.6[c]	55.7[d]
Utility	14.9[a]	47.4[b]	55.6[c]	50.5[bc]
Commute	11.4[a]	40.5[b]	46.5[c]	38.6[b]
Biked in Summer '18				
Yes	45.4[a]	71.2[b]	81.0[c]	81.9[c]
Last Biked				
*Never**	2.5[a]	1.3[a]	0.8[a]	1.0[a]
In my childhood	12.1[a]	4.3[b]	2.2[c]	1.0[c]
Several years ago	29.2[a]	13.3[b]	9.0[c]	12.1[bc]
1-2 years ago	6.7[ab]	6.8[a]	4.4[bc]	2.0[c]
Within the last year	49.5[a]	74.3[b]	83.5[c]	83.9[c]

Note: All variables are statistically significantly different (Chi-square, $p < 0.05$)

[a, b, c,] Pairwise significant differences ($p < 0.05$). Cyclist types sharing the same letter for a given variable are not statistically different.

* Low-count cells: statistical significance must be considered with caution

5.3.2.3 'Frequency and Purpose' Segmentation

For this final segmentation, Table 5.2 shows that both the three-cluster and four-cluster segmentations would be suitable candidates.

An examination of the three-cluster solution showed unintuitive results that are unlikely to generate a useful typology. Indeed, a very small and highly stable cluster (9.4% of respondents) corresponded to year-round daily commuters while the remainder were divided between somewhat to very uncomfortable cyclists (38.1%) and everybody else (52.5%), generally on the more comfortable side. These two large clusters had quite heterogeneous within-cluster infrastructure preferences, such that application for active transportation policy and planning would be difficult.

The examination of the four-cluster solution yielded a segmentation that retained the year-round daily commuter cluster, but assigned all remaining respondents in a similar fashion to the 'Video Equivalent' segmentation, making this typology easier to interpret and more useful than the three-cluster solution discussed above. The significant variable-categories for this segmentation are presented in Table 5.10. Once again, the intent variable is only significant for the Uncomfortable or Uninterested cluster, and follows the same trend as is the other segmentations.

Interestingly, the Year-round Daily Commuters cluster is only defined by cycling frequency and purpose variables; none of the video clip variables actively contribute to defining class membership. Cycling frequency is simply a more salient characteristic for this group compared to comfort. This is reflected in the comfort ratings for each location, as shown in Figure 5.6. While the within-group ratings are relatively homogenous for a given location for the first three groups, Year-round Daily Commuters often have a more varied distribution among the four levels of comfort. This is particularly true of the mixed traffic and bicycle lane locations. The heterogeneous response patterns in this group indicates that not all highly dedicated cyclists are necessarily very comfortable cyclists. Put in other terms, it is not necessary to be a very confident cyclist to undertake daily bicycle commuting. This finding corroborates the existence of a wide range of cycling determinants of which comfort is only one element. Access to suitable infrastructure and proximity of destinations play an important role, as do many other determinants, including psychological factors (Cole-Hunter et al., 2015; Heinen et al., 2010). The repetitive nature of commuting may also explain in part the heterogeneity observed: the commuter's particular route becomes acceptable because of familiarity. It does not imply high comfort on other routes, even with a similar supply of infrastructure.

Table 5.10 Significant Variable-Categories – 'Frequency and Purpose' Segmentation

Cluster # 1 (53.5%) *Description: Cautious Majority*		
Variable		*Category*
BL_1, BL_2, MT_5	=	Somewhat Comfortable
Cluster #2 (23.5%) *Description: Uncomfortable or Uninterested*		
Variable		*Category*
All videos† except Path	=	Very Uncomfortable
PBL_1*, PBL_2, PBL_3*, CF, MT_1*, MT_2*	=	Somewhat Uncomfortable
Path, PBL_1	=	Somewhat Comfortable
Intent	=	Strongly Disagree
Cluster #3 (14.2%) *Description: Very Comfortable Cyclists*		
Variable		*Category*
PBL_3, CF*, BL_1*, BL_2*, BL_3*, MT_1, MT_2, MT_3*, MT_4*, MT_5*, MT_6*, MT_7*, MT_8*	=	Very Comfortable
MT_7*	=	Somewhat Comfortable
Cluster #4 (8.8%) *Description: Year-round Daily Commuters*		
Variable		*Category*
Cycling frequency in the past eight seasons*	=	Daily
Purpose_Commute	=	Yes

Note: All variable-categories have at least standardized residuals > 2
* Standardized residuals > 3
† Standardized residual >3 for all except PBL_1 and PBL_2, with std. res. > 2.

Figure 5.6 Stated Comfort for Video Clips – 'Frequency and Purpose' Segmentation

Figure 5.7 shows the cycling frequency for members of each of the four categories while Table 5.11 shows the demographic and cycling characteristics of each. Although they already have a much higher cycling frequency than any other group –on average 86.3% of Year-round Daily Commuters cycled daily in spring, summer, and fall of the previous year– 76.6% agree that they would like to cycle more than they do now, a similar proportion to the Cautious Majority. This is a group of extremely dedicated cyclists for whom biking is a major part of their identity and way of life. Compared to other groups, Year-round Daily Commuters are more likely to be male, younger, higher income earners (and much likelier to disclose their incomes), and have the highest proportion of university educated members. These results are generally in line with previous observations of Edmontonians who cycle for utility (Cabral et al., 2018). They also fit the stereotype of a bicycle commuter (Gatersleben & Haddad, 2010), and the general trend in North America (Pucher et al., 2011).

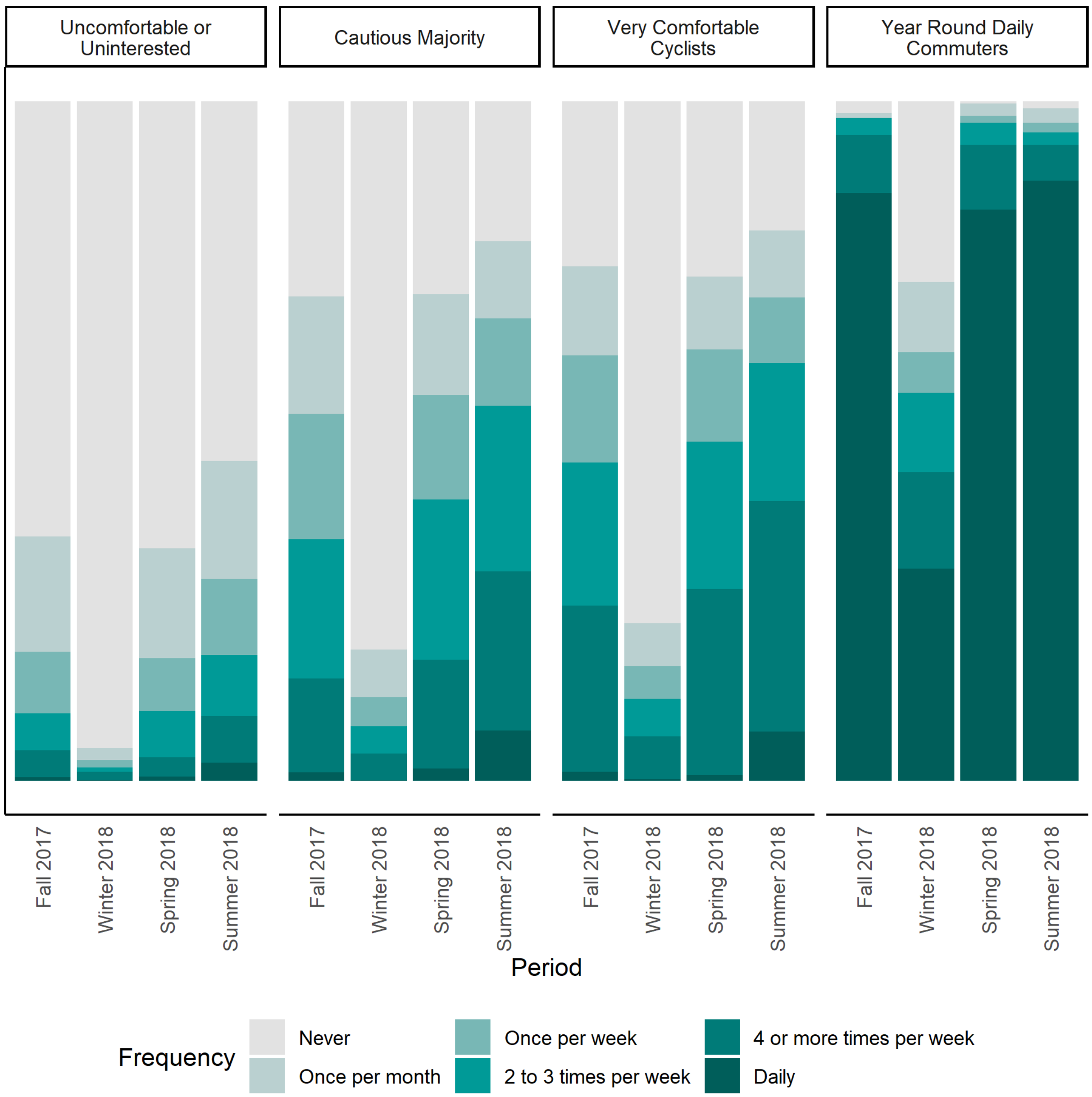


Figure 5.7 Proportion of the Stated Cycling Frequency per Season in the Previous Year for Each Cyclist Type – 'Frequency and Purpose' Segmentation

Table 5.11 Demographic and Cycling Characteristics for 'Frequency and Purpose' Empirical Segmentation (Percent in Category)

Variable	Uncomfortable or Uninterested	Cautious Majority	Very Comfortable Cyclists	Year-round Daily Commuters
Gender				
Not male	56.9[a]	47.0[b]	31.7[c]	34.0[c]
Age†				
15 – 24	3.3[a]	4.0[a]	3.9[a]	7.1[a]
25 – 44	41.9[a]	50.0[b]	36.3[a]	59.6[c]
45 – 64	35.5[a]	33.6[a]	48.4[b]	31.2[a]
65 – 98	18.2[a]	11.7[b]	10.3[b]	2.1[c]
Income				
< 50,000	11.0[ab]	8.4a	10.7[ab]	14.2[b]
50,000 to 99,999	25.2[ab]	28.4[a]	21.9[b]	23.8[ab]
100,000 or more	41.9[a]	48.2[b]	49.5[b]	54.3[b]
Prefer not to answer	21.9[a]	15.0[b]	17.9[ab]	7.8[c]
Education†				
High school or less	11.5[a]	9.0[a]	12.0[a]	11.3[a]
Technical school	26.0[a]	22.1[a]	24.5[a]	14.2[b]
University degree	61.7[a]	68.5[b]	61.5[a]	73.8[b]
Intent				
Somewhat or strongly agree	50.7[a]	73.0[b]	51.9[a]	76.6[b]
Purpose				
Recreation	46.0[a]	73.0[b]	71.2[b]	90.4[c]
Fitness	20.0[a]	45.4[b]	55.1[c]	62.4[d]
Utility	20.2[a]	53.5[b]	48.5[c]	90.8[d]
Commute	15.0[a]	43.2[b]	35.7[c]	95.7[d]
Biked in Summer '18				
Yes	49.5[a]	79.3[b]	80.9[b]	98.9[c]
Last Biked				
*Never**	2.5[a]	0.9[b]	0.9[b]	0.0[b]
*In my childhood**	9.0[a]	2.7[b]	1.1[bc]	0.0[c]
Several years ago	24.9[a]	9.7[b]	12.8[b]	0.0[c]
1-2 years ago	9.4[a]	4.9[b]	2.5[c]	0.0[d]
Within the last year	54.2[a]	81.8[b]	82.7[b]	100.0[c]

Note: All variables are statistically significantly different (Chi-square, $p < 0.05$)

[a, b, c,] Pairwise significant differences ($p < 0.05$). Cyclist types sharing the same letter for a given variable are not statistically different.

* Low-count cells: statistical significance must be considered with caution

As noted previously, the three other groups in this segmentation roughly match the characteristics of the 'Geller' and 'Video Equivalent' segmentations. Comparing results from Table 5.6 and Table 5.11, most variables do follow similar trends. The gender gaps are slightly more pronounced in the 'Purpose and Frequency' segmentation and the non-male proportion is just above a third for the Year-round Daily Commuters. A more notable difference is in the intent variable: about half of both the Uncomfortable or Uninterested and Very Comfortable Cyclists agree to some extent they would like to cycle more often. In the other segmentations, the proportions were notably lower for the former, and higher for the latter. Table 5.11 reports the proportion of respondents who agree with the intent statement. However, we can uncover differences in intent between the two groups by considering disagreement and indifference (neither agree nor disagree). Indeed, Very Comfortable Cyclists are more likely to be indifferent about increasing their cycling frequency as opposed to Uncomfortable or Uninterested: 27% of the first group disagrees to some degree with the intent statement, while 36% of the second group disagrees.

5.4 Discussion

Our work uncovers some new and important empirical findings about the Four Types of Cyclists typology. First, and most critically, we find the rule-based method by which survey respondents are classified into the four types yields quite heterogeneous groups, particularly with respect to perceived comfort. We also find that our empirical segmentation leads to three cyclist types instead of four: Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists. Even the four-group typology resulting from the 'All Videos' segmentation was very similar in structure to the three types of cyclists. However, it offered more detail regarding the majority group of Cautious Cyclists by splitting it according to level of cautiousness: about half seek physical protection from motorized vehicles while the other half is comfortable riding with traffic on quiet residential streets. This new three-group typology fulfills the other main goal of our research – to define cyclist types that can be used to inform policies regarding infrastructure choice. The typology can be the basis for a re-evaluation of the LTS framework, in light of a better understanding of cyclist types and their comfort on different types of infrastructure.

We also find that intent plays a fairly minor role in defining cyclist types. Only the Uncomfortable or Uninterested group is defined by interest, or rather lack thereof, in traveling by bicycle more often. The addition of cycling frequency and purpose to the segmentation variables still supports the three-group typology. However, we find that a fourth niche group emerges: Year-Round Daily Commuters, for whom the high cycling frequency is a more salient trait than comfort is. This is a group of highly dedicated cyclists. Interestingly, they are not necessarily the most comfortable cyclists; the level of comfort is in fact quite heterogenous for this group. This typology, created from the 'Frequency and Purpose' segmentation is not very useful in itself for infrastructure planning purposes. While quite distinct infrastructure preferences can be observed for the first three groups, members of the Year-Round Daily Commuter group do not necessarily prefer the same type of infrastructure. The typology highlights that determinants other than infrastructure play a role in encouraging daily bicycle commuting; these other determinants, which have been explored elsewhere (Cole-Hunter et al., 2015; Handy & Xing, 2011; Heinen et al., 2013; Heinen et al., 2011) can help inform non infrastructure-based policies to increase bicycle commuting.

Although it might seem unintuitive to have a typology devoid of a dedicated non-cyclist category similar to the No Way No How, we do not believe this to be problematic. Indeed, as pointed out by Damant-Sirois et al. (2014), the Four Types of Cyclists typology is mostly useful for infrastructure policy recommendations. Just like Year-Round Daily Commuters' behaviour seems driven by reasons other than their comfort, encouraging the initiation of cycling among those who are very uncomfortable or unwilling to cycle would likely require policies to target other aspects of the choice to cycle (cultural biases, education, financial incentives, land use densities, etc.), which the Four Types of Cyclists was not initially intended for. In terms of infrastructure, the only comfortable environment for this very uncomfortable or unwilling group appears to be completely segregated cycling or multi-use trails. Building or upgrading trails is therefore the only infrastructure improvement that could accommodate respondents in this group, whether non-cyclists or uncomfortable cyclists.

Our segmentations yielded ordinal cyclist typologies, with the exception of the 'Frequency and Purpose' segmentation, which contains three ordered groups and the Year-Round Daily Cyclists group. Griswold et al. (2018) argued that a segmentation designed to help us understand infrastructure preference need not be ordinal, as comfort can be related to factors other than an increasing preference for separation from traffic. While we did not plan for our classification to be ordinal, it does appear our segmentation method, using stated comfort on different types of facilities as its main input, yielded an ordinal cyclist typology.

5.5 Conclusion

Overall, surveyed Edmontonians were found to naturally group in three types of cyclists (Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists) based on an empirical segmentation using inputs similar to those used for the Four Types of Cyclists. We find that the Four Types of Cyclists typology does not form groups of cyclists with homogeneous perceptions of comfort on different types of infrastructure and therefore constitutes an unstable basis to make informed decisions on infrastructure policy. In particular, our work has implications for the Level of Traffic Stress framework, which uses the

Four Types of Cyclists as its basis to define the stress levels imposed by different types of cycling environments. Adjusting the LTS framework to align with the comfort levels of the types of cyclists defined through the empirical segmentation is the object of the next chapter.

Our work has several limitations, the first of which stems from the non-random sampling of survey respondents. Given the large sample size, we feel the typology itself is likely fairly representative of the total population. However, the proportion of respondents in each type are likely not reflective of the population as a whole. In particular, we expect the Uncomfortable or Uninterested to be underrepresented in our sample. In addition to repeating this survey with a random sample in Edmonton, it would be beneficial to reproduce the survey in other locales to verify if the typology is transferable, or if it reflects particularities of the cycling infrastructure available in Edmonton and of its cycling and non-cycling population.

Another limitation is the introduction of some variations to the questionnaire used by Dill and McNeil (2013), including changes in wording for the facility descriptions to reflect a local Canadian context and a reduction in the number of statements. Our criteria to define current cyclists also differed: rather than biking at least once in the last month, our method included those who cycled at least once a month in the previous season (summer 2018) as current cyclists. These differences may in part explain some of the variations observed in our work, both in the evaluation of the Four Types of Cyclists, and in the subsequent empirical segmentations.

CHAPTER 6 LEVEL OF CYCLING COMFORT FRAMEWORK DEVELOPMENT AND APPLICATION

In this chapter, we review updates to the LTS framework that have been proposed in the past and outline their limitations. We then create a new network assessment scheme that addresses these limitation and is adapted to the comfort level of each cyclist type, from the new typology developed in Chapter 4. We name this new framework Level of Cycling Comfort (LCC) and use the LTS framework as a starting point for its development. We then apply the new framework to assess Edmonton's network connectivity after the construction of the bike lanes, and contrast the results with those obtained in Chapter 3.

6.1 Literature Review: Updates to the LTS Framework

Adaptations of the LTS framework have been proposed by other researchers. Notably, one of its authors proposed LTS 2.0 which integrates average daily traffic criteria for mixed-traffic riding (Furth et al., 2018). The thresholds were mostly based on expert knowledge of planners and cyclists in Delaware. The bike lane blockage criterion is also removed and instead, blocked lanes are evaluated as mixed-traffic environments. Overall, the update increases the level of detail of the framework and makes it more specific to a particular region, but does not address the lack of empirical basis for the thresholds and the subjective cyclist typology it is based on.

Bearn et al. (2018) proposed a more extensive revision of the LTS framework. Some important changes include the addition of average annual daily traffic and functional class as criteria, and the addition of two tables to define criteria for buffered bike lanes. This study referred extensively to existing literature to ground its criteria in empirical evidence. However, their work did not include a direct assessment of cyclist preferences through a survey of cyclists or potential cyclists, and the decision-making process to determine thresholds remains unclear. Finally, their four LTS levels map to the Cycle Atlanta typology, an adaptation of the original Four Types of Cyclists, and thus, retains the subjective underlying typology.

6.2 Methodology

The methodological framework for this chapter is presented in Figure 6.1. Three elements are used to guide our update of the LTS framework: ratings of the 16 videos by respondents categorized as one of the three types of cyclists defined in the previous chapter, binary logistic regressions developed to understand which characteristics of the infrastructure increase or decrease comfort for each cyclist type, and results from the optional mapping module.

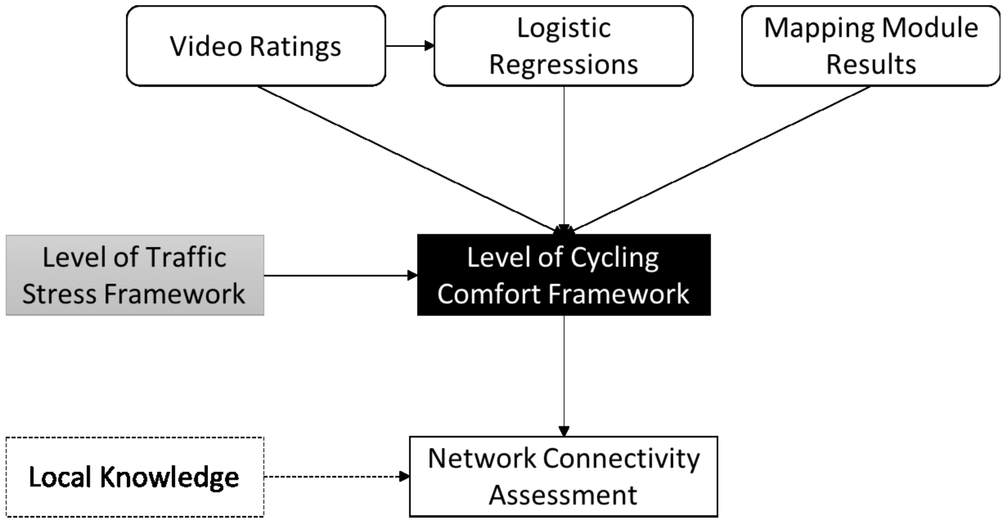


Figure 6.1 Methodological Framework for the Development of the Level of Cycling Comfort Framework and the Reassessment of Edmonton's Network Connectivity

6.2.1 Video Comfort Ratings

The video ratings are used as a guiding tool in the LCC framework development. Note that the typology used for this chapter is the same three-group typology as defined in the previous chapter (Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists). However, we use the membership assignments obtained from segmenting using the 16 videos rather than only the eight equivalent. Recall from 5.3.2.2 that the ASW, ARI, and Jaccard Index values indicated both the three-cluster and four-cluster solutions were acceptable choices. The level of agreement between the three-cluster solution with all videos and the 'Video Equivalent' segmentation is over 90%, making the two segmentations largely equivalent. Using the 16 videos allows us to assess the wider range of facility types captured by the complete set of video clips.

For this section of the research, we deem an infrastructure adequate for a given cyclist type if at least 50% of its membership rates the location *very comfortable*. We elected to exclude *somewhat comfortable* ratings in the assessment because the four-point scale allows little nuance; we aim to develop the LCC framework such that it captures where cyclists in each category are truly comfortable. The 50% *very comfortable* ratings threshold ensures a simple majority of respondents are very comfortable on the infrastructure, and that most cyclists will be at least somewhat comfortable. This approach is also what prompted renaming the framework as 'Level of Cycling Comfort'; we concentrated our efforts on understanding the perception of comfort, not the perception of stress. In the results, we simply report the proportion of *very comfortable* ratings for each video and each cyclist type. A general overview of the proportion of ratings for the four levels of comfort is available from Appendix 4.

6.2.2 Binary Logistic Regressions

We developed the logistic regressions with the same logic in mind: the outcome variable is the comfort rating transformed into a binary variable: *very comfortable* (1) or *not very comfortable* (0). We developed a binary logistic regression for each of the cyclist types to understand which characteristics of the infrastructure increase or decrease the high comfort perception for each group. Note that the Path video was excluded from the analysis, as it shares almost none of the characteristics of on-street facilities. It is also clear that paths and trails are the most comfortable type of infrastructure overall and are appreciated by all cyclist types.

We initially considered a large set of explanatory variables, including those listed in Table 4.2. We first eliminated potential explanatory variables that had no significant association with the outcome variable. The association was measured with a chi-square test of independence for categorical variables and a univariate logistic regression for continuous variables (R package *stats (R Core Team, 2019)*). We also tested for multicollinearity with variance inflation factors (VIF), using R package *car (Fox & Weisberg, 2011).* We found many variables were multicollinear; mainly due to the phenomenon colloquially known as the "dummy variable trap," where one level of a categorical variable perfectly or almost perfectly predicts one or many other levels of categorical variables. Since most of our data is categorical (or ordinal) in nature, our regressions were particularly vulnerable to this phenomenon. Finally, we eliminated many continuous variables because they violated the assumption of linearity to the odds of the outcome variable. Note that prevailing speed does not quite conform to the linearity to the odds assumption; however, given its importance in the LTS framework and as a determinant of cycling, we made the decision to keep the variable in the model.

We ran the binary logistic regression models using R package *stats* (R Core Team, 2019) and discriminated between models using AIC (Akaike Information Criterion) values and likelihood ratio tests (R package *lmtest* (Zeileis & Hothorn, 2002). We assessed goodness of fit using the Tjur pseudo R^2 (Tjur, 2009), implemented in R package *sjstats* (Lüdecke, 2019). Standardized coefficients and corresponding odds ratios were calculated with R package *reghelper* (Hugues, 2018). Finally, with the help of R package *stats (R Core Team, 2019)* we used the logistic model equations to predict the proportion of cyclists of each type who would be highly comfortable given a set of infrastructure conditions, and a confidence interval for these predicted proportions. We assessed prediction accuracy using R package *caret* (Kuhn et al., 2019). The final set of variables and the associated coefficients and model statistics are presented in section 6.3.

6.2.3 Mapping Module Statistics

The last source of evidence we explored is the set of route characteristics from the 100 respondents who participated in the optional mapping module. We first divided routes according to cyclist type and generated summary statistics for the type of infrastructure used. Because these samples are small, the resulting summary statistics must be interpreted with great caution. Any mixed-traffic riding was simply recorded as 'Street' during the interviews (or, occasionally, 'Sharrow', which are considered equivalent to mixed-traffic). To more clearly understand the use of streets by different cyclist types, we used a spatial selection tool in ArcMap to detect street segments used by respondents from our base map, which contains details of the street segments, including the street's functional class. From this data, we calculated the proportion of each functional class used by the three cyclist types. We note that the use of a particular street type does not imply high comfort. In many interviews, respondents made comments regarding particular sections of their routes that they found more or less comfortable. Regrettably, we did not record this information systematically, and thus, cannot report on the comfort level associated with precise segments of the cyclists' routes. We can, however, use the route characteristic information to gain insights into the actual use of the cycling infrastructure by a subset of all survey respondents.

Finally, we also compute the shortest path between each respondent's origin and destination using the same tool described in section 3.3.2. This allows us to calculate a detour factor, as was done in the previous map analyses.

6.2.4 Level of Cycling Comfort Framework Development and Application

Emulating the LTS framework, we define LCC 1 as the infrastructure comfortable for the Uncomfortable or Uninterested, LCC 2, for the Cautious Majority, and LCC 3, for the Very Comfortable Cyclists. We do not define a level specifically for children as the recommendations for Uncomfortable or Uninterested are likely to cater to children who are able to safely cross roads, the level of ability at which LTS 1 was aimed. As with the LTS framework, the LCC levels are cumulative, e.g. LCC 2 contains LCC 1, etc. As noted in the previous chapter, even Very Comfortable Cyclists can benefit from some infrastructure in certain situations. It would be untrue to say that all streets, including highways, are very comfortable for most of Very Comfortable Cyclists. Since the framework aims to capture comfort, we also define another level: Uncomfortable Infrastructure (UI). These are segments where only a handful of cyclists are likely to feel truly comfortable.

The three sources of evidence discussed above are taken into account to decide which infrastructure conditions should be assigned to each level. Despite the use of empirical evidence, this classification exercise remains highly subjective, particularly when the three sources of evidence provide differing information. In section 6.4, we attempt to succinctly present the evidence and provide a rationale for the final choices made.

Once the framework is developed, we apply it to Edmonton's network and assess comfortable connectivity by using the LCC 2 network (inclusive of LCC 1 and LCC 2 links). Frameworks such as LTS and LCC are a basis for classification that cannot capture the numerous variations and subtleties of a given city's transportation network. Where necessary, adjustments to the base classification are made to reflect local knowledge and practices. Finally, we apply the same connectivity metrics described in section 3.3.2 to Edmonton's network, as classified using LCC. Note that to ensure comparability with the results presented in Chapter 3, we use the bicycle network as it existed at the end of 2017 to complete the analysis.

6.3 Findings from the Three Sources of Evidence

6.3.1 Video Comfort Ratings

Table 6.1 shows the proportion of *very comfortable* ratings given for each video clip by the three cyclist types. As noted in the previous chapter, the Path video is the only video that is perceived as comfortable by the Uncomfortable or Uninterested. Protected bike lane videos are perceived differently from paths, even though they provide physical separation from traffic. We propose that a reasonable explanation for the drop in rating for PBL_3 compared to PBL_1 and PBL_2 is the lack of physical separation on that particular stretch of the protected bike lane network, which has no concrete median or bollards to accommodate residential driveways, combined with a narrow roadway (see Table 4.1).

Painted bike lane videos and the contra-flow lane video are perceived as truly comfortable only by the Very Comfortable Cyclists. Note that all bike lanes in the videos were on collector roads whereas the contra-flow lane was on a residential street. This may partially explain the higher proportion of *very comfortable* ratings given by the Cautious Majority for the contra-flow lane (32.1%) compared to the painted bike lane videos (6.1% to 10.9%). The Cautious Majority appear more likely to be comfortable on residential streets compared to other streets; MT_1 and MT_2 are the only two mixed-traffic residential roads shown in the videos and both obtain above 50% *very comfortable* ratings, whereas all other mixed-traffic videos have a low percentage of approval (1.1% to 11.9%). Finally, for Very Comfortable Cyclists, the only mixed-traffic environments that do not reach 50% *very comfortable* ratings are MT_7 and MT_8, both arterials. Compared to MT_6, which is an arterial comparable to MT_7 with more than 50% approval, the latter has parked cars in the outer lane.

Table 6.1 Percentage of *Very Comfortable* Ratings for Each of the Video Clips and Types of Cyclist

Video	Uncomfortable or Uninterested	Cautious Majority	Very Comfortable Cyclists
Path	65.1[a]	89.1[b]	92.6[c]
PBL_1	38.5[a]	79.9[b]	86.0[c]
PBL_2	31.6[a]	66.2[b]	73.6[c]
PBL_3	7.1[a]	42.4[b]	75.0[c]
CF	3.8[a]	32.1[b]	78.1[c]
BL_1	1.1[a]	7.0[b]	82.5[c]
BL_2	1.0[a]	10.9[b]	80.8[c]
BL_3	0.7[a]	6.1[b]	64.7[c]
MT_1	17.1[a]	54.1[b]	94.8[c]
MT_2	15.2[a]	50.6[b]	89.1[c]
MT_3	0.4[a]	3.6[b]	60.4[c]
MT_4	0.8[a]	3.7[b]	75.9[c]
MT_5	2.5[a]	11.9[b]	88.7[c]
MT_6	0.8[a]	1.7[a]	55.9[b]
MT_7	1.4[a]	1.1[a]	32.2[b]
MT_8	0.8[a]	1.9[a]	48.2[b]

[a, b, c] Pairwise significant differences ($p < 0.05$). Cyclist types sharing the same letter for a given variable are not statistically different.

6.3.2 Binary Logistic Regressions

Our analysis in the previous section reinforces that many factors are likely to inform comfort ratings, but we can only speculate on the relative contribution of specific factors when looking at ratings only. We fitted three logistic regressions to understand the importance of various cycling environment characteristics on the likelihood of rating a particular environment as *very comfortable*. The results are presented in Table 6.2 with the final set of variables: Facility Type, Lanes per Direction, Parking Occupation, Speed (kph), and Land Use. As noted in the methodology (6.2.2), multicollinearity was a recurrent issue when developing the models. We prioritized variables that are currently part of the LTS framework, as the objective is to provide an empirical basis to update the framework. Two core variables from LTS are used directly: Lanes per Direction and Prevailing Speed. With the Facility Type variable, we added more detail compared to the LTS framework, which only considered painted bike lanes. Similarly, rather than assessing only the presence of a parking lane, we included three conditions: no parking lane present, parking lane with no cars parked, and occupied parking lane. Finally, we added a new variable to account for surrounding land uses. Land use often provides some indication of expected traffic volumes and roadway widths. Edmonton's road functional classification includes the street type (arterial to local) and the land use context (commercial, industrial, residential). A local residential street and a local industrial street may both have one lane per direction and the same speed limit. However, the perceived riding environment from the point of view of a cyclist is likely to be very different, hence the decision to add this variable to the model.

As shown in Table 6.2, all variables in the model are significant for the Very Comfortable Cyclists. For the Cautious Majority, painted bike lanes, three lanes per direction, and an occupied parking lane do not have a significant effect on the probability of rating a facility as *very comfortable*. Only the facility type, prevailing speed, and commercial or institutional land use are significant for the Uncomfortable or Uninterested. As a reminder, β is the coefficient in log-odds units and *OR* is the odds ratio. For example, for Very Comfortable Cyclists, a painted lane decreases by 0.23 units the log-odds of being *very comfortable*. It is easier to interpret the odds ratio: painted lanes reduce by 21% (1 – 0.79) the odds of being *very comfortable* compared to mixed-traffic riding. The equivalent standardized values allow to compare the relative importance of different variables within a model.

Table 6.2 Logistic Regression Results for Each Cyclist Type (Outcome: Very Comfortable)

Variables	Uncomfortable or Uninterested				Cautious Majority				Very Comfortable Cyclists			
	β	*OR*	*Std.* β	*Std. OR*	β	*OR*	*Std.* β	*Std. OR*	β	*OR*	*Std.* β	*Std. OR*
Facility Type[a]												
Painted Lane	-0.66 **	0.52	-0.30	0.74	0.01	1.01	0.00	1.00	-0.23 **	0.79	-0.11	0.90
Contra-flow	-0.65 *	0.52	-0.17	0.84	-0.19 *	0.83	-0.05	0.95	-0.84 ***	0.43	-0.22	0.80
Protected Lane	4.44 ***	84.80	1.55	4.73	5.66 ***	286.18	1.98	7.24	1.33 ***	3.78	0.47	1.59
Lanes Per Direction[b]												
Two	0.13	1.14	0.06	1.07	-1.61 ***	0.20	-0.80	0.45	-1.12 ***	0.33	-0.56	0.57
Three	1.18	3.27	0.30	1.36	-0.31	0.74	-0.08	0.92	-1.00 ***	0.37	-0.26	0.77
Parking Occupation[c]												
Not Occupied	0.28	1.32	0.11	1.12	0.78 ***	2.17	0.32	1.38	0.77 ***	2.17	0.32	1.37
Occupied	-0.35	0.70	-0.14	0.87	0.08	1.08	0.03	1.03	-0.22 *	0.80	-0.09	0.91
Prevailing Speed (kph)	-0.12 ***	0.88	-1.04	0.36	-0.05 ***	0.95	-0.41	0.66	0.02 ***	1.02	0.19	1.21
Land Use[d]												
Commerc./Institutional	-0.89 **	0.41	-0.45	0.64	-2.08 ***	0.13	-1.04	0.35	-1.63 ***	0.20	-0.82	0.44
Other	-0.34	0.71	-0.09	0.92	-1.27 ***	0.28	-0.33	0.72	-0.89 ***	0.41	-0.23	0.80
No. of observations	10,108				27,594				7,210			
Goodness of fit												
Tjur's R^2	0.20				0.38				0.11			

[a] Relative to mixed-traffic
[b] Relative to one lane per direction
[c] Relative to no parking lane
[d] Relative to residential land use
* Significant (p < 0.05)
** Significant (p < 0.01)
*** Significant (p < 0.001)

For all cyclist types, where significant, both painted bike lanes and contra-flow lanes have a negative effect on the probability of rating a facility as *very comfortable*, compared to mixed-traffic riding. The negative perception is in line with empirical evidence showing bike lanes decrease motorized vehicle passing distance and decrease objective safety compared to mixed-traffic riding (Beck et al., 2019). Conversely, protected bike lanes are the most important predictor of higher comfort across all models (std. odds ratios of 4.73, 7.24, and 1.59 for the Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists, respectively). As expected, a higher number of lanes per direction and higher speed decrease perceived comfort. There is one exception to this: for Very Comfortable Cyclists, there is a small but significant positive effect associated with speed. The range of speeds included in the videos is limited to 60 kph at the highest, hence we cannot verify if this relationship holds at higher speeds, which would be objectively unsafe. Where significant, the effect of parking also follows intuitive logic: compared with the absence of a parking lane, an empty parking lane increases the odds of rating a facility as *very comfortable* whereas an occupied parking lane decreases comfort. We expect these effects as an empty parking lane provides the equivalent of a wide shoulder for cyclists to use while occupied parking increases the risk of dooring and forces the cyclist to ride with traffic, or sandwiched between moving traffic and parked vehicles in the case of a bike lane. Finally, we find that both commercial/institutional land use and riding on a bridge (land use = other) decrease comfort perception compared to residential land use.

The models' goodness of fit statistics are not particularly high, indicating significant unexplained variance; this is expected given the multicollinearity issues which restricted our set of potential variable combinations. Nonetheless, we find the prediction accuracy to be adequate to very good: 92.5% for the Uncomfortable or Uninterested, 87.8% for the Cautious Majority, and 73.6% for the Very Comfortable Cyclists. In Table 6.3, we present the predicted probability (and confidence interval) of *very comfortable* ratings for various riding environments. The set of conditions presented in the table vary for each type of cyclist based on the relevance of presenting those conditions to provide guidance in updating the LTS framework. Note that in most cases, we assume the presence of parked cars in the parking lane as this usually reflects actual conditions in locations where a parking lane is available, at least in Edmonton.

Table 6.3 Predicted Probability of *Very Comfortable* Ratings for Each Cyclist Type in Various Riding Conditions; Ordered from Least Comfortable to Most Comfortable

Uncomfortable or Uninterested						
Facility Type	*Lanes per Dir*	*Prev. Speed (kph)*	*Parking Occupation*	*Land Use*	*Probability (%)*	*Confidence Interval (%)*
Mixed-traffic	1	30	Not Occupied	Residential	15.5	9.7 – 23.9
Protected Lane	1	50	No Parking	Comm./Inst.	28.9	15.9 – 46.5
Protected Lane	1	50	No Parking	Residential	49.7	23.6 – 76.0
Cautious Majority						
Facility Type	*Lanes per Dir*	*Prev. Speed (kph)*	*Parking Occupation*	*Land Use*	*Probability (%)*	*Confidence Interval (%)*
Mixed-traffic	1	30	Occupied	Comm./Inst.	9.0	7.6 – 10.7
Contra-flow	1	40	No Parking	Residential	27.0	24.6 – 29.5
Mixed-traffic	1	30	Occupied	Residential	44.3	41.6 – 47.0
Protected Lane	1	50	No Parking	Comm./Inst.	90.7	87.8 – 93.0
Protected Lane	1	50	No Parking	Residential	98.7	97.9 – 99.2
Very Comfortable Cyclists						
Facility Type	*Lanes per Dir*	*Prev. Speed (kph)*	*Parking Occupation*	*Land Use*	*Probability (%)*	*Confidence Interval (%)*
Contra-flow	2	50	No Parking	Comm./Inst.	24.1	18.6 – 30.5
Painted Lane	2	50	Occupied	Comm./Inst.	31.9	27.3 – 37.0
Mixed-traffic	2	50	Occupied	Comm./Inst.	37.2	33.5 – 41.1
Contra-flow	1	50	No Parking	Comm./Inst.	49.2	42.1 – 56.4
Painted Lane	2	50	Not Occupied	Comm./Inst.	55.8	51.2 – 60.2
Painted Lane	1	50	Occupied	Comm./Inst.	58.9	51.8 – 65.7
Mixed-traffic	2	50	Not Occupied	Comm./Inst.	61.5	58.1 – 64.7
Mixed-traffic	1	50	Occupied	Comm./Inst.	64.4	58.5 – 70.0
Painted Lane	2	50	Occupied	Residential	70.6	66.3 – 74.6
Mixed-traffic	2	50	Occupied	Residential	75.2	71.0 – 79.0
Contra-flow	1	50	No Parking	Residential	83.3	78.8 – 86.9
Mixed-traffic	1	50	Occupied	Residential	90.3	86.8 – 92.9

For the Uncomfortable or Uninterested, only a protected bike lane in a residential environment has a reasonable probability of being comfortable for a majority of the group (49.7%, [23.6, 76.0]); equivalent conditions in a commercial or institutional environment are not considered as comfortable. Mixed-traffic riding is not considered comfortable, even with all the most comfortable conditions in place: a very low speed residential environment with unoccupied parking (15.5%, [9.7, 23.9]). The Cautious Majority are similarly wary of mixed-traffic riding: in a low-speed (30 kph) residential setting with parked cars, a common environment in Edmonton's core, less than half of this group would be very comfortable. Equivalent conditions in a commercial or institutional setting yield the lowest comfort reported for this group in Table 6.3. As per the logistic model results, contra-flow lanes have a negative effect on comfort and painted bike lanes have a non-significant and negligible effect. In fact, only protected bike lanes are considered very comfortable by most of the Cautious Majority group, independent of land use type. Finally, Very Comfortable Cyclists are comfortable in most conditions explored, although there is a clear preference for residential environments compared to commercial or institutional. Nonetheless, this latter type of land use combined with one lane of traffic per direction, parked cars and a prevailing speed of 50 kph is still considered comfortable to ride in mixed-traffic for a majority of this group (64.4%, [58.5, 70.0]). The same conditions with a painted bike lane are also considered adequate for Very Comfortable Cyclists (58.9%, [51.8, 65.7]); contra-flow lanes are just under the 50% threshold, although contra-flow lanes in non-residential environments do not seem to exist in Edmonton. For mixed-traffic and bike lanes, two lanes per direction in a non-residential setting is only adequate if there is a parking lane that does not contain parked cars. All residential environments, independent of speed (up to 60 kph), facility type, number of lanes, and parking occupation are comfortable for the Very Comfortable Cyclists.

6.3.3 Mapping Module Statistics

Based on the cyclist type assignment obtained from the segmentation, 10 of the 100 mapping module respondents are categorized as Uncomfortable or Uninterested, 68 are part of the Cautious Majority, and 22 are Very Comfortable Cyclists. With such small samples sizes we must consider results with great caution, particularly for the 10 Uncomfortable or Uninterested who are uncomfortable, but not uninterested, and thus most certainly do not represent the whole group. Figure 6.2 to Figure 6.4 show all the identified routes for cyclists within each of the three groups. We display the facility type used, but note that if more than one cyclist uses a particular segment, the map drawing order determines the facility type displayed (i.e. segments are staked over each other and only the top segment is displayed). These maps aim to provide context to mapping module results, but the analysis is mainly based on Table 6.4 and Table 6.5. These tables list summary statistics regarding the proportion of each respondents' route spent on different facility types and street functional class, respectively.

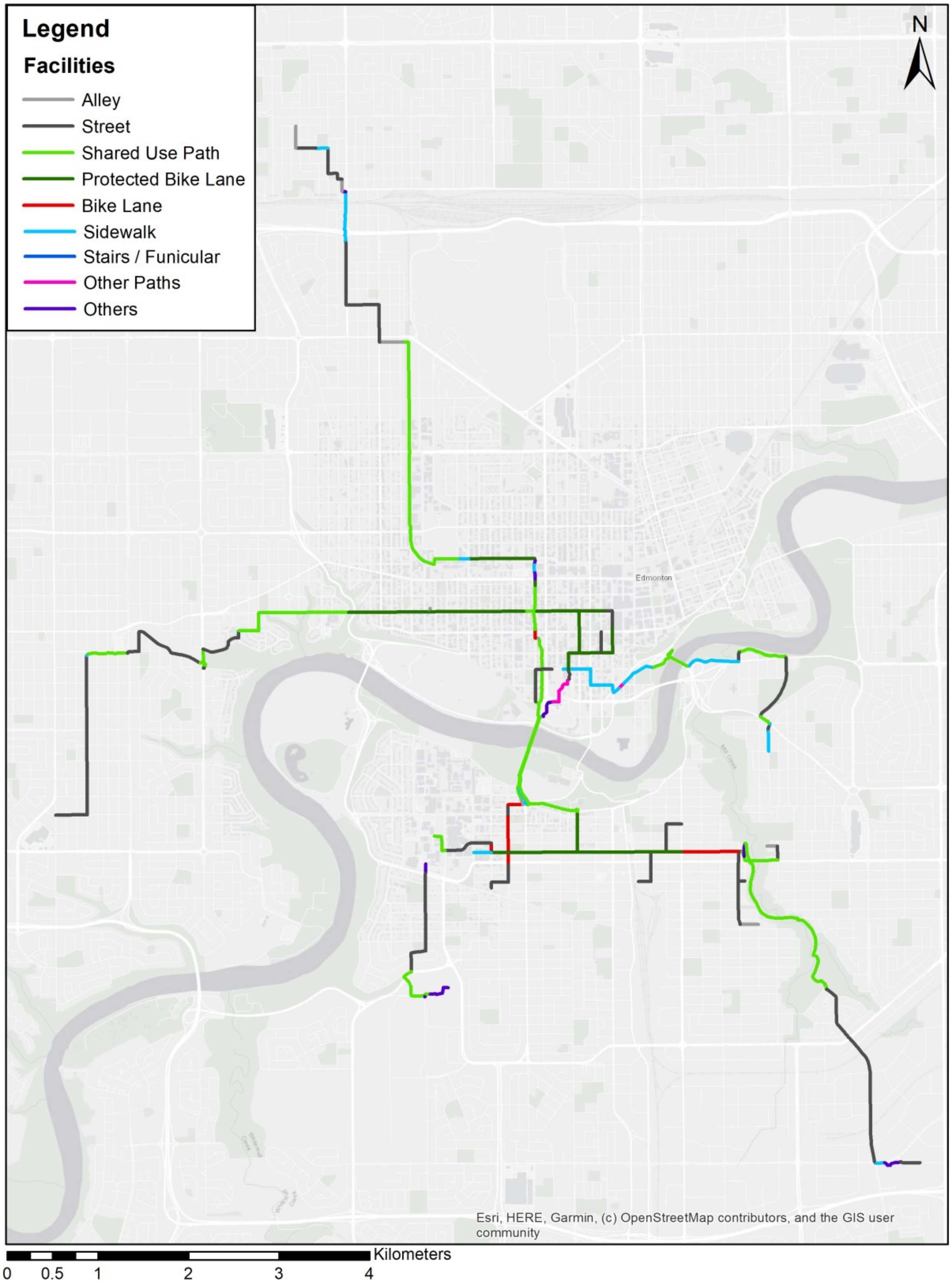


Figure 6.2 Route Map and Facility Type used by the 10 Uncomfortable or Uninterested Respondents

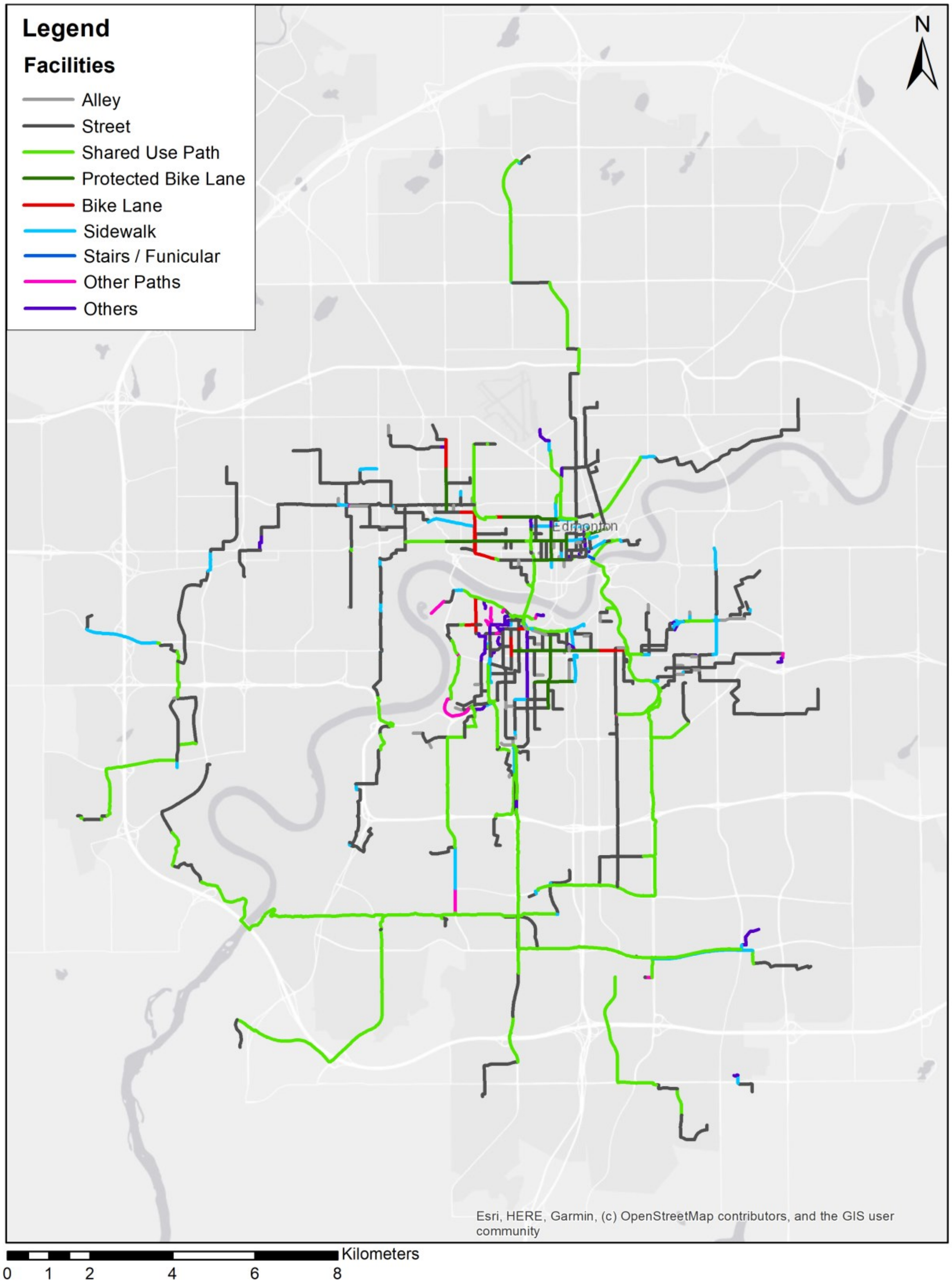


Figure 6.3 Route Map and Facility Type used by the 68 Cautious Majority Respondents

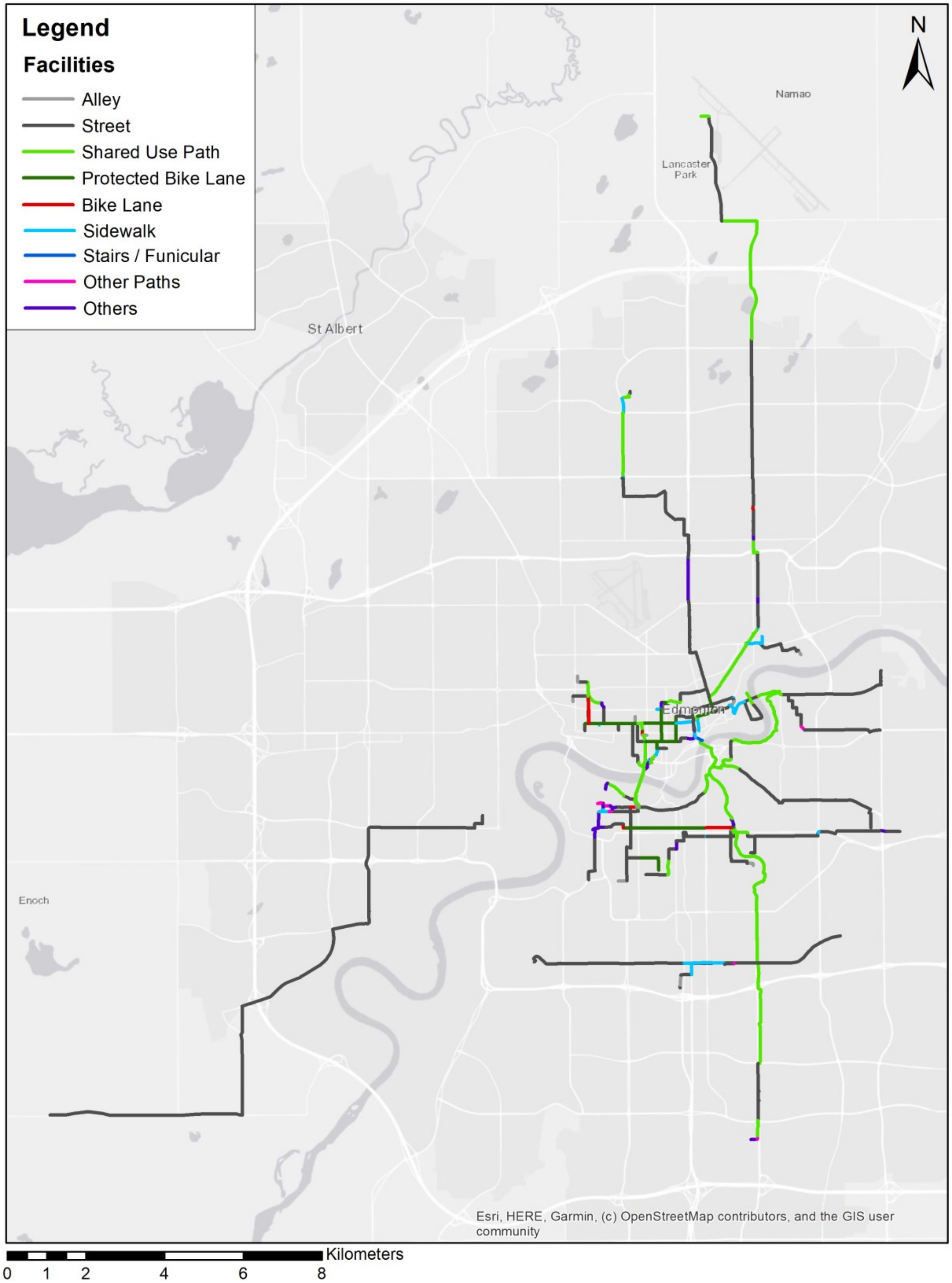


Figure 6.4 Route Map and Facility Type used by the 22 Very Comfortable Cyclists

From Table 6.4 we find that all groups use three categories of infrastructure for the majority of their trips, the same three that were dominant in the overall sample (section 4.4): streets, which include sharrow roads as well as completely unmarked streets, shared-use paths, and protected bike lanes. Other fairly abundant infrastructure types, such as alleys, are not used very heavily by cyclists in any group. As noted in Chapter 3, alleys are not particularly welcoming cycling environments in Edmonton.

For the Uncomfortable or Uninterested, protected bike lanes are the most used type of infrastructure (median = 34.0%), followed by shared-use paths (median = 27.5%), and finally streets (median = 20.6%). Given the Uncomfortable or Uninterested gave paths much higher comfort ratings compared to protected bike lanes, we would have expected a higher use of the those paths. An assessment of the particular routes taken by the ten respondents (Figure 6.2) indicates they are generally accessing shared-use paths if available between their origin and destination. However, considering access, egress, and links between these paths, other types of facilities make up a larger proportion of the routes. Overall, eight out of 10 respondents used protected bike lanes as part of their route, all used streets, and nine used shared use paths.

Almost all in the Cautious Majority group (66) used streets as part of their route, which is the most used type of infrastructure (median: 32.4%). The second most used type of infrastructure is shared-use paths (median: 23.5%) followed by protected bike lanes, although the use of these lanes is much lower (median: 7.7%). Shared-use paths are used by 57 out of 68 respondents (~84%) while protected bike lanes are used by ~63% of the Cautious Majority respondents. Such an important use of the regular street network is not entirely intuitive given this group's preferences as measured by the video ratings, and the logistic model results discussed in the previous section. As with the Uncomfortable or Uninterested, an analysis of the route maps (summarized in Figure 6.3) seems to suggest mixed-traffic riding is often used as access, egress, and link between other bicycle-specific infrastructures, or in locations where no such infrastructure is easily and closely accessed.

All 22 Very Comfortable Cyclists use streets on their route, with a median proportion of 35.4% of the total route. For at least one respondent, this includes choosing to ride in mixed traffic even when shared-use paths are provided directly parallel to the road. The second most frequent infrastructure type is shared-used paths (median 26.5%); these are used by 18 of the 22 respondents. Protected bike lanes are also used, but similarly to the Cautious Majority, to a much lesser extent (median: 3.6%) and by less respondents (~64%) than other infrastructure types.

Table 6.4 Proportion of Route Travelled on Different Types of Infrastructure and Total Route Length for the Three Types of Cyclists

Facility Type	Uncomfortable or Uninterested				Cautious Majority				Very Comfortable Cyclists			
	# Null	*Range*	*Median*	*Mean*	*# Null*	*Range*	*Median*	*Mean*	*# Null*	*Range*	*Median*	*Mean*
Alley	6	0.0 - 6.5	0.0	1.6	27	0.0 - 20.7	1.5	3.3	10	0.0 - 10.6	0.6	2.2
Protected Bike Lane*	2	0.0 - 81.5	34.0	29.7	25	0.0 - 65.5	7.7	14.4	8	0.0 - 73.0	3.6	12.0
Painted Bike Lane	6	0.0 - 16.6	0.0	5.2	43	0.0 - 31.4	0.0	4.3	15	0.0 - 40.0	0.0	2.9
Shared-Use Path	1	0.0 - 46.1	27.5	24.9	11	0.0 - 88.9	23.5	27.7	4	0.0 - 70.2	26.5	25.2
Streets	0	10.3 - 56.3	20.6	27.9	2	0.0 – 92.9	32.4	36.2	0	12.2 - 100.0	35.4	44.4
Sidewalk	4	0.0 - 47.3	0.8	6.6	21	0.0 - 50.0	3.2	7.9	7	0.0 - 48.8	1.4	6.4
Stairs or Funicular	10	0.0 - 0.0	0.0	0.0	62	0.0 - 4.7	0.0	0.2	20	0.0 - 4.0	0.0	0.2
Other Path	8	0.0 - 8.0	0.0	1.0	54	0.0 - 19.0	0.0	0.9	14	0.0 - 13.1	0.0	1.1
Other	6	0.0 - 18.6	0.0	3.1	34	0.0 - 50.3	0.3	4.5	8	0.0 - 29.3	3.3	5.5
Total Distance (km)	0	2.2 – 11.5	4.7	5.5	0	0.85 – 21.0	4.9	6.3	0	1.1 – 20.8	5.8	7.3

* Statistically significant difference between cyclist types ($p < 0.05$); to be considered with caution given small sample sizes.

Table 6.5 Proportion of Street Functional Class Use and Total Distance Travelled on Streets for the Three Types of Cyclists

Functional Class	Uncomfortable or Uninterested				Cautious Majority				Very Comfortable Cyclists			
	# Null	*Range*	*Median*	*Mean*	*# Null*	*Range*	*Median*	*Mean*	*# Null*	*Range*	*Median*	*Mean*
Arterial												
Class A and B	10	0.0 - 0.0	0.0	0.0	67	0.0 - 0.2	0.0	0.0	21	0.0 - 7.4	0.0	0.3
*Class C and D **	5	0.0 - 26.4	0.2	3.0	33	0.0 - 90.9	0.7	13.6	8	0.0 - 97.1	25.2	32.5
Collector												
Residential	3	0.0 - 86.1	24.5	34.1	17	0.0 - 100.0	12.8	19.4	5	0.0 - 100	16.7	22.6
Comm./Inst.	8	0.0 - 48.0	0.0	5.5	59	0.0 - 66.4	0.0	3.3	20	0.0 - 21.1	0.0	1.4
Local												
*Residential **	1	0.0 - 100.0	50.0	53.1	3	0.0 - 100.0	62.2	57.4	4	0.0 - 100.0	27.5	36.5
Comm. /Inst.	9	0.0 - 43.4	0.0	4.3	53	0.0 - 25.2	0.0	2.5	17	0.0 - 56.3	0.0	6.3
Others	10	0.0 - 0.0	0.0	0.0	58	0.0 - 10.8	0.0	0.8	21	0.0 - 7.5	0.0	0.3
Total Distance (km) *	0	0.23 – 4.2	0.94	1.6	2	0.0 – 8.6	1.6	2.3	0	2.2 – 17.6	1.8	3.8

* Statistically significant difference between cyclist types ($p < 0.05$); to be considered with caution given small sample sizes.

Mixed-traffic riding is an important route component for all three cyclist types. A further analysis of the streets' functional class uncovers differences between the groups, as shown in Table 6.5. Keeping in mind that the sample size is small, particularly for the Uncomfortable or Uninterested and Very Comfortable Cyclists, we must be careful in our interpretation. However, important and expected differences arise, particularly in the use of local-residential streets and arterials. Median values for local-residential street use are 50.0%, 62.2%, 27.5% for the Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists, respectively. When combining all routes within each group, we find local-residential street riding represents 68.9%, 48.0%, and 24.9% of the total street use for the three types, respectively. As a comparison point, local residential streets represent approximately 43% of Edmonton's entire street network. Class C and D arterials (low speeds, truck or non-truck routes), which compose approximately 21% of Edmonton's network, also show important differences in use for each of the groups. These two types of arterials combined represent 1.0%, 18.4%, and 56.0% of the total street use for the combined routes of the Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists, respectively. The median values for the individual routes, in the same order, are 0.2%, 0.7%, and 25.2%, respectively. For the Uncomfortable or Uninterested and Cautious Majority, local-residential streets are very clearly preferred over arterials. On the contrary, Very Comfortable Cyclists use class C and D arterials approximately in the same proportion as these facilities are provided on the entire city network and limit their use of residential streets. This may be linked to a desire for direct routes, which may be achieved by riding on arterials. The median detour ratio (route length/shortest route) is indeed lower for Very Comfortable Cyclists at 1.075, compared to 1.119 and 1.110 for the Uncomfortable or Uninterested and the Cautious Majority, respectively. Finally, class A and B arterials (primary or non-primary highways, truck routes) are almost entirely avoided by all respondents.

6.4 Level of Cycling Comfort Framework: Presentation and Justification

A few notes apply to the overall development of the framework:

1. From the results presented in previous sections, it appears the LTS framework tends to overestimate the comfort of cycling environments. Therefore, we use the LTS ratings as an upper bound to guide the LCC ratings.
2. Our video clips do not include industrial land use. We assume its effect to be similar to commercial land use. The volume of vehicular traffic is likely to be lower compared to commercial land use, but the share of heavy vehicles is likely to be higher. For this framework, all non-residential land uses are considered equivalent.

3. Except otherwise stated, we assume there are parked cars on the side of the road. This reflects the most common circumstance, at least in Edmonton. However, contra-flow lanes are assumed to have no parking lane adjacent to the lane, as this situation does not exist in Edmonton (and would be extremely dangerous).

In sections 6.4.1 to 6.4.3, we detail the decision-making process used to choose the final set of conditions that define the LCC framework levels. Finally, in section 6.4.4 we present the integrated LCC framework in a straightforward table form, similar to those used in the LTS framework.

6.4.1 Uncomfortable or Uninterested (LCC 1)

The video ratings indicate that trails are considered comfortable for the Uncomfortable or Uninterested. All trails, shared-use paths, and other facilities completely segregated from motorized traffic are therefore classified as LCC 1. The logistic regression predictions suggest protected bike lanes may be very comfortable for this group in a residential context (49.7%, [23.6, 76.0],Table 6.3), but not for other land uses. However, protected lanes that were not in a residential environment obtained the highest ratings in the video assessments for this group. The mapping module also shows a high use of the protected lanes, some of which are not in residential areas. From the video rating results, we hypothesize that the absence of physical barriers to accommodate the presence of driveways plays an important role in the comfort perception; this was not tested in the logistic regressions, and no further insight is available. Based on available evidence, we make the decision to classify segments with more than one mid-block conflict, or with a long conflict that accommodates several driveways, as LCC 2 while other segments with one conflict or less are classified as LCC 1. No mixed-traffic environment or any form of painted bike lane is considered comfortable for the Uncomfortable or Uninterested.

6.4.2 Cautious Majority (LCC 2)

As noted above, protected bike lanes with more than one mid-block conflict (or a long conflict) are considered comfortable for the Cautious Majority. The predictions obtained from the logistic model for this group suggest mixed-traffic riding in commercial or institutional areas is out of the question. Residential land use with very low speeds (30 kph), parked cars, and one lane of traffic per direction does not reach the 50% *very comfortable* threshold we have been using for guidance (predicted range: [41.6, 47.0]). However, local-residential streets were well rated in video clips, and residential mixed-traffic riding is quite common among respondents to the mapping module. We therefore classify residential streets with a prevailing speed of 30 kph and one lane of traffic per direction, independent of the parking situation, as LCC 2. As per the logistic model, painted bike lanes have no effect on comfort for this group;

they can therefore be assessed with the same criteria as mixed-traffic streets. Contra-flow lanes have a negative effect on comfort and are not considered suitable to be rated as LCC 2 in any conditions.

6.4.3 Very Comfortable Cyclists (LCC 3)

All environments beyond mixed-traffic or bike lanes at 30 kph in residential areas are considered LCC 3, up to the limits we describe here.

In the LTS framework, any mixed-traffic environment with three lanes per direction or more is classified as LTS 4. The maximum number of lanes per direction allowed for an LCC 3 rating in mixed traffic is therefore two. In residential areas, prevailing speeds up to 60 kph with any parking condition are considered comfortable for the Very Comfortable Cyclists. Painted bike lanes and contra-flow lanes are also considered adequate for this speed and number of lanes in residential areas.

In non-residential environments, if there are parked cars, only one lane of traffic per direction and prevailing speeds up to 60 kph are considered suitable for mixed-traffic riding, painted lanes, and contra-flow lanes (no parking lane in this case), as per the logistic regression results. If there is a parking lane but the particular street segment is known for not having parked cars (or parking is not permitted even if there is enough space) then two lanes per direction and prevailing speeds up to 60 kph are suitable conditions for mixed traffic and painted lane riding.

6.4.4 Integrated LCC Framework

Table 6.6 presents the LCC framework. Overall, it is a much simpler framework than LTS as it is comprised of a single table rather than three. There are several reasons for the increased simplicity. First, the blockage of a bike lane would result in a cyclist having to ride with traffic; given bike lanes are assessed in the same way as mixed-traffic, we entirely eliminated the bike lane blockage variable present in the LTS framework. The width of painted bike lanes (and parking lanes, if applicable) is also eliminated as a variable for several reasons. First, this data is unlikely to be easily available to most jurisdictions and complicates the application of the framework; second, the variable could not be assessed in our binary logistic regressions because it violated model assumptions; third, if a bike lane is known not to be wide enough to avoid riding in the dooring zone, the facility should be considered inexistent (i.e. considered as mixed-traffic) since riding with traffic would be the safer option for a cyclist. The presence of parking plays a much smaller role in our framework given it is often statistically insignificant for commonly found conditions. The increased simplicity also stems from the lower number of conditions that are considered comfortable for all cyclist types compared to the LTS framework.

Table 6.6 Level of Cycling Comfort Framework

<table>
<tr><td>Trails/Paths</td><td colspan="6">LCC 1</td></tr>
<tr><td rowspan="2">Protected Bike Lane</td><td colspan="3">≤ 1 mid-block conflict</td><td colspan="3">> 1 mid-block conflict</td></tr>
<tr><td colspan="3">LCC 1</td><td colspan="3">LCC 2</td></tr>
<tr><td rowspan="5">Mixed-traffic and Painted Lane*</td><td rowspan="2">Lanes/dir</td><td colspan="3">Residential land use</td><td colspan="2">Non-Residential land use</td></tr>
<tr><td>≤ 30 kph</td><td>(30, 60] kph</td><td>> 60 kph</td><td>≤ 60 kph</td><td>> 60 kph</td></tr>
<tr><td>1</td><td>LCC 2</td><td>LCC 3</td><td>UI</td><td>LCC 3</td><td>UI</td></tr>
<tr><td>2</td><td>LCC 3</td><td>LCC 3</td><td>UI</td><td>UI**</td><td>UI</td></tr>
<tr><td>3</td><td>UI</td><td>UI</td><td>UI</td><td>UI</td><td>UI</td></tr>
</table>

* Contra-flow lanes are LCC 3 for all conditions that are not UI.
** LCC 3 for mixed-traffic and painted lane if there is a parking lane where it is unusual for cars to park. We expect this to be a rare condition.

Although bike lanes are rated in the same way as mixed traffic and have recently been shown to be less safe than mixed-traffic riding (Beck et al., 2019), pavement markings (not necessarily lanes) can still have value as wayfinding tools. We know that increasing the number of cyclists on the road creates a safety-in-numbers effect (Elvik & Bjørnskau, 2017; Jacobsen, 2015); using pavement markings to guiding cyclists to preferred mixed-traffic routes may help in this regard.

6.5 Application of the Level of Cycling Comfort Framework

For Edmonton specifically, local-residential streets normally have a speed limit of 50 kph. In our own application of the framework, it would be unduly restrictive, and not reflective of reality, to classify all those streets as LCC 3, as our framework dictates they should. Ideally, speed surveys would allow an assessment of the prevailing speed rather than relying on speed limits. This information is not available for Edmonton local residential streets and therefore does not allow us to discriminate between streets. Particularly in the core areas of the city, where intersection density is high and streets are comparatively narrow, it is reasonable to expect prevailing speeds to be much lower than the speed limit. Because our connectivity analysis concentrates on core neighbourhoods, we classify all local-residential streets as LCC 2, but note that better data regarding prevailing speeds would be needed to implement the framework with greater accuracy. The rating of all local-residential streets as LCC 2 is also reflective of a certain level of redundancy in residential neighbourhoods; while not all local-residential streets are likely to truly be LCC 2, it is reasonable to expect at least one will be available and suitable to direct the Cautious Majority cyclist to a collector, or bicycle-specific infrastructure, to exit the neighborhood.

Figure 6.5 compares the LTS assignment to the LCC assignment of Edmonton's network. We use the same colour scheme to facilitate a comparison and also include a map highlighting links assigned with new ratings. Overall, 2.9% of links (3.3% of the network length) have a different rating. However, as per our discussion in the previous sections, the levels cater to slightly different groups of people, and therefore an LCC 2 rating does not quite equate to an LTS 2 rating, and so on. The most salient changes include the increase of residential streets from LTS 1 to LCC 2 in three neighbourhoods. Even though these streets have a lower speed limit (40 kph), our results indicate even lower speeds (30 kph) do not seem to be comfortable for most of the Cautious Majority, let alone the Uncomfortable or Uninterested. Some other changes to the comfort evaluation of more isolated links have a profound effect on network connectivity, as we show in the next section.

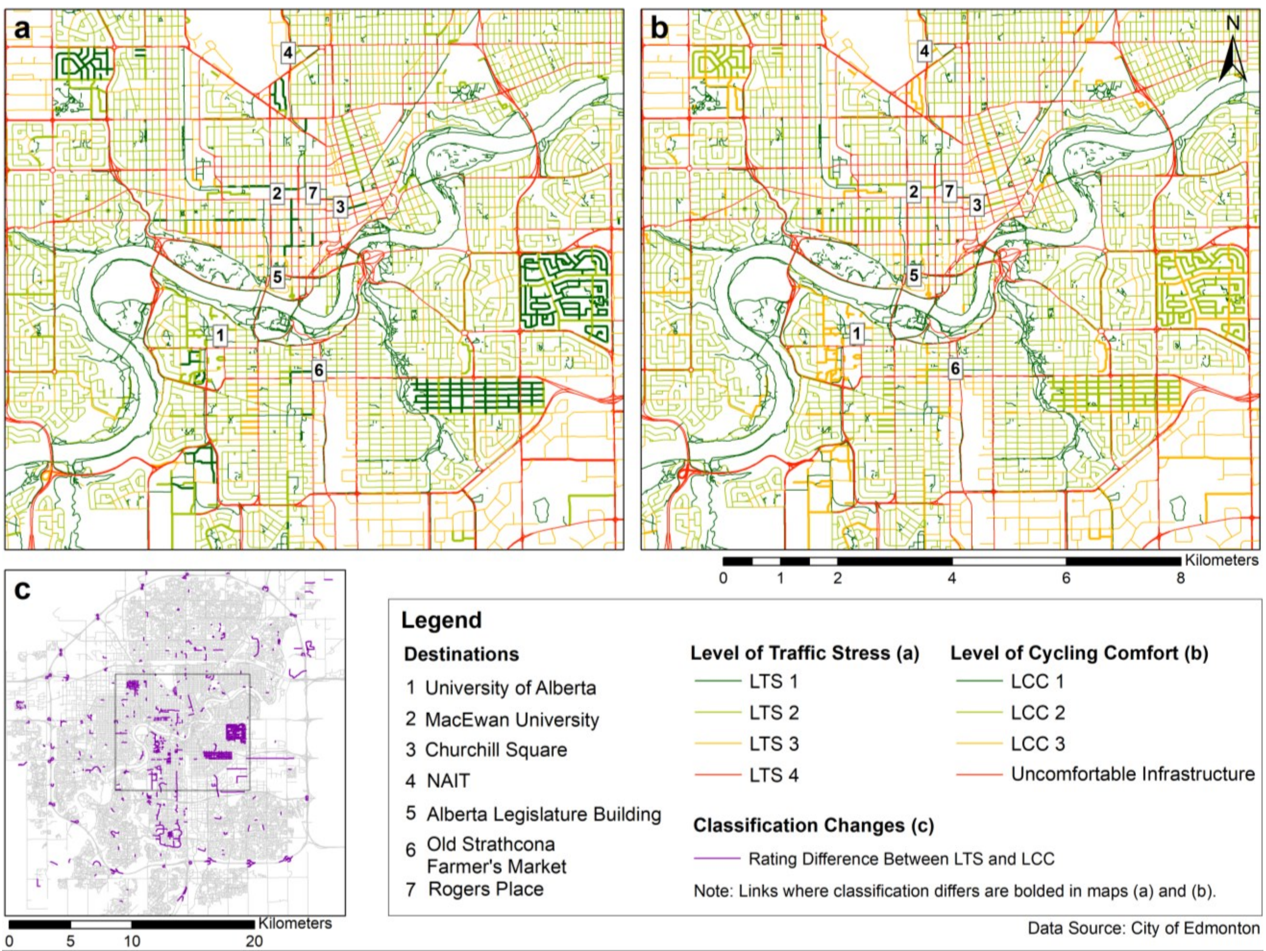


Figure 6.5 Comparison of LTS (a) and LCC (b) Network Ratings, and Overview of Locations Where Classification Differs Between the Two Frameworks (c)

6.5.1 Bikeshed Analysis

Figure 6.6 shows the bikeshed areas for each of the seven destinations studied in Chapter 3. Compared with the bikesheds obtained using the LTS 2 network, the LCC 2 bikesheds are much smaller (represented in green as opposed to LTS 2 which is represented in both green and blue); area values are presented in Table 6.7. The sharpest decrease is seen in MacEwan University's bikeshed area, which reduces from 56.2 km^2 to 19.0 km^2.

We find the LCC 2 bikeshed extent is almost identical for the Alberta Legislature Building, Old Strathcona Farmer's Market and University of Alberta Transit Center. Similarly, Churchill Square, Rogers Place and MacEwan University share a common bikeshed. This is also shown in Figure 6.7, where most of Edmonton's central neighbourhoods have three accessible destinations. The total bikeshed area is effectively divided into three: a south bikeshed, a north bikeshed, each giving access to three different destinations, and NAIT's isolated small bikeshed. The total combined bikeshed area is only reduced by 5.4 km^2 with the LCC framework, with most of the reduction in the southmost portion of the bikeshed area. However, the network integration is not as high as we initially assessed using the LTS framework.

We mainly attribute the division of the large LTS bikeshed into two separate bikesheds to the reclassification of three small road segments. These three segments act as links between two shared-use paths that allow the connection of the network south of the river, through the CBD, and up to what is known as the North Edge, the north limit of the CBD. When exiting the south shared-use path, cyclists have to turn onto a busy alley (access point to a residential parkade, an office building parkade, and surface parking), use a street segment where a painted bike lane disappears to share a right-turn lane with motorized traffic, cross a major downtown arterial, and cross traffic from a commercial plaza entranceway to finally access the north shared-use path. The distance between the two shared-use paths is just under 150 m, but this short gap is filled with quite uncomfortable segments from the point of view of the Cautious Majority. Cyclists still use this route extensively because there is no low-stress alternative nearby. The important effect of the reclassification of this set of links as LCC 3 also highlights the lack of redundancy in the low-stress/comfortable network; the bikesheds would not be separated if other low-stress links were available nearby. Finally, this finding emphasizes the impact small missing links can have on overall network connectivity.

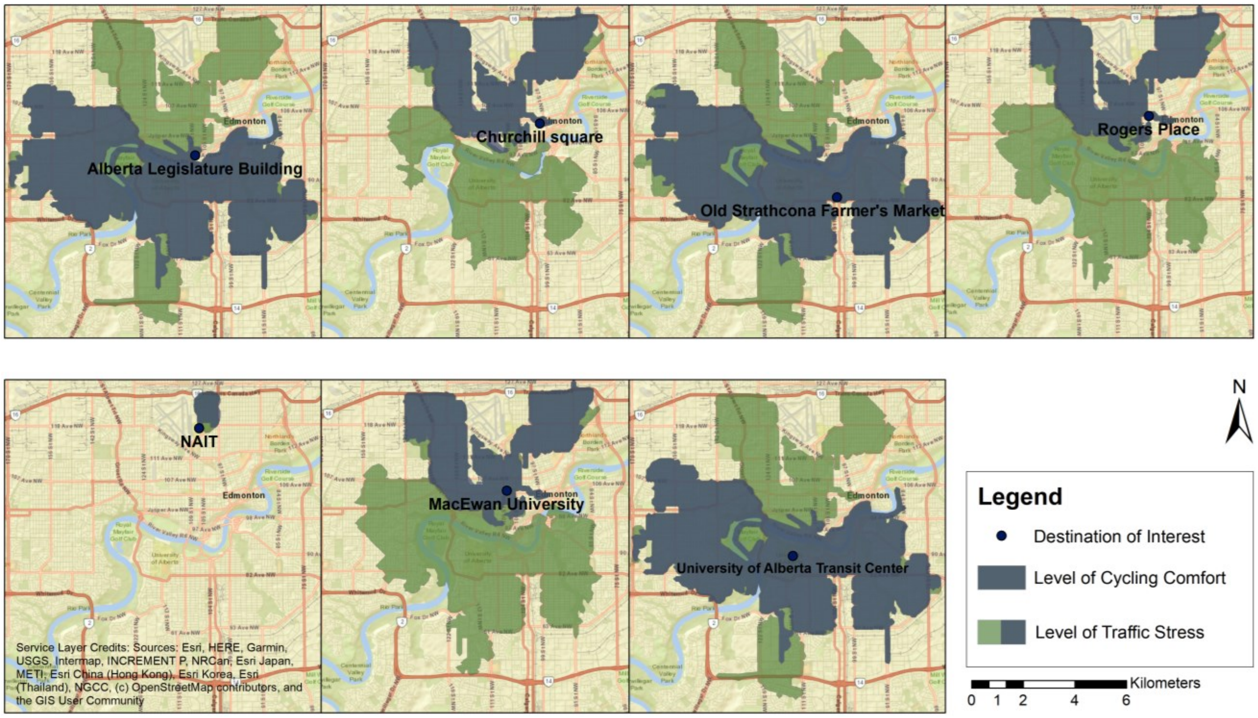


Figure 6.6 Bikeshed area for each destination as assessed with the LCC and LTS frameworks (LTS includes LCC)

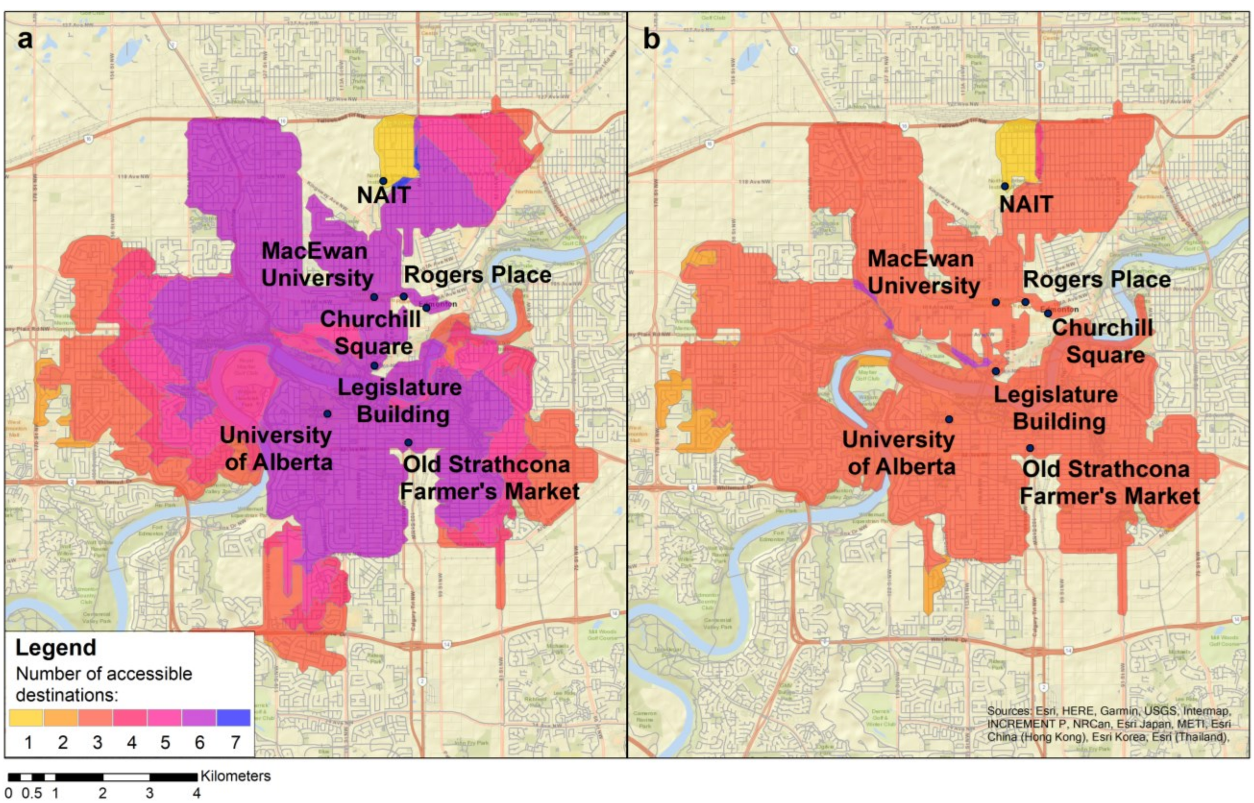


Figure 6.7 Bikeshed Area for All Destinations Combined, (a) LTS framework and (b) LCC framework

6.5.2 Origin-destination Connectivity, Shortest Path, and Detour Factor

Table 6.7 contains a comparison of the connectivity metrics between the two frameworks. Consistent with the separation of the main bikeshed under LTS into two separate bikesheds under LCC, the individual bikeshed areas for each destination are much smaller under the new framework. The number of connected origins follows the same pattern and confirm the bikeshed area conclusions: the University of Alberta, Legislature Building, and Old Strathcona Farmers Market share a common bikeshed, which is separated from the MacEwan University/Churchill Square/Rogers Place bikeshed. As with the LTS assessment, NAIT remains isolated.

Table 6.7 Comparison of Connectivity Metrics Between LTS 2 and LCC 2 Network Assessments

		University of Alberta	MacEwan University	Churchill Square	NAIT	Legislature Building	Old Strathcona Farmers Markets	Rogers Place	Total
Bikeshed Area (km^2)	LTS	67.9	56.2	41.1	1.3	69.0	65.5	50.6	70.5
	LCC	43.4	19.0	19.0	1.2	43.4	41.4	19.0	65.1
Connected origins	LTS	177	177	177	4	177	177	177	1066
	LCC	100	62	62	3	100	100	62	489
Avg. trip length (all trips) (km)	LTS	6.3	7.7	8.9	0.9	6.3	6.9	8.1	7.3
	LCC	6.3	4.5	5.4	1.1	6.2	6.3	4.6	5.7
Avg. trip length (common*) (km)	LTS	5.3	3.6	4.5	1.1	5.9	5.6	3.7	4.9
	LCC	6.3	4.5	5.4	1.1	6.2	6.3	4.6	5.7
Avg. detour length (common*) (km)	LTS	0.8	1.2	1.7	0.1	1.2	0.9	1.2	1.1
	LCC	1.9	2.0	2.6	0.1	1.6	1.6	2.1	1.9
Avg. detour factor (common*)	LTS	1.2	1.9	2.2	1.2	1.3	1.2	1.9	1.5
	LCC	1.5	2.8	3.0	1.2	1.4	1.4	2.6	1.9
% trips w/ detour factor ≤ 1.25 *	LTS	78.0	49.2	26.2	66.7	68.0	76.0	18.1	61.3
	LCC	24.0	45.9	24.6	66.7	58.0	49.0	45.9	41.5

* Trips that are possible both with LTS and LCC frameworks

Generally, average trip lengths decrease with the LCC framework because there are less origins connected to the seven major destinations. However, when considering only trips between origins and destinations that are connected under both frameworks, we find the trip lengths are longer by 0.8 km on average for all destinations with the LCC framework, indicating less direct routes are available to cyclists. Consistent with this finding, the average detour lengths and average detour factors are systematically higher for the LCC framework compared to the LTS framework, with the exception of NAIT, where both are equal. Finally, for trips that are possible under both frameworks, we calculated the proportion of trips with a detour factor below the 1.25 threshold mentioned in Chapter 3; these are trips that should in fact be considered connected since they are within a reasonable distance from the shortest path. The contrast in proportion of truly connected origins and destinations between the two frameworks is particularly visible for the three destinations part of the south bikeshed, with the University of Alberta showing the steepest drop in connected trips (78% to 24%). Overall, in 245 cases (50.4% of all common trips), the trip length is longer with LCC 2 than with LTS 2 (range: 30 m to 6.6 km). There are only 13 cases where the trip length is shorter (30 m to 550 m, and in one case, 1.2 km). All other connected trips that are possible using both LTS 2 and LCC 2 (228, 46.9%) have a negligible trip length difference (lower than 10 m).

6.6 Discussion and Conclusions

In this chapter, we used three sources of evidence (direct comfort ratings, logistic regression results, and mapping module results) to uncover what makes the three cyclists types defined in Chapter 5 very comfortable. We then used this information to create an updated version of the LTS framework. The LCC framework aligns with our three cyclist types and emphasizes comfort rather than stress. We applied the LCC framework to Edmonton's network and compared level 2 network connectivity metrics to those obtained when applying the LTS level 2 framework.

Overall, we found the LCC framework yields less optimistic results of network connectivity compared to the LTS equivalent; bikesheds are smaller, the network is less integrated, and detour factors are higher. This is the result of creating a framework that specifically aims to assess high comfort rather than low stress. In this sense, we believe the LCC framework better reflects truly comfortable connectivity. Current cyclists may tolerate the occasional use of segments that are less than very comfortable, particularly if these segments are part of a regular route. However, potential cyclists may be deterred from cycling by those segments. Particularly if the goal of applying the framework is to detect missing links, a more stringent tool can help identify a greater variety of sub-optimal segments, some of which may be short and critical, such as the ~150 m stretch we described earlier.

The LCC framework we developed defines data-driven thresholds to discriminate between LCC levels while maintaining the positive characteristics of the LTS framework: its ease of use and limited number of data inputs. Our own application of the framework recognizes that any such tool provides a baseline to assess the suitability of a network for cycling; however, frameworks do not exist in a vacuum and extensive expert knowledge can, and should, help adapt them to the local context.

There are several limitations to our work, in addition to those stated in Chapter 4 and Chapter 5. First and foremost, our framework only allows the assessment of segments; intersections were not within the scope of this research. Given the importance of intersections to comfort perception and objective safety, creating a similar framework for intersection treatments should be the object of future research. In addition, our results are limited by the use of only 16 videos. Several types of environments were not depicted. In particular, it would have been pertinent to assess the comfort of raised bike lanes (sidewalk level, no vertical delineators), and to include more collector roads. Finally, our framework is applicable to summer only as our comfort assessment did not include winter environments. For a northern city like Edmonton, understanding network connectivity in winter is important given the length of the winter season.

CHAPTER 7 CONCLUSION

To conclude this work, we first review the goals and main tasks undertaken in this research and outline the main findings. We then outline our contributions and list limitations and work to be conducted in the future.

7.1 Overview of Research

The overall goal of this research was to understand how different types of cyclists perceive different cycling environments and how these perceptions impact bicycle network connectivity. We first assessed network connectivity by adapting a popular framework, the Level of Traffic Stress, to a Canadian context and developing easily implemented metrics based on existing literature. We assessed connectivity before and after the implementation of a network of protected bike lanes in Edmonton's core from the point of view of Interested but Concerned cyclists. We then questioned the suitability of the LTS framework and of its foundational basis, the Four Types of Cyclist typology. We prepared and distributed a survey to assess (potential) cyclist comfort on different types of infrastructure. Using an empirical segmentation method, we developed a new typology that better reflects the groups of cyclists present in Edmonton based on comfort and cycling intent. We then used this typology as a basis to update the LTS framework and thus create the Level of Cycling Comfort framework, which aligns level thresholds with infrastructure preferences of the cyclist types previously defined. Finally, we used the LCC framework to assess network connectivity for the Cautious Majority cyclist type and compare results with those obtained using the LTS framework.

7.2 Main Findings

In Chapter 3, we showed that low-stress network connectivity, as assessed with the LTS framework, increased importantly with the implementation of the protected bike lane network in 2017. The number of connected origin-destination pairs increased almost four-fold and we showed network integration also increased dramatically. A network connectivity increase would be expected from a well-implemented network of new cycling infrastructure; our research allowed to quantify the connectivity increase and identify remaining high-stress links to guide future network improvements.

In Chapter 5, our empirical reappraisal of the Four Types of Cyclist, based on a non-random survey, showed Edmonton's (potential) cycling population is best described with a three-level typology. We identified three groups of relatively homogeneous cyclist types: Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists. We also showed that the Four Types of Cyclists typology does not yield very homogenous groups of cyclists, based on comfort and infrastructure preferences, and is therefore a poor basis for the LTS framework.

Finally, in Chapter 6 we used our survey data to provide an empirical basis for the development of the LCC framework. Our framework has three levels aimed at the comfort and infrastructure preferences of our three types of cyclists as well as a fourth level, *uncomfortable infrastructure*, which groups cycling environments that are likely only comfortable for a handful of cyclists. Broadly, paths and protected lanes with few gaps in physical protection are suitable for the Uncomfortable or Uninterested. Other protected lanes and very calm residential environments are adequate for members of the Cautious Majority. Finally, most other environments up to 60 kph and 2 lanes per direction are suitable for Very Comfortable Cyclists. We used this newly developed framework to assess network connectivity in Edmonton based on the network as it was at the end of 2017. Comparing results to those obtained from the equivalent LTS assessment, we showed network connectivity was not as high as initially found. We also found the reclassification of a few links caused a bikeshed to be separated in two, highlighting the lack of redundancy in the comfortable cycling network and the importance critical connections have on overall network connectivity.

7.3 Contributions

The key contribution of our work is the creation of updated, data-driven versions of two popular and extensively used classification schemes arising from our critical and empirical assessment of those schemes. The Four Types of Cyclists typology had been developed using a top-down (subjective) rather than a bottom-up (empirical) approach. Our assessment uncovered and confirmed flaws from the Four Types of Cyclists typology, which led us to develop a new typology. This in turn required the LTS framework to be re-evaluated such that infrastructure characteristics and thresholds could be realigned based on our empirical assessment of cyclist comfort. We developed the LCC framework such that it maintains the desirable qualities of the LTS framework, namely the easy rule-based application and the limited number of variable inputs, while also ensuring that thresholds and infrastructure characteristics correspond to the comfort of the three types of cyclists, as measured through survey data rather than based on prior expectations of suitable infrastructure for each cyclist type. This empirically-based update to the LTS framework is an important contribution given this framework has been and continues to be used in multiple North American cities for various purposes, including identifying network gaps and evaluating the impact of new infrastructure.

Another important contribution of our work is the use of cluster correspondence analysis as a segmentation method. Our four-point scale response data prompted us to look beyond the tandem PCA-k-means clustering approach often employed in the cycling literature and led us to test another segmentation method presented as superior to the tandem approach. The method produced intuitive and valuable results and could be useful to other researchers seeking to create cyclist typologies for their own research purposes.

From a practical point of view, our research provided valuable insight into Edmonton's network connectivity, highlighting the connectivity improvements from a specific set of interventions: the construction of several protected bike lanes in core neighborhoods. In addition, our survey of Edmontonians contains a wealth of data of which only a fraction was presented in this work. This data portrays some characteristics of the cycling population, including age and gender, cycling purpose and frequency (presented here) as well as the practice and purpose of cycling with children, cycling in the immigrant population, the use of route tracking smartphone applications, etc. (not presented here). As this work was a partnership with the City of Edmonton, the administration has access to the data and can use it to investigate other questions of interest.

7.4 Limitations and Future Work

Overall, this work has three major limitations. First, both the LTS and LCC frameworks ignore the stress/comfort of intersections, despite being recognized as the most dangerous and uncomfortable parts of a cycling trip. For the original LTS framework, an intersection assessment was possible, but the data obtained for this thesis did not allow us to implement this aspect of the framework. In the case of the updated framework presented in the previous chapter, the survey instrument used to inform changes did not contain an assessment of intersections. Even if intersection data had been available, no update based on empirical data would have been possible. In practice, numerous network designs abandon cyclists at the intersection. The need for added protection at these conflict and crash-prone areas (Klassen et al., 2014) is being increasingly recognized and this has been translated in new practice guidance, including NACTO's recent guide 'Don't Give Up at the Intersection' developed to help active transportation professionals make more appropriate intersection designs (National Association of City Transportation Officials, 2019). As new designs emerge, further empirical assessment of the comfort of different types of intersections will be necessary. This area of research should be pursued in the future, both to rectify limitations of our particular study of Edmonton and to continue informing best practices.

The second major limitation of this research is the absence of any assessment of winter conditions. Throughout this work, we have discussed with members of the cycling community, and this absence of winter conditions was often remarked upon. Indeed, our survey instrument depicted only summer scenes. This work emphasizes the importance of assessing connectivity based on different levels of comfort, but fails to measure the impact of winter conditions on comfort. Any winter cyclist can attest that the extent and connectivity of the network contracts significantly during the cold months, particularly if proper snow-clearing policies are not in place. Future work should include winter scenes and build on the current body of knowledge regarding winter cyclists and winter cycling to assess their impact on network connectivity.

Finally, the third major limitation is the non-random respondent recruitment method used for the survey. Given the large sample size, we still believe cyclist types and general conclusions hold. However, repeating the survey with a random sample and with the intentional recruitment of underrepresented groups would allow confirmation of this hypothesis. It would also allow us to make inferences about the true proportions of cyclist types in Edmonton.

Beyond exploring or rectifying limitations of the research, future work should make use of the extensive data collected in the Bicycle Ridership and Traffic Stress Tolerance Survey. Notably, we asked respondents if and why they use the route tracking application Strava to record their cycling trip. This information can be used to relate the types of cyclists and their riding characteristics, and inform the use of Strava data as a cycling volume estimation tool. The mapping module route data can also be explored more extensively, for example, to assess patterns of safety-related illegal behaviour, such as riding on sidewalks, or to model route choice characteristics.

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APPENDIX 1 – SURVEY QUESTIONNAIRE

Block 1: Ridership, ownership and Strava use

Block 1 introduction: Thank you for participating in this survey. First, we would like to learn more about your cycling habits.

1. Have you ever bicycled at any point in your life?
    a. Yes
    b. No

Branching: For those who answer "No" skip to Question 6

2. In the last year, did you ride a bicycle at least once?
    a. Yes
    b. No

3. *Branching: Q. 3a if answered "Yes" to Q. 2 and Q. 3b if answered "No" to Q. 2*
    a. How long have you been riding?
        i. Since my childhood
        ii. Several years
        iii. One year or less
        iv. Just trying it/Just started
    b. When did you last ride a bicycle?
        i. In my childhood
        ii. Several years ago
        iii. One to two years ago

4. In the last year (Sept. 2017 to August 2018) how often did you ride a bike during each season? Please indicate your cycling frequency only if you lived in Edmonton during each period.

	Daily	4 or more times per week	2 to 3 times per week	Once per week	Once per month	Never	Lived outside Edmonton at the time
Fall 2017							
Winter 2018							
Spring 2018							
Summer 2018							

5. Think back to the previous year (Sept. 2016 to August 2017). How often did you ride a bike during each season? Please indicate your cycling frequency only if you lived in Edmonton during each period.

	Daily	4 or more times per week	2 to 3 times per week	Once per week	Once per month	Never	Lived outside Edmonton at the time
Fall 2016							
Winter 2017							
Spring 2017							
Summer 2017							

6. Please indicate your level of agreement or disagreement with the following statement: I would like to travel by bike more than I do now.
    a. Strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, strongly agree

Branching: exclude those that have never ridden (from Q. 1)

7. How many bicycles do you own? For example, if you and your spouse each have a personal bike but also share a third bike, your answer would be "2". Include bicycles you don't regularly use, but are still in working order.

Branching: exclude those that answered "Never" to all seasons in Q. 4.

8. In the last year (Sept. 2017 to August 2018), for which reasons did you ride your bike? Select all that apply.[1]
    a. For recreation/leisure
    b. For fitness/performance
    c. For utility trips (running errands, visiting friends, and any other non-commute trip)
    d. To commute to school or work
    e. Other reasons (please specify)

9. In the last year (Sept. 2017 to August 2018), did you use the mobile application Strava to record any of your bicycle trips?
    a. Yes, I used Strava at least once in the last year
    b. No, I didn't use Strava
    c. I don't know / I can't remember

Branching: exclude those that answered No/Don't know

10. For the following types of trips could you describe in which circumstances you decide to use or not use Strava? Please select all that apply.
    a. For each type[2], these are the response options
        i. I never record this type of bicycle trip on Strava.
        ii. I use Strava to record this type of trip when biking with other people.
        iii. I use Strava to record this type of trip when biking to improve my time or speed.
        iv. I use Strava to record this type of trip so I can share my experiences with my network.
        v. I use Strava for this type of trip as a habit.

[1] Randomize
[2] Refer to trip categories listed in Question 8

vi. I use Strava for this type of trip to keep track of how much I bike.
vii. Other (please specify)

11. Overall, how often did you use Strava to record bicycle trips this year (Sept. 2017 to August 2018)?
    a. Daily
    b. 4 or more times a week
    c. 2 to 3 times a week
    d. Once a week
    e. Once a month
    f. Less than once a month

Block 2: Traffic Stress Tolerance[3]

Block 2 introduction: The next few questions are written descriptions and short video clips of different types of cycling facilities. We would like to know how comfortable you would feel cycling on each type of infrastructure described or shown. For this survey, comfort relates to places you could ride a bike, without hesitation or fear for your safety, in each specific scenario.

Please watch the videos with the sound turned on.

Part 1: Descriptions

How comfortable would you feel riding in these different environments?

(Possible answers: Very Uncomfortable, Somewhat Uncomfortable, Somewhat Comfortable, Very Comfortable)

1. A path or trail separated from the street.
2. A quiet residential street with low traffic speeds.
3. A quiet residential street with bike route signs and shared-use lane or sharrow markings.
4. A neighborhood commercial shopping street with one lane in each direction, traffic speeds of 40 to 50 kphour, on-street car parking, and no reserved (painted) bike lane.
5. A neighborhood commercial shopping street with one lane in each direction, traffic speeds of 40 to 50 kphour, on-street car parking, and a reserved (painted) bike lane.
6. A major street with two lanes in each direction, on-street parking, traffic speeds of 50 to 60 kphour and no reserved (painted) bike lane.

[3] Randomize part 1 and part 2 so that some see videos first and some see descriptions first. Randomize order of questions within each part.

7. A major street with two lanes in each direction, on-street parking, traffic speeds of 50 to 60 kphour and a reserved (painted) bike lane.
8. A major street with two lanes in each direction, on-street parking, traffic speeds of 50 to 60 kphour and a bike lane physically protected from traffic by bollards or planters.

Part 2: Video[4]

Please watch the following video clips and indicate how comfortable or uncomfortable you would feel riding in these different environments.

(Possible answers: Very Uncomfortable, Somewhat Uncomfortable, Somewhat Comfortable, Very Comfortable)

Video 1 - Ribbon_of_Steel (Path)

Video 2 - 130St_102Ave (MT_1)

Video 3 - 136St_StonyPlain (MT2)

Video 4 - 42St_Clareview (MT_4)

Video 5 - 139Ave_Clareview (BL_2)

Video 6 - 106St_35Ave (MT_5)

Video 7 - 109St_University (MT_8)

Video 8 - White_107St (MT_6)

Video 9 - 124St_108Ave (MT_7)

Video 10 - 106St_31Ave (BL_1)

Video 11 - 106St_Whitemud (BL_3)

Video 12 - 102Ave_108St (PBL_2)

Video 13 - 102Ave_Groat (PBL_1)

Video 14 - 80Ave_107St (CF)

Video 15 - 112St_Jasper (MT_3)

[4] The video clips last about 8 to 15 seconds each.

Video 16 - 102Ave_116St (PBL_3)

Part 3: Agreement with protected bike lanes

Please indicate your level of agreement or disagreement with the following statement:

The protected bike lane network is a worthwhile addition to the City's infrastructure.

(Possible answers: 5-point scale from completely disagree to completely agree)

Block 3: Demographics

Block 3 introduction: Before we let you go, we have a few questions for classification purposes.

1. Are you
    a. Male
    b. Female
    c. Neither option describes me
    d. Prefer not to answer

2. Do you have children 18 or under living at home?
    a. Yes
    b. No

Branching: for people who do have children at home and indicated that they bike (i.e. in Q. 4 and 5 from Block 1, there are answers other than "Never")

2.1 In the last year (Sept. 2017 to August 2018), for which reasons did you ride with your children? Select all that apply.[5]

a. For recreation/leisure
b. For fitness/performance
c. For utility trips (running errands, visiting friends, and any other non-commute trip)
d. To commute to school or work

[5] Randomize

e. Other reasons (please specify)
f. I did not ride with my children in the last year

Branching: keep only those who answered utility trips and/or commute trips

2.2 How often did you bike with your children in the last year (Sept. 2017 to Aug. 2018)?

	Daily	4 or more times per week	2 to 3 times per week	Once per week	Once per month	Never
Fall 2017						
Winter 2018						
Spring 2018						
Summer 2018						

3. Were you born in Canada?
   a. Yes
   b. No

4. What is your current employment status?
   a. Employed full-time (30+ hours a week)
   b. Employed part-time (0-30 hours a week)
   c. Homemaker
   d. Post-secondary student
   e. High school student
   f. Unemployed
   g. Permanently unable to work
   h. Retired
   i. Other (specify)

5. What is your main mode of transportation to get around in Edmonton, excluding recreational trips?
   a. Car/truck/van as Driver

    b. Car/truck/van as Passenger
    c. Public transit
    d. Walk
    e. Bicycle
    f. Other (specify)
6. What is your second most important mode of transportation to get around in Edmonton, excluding recreational trips?
    a. Only use one mode of transportation
    b. Car/truck/van as Driver
    c. Car/truck/van as Passenger
    d. Public transit
    e. Walk
    f. Bicycle
    g. Other (specify)

7. How many cars do you and others in your household own? Please indicate the total number.
    a. Text box.

8. How long is your typical commute to work or school
    a. Box for distance (km)
    b. Option for "I don't have a typical commute."
    c. Don't know

9. Which of the following categories best describes your total household income in 2017 before taxes?
    a. Under 20,000
    b. 20,000 to 29,999
    c. 30,000 to 39,999
    d. 40,000 to 49,000
    e. 50,000 to 59,000
    f. 60,000 to 79,000
    g. 80,000 to 99,000
    h. 100,000 to 149,999
    i. 150,000 and over
    j. Prefer not to answer

10. What is the highest level of education you have completed?
    a. Elementary/grade school graduate
    b. High school graduate
    c. College/technical school graduate
    d. University undergraduate degree
    e. Postgraduate degree or professional school degree (e.g. medicine, dentistry veterinary medicine, optometry)

11. Please enter your postal code
    a. Text box

12. In what year were you born?
    a. Text box, not drop down menu

Block 4: Route choice (optional in-person module introduction)

Only visible for cyclists (i.e. have answers other than "Never" in Q. 4 and52 Block 1).

Block 4 introduction:

Invitation to participate in an optional module

We are looking for further in-person insight!

We are interested to know what bike routes and facilities different people use. If you choose to volunteer for this optional module and are selected to participate, you would be asked to meet one of the Center for Smart Transportation researchers for 15 minutes to one hour at the University of Alberta. In the meeting, the researcher will use a mapping tool to record a route you take while cycling. The University of Alberta will provide participants who are selected for and complete this optional module a **$15 gift card** from Mountain Equipment Coop (MEC) in recognition of their time and effort. In addition, they will be entered in a draw administered by the University of Alberta for an additional **$50 gift card** from MEC. **Only those who are selected will be contacted.**

For further questions about this in-person research, please contact Laura Cabral at lcabral@ualberta.ca.

Would you be interested in completing this in-person survey module?

1. Yes
2. No

Branching: If yes

This information is collected under the authority of section 33(c) of the Freedom of Information and Protection of Privacy Act (Alberta) (FOIP Act) for use in connection with the City of Edmonton's research into cycling trends. Your information will be shared with a panel of experts external to the City who are assisting with the City with this project. Your personal information will be kept confidential. If you have any questions about the collection, use, or disclosure of your information, please contact the Corporate Research Unit at Research@edmonton.ca or 780-496-4173.

Please note: The Center for Smart Transportation at the University of Alberta has been contracted by the City of Edmonton to complete this in-person research. A representative from the University of Alberta may be in contact with you if you are selected.

Please provide us with the following contact information:

Name:

Email:

Block 5: Closing statement

Thank you for your participation in the Bicycle Ridership and Traffic Stress Tolerance Survey!

Please click the "Next" button to submit your responses.

APPENDIX 2 – AVERAGE SILHOUETTE WIDTH COMPUTATION

Average Silhouette Width (Rousseeuw, 1989)

1. For object *i* that belongs to cluster *A*, calculate the average dissimilarity (distance) a_i to all other points of cluster A.
2. Calculate the average dissimilarity to all objects within each of the other clusters *C*, noted *d(i, C)*. $b_i = min_C\, d(I, C)$, where b_i is the average dissimilarity to the nearest neighboring cluster.
3. The silhouette width for object *i* is $s_i = (b_i – a_i)/max(a_i, b_i)$
4. The average silhouette width is the average of s_i for all objects *i* regardless of cluster membership.

APPENDIX 3 – EXAMPLE CODE FOR CLUSTER CORRESPONDENCE ANALYSIS

Example of cluster correspondence analysis computation using *clustrd* package in R. Example for the "Geller" classification.

```
# Use tuneclus function to obtain ASW values across 3 to 8 clusters and 2 to 7 dimensions
>Geller_test_CCA <-tuneclus(select(Segmentation_Data, contains("Comfort"), "Intent", "Freq_S18_YesNo"),
                           nclusrange = 3:8,
                           ndimrange = 2:7,
                           method = "clusCA",
                           criterion = "asw")

# Output
> Geller_test_CCA

The best solution was obtained for 3 clusters of sizes 1978 (61.7%), 804 (25.1%), 426 (13.3%) in 2
dimensions, for a cluster quality criterion value of 0.17.

Cluster quality criterion values across the specified range of clusters (rows) and dimensions (columns):
      2     3     4     5     6     7
3  0.17
4  0.16 0.161
5 0.135 0.153 0.163
6 0.088  0.11 0.122 0.146
7 0.079 0.091 0.116 0.111 0.126
8 0.068 0.086 0.098 0.101  0.12 0.134

Cluster centroids:
            Dim.1   Dim.2
Cluster 1 -0.0467  0.5183
Cluster 2  1.0681 -0.7794
Cluster 3 -1.7991 -0.9357
```

```
Within cluster sum of squares by cluster:
[1] 575.7280 323.7803 460.3119
 (between_SS / total_SS =  73.09 %)

Objective criterion value: 1558.7704

Available output:

[1] "clusobjbest" "nclusbest"   "ndimbest"    "critbest"    "critgrid"

# Test global stability
> Geller_test_CCA_Global <- global_bootclus(select(Segmentation_Data, contains("Comfort"),"Intent",
"Freq_S18_YesNo"),
                                          nclusrange = 3:6,
                                          method = "clusCA",
                                          nboot = 50,
                                          nstart = 50,
                                          seed = 1234)

# Output
> summary(Geller_test_CCA_Global$rand)
       3                 4                 5                 6
 Min.   :0.2817   Min.   :0.4242   Min.   :0.4309   Min.   :0.3755
 1st Qu.:0.8827   1st Qu.:0.8860   1st Qu.:0.7416   1st Qu.:0.6102
 Median :0.9191   Median :0.9093   Median :0.8109   Median :0.7444
 Mean   :0.8879   Mean   :0.8775   Mean   :0.7939   Mean   :0.7278
 3rd Qu.:0.9424   3rd Qu.:0.9285   3rd Qu.:0.8803   3rd Qu.:0.8697
 Max.   :0.9633   Max.   :0.9527   Max.   :0.9506   Max.   :0.9528
```

```
# Test local stability of 3 clusters (repeat for all desired numbers of clusters)
Geller_test_CCA_Local <- local_bootclus(select(Segmentation_Data, contains("Comfort"),"Intent",
"Freq_S18_YesNo"),
                                       nclus = 3,
                                       method = "clusCA",
                                       nboot = 50, nstart = 50, seed = 1234)

# Output
> summary(Geller_test_CCA_Local$Jaccard)
       1                 2                 3
 Min.   :0.7270   Min.   :0.6961   Min.   :0.6409
 1st Qu.:0.8904   1st Qu.:0.8822   1st Qu.:0.7442
 Median :0.8979   Median :0.8894   Median :0.7616
 Mean   :0.8944   Mean   :0.8902   Mean   :0.7658
 3rd Qu.:0.9050   3rd Qu.:0.9081   3rd Qu.:0.7921
 Max.   :0.9169   Max.   :0.9341   Max.   :0.8332

# Having established that a 3 cluster solution is best, we run CCA with 3 clusters and extract variable-
categories
Geller_CCA <- clusmca(select(Segmentation_Data, contains("Comfort"),"Intent", "Freq_S18_YesNo"),
                           nclus = 3,
                           ndim = 2,
                           method = "clusCA")

Geller_CCA_stdres <- plot(Geller_CCA, cludesc = T, topstdres = nrow(Geller_CCA[["attcoord"]]), subplot = T)
write.csv(Geller_CCA_stdres[["stdres"]][[1]][["data"]] %>% arrange(desc(value)), "Geller_clus1.csv")
write.csv(Geller_CCA_stdres[["stdres"]][[2]][["data"]] %>% arrange(desc(value)), "Geller_clus2.csv")
write.csv(Geller_CCA_stdres[["stdres"]][[3]][["data"]] %>% arrange(desc(value)), "Geller_clus3.csv")
```

```
# Example output for first Geller cluster (col. "value" is std.res and col. "lbls" is variable category).
First 20 lines only.
> Geller_CCA_stdres[["stdres"]][[1]][["data"]] %>% arrange(desc(value))
         value place                              lbls  newplace
1   4.44605001    18    Facility_5.Somewhat comfortable       37
2   3.52506867    27  Facility_7.Somewhat uncomfortable       34
3   3.04410393    19  Facility_5.Somewhat uncomfortable       32
4   2.84461692    15  Facility_4.Somewhat uncomfortable       30
5   2.67968793    30    Facility_8.Somewhat comfortable       29
6   2.67717078    10    Facility_3.Somewhat comfortable       28
7   2.29759878     6    Facility_2.Somewhat comfortable       25
8   2.05649821    26    Facility_7.Somewhat comfortable       23
9   1.73475931    24      Facility_6.Very uncomfortable       20
10  0.77662030    33              Intent.Strongly agree       12
11  0.72403924    23  Facility_6.Somewhat uncomfortable       10
12  0.53933087    31  Facility_8.Somewhat uncomfortable        9
13  0.53480102    34              Intent.Somewhat agree        8
14  0.26985148     2    Facility_1.Somewhat comfortable        6
15  0.24267848     1        Facility_1.Very comfortable        5
16  0.18090460    16      Facility_4.Very uncomfortable        4
17  0.10978708    36           Intent.Somewhat disagree        3
18  0.01792378    38               Freq_S18_YesNo.Never        2
19 -0.01049454    39               Freq_S18_YesNo.Biked        1
20 -0.41832240    35  Intent.Neither agree nor disagree        7
```

APPENDIX 4 – VIDEO COMFORT RATINGS FOR THE THREE GROUP TYPOLOGY USING ALL VIDEOS