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An Empirical Reappraisal of the Level of Traffic Stress Framework.

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ABSTRACT

The Level of Traffic Stress (LTS) framework is widely used to assess the suitability of roadway environments for cycling. Its main strength is the identification of infrastructure characteristics that meet the needs of different cyclist groups. The four levels of infrastructure ratings, LTS 1 to LTS 4, roughly map to the cyclist types defined by the Four Types of Cyclist typology. Despite its popularity, the LTS framework has several limitations, including reliance on a cyclist typology that was developed subjectively, and a lack of empirical evidence to define thresholds between levels. This work builds on our previous empirically-based findings that cyclists form three groups rather than four: Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists. We use survey data from Edmonton, Canada, to update the LTS framework such that levels match the three types of cyclists. Direct infrastructure ratings, binary logistic regression, and route choice data provide the empirical foundation to determine infrastructure characteristics that are suitable for the three types of cyclists. This adjusted framework is called Level of Cycling Comfort (LCC). We apply the framework to Edmonton and compare connectivity outcomes using both LTS and LCC frameworks. Overall, the LCC framework yields more conservative estimates of connectivity.

Keywords: Level of Traffic Stress (LTS), Level of Cycling Comfort (LCC), bicycle network, cyclist comfort, cycling infrastructure, connectivity.

1 INTRODUCTION

A well-connected bicycle network and direct routes are associated with greater levels of cycling (Schoner & Levinson, 2014), which has been identified as a mode of transportation that can mitigate congestion and reduce air pollution and greenhouse gas emissions in urban environments (Guttenplan, Davis, Steiner, & Miller, 2003; Lindsay, Macmillan, & Woodward, 2011). As such, the connectivity of bicycle networks has become an increasing focus of research since the 1990s (Buehler & Dill, 2016). Many metrics, such as connected origin-destination pairs or number of accessible jobs, have been created to measure bicycle network connectivity and its related topics of cycling accessibility and bikeability (e.g. Boisjoly & El-Geneidy, 2016; Lowry, Furth, & Hadden-Loh, 2016; McNeil, 2011; Schoner & Levinson, 2014). These rely on frameworks or equations that define what constitutes acceptable cycling infrastructure which are used to identify segments of the full network that are suitable for cycling. However, other research has shown that cyclists have diverse perceptions of what constitutes a safe and comfortable riding environment (Abadi & Hurwitz, 2018; Larsen & El-Geneidy, 2011; Stinson & Bhat, 2005; Veillette, Grisé, & El-Geneidy, 2019), such that different cyclists will perceive the connectivity of a network differently.

One of only a few tools designed to measure the suitability of infrastructure for cycling while specifically accounting for the diversity of cyclist preferences (as per a cyclist typology) is the Level of Traffic Stress (LTS) framework (Mekuria, Furth, & Nixon, 2012). It defines infrastructure characteristics that are suitable for cyclist categories known as the Four Types of Cyclists, a typology originally developed by City of Portland bicycle coordinator Roger Geller (Geller, 2006), and later affirmed by Dill & McNeil (2013, 2016). In the LTS framework, facilities categorized as causing the highest level of cycling stress, LTS 4, are considered suitable only for the Strong and Fearless cyclist type. LTS 3 facilities are matched to the Enthused and Confident, and LTS 2 to the Interested but Concerned. Although the typology contains a fourth cyclist type, No Way No How (i.e., those who will not or cannot cycle), LTS 1 facilities are rather considered to be those suitable for children. Recently, the framework was used on a national scale in the United States to compare job accessibility by bike in 50 major U.S. cities (Owen & Murphy, 2019). The ease of use and limited data requirements have undoubtedly contributed to the widespread application of this framework.

Despite its popularity, the LTS framework has a notable limitation: it was subjectively developed using expert knowledge and existing design criteria (Mekuria et al., 2012) rather than empirical evidence. The Four Types of Cyclists typology on which it is based was also subjectively developed (Geller, 2006). Using survey data collected in Edmonton, Canada, we found that cyclists naturally form three categories rather than four: Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists (L. Cabral & Amy M. Kim, 2019). We used statistical methods to derive this empirical typology, using variables as similar as possible to the Four Types of Cyclists in order to obtain a typology that is functionally similar, but divides Edmonton's population into cyclist types that are reflective of its particularities. In this paper, we adjust the LTS framework using empirical data to reflect the comfort of each group in this new typology, thus ensuring connectivity assessments are reflective of the perception of infrastructure for diverse cyclist types. We also compare connectivity, as assessed with LTS, with our updated framework.

2 LITERATURE REVIEW

Many tools exist to assess the suitability of different bicycle infrastructure types, including the Highway Capacity Manual's Bicycle Level of Service (BLOS) (Transportation Research Board) and the Federal Highway Administration's Bicycle Compatibility Index (BCI) (Harkey, Reinfurt, Knuiman, Stewart, & Sorton, 1998). Yet, few explicitly consider different cyclist types and their level of stress or comfort. An early example of this is Sorton and Walsh (1994) who measured the impact of several infrastructure characteristics on the stress level of three different types of cyclists (Youth, Casual, and Experienced). Another example is Griswold, Yu, Filingeri, Grembek, and Walker (2018), who used a latent class choice model to simultaneously define cyclist types and quantify the level of service of different roadway environments. However, the most well-known and widely adopted of these stress-sensitive frameworks is LTS (Mekuria et al., 2012), which has been used in many applications, such as measuring low-stress connectivity, identifying missing links, prioritizing projects, and finding associations between level of stress and safety outcomes (Chen et al., 2017; Kent & Karner, 2018; Moran, Tsay, Lawrence, & Krykewycz, 2018; Semler et al., 2017).

The LTS framework uses a simple rule-based approach to identify infrastructure characteristics that make a facility suitable for children and three of the cyclist types defined by the Four Types of Cyclists typology. For roadway segments, data inputs include the number of through lanes per direction, the presence of bicycle facilities, the posted speed limit, the width of a bike lane, the presence of a parking lane, and bike lane blockage. Dutch design criteria anchor the LTS 2 specification, which should be a tolerable level of stress for Interested but Concerned cyclists, a group representing most of the adult population. The Dutch design criteria were chosen by the authors because they are associated with high levels of cycling in the Netherlands (Mekuria et al., 2012). LTS 3 and LTS 4 have incrementally increasing levels of interaction with vehicular traffic compared to LTS 2, although it is not clear how the thresholds were determined. Three tables form the overall framework to assess LTS levels for segments (i.e. between intersections): one contains criteria for painted bike lanes alongside a parking lane, another without a parking lane, and one for mixed-traffic environments. Adopting a weakest link approach, the most severe condition along a segment determines its overall LTS level. Both paths/trails and protected bike lanes are considered LTS 1.

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 (ADT) criteria for mixed-traffic riding (Furth, Putta, & Moser, 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, LTS 2.0 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, Mingus, and Watkins (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 using 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 (Interested but Concerned, Comfortable but Cautious, Enthused and Confident, and Strong and Fearless), which is adapted from the original Four Types of Cyclists. Thus, the framework retains the subjective underlying typology.

In this work, we introduce a new framework, called Level of Cyclist Comfort (LCC). The name of our framework emphasizes its focus on cyclist comfort, rather than stress. Mekuria et al. (2012) stated they defined the level of stress that could be *tolerated* by each cyclist type. Tolerating some stress might be suitable for current cyclists. However, as cities seek to increase their cycling levels, building a network of cycling infrastructure that is perceived as comfortable by its intended users should be a priority, hence the focus of this work is on high comfort rather than low stress. Comfort (and feeling of safety) was also the construct measured in the original formulation of segment BLOS (Landis, Vattikuti, & Brannick, 1997).

In our framework, we aim to maintain the LTS's ease of use and limited number of data inputs, but also provide an empirical basis for the thresholds used to distinguish different levels, using an empirically-developed cyclist typology as its foundation. We use survey data, as described in the next section, to determine infrastructure characteristics that make facilities comfortable for each of our three cyclist types and develop the LCC framework. Finally, we apply the framework to Edmonton and compare connectivity results with LTS.

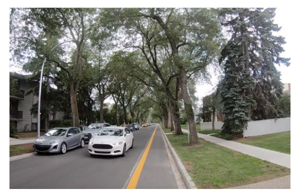
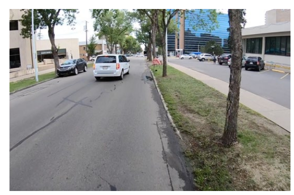
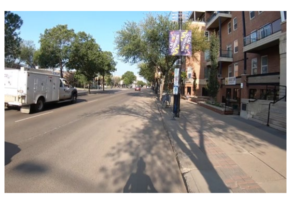
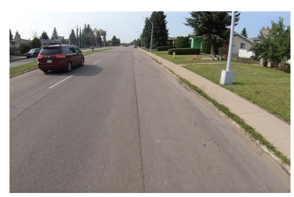
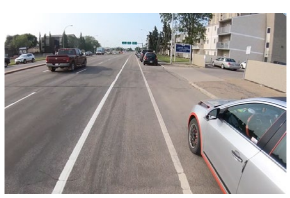
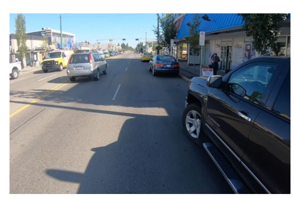
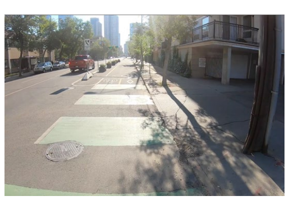
3 METHODOLOGY

3.1 Data

We developed the Bicycle Ridership and Traffic Stress Tolerance survey to collect cycling comfort data. Collaborating with the City of Edmonton, we distributed the survey to the Insight Community, a panel of Edmontonians to whom the City sends surveys monthly (2193 responses collected, 24% response rate). An open link was also advertised to collect responses from Edmontonians who are not part of the panel, with the aim of collecting a more diverse response set to supplement that from the Insight Community (1013 responses collected). The survey, which took approximately 15 to 30 minutes to complete, was made available from August 27 to September 17, 2018. A more complete description of the survey instrument and of respondents' key demographic characteristics is available in L. Cabral and Amy M. Kim (2019), but it should be noted that the non-random survey sample differs from the federal census data for Edmonton (Statistics Canada, 2017) in terms of age, income and education, but not gender. Broadly, 15 to 24 year-olds and respondents living in households with incomes below CAD 50,000 are underrepresented, while university-educated respondents are overrepresented (L. Cabral & Amy M. Kim, 2019).

A central element of the survey was a series of 16 video clips (8-12s each) filmed in various environments by the research team using a GoPro Hero 6 camera which has built-in image stabilization and thus provided smooth recording (Laura Cabral & Amy M. Kim, 2019). A representative frame of each video clip is presented in Table 1. Survey respondents were asked to rate each video clip, presented in a randomized order, on a four-point scale from *very uncomfortable* to *very comfortable*.

Table 1 Representative Frame of Video Clips

V_Path		**V_Major_Bridge_PBL**[2]	
V_Quiet_Residential		**V_Residential_PBL_Conflict**[2]	
V_Sharrow		**V_Residential_2ln_BL**[1,3]	
V_Local_Commercial		**V_Contraflow**	
V_Local_Commercial_BL[1]		**V_nonResidential_1ln**[3]	
V_Major		**V_Residential_2ln**[3]	
V_Major_BL[1]		**V_Major2**	
V_MajorPBL[2]		**V_Major3**	

[1] "BL" stands for "Bicycle Lane"
[2] "PBL" stands for "Protected Bicycle Lane"
[3] "ln" stands for "Lane" and refers to the number of vehicle traffic lanes per direction

The main characteristics for each video are presented in Table 1. In particular, we measured all variables that are inputs to the LTS framework (e.g. speed limit, etc.; see list in the Literature Review section). Note that bike lane blockage is not reported as we only recorded bike lanes without blockages. We also added other variables that have been shown to influence comfort (Li, Wang, Liu, & Ragland, 2012) and propensity to commute (Heinen, van Wee, & Maat, 2010), or could otherwise influence comfort ratings, as recorded in Table 2. These include pavement surface quality, presence of vegetation, adjacent land use, presence of a visible intersection ahead in the clip, and an assessment of traffic volume (low, medium, high) based on number of moving vehicles passing the rider in each video, with “low” being none and “high” being three or more.

Videos have been used by researchers to assess cycling environments and have been shown to be effective assessment tools (Griswold et al., 2018; Harkey, Reinfurt, & Knuiman, 1998; Jensen, 2007; Landis et al., 1997; Lehtonen, Havia, Kovanen, Leminen, & Saure, 2016; Parkin, Wardman, & Page, 2007). Videos also have the advantage of allowing a wide array of respondents to participate as no prior cycling knowledge or ability is required. In addition, data collection through an online survey is faster than a field study since participants do not have to be physically present, which also minimizes risk for respondents since they do not have to interact with motorized traffic in cycling conditions that may feel unsafe to them. Finally, the use of videos ensures uniform conditions are presented to all survey participants. However, a limitation of the use of videos is that it is not possible to control which subset of stimuli within the video and sound a particular respondent will pay most attention to. Given the real world, on-road testing environment, our ability to control for certain variables, notably prevailing speed and traffic volume, is also limited.

Table 2 Selected Video Characteristics

Video Name	Facility Type	Prevailing Speed (kph)	Speed Limit (kph)	Lanes per Dir.	Centerline	Intersection Visible	Traffic	Width of Bike & Parking	Parking Occupation	Land Use	Vegetation	Surface	LTS
V_Path	Shared-Use Path	-	-	-	-	No	-	-	-	Green Space	Plenty	Good	1
V_Major_Bridge_PBL	Protected Lane	52	60	2	Yes	No	High	2.77	No Parking Lane	Other (Bridge)	None	Good	1
V_Major_PBL	Protected Lane	50	50	2	No	Yes	High	3.07	No Parking Lane	Commercial or Institutional	Some	Good	1
V_Residential_PBL_Conflict	Protected Lane	30	50	1	No	Yes	Med	2.74	No Parking Lane	Residential	Plenty	Good	1
V_ContraFlow	Contra-flow	35	50	1	No	No	Med	1.24	No Parking Lane	Residential	Plenty	Good	2
V_Residential_2ln_BL	Bike Lane	44	50	2	Yes	No	Med	1.17	No Parking Lane	Residential	Some	Bad	2
V_Local_Commercial_BL	Bike Lane	40	50	1	Yes	Yes	High	3.56	Not Occupied	Commercial or Institutional	None	Good	3
V_Major_BL	Bike Lane	48	50	2	Yes	No	Med	4.21	Occupied	Residential	None	Good	3
V_Quiet_Residential	Mixed Traffic	-	50	1	No	No	Low	-	Occupied	Residential	Plenty	Good	1
V_Sharrow	Mixed Traffic	25	50	1	No	Yes	Low	-	Occupied	Residential	Plenty	Good	1
V_nonResidential_1ln	Mixed Traffic	46	50	1	No	Yes	High	-	No Parking Lane	Commercial or Institutional	Plenty	Bad	2
V_Local_Commercial	Mixed Traffic	49	50	1	No	Yes	High	-	No Parking Lane	Commercial or Institutional	Some	Good	3
V_Residential_2ln	Mixed Traffic	47	50	2	Yes	Yes	Low	-	Not Occupied	Residential	None	Good	3
V_Major	Mixed Traffic	50	50	2	Yes	No	High	-	Not Occupied	Commercial or Institutional	Some	Good	4
V_Major2	Mixed Traffic	40	50	2	Yes	Yes	High	-	Occupied	Commercial or Institutional	Some	Good	3
V_Major3	Mixed Traffic	55	50	3	Yes	Yes	High	-	No Parking Lane	Commercial or Institutional	Plenty	Bad	4

For the development of the LCC framework, we use the three cyclist types derived through Cluster Correspondence Analysis from the same survey data[1] (L. Cabral & Amy M. Kim, 2019): Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists. Each group is described in detail in L. Cabral and Amy M. Kim (2019) along with the methodology used to obtain the typology. The salient characteristics for each group are as follows:

Uncomfortable or Uninterested

- More likely than all respondents to rate all videos as *very uncomfortable*
- More likely than all respondents to strongly disagree they would like to cycle more often
- More likely than all respondents to not have bicycled in the previous summer

Being uncomfortable in most riding environments is the necessary characteristic of this group, while being uninterested will also allow for inclusion. Respondents in this group tend to be older with a higher representation of women.

Cautious Majority

- More likely than all respondents to rate all videos as somewhat comfortable or somewhat uncomfortable

The Cautious Majority have a more balanced gender distribution and the about half of those in the group are 25-44 years old, with 45-65 year-olds the second most important age group.

Very Comfortable Cyclists

- More likely than all respondents to rate all videos as *very comfortable*

This group is heavily skewed towards male respondents with just under half the respondents between 45-64 years old.

We also collected detailed route data for 100 respondents who participated in an optional module. Summary demographic characteristics are shown in Table 3. Respondents typically have a high education and income, and are most likely to be aged 25 to 44 years old. These participants were asked to indicate the intersection closest to their house and, from there, to describe their commute route to work or their place of study. Those who did not work or study described their route to another regular utility destination (e.g. shopping, place or worship, etc.). Using Esri's ArcMap software, we recorded the route and the facility type for each segment traversed (e.g., road, painted bike lane, protected bike lane, etc.). In addition to the researchers' own knowledge of the network, a map of Edmonton's bicycle network produced by the City of Edmonton was used to help respondents identify the facility type they were using if they were unfamiliar with the distinction between types of bikeways.

[1] However, we use the membership assignments obtained from segmenting using the 16 videos sample, not the eight. The level of agreement between the three-cluster solution with 16 videos and eight videos is over 90%, making the two segmentations equivalent. Using the 16 videos allows us to assess the wider range of facility types captured by the complete set of video clips.

Table 3 Summary Demographic Statistics for Optional Module Respondents

Variable	*Percent in Category*
Gender	
Female	44.0
Male	56.0
Other	0.0
Age (Years)†	
19 – 24	4.0
25 – 44	63.0
45 – 64	25.0
65 – 78	8.0
Income ($ CAD)	
< 50,000	7.0
50,000 to 99,999	26.0
100,000 or more	59.0
Prefer not to answer	8.0
Education	
High school or less	9.0
Technical school	13.0
University degree	78.0

Finally, the network and origin-destination data required to implement the LCC framework and compare to LTS results is described in a previous paper (Cabral, Kim, & Shirgaokar, 2019). The destinations are seven points of interest in Edmonton's core that are known to or could attract high cycling traffic: three higher education institutions, the University of Alberta, MacEwan University, and NAIT (Northern Alberta Institute of Technology); two governmental locations, the Alberta Legislature Building (provincial) and Churchill Square (municipal); and two centers of social life, the Rogers Place arena and the Old Strathcona Farmers' Market. We also generated 298 hypothetical origins consisting of Traffic Analysis Zone centroids in the city's core neighborhoods.

3.2 Analysis

The methodological framework is presented in Figure 1. Three elements are used as guides to develop the LCC framework: ratings of the 16 videos by each cyclist type, 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. The following sections detail how each element was considered in the development of the LCC framework.

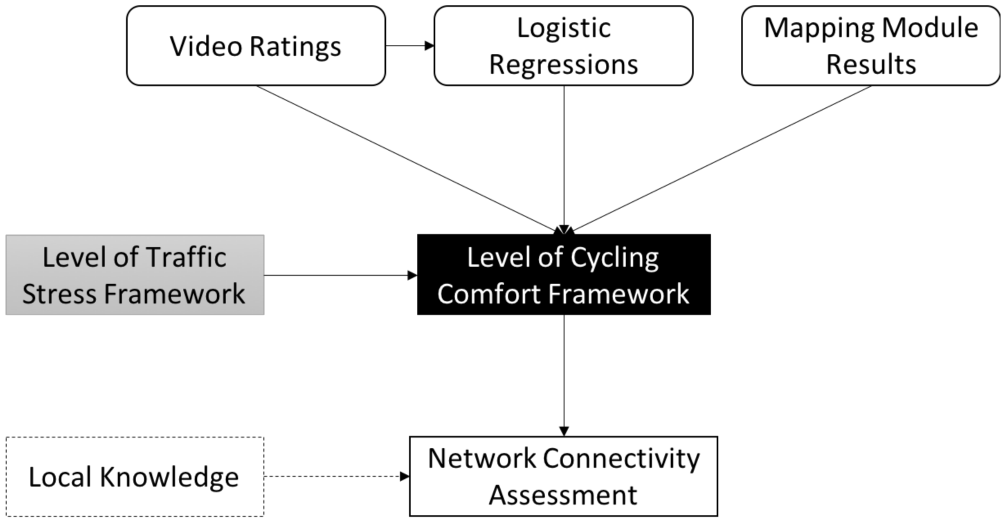


Figure 1 Methodological Framework for the Development of the Level of Cycling Comfort (LCC) Framework and the Reassessment of Edmonton's Network Connectivity

3.2.1 Video Ratings

We deem an infrastructure adequate for a given cyclist type if at least 50% of its membership rates the location *very comfortable*. We excluded *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 is arbitrary but was chosen to ensure a simple majority of respondents are very comfortable on the infrastructure, and that most cyclists will be at least somewhat comfortable (i.e. adding *very comfortable* and *somewhat comfortable* ratings).

3.2.2 Logistic Regressions

We use the same logic for logistic regressions: the outcome variable is the comfort rating transformed into a binary variable: *very comfortable* (1) or *not very comfortable* (0). Three models were developed, one for each cyclist type. Modelling was done using R package *stats* (R Core Team, 2019) with some helper functions from *lmtest* (Zeileis & Hothorn, 2002), *reghelper* (Hugues, 2018), and *caret* (Kuhn et al., 2019).

We initially considered a large set of explanatory variables, including those listed in Table 1. We eliminated variables that were not correlated to the outcome and those that violated multicollinearity and linearity to the odds assumptions. We prioritized variables that are currently part of the LTS framework to be included in the regression models.

The final set of variables includes facility type, lanes per direction, parking occupation, prevailing speed, and land use. The latter often provides some indication of expected traffic volumes and roadway widths. Edmonton's roadway 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.

3.2.3 Mapping Module

The last source of evidence used to develop the LCC framework is the set of route characteristics from the optional mapping module. We first divided routes according to cyclist type and examined the distribution of infrastructure types used. Any mixed-traffic riding was recorded as 'Street' during the interviews. To increase our understanding of street use, we extracted the functional class for these segments from our base map through spatial selection in ArcMap (Esri). We note that the use of a particular street type does not imply high comfort. In many interviews, respondents made comments regarding sections of their routes they found less comfortable; however, we did not systematically record this information.

3.2.4 Defining the Level of Cycling Comfort Framework

Following the structure of the LTS framework, we define LCC 1 as the infrastructure comfortable for Uncomfortable or Uninterested, LCC 2 for Cautious Majority, and LCC 3 for Very Comfortable Cyclists. We do not define a level specifically for children as this demographic was not assessed in the survey. We propose that the recommendations for Uncomfortable or Uninterested will likely be suitable for children as well, although a separate assessment would be required to confirm this assumption.

As with the LTS framework, the LCC levels are cumulative. We found it would be untrue to say all streets, including freeways, are very comfortable for most Very Comfortable Cyclists (L. Cabral & Amy M. Kim, 2019). Since the framework aims to capture comfort, we also define another level: Uncomfortable Infrastructure (UI), which only a handful of the most experienced, confident, and aggressive cyclists are likely to find comfortable and use. These facilities should not be considered part of the cycling network.

The three sources of evidence are used to designate infrastructure conditions to each level. Once the framework is developed, we apply it to Edmonton's network and assess comfortable connectivity using the LCC 2 network. We apply the same connectivity metrics described in Cabral et al. (2019) and compare results using LTS and LCC. These include the bikeshed area (area reachable from a given origin using only low-stress/comfortable links, up to 12 km of network distance), origin-destination (OD) connectivity, shortest path, and detour factor.

4 FINDINGS

4.1 Video Comfort Ratings

Figure 2 shows the proportion of *very comfortable* ratings given to each video clip by the three cyclist types. The V_Path video is the only one 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 V_Residential_PBL_Conflict compared to V_Major_Bridge_PBL and V_Major_PBL is the lack of physical separation on most of the stretch shown in the video, where the concrete median and bollards are missing to accommodate residential driveways. Note that it is still evident that the video depicts a protected bike lane, as the median is visible towards the end of the clip, and the bike lane has a two-way configuration.

Painted bike lane videos and the contra-flow lane video are perceived as truly comfortable only by Very Comfortable Cyclists. The Cautious Majority appears more likely to be comfortable on residential streets compared to other streets; V_Quiet_Residential and V_Sharrow 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 V_Major2 and V_Major3, both arterials. Compared to V_Major, which is an arterial similar to V_Major2 with more than 50% approval, the latter has parked cars in the outer lane.

Figure 2 Distribution of Comfort Ratings and Percent *Very Comfortable* ratings for Each Video Clip and Cyclist Type

4.2 Logistic Regressions

Table 3 shows the results of the three logistic regressions, with coefficients and odds ratios, and their standardized counterparts reported. 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.

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 *very comfortable*, compared to mixed-traffic riding. The negative perception is in line with recent empirical evidence that shows bike lanes decrease motorized vehicle passing distance (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 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 *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 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.

While the models' goodness of fit statistics are not high, we find the prediction accuracy adequate to very good: 92.5% for Uncomfortable or Uninterested, 87.8% for Cautious Majority, and 73.6% for Very Comfortable Cyclists. We assessed prediction accuracy using R package *caret* (Kuhn et al., 2019). Table 4 presents the predicted probabilities (and confidence intervals) of *very comfortable* ratings for various riding environments. The set of conditions vary for each type of cyclist based on their relevance 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 4 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 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 the mildest conditions: a very low speed residential environment with unoccupied parking (15.5%, [9.7, 23.9]).

Table 5 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

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 in Table 4 for this group. 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 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: all residential settings, independent of speed (up to 60 kph), facility, lanes, and parking are comfortable. Nonetheless, commercial or institutional 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 (58.9%, [51.8, 65.7]). Contra-flow lanes are just under the 50% threshold, although we do not know of any contra-flow lanes in non-residential environments 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 without parked cars.

4.3 Mapping Module Results

Ten of the 100 mapping module respondents are 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 caution, particularly for the 10 Uncomfortable or Uninterested who are all uncomfortable but not uninterested, and thus do not represent their entire group.

From Table 6, we find that all groups use three categories of infrastructure for the majority of their trips: streets (mixed-traffic riding, including sharrows), shared-use paths, and protected bike lanes. Other fairly abundant infrastructure types, such as alleys, are not heavily used by cyclists in any group; they are not particularly welcoming cycling environments in Edmonton. To put this information in context, it is useful to understand the composition of Edmonton's cycling network. There are about 20 km of protected bike lanes, all in the central core neighbourhoods, over 1150 km of shared-use paths, about 30 km of painted bike lanes, and about 160 km of signed shared roadway.

For the Uncomfortable or Uninterested, protected bike lanes are used the most (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 than protected bike lanes, we could have expected a higher use of the former. However, the use of particular facilities is a function of availability in the general corridor between each cyclist's origin and destination. An assessment of the particular routes taken by the ten respondents (available in (Cabral, 2019)) indicates they are generally accessing shared-use paths if available. When considering access, egress, and links between these paths, other types of facilities make up a larger proportion of the routes.

Almost all in the Cautious Majority group used streets as part of their route, which is the most used type of infrastructure (median: 32.4%), followed by shared-use paths (median: 23.5%). Such frequent 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. However, again, facility availability must be taken into account. As with the Uncomfortable or Uninterested, an analysis of the route map suggests mixed-traffic riding is often used as access, egress, and link between other bicycle-specific infrastructures, or in locations where no such infrastructure accessible.

All Very Comfortable Cyclists use streets on their route (median: 35.4%). 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 frequently-used infrastructure type is shared-used paths (median 26.5%). Protected bike lanes are also used, but similar to the Cautious Majority, to a much lesser extent.

Mixed-traffic riding is an important route component for all three cyclist types. Table 6 uncovers differences in functional class use between the groups. Note that Edmonton's functional classification includes land use for local and collector roads (e.g. local-residential, local-industrial, etc.) Differences between groups are particularly salient for local-residential streets and arterials. Median values for the local-residential streets are 50.0%, 62.2%, 27.5% for Uncomfortable or Uninterested, Cautious Majority, and Very Comfortable Cyclists, respectively. As a comparison point, local-residential streets represent ~43% of Edmonton's street network. Class C and D arterials (low speeds, truck or non-truck routes), which comprise ~21% of Edmonton's network, also show important differences in use. The median values for the two types of arterials combined are 0.2%, 0.7%, and 25.2%, for each cyclist type, respectively. For the Uncomfortable or Uninterested and Cautious Majority, local-residential streets are clearly preferred over arterials. However, Very Comfortable Cyclists use class C and D arterials approximately in the same proportion as these facilities are provided on the entire city network. They limit their use of residential streets, which may be linked to a desire for direct routes, achieved by riding on arterials. The median detour ratio (route length/shortest route) is indeed lower for Very Comfortable Cyclists at 1.08, compared to 1.12 and 1.11 for the Uncomfortable or Uninterested and the Cautious Majority, respectively.

Table 6 Proportion of Route Travelled on Different Types of Infrastructure and of Street Functional Class Used, and Total Route Distance

	Uncomfortable or Uninterested				**Cautious Majority**				**Very Comfortable Cyclists**			
	# Null	*Range*	*Median*	*Mean*	*# Null*	*Range*	*Median*	*Mean*	*# Null*	*Range*	*Median*	*Mean*
Facility Type												
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
Street	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
Functional Class (for facility type = Streets)												
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.

4.4 Level of Cycling Comfort Framework: Presentation and Justification

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

1. Based on the results presented, 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 when otherwise stated, we assume there are on-street parked cars. This reflects the most common circumstance in Edmonton. However, contra-flow lanes are assumed to have no adjacent parking lane, as this situation does not exist in Edmonton (and would be dangerous).

In the following three sections, we detail the decision-making process used to choose the final set of conditions that define the LCC levels. We then present the integrated LCC framework in a table form, similar to that used for the LTS framework.

4.4.1 Uncomfortable or Uninterested (LCC 1)

All shared-use paths and other facilities completely segregated from motorized traffic are classified as LCC 1. The logistic regression results suggest protected bike lanes could be suitable for this group in a residential context, but not for other land uses. However, videos of protected lanes that were not in a residential environment were given very high ratings by the 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.

4.4.2 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 logistic model predictions suggest mixed-traffic riding in commercial or institutional areas is not suitable for this group. Residential land use with very low speeds (30 kph), parked cars, and one lane of traffic per direction does not reach the 50% probability threshold we use for guidance. 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 regression model results, painted bike lanes have no effect on comfort for this group and they can be assessed with the same criteria as mixed-traffic. Contra-flow lanes have a negative effect on comfort and are not considered LCC 2 in any condition.

4.4.3 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.

A maximum of two lanes per direction allows for an LCC 3 rating. This is supported by the lower rating of the V_Major3 video depicting three lanes of traffic, the negative effect of three lanes in the logistic regressions, and the fact that all environments with this number of lanes are considered LTS 4 in the LTS framework. In residential areas, prevailing speeds up to 60 kph with any parking condition are considered comfortable for Very Comfortable Cyclists, whether in mixed-traffic, painted bike lanes, or contra-flow lanes.

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 considered suitable conditions for mixed traffic and painted lane riding. Table 7 presents the LCC framework.

Table 7 Level of Cycling Comfort Framework

<table>
<tr><th>Trails/Paths</th><td colspan="6">LCC 1</td></tr>
<tr><th rowspan="2">Protected Bike Lane</th><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><th rowspan="5">Mixed-traffic, painted lane (and contra-flow lanes for LCC 3 only)</th><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>

* 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.

The LCC framework is contained in a single table compared to three for LTS (segment assessment only). There are several reasons LCC's comparative simplicity to LTS. First, the blockage of a bike lane would result in a cyclist having to ride with traffic; given bike lanes are assessed as equivalent to mixed-traffic in our framework, we eliminated this variable, as Furth et al. (2018) did in their LTS update. The width of painted bike lanes (and parking lanes, if applicable) is also eliminated because a) this data is unlikely to be easily available to most jurisdictions (Bearn et al., 2018); b) the variable could not be assessed in our binary logistic regressions because it violated model assumptions; c) if a bike lane is known not to be wide enough to avoid riding in the dooring zone, the facility should be considered non-existent since riding with traffic is safer option when there are parked cars in the parking lane. The presence of parking also plays a much smaller role in our framework, given it is often statistically insignificant for commonly observed conditions, based on our modelling. The increased simplicity also stems from the lower number of conditions that are considered comfortable for all cyclist types compared to LTS.

Although painted bike lanes are rated in the same way as mixed traffic and may possibly even be less safe than mixed-traffic riding (Beck et al., 2019), pavement markings (not necessarily lanes) can still have value as wayfinding tools, at least in summer. 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 guide cyclists to preferred mixed-traffic routes may help in this regard.

4.5 Application of the Level of Cycling Comfort Framework

In Edmonton, local-residential streets normally have a speed limit of 50 kph. In our application of the framework, it would be unduly restrictive, and not reflective of reality, to classify all these streets as LCC 3, as our framework dictates they should. Because our connectivity analysis concentrates on core neighbourhoods where intersection density is high and streets are comparatively narrow, yielding lower prevailing speeds, we classify these streets as LCC 2, but note that better data would be desirable to implement the framework with greater accuracy. The rating of all local-residential streets as LCC 2 acknowledges 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 suitable for the Cautious Majority cyclist to exit the neighbourhood. The municipal council has recently (2020) voted in favor of a posted speed limit reduction to 40 kph on all residential streets in Edmonton as well as some major pedestrian-oriented streets. When that speed reduction is implemented, the connectivity results we show here will be further realized.

Figure 3 compares the LTS assignment to the LCC assignment of Edmonton's network. We use the same colour scheme to facilitate a comparison (e.g. LCC 1 and LTS 1 are both in dark green) 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; these are bolded in Figure 3a and b, and specifically marked in Figure 3c. 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 visible 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), which explains their original rating as LTS 1, our results indicate even lower speeds, in a mixed-traffic environment, are not perceived as comfortable by the Uncomfortable or Uninterested. Some other changes to the comfort evaluation of more isolated links have a profound effect on network connectivity, as we discuss below.

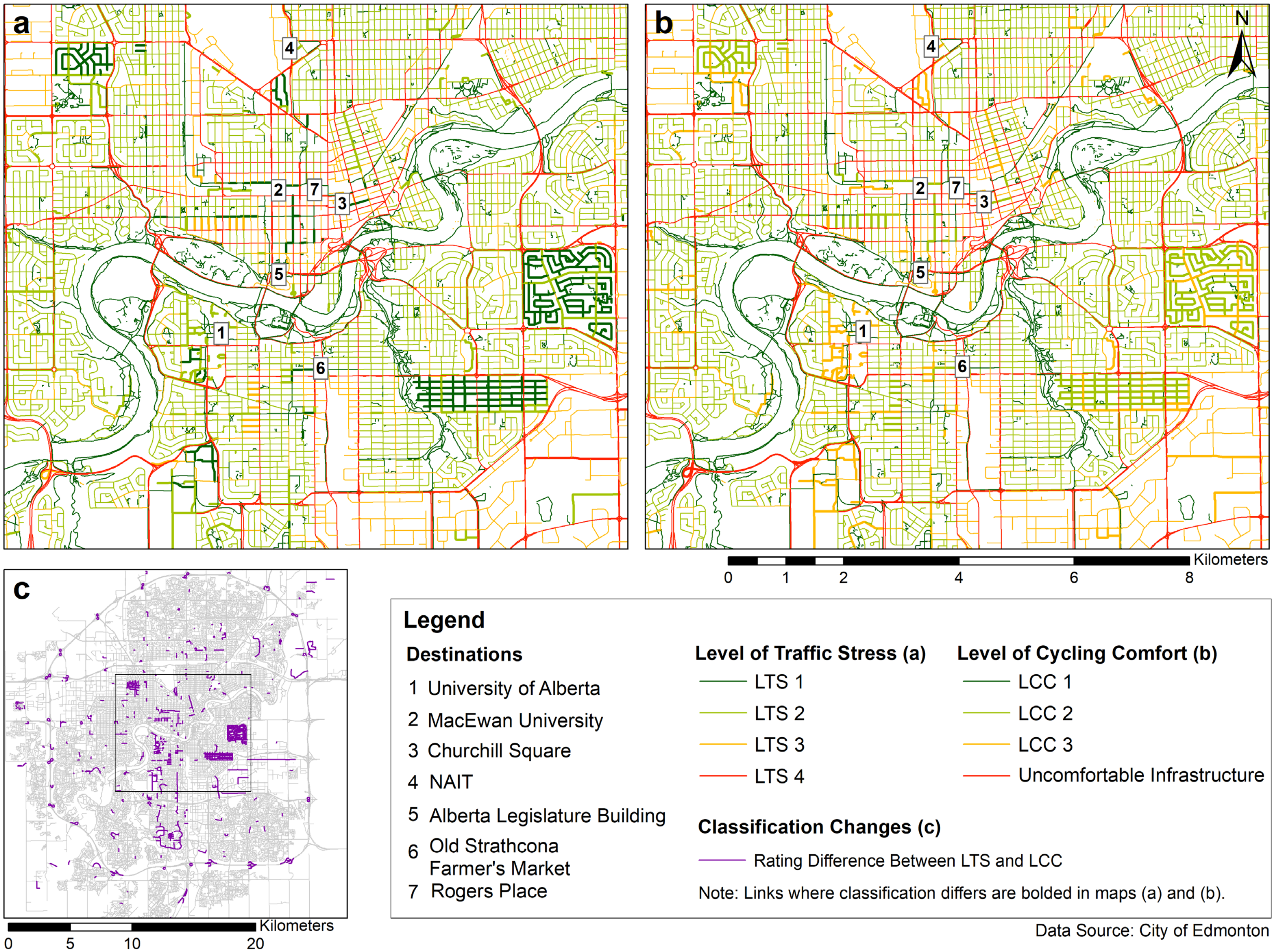


Figure 3 Comparison of LTS (a) and LCC (b) Network Ratings, and Overview of Locations Where Classification Differs Between the Two Frameworks (c)

Figure 4 shows the bikeshed areas for each of the seven destinations listed in Figure 3 (up to 12 km from each destination) and described in our previous work (Cabral et al., 2019). Compared with the bikesheds obtained using the LTS 2 network, the LCC 2 bikesheds are much smaller (represented in Figure 4; LTS 2 is comprised of both green and blue); area values are presented in Table 8. 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 areas for the Alberta Legislature Building, Old Strathcona Farmer's Market, and University of Alberta Transit Center are nearly identical. Similarly, Churchill Square, Rogers Place and MacEwan University share a common bikeshed. This is also shown in Figure 5b, where most of Edmonton's central neighbourhoods have three accessible destinations. The total bikeshed area is effectively divided into three: a south bikeshed and north bikeshed, each giving access to three different destinations, and NAIT's small isolated 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 southernmost portion of the bikeshed area. However, the network integration is not as high as we initially assessed using the LTS framework, where all areas in purple (Figure 5a) had six destinations accessible within a 12 km bike ride.

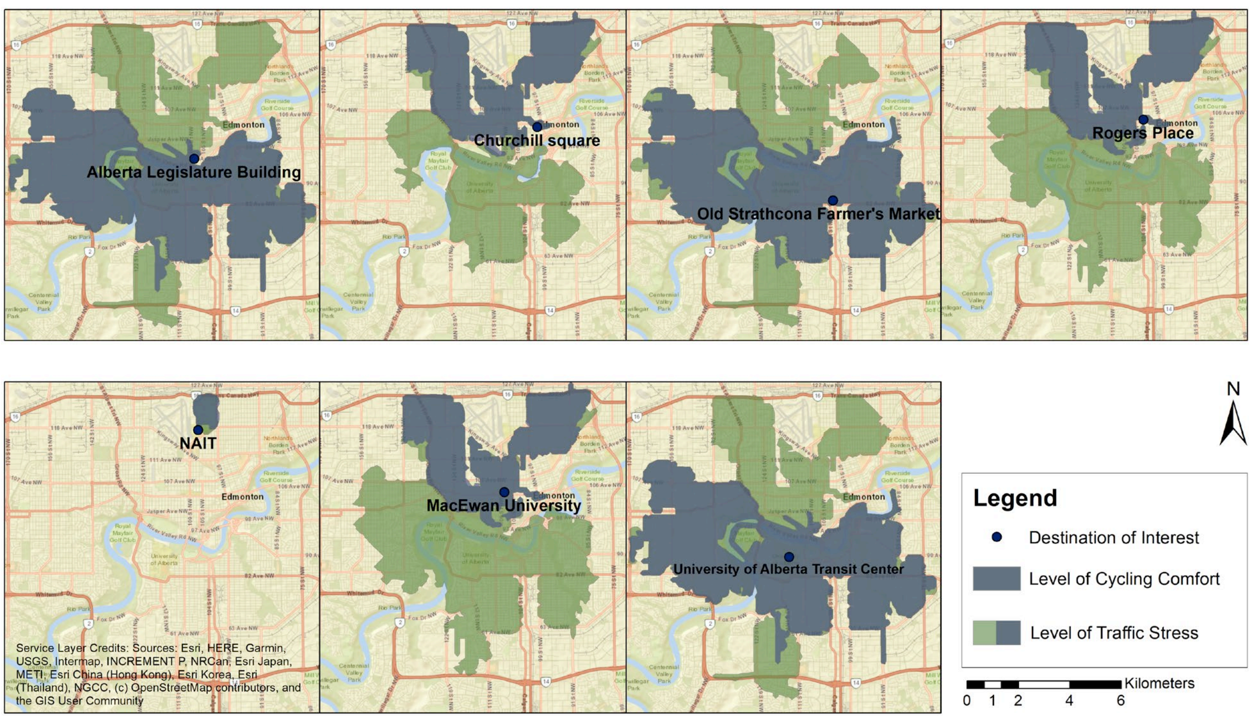


Figure 4 Bikeshed area for each destination as assessed with the LCC framework (blue area) and LTS framework (both blue and green areas)

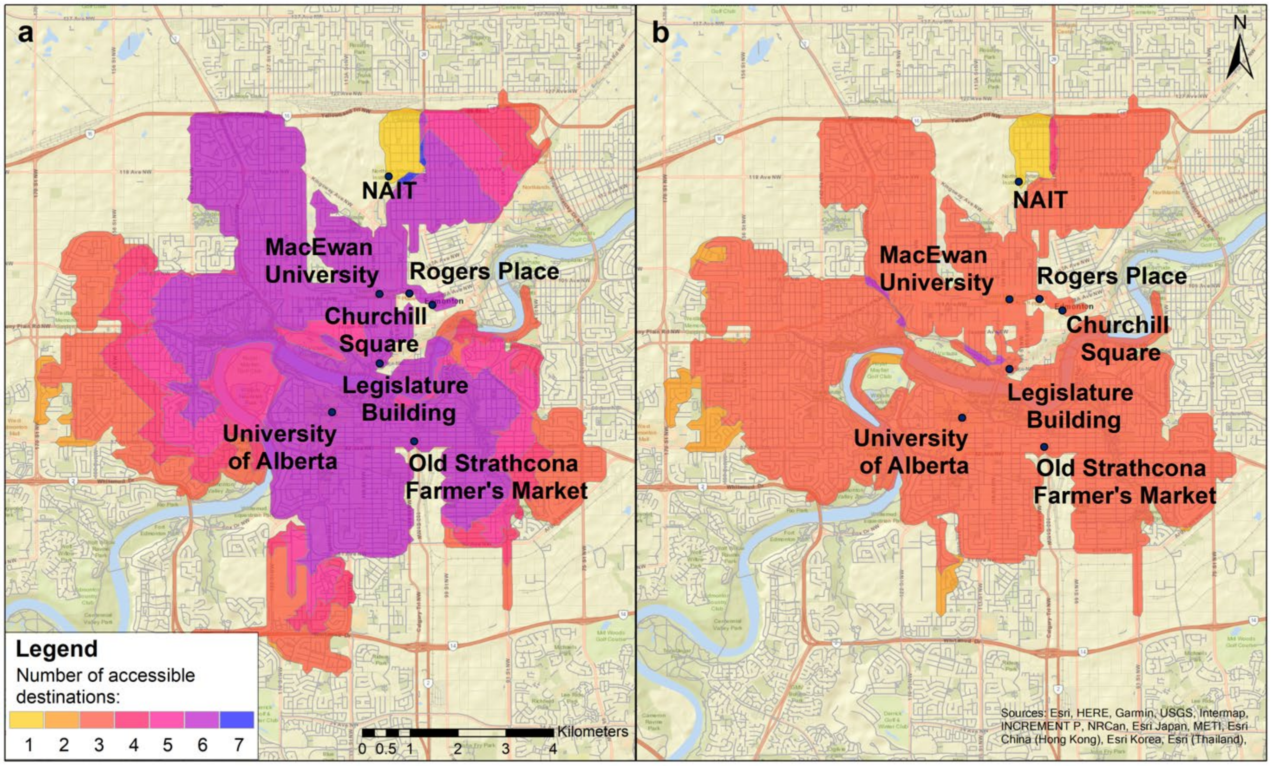


Figure 5 Bikeshed Area for All Destinations Combined, (a) LTS framework and (b) LCC framework

We mainly attribute the division of the large cyclable area illustrated in Figure 5a into two separate bikesheds (north and south bikesheds, as discussed above) to the reclassification of three small road segments to LCC 3. These three segments, shown in Figure 6, 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 the north limit of the CBD; we collectively name them the Jasper Crossing since they cross Jasper Avenue. Segment A in Figure 6 is an alley that has particularly high vehicular traffic since it is an access point to a mid-rise residential building parkade, a high-rise office building parkade, and two surface parking lots. Segment B is a one-way street segment; going north, there is a painted bike lane that disappears to share a right-turn lane with vehicular traffic, and going south, there is a contra-flow lane and cyclists have to cross traffic to access segment A described above. Finally, segment C is the entrance to a commercial plaza, which is busy and has limited sight distance due to a bend in the horizontal alignment, as shown in Figure 6. The distance of the Jasper Crossing between the two shared-use paths is just under 150 m, but this short gap is filled with segments considered uncomfortable by the Cautious Majority. Cyclists still use this route extensively because there is no comfortable alternative nearby. Indeed, the Jasper Crossing has been identified by the City of Edmonton as an area for cycling (and walking) accessibility improvement, supporting our classification.

This finding emphasizes the impact small missing links can have on overall network connectivity. Even though only a small percentage of all links in Edmonton's network changed numerical level between LTS and LCC, the change allowed us to identify meaningful missing links such as the Jasper Crossing.

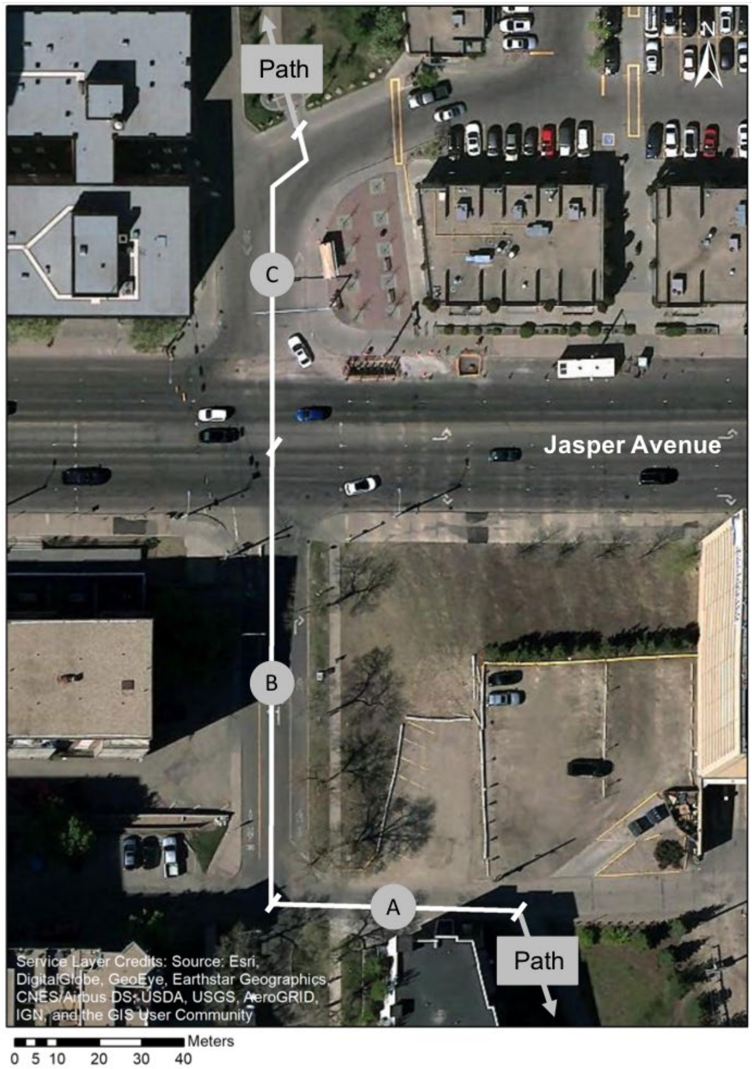


Figure 6 Jasper Crossing: Set of Three Critical Links Reclassified as LCC 3 Rather Than LTS 2

The effect of improving these links is shown in Figure 7; the bikesheds would be integrated (except NAIT), and many destinations available within a 12-km ride. 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 comfortable links were available nearby.

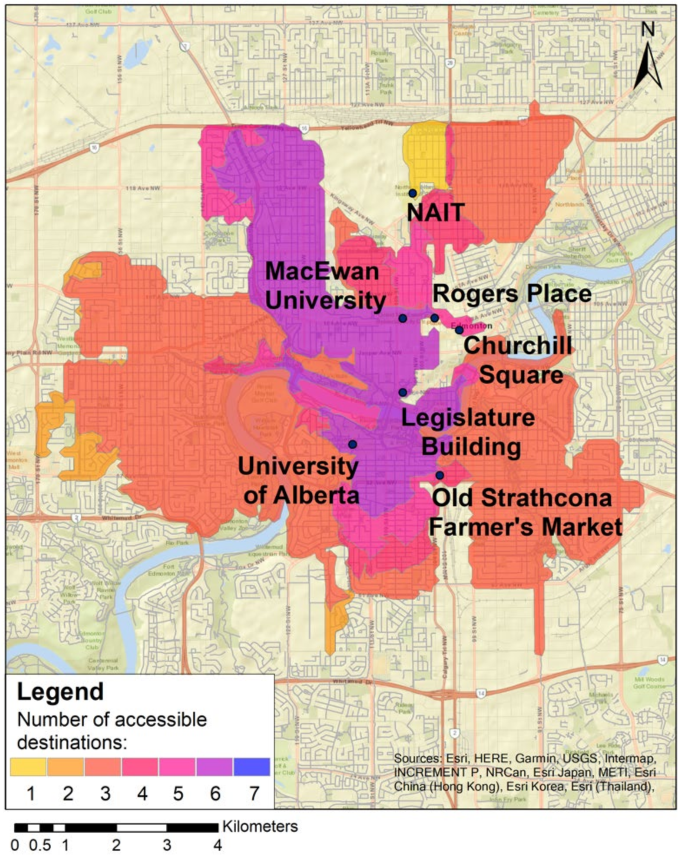


Figure 7 Potential Bikeshed Area for All Destinations Combined if Jasper Crossing Missing Links Were Upgraded

Table 7 contains a comparison of the connectivity metrics between the two frameworks. The individual bikeshed areas for each destination are much smaller under the new framework. The number of connected origins follows the same pattern and indicates 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.

Generally, average trip lengths decrease with the LCC framework, but this is because fewer OD pairs are connected. However, when considering only OD pairs connected under both frameworks, we find trip lengths are longer by 0.8 km on average with LCC, indicating fewer direct routes are available to cyclists according to the LCC classification. Consistent with this finding, the average detour lengths and average detour factors are systematically higher for LCC compared to LTS, 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 1.25; these are trips that should be considered connected since they are within a reasonable distance from the shortest path, as per Mekuria et al. (2012)[2]. 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, for 245 OD pairs (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). Most other connected trips that are possible using both LTS 2 and LCC 2 have a negligible trip length difference (lower than 10 m).

Table 8 Comparison of Connectivity Metrics Between LTS 2 and LCC 2 Network Assessments

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

5 DISCUSSION AND CONCLUSIONS

Understanding the comfort of different types of cyclists is important when assessing the suitability and connectivity of current and future cycling infrastructure. Although the LTS framework fills this need for a stress-sensitive infrastructure assessment method, it has several limitations, mainly associated with the subjectively developed underlying cyclist typology and choice of level thresholds.

In this work, we used three sources of empirical evidence to determine which cycling environment characteristics make Uncomfortable or Uninterested, Cautious Majority and Very Comfortable

[2] As a note, only 15 of the 100 mapping module respondents had a detour ratio above 1.25.

Cyclists very comfortable. These cyclist types were empirically developed in previous work. 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 LCC level 2 network connectivity metrics with similar LTS results.

One of the major differences of the LCC framework compared to LTS is the assessment of painted bike lanes as mixed-traffic environments; indeed, our evidence showed these lanes do not increase perceived comfort compared to mixed traffic. Although, as noted previously, this result seems to align with recent research showing passing distance is lower when painted lanes are present (Beck et al., 2019), it contrasts with evidence from other research (Landis et al., 1997). This result should ideally be validated with a greater sample of videos depicting painted lanes. We note that our assessment did not include buffered bike lanes (painted buffer only) as there is no example of this type of infrastructure in Edmonton.

Another important difference between LCC and LTS is that the lowest level, LCC 1, includes no mixed-traffic environments, which are perceived as very low comfort by the Uncomfortable or Uninterested. Finally, our framework defines the "UI" level, which stands for Uncomfortable Infrastructure and is not considered part of the cycling network, since we theorize that only a handful of cyclists will be entirely comfortable using it.

We found the LCC framework yields less optimistic results of network connectivity compared to LTS; bikesheds are smaller, the network is less integrated, and detour factors are higher. We obtain this result despite being liberal in our application of the framework, given our assumption of low prevailing speeds on residential streets and of network redundancy in residential neighbourhoods.

The lower network connectivity of LCC compared to LTS 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 and can help identify a greater variety of suboptimal segments, some of which may be critical to connectivity. As evidenced from the route mapping module, current cyclists tolerate the occasional use of segments that are less than very comfortable, in the context of a regular cycling route. However, these segments may deter potential cyclists from considering biking as a transportation option. With its comfort focus, the LCC framework can help identify a greater variety of sub-optimal segments, such as the major arterial crossing discussed previously.

Our LCC framework uses data to define the thresholds between LCC levels, while maintaining the ease of use and limited number of data inputs of the LTS framework. It provides empirical guidance to assess the suitability of a network for cycling. However, by definition, frameworks reduce complex infrastructure characteristics to a limited set of variables and sometimes mask important elements; extensive expert knowledge can, and should, help adapt them to the local context, as shown in our own application of the framework to assess Edmonton's network connectivity.

One of the main limitations of our work is that the 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, integrating intersection treatments should be explored in 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 (sidewalk level) bike lanes. Moreover, like many other frameworks, LCC is applicable only to summer as we did not assess winter environments. For a northern city like Edmonton, understanding network connectivity in winter is important given the length of this season. The results are also limited by the non-random sampling of Edmonton's population; a new survey with random sampling and purposeful sampling of underrepresented groups (low-income, non-English speakers, etc.) would be desirable. This limitation is also present for the optional mapping module analysis, which should be strengthened by increasing the sample size and analyzing more formally available alternative routes. Finally, future research could explore how this LCC framework may be used in the analysis of accessibility.

REFERENCES

Abadi, M.G., & Hurwitz, D.S. (2018). Bicyclist's perceived level of comfort in dense urban environments: How do ambient traffic, engineering treatments, and bicyclist characteristics relate? *Sustainable Cities and Society, 40,* 101-109. doi: 10.1016/j.scs.2018.04.003

Bearn, C., Mingus, C., & Watkins, K. (2018). An adaption of the level of traffic stress based on evidence from the literature and widely available data. *Research in Transportation Business & Management, 29*, 50-62. doi:10.1016/j.rtbm.2018.12.002

Beck, B., Chong, D., Olivier, J., Perkins, M., Tsay, A., Rushford, A., . . . Johnson, M. (2019). How much space do drivers provide when passing cyclists? Understanding the impact of motor vehicle and infrastructure characteristics on passing distance. *Accident Analysis & Prevention, 128*, 253-260. doi:10.1016/j.aap.2019.03.007

Boisjoly, G., & El-Geneidy, A. (2016). *Are we connected? Assessing bicycle network performance through directness and connectivity measures, a Montreal, Canada case study.* Paper presented at the Transportation Research Board 95th Annual Meeting, Washington, D.C.

Buehler, R., & Dill, J. (2016). Bikeway networks: A review of effects on cycling. *Transport Reviews, 36*(1), 9-27. doi:10.1080/01441647.2015.1069908

Cabral, L. (2019). *Analyzing network connectivity by cyclist comfort: An empirical reappraisal of the Four Types of Cyclists typology and Level of Traffic Stress framework.* (Master of Science), University of Alberta, Edmonton, AB, Canada.

Cabral, L., & Kim, A. M. (2020). An empirical reappraisal of the Four Types of Cyclists. *Transporation Research Part A, 137*, 206-221. doi:10.1016/j.tra.2020.05.006

Cabral, L., & Kim, A. M. (2019). *Video Clips of Cycling Environments Used in the 2018 Bicycle Ridership and Traffic Stress Tolerance Survey (Edmonton)*. Retrieved from: https://doi.org/10.7939/DVN/L3CUCA

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

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

Dill, J., & McNeil, N. (2013). Four types of cyclists? Examining a typology to better understand bicycling behavior and potential. *Transportation Research Record: Journal of the Transportation Research Board, 2387*(1), 129-138. doi:10.3141/2387-15

Dill, J., & McNeil, N. (2016). Revisiting the four types of cyclists. *Transportation Research Record: Journal of the Transportation Research Board, 2587*(1), 90-99. doi:10.3141/2587-11

Elvik, R., & Bjørnskau, T. (2017). Safety-in-numbers: A systematic review and meta-analysis of evidence. *Safety Science, 92*, 274-282. doi:10.1016/j.ssci.2015.07.017

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

Geller, R. (2006). Four types of cyclists. Retrieved from https://www.portlandoregon.gov/transportation/article/264746

Griswold, J. B., Yu, M., Filingeri, V., Grembek, O., & Walker, J. L. (2018). A behavioral modeling approach to bicycle level of service. *Transportation Research Part A: Policy and Practice, 116*, 166-177. doi:10.1016/j.tra.2018.06.006

Guttenplan, M., Davis, B., Steiner, R., & Miller, D. (2003). Planning-Level Areawide Multimodal Level-of-Service Analysis: Performance Measures for Congestion Management. *Transportation Research Record: Journal of the Transportation Research Board, 1858*, 61-68. doi:10.3141/1858-09

Harkey, D. L., Reinfurt, D. W., & Knuiman, M. (1998). Development of the Bicycle Compatibility Index. *Transportation Research Record: Journal of the Transportation Research Board, 1636*(1), 13-20.

Heinen, E., van Wee, B., & Maat, K. (2010). Commuting by Bicycle: An Overview of the Literature. *Transport Reviews, 30*(1), 59-96. doi:10.1080/01441640903187001

Hugues, J. (2018). reghelper: Helper Functions for Regression Analysis. R package version 0.3.4. Retrieved from https://CRAN.R-project.org/package=reghelper

Jacobsen, P. L. (2015). Safety in numbers: more walkers and bicyclists, safer walking and bicycling. *Injury Prevention, 21*(4), 271-275. doi:10.1136/ip.9.3.205rep

Jensen, S. (2007). Pedestrian and bicyclist level of service on roadway segments. *Transportation Research Record: Journal of the Transportation Research Board, 2031*(1), 43-51. doi:10.3141/2031-06

Kent, M., & Karner, A. (2018). *Prioritizing Low-Stress and Equitable Bicycle Infrastructure Using a Novel Accessibility Measure*. Paper presented at the Transportation Research Board 97th Annual Meeting, Washington DC.

Kuhn, M., Wing, J., Weston, S., Williams, A., Keefer, C., Engelhardt, A., . . . Hunt, T. (2019). caret: Classification and Regression Training. R package version 6.0-84. Retrieved from https://CRAN.R-project.org/package=caret

Landis, B. W., Vattikuti, V. R., & Brannick, M. T. (1997). Real-time human perceptions: Toward a bicycle level of service. *Transportation Research Record: Journal of the Transportation Research Board, 1578*(1), 119-126. doi:10.3141/1578-15

Larsen, J., & El-Geneidy, A. (2011). A travel behavior analysis of urban cycling facilities in Montréal, Canada. *Transportation Research Part D: Transport and Environment, 16*(2), 172-177. doi:https://doi.org/10.1016/j.trd.2010.07.011

Lehtonen, E., Havia, V., Kovanen, A., Leminen, M., & Saure, E. (2016). Evaluating bicyclists' risk perception using video clips: Comparison of frequent and infrequent city cyclists. *Transportation Research Part F: Traffic Psychology and Behaviour, 41*, 195-203. doi:10.1016/j.trf.2015.04.006

Li, Z., Wang, W., Liu, P., & Ragland, D. R. (2012). Physical environments influencing bicyclists' perception of comfort on separated and on-street bicycle facilities. *Transportation Research Part D: Transport and Environment, 17*(3), 256-261. doi:10.1016/j.trd.2011.12.001

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

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

McNeil, N. (2011). Bikeability and the 20-min neighborhood. *Transportation Research Record: Journal of the Transportation Research Board, 2247*, 53-63. doi:10.3141/2247-07

Mekuria, M. C., Furth, P. G., & Nixon, H. (2012). Low-stress bicycling and network connectivity. In: Mineta Transportation Institute Publications.

Moran, S. K., Tsay, W., Lawrence, S., & Krykewycz, G. R. (2018). Lowering bicycle stress one link at a time: Where should we invest in infrastructure? *Transportation Research Record: Journal of the Transportation Research Board, 2672*(36), 33-41. doi:10.1177/0361198118783109

Owen, A., & Murphy, B. (2019). *Access Across America: Biking 2017*. Retrieved from Accessibility Observatory, University of Minnesota: http://access.umn.edu/research/america/biking/2017/

Parkin, J., Wardman, M., & Page, M. (2007). Models of perceived cycling risk and route acceptability. *Accident Analysis & Prevention, 39*(2), 364-371. doi:10.1016/j.aap.2006.08.007

R Core Team. (2019). R: A language and environment for statistical computing. Retrieved from https://www.R-project.org/

Schoner, J. E., & Levinson, D. M. (2014). The missing link. Bicycle infrastructure networks and ridership in 74 US cities. *Transportation, 41*(6), 1187-1204. doi:10.1007/s11116-014-9538-1

Semler, C., Sanders, M., Buck, D., Graham, J., Pochowski, A., & Dock, S. (2017). Low-Stress Bicycle Network Mapping: The District of Columbia's Innovative Approach to Applying Level of Traffic Stress. *Transportation Research Record: Journal of the Transportation Research Board, 2662*(1), 31-40. doi:10.3141/2662-04

Sorton, A., & Walsh, T. (1994). Bicycle stress level as a tool to evaluate urban and suburban bicycle compatibility. *Transportation Research Record: Journal of the Transportation Research Board, 1438*(1), 17-24.

Statistics Canada. (2017). Census Profile, 2016 Census. Retrieved from http://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E

Stinson, M. A., & Bhat, C. R. (2005). *A comparison of the route preferences of experienced and inexperienced bicycle commuters* Paper presented at the Transportation Research Board 84th Annual Meeting, Washington, D.C.

Transportation Research Board. *Highway Capacity Manual: A guide for multimodal mobility analysis* (Sixth ed.). Washington, D.C.: Transportation Research Board.

Veillette, M.-P., Grisé, E., & El-Geneidy, A. (2019). Does one bicycle facility type fit all? Evaluating the stated usage of different types of bicycle facilities among cyclists in Quebec City, Canada. *Transportation Research Record: Journal of the Transportation Research Board*. doi:10.1177/0361198119844741

Zeileis, A., & Hothorn, T. (2002). Diagnostic Checking in Regression Relationships. *R News, 2*(3), 7-10.