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Low-stress bicycling connectivity: Assessment of the network build-out in Edmonton, Canada.

**AUTHOR POST PRINT VERSION**

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**ABSTRACT**

Studies have shown that a network of safe, connected, and direct facilities can increase urban cycling levels. During summer 2017, the city of Edmonton, Canada, constructed nearly 20 kilometers of protected bicycle lanes on its core neighborhood streets. A rapid and coordinated network implementation was preferred to the more traditional incremental approach to bike lane construction. In this paper, we evaluate the low-stress connectivity improvements afforded by this network build-out. We first classify streets and trails according to the Level of Traffic Stress (LTS) framework, which we adapt to the metric system. Using only LTS 2 and LTS 1 network links, posited to be adequate for most adults, we apply three analyses. First, we draw "Bikeshed" maps, which show areas of connectivity around seven central destinations. Our comparison before and after the build-out points to a better integration of the network, with previously separate bikesheds overlapping and allowing uninterrupted low-stress travel to more destinations. This analysis also allows us to identify several central neighborhoods which are disconnected due to remaining high-stress links. Second, we generate roughly three-hundred hypothetical origins located in the central neighborhoods of the city. Reflecting the improved bikeshed integration, we observe a four-fold increase in connected origin-destination pairs. Finally, we find small reductions in trip lengths between connected pairs for some of the trips that were possible before the build-out. However, important detours are still necessary to remain on an exclusively low-stress network when compared to the shortest path using the full network, regardless of LTS. The primary contribution of our research is to develop a method of analysis, based on straightforward tools, to study the city-wide impacts of targeted infrastructure improvements and is most relevant for cities in the initial stages of bicycle network development.

*Keywords*: Bicycling; Connectivity; Level of traffic stress.

## 1 INTRODUCTION

Despite Canada's employed population growing 1.2 million between 2006 and 2016 (to 15.9 million as of 2016) (Statistics Canada 2009, Statistics Canada 2017), 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 and Burda 2015). However, mid-size metropolitan regions such as Edmonton (pop. 1.3 million (Statistics Canada 2017)) have only recently started to make significant investments in bicycling infrastructure.

Edmonton is a post-war city largely designed for car travel. Eighty-two percent of Edmonton's workers relied on an automobile for their commute, while only one percent of all commuters in 2016 bicycled to work (Statistics Canada 2017). 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 you build the infrastructure, 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. The City of Edmonton made a bold investment in urban bicycling in 2017 by building a traffic-separated downtown grid of 7.8 kilometers at the cost of C$ 7.5 million (City of Edmonton 2016). It was the central piece of a larger project, which resulted in the construction of about 20 kilometers of protected bike lanes in the central city neighborhoods that year.

Given that researchers have studied bicycling extensively, there is a rich body of knowledge on why people do or do not choose to cycle. Infrastructure and environmental factors such as traffic separated bike lanes, signalized intersections with bicycle priority, bike boxes for turning against traffic, connectivity to multiple destinations, and relatively flat topography have been widely found to encourage bicycling (Heinen, van Wee et al. 2010, Pucher, Dill et al. 2010, Buehler and Dill 2016). 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 bicycling choice (Heinen, van Wee et al. 2010, Shirgaokar and Gillespie 2016). Few locations in North America supply sufficient infrastructure for the risk-adverse person to feel confident cycling for everyday transportation. Many practitioners recognize that making bicycling convenient with strategies such as building extensive traffic-separated networks can be helpful in achieving higher cyclist mode share. However, in practice, most jurisdictions incrementally add cycling facilities to existing car-centric infrastructure. Policymakers, transportation planners, and engineers in local governments can benefit from tools developed to study the efficacy of these incrementally supplied bicycle infrastructures.

In this research we adapt a Level of Traffic Stress (LTS) framework (Mekuria, Furth et al. 2012) to evaluate the low-stress network investment in Edmonton, Canada. We ask: does the development of the downtown bicycle grid expand low-stress connectivity from central origins to major destinations within Edmonton? We use geo-spatial tools to evaluate the connectivity impacts of the bicycle grid implementation. We also apply connectivity measures inspired from the existing literature. The primary contribution of our research is to develop a method of analysis, based on straightforward tools, to study the city-wide impacts of targeted infrastructure improvements. A secondary contribution of this work is the translation of the LTS criteria to the metric system. To our knowledge, such ex post evaluation mechanisms for bicycling network build-outs have not yet been reported in the academic literature.

In the next section, we review the literature on bicycling stress, cyclist classification, and connectivity. Section 3 describes the case and data while Section 4 describes the geo-spatial analysis approach. In Section 5 we describe how "bikesheds" can change with infrastructure investments, thus improving connectivity. Sections 6 and 7 contain a brief discussion of policy implications, the strengths/limitations of this research, and concluding thoughts.

## 2 LITERATURE REVIEW

### 2.1 Bicycling Stress and Cyclist Classifications

Researchers have identified safety concerns, both actual and perceived, as the main barrier to bicycling for transportation (Dill and Voros 2007, Winters, Davidson et al. 2011, Sanders 2015, Manaugh, Boisjoly et al. 2017). Identifying the factors that contribute to the perceived safety or risk of cycling in different environments has garnered much academic attention. Exposure to motorized traffic has repeatedly been found to be a main source of stress for cyclists and potential cyclists (Parkin, Wardman et al. 2007, Sener, Eluru et al. 2009, Winters, Davidson et al. 2011, Manton, Rau et al. 2016). Regular cyclists perceive more risks and hazards given their greater experience (Lehtonen, Havia et al. 2016), and worry more frequently and for different aspects of drivers' behaviors compared to occasional cyclists (Sanders 2015). Consistent with these findings, cyclists have been found to prefer segregated paths or dedicated facilities, often taking a detour to use such infrastructure, although preference for these facilities decreases with experience (Dill and Voros 2007, Winters, Teschke et al. 2010, Larsen and El-Geneidy 2011, Manton, Rau et al. 2016, Manaugh, Boisjoly et al. 2017).

Several cyclist classification frameworks have evolved to integrate the notions of traffic stress tolerance, comfort, or experience, either directly or indirectly (Wilkinson, Clarke et al. 1994, Bergström and Magnusson 2003, Larsen and El-Geneidy 2011, Damant-Sirois, Grimsrud et al. 2014), given these factors' importance in the decision to ride. Roger Geller from the Portland

Department of Transportation proposed a classification which has gained traction both in the academic world and in practice (Geller c. 2007). His four types of cyclists (No Way No How, Interested but Concerned, Enthused and Confident, and Strong and Fearless) have been empirically tested and found to be adequately representative of the American adult population (Dill and McNeil 2013, Dill and McNeil 2016). This categorization includes both comfort level relative to traffic stress and interest in cycling. Recent work has further expanded the inclusion of socio-psychological factors such as the inclination to bicycle in increasing active travel mode choice (Shirgaokar and Nurul Habib 2018).

The four-class typology has been translated to an infrastructure classification scheme which allows the assessment of low-stress connectivity (Mekuria, Furth et al. 2012). The classification has been used extensively by academics in various locales to assess connectivity, prioritize future projects, analyze collisions, etc. (Chen, Anderson et al. 2017, Kent and Karner 2018, Moran, Tsay et al. 2018, Semler, Sanders et al. 2018). Four levels of traffic stress (LTS) are defined, as shown in Table 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, Furth et al. 2016).

**Table 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, Furth et al. (2012)

| LTS Level | | LTS1 | LTS2 | LTS3 | LTS4 |
|---|---|---|---|---|---|
| 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 km/h[a] | Street width: 2-3 lanes AND speed limit up to 50 km/h[a] | Street width: 4-5 lanes AND speed limit up to 40 km/h | Any street width if speed limit 60 + km/h OR Any speed limit if 6 + lanes OR Street width: 4-5 lanes AND speed limit 50 + km/h |
| Criteria for streets with bicycle facilities[b] | Number of lanes per direction | 1 | (no effect) | 2 or more | (no effect) |
| | Speed limit | 40 km/h or less | 50 km/h | 60 km/h | 70 km/h 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 4.1 for details.

## 2.2 Connectivity

Another major consideration when contemplating cycling as a transportation mode is the directness and connectivity of a route (Titze, Stronegger et al. 2008, Schoner and Levinson 2014, Shirgaokar and Gillespie 2016). 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.

Dill (2004) was among the first to apply connectivity measures specifically to cycling. The connectivity measures tested in this early publication were still related almost exclusively 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 idea of "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 and Handy 2012, p. 49). In Section 4.2.1 we propose a slightly altered "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 (detour compared to shortest path divided by 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 with at least 50% bicycle facilities and 12% detour or less were considered connected.

A different approach was adopted by Mekuria, Furth 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, Saraiva et al. 2016). Both cycling accessibility (Tal and Handy 2012, Saghapour, Moridpour et al. 2016, Houde, Apparicio et al. 2018, Kent and Karner 2018) and the related field of bikeability (McNeil 2011, Lowry, Callister et al. 2012, Winters, Brauer et al. 2013) have been studied extensively, with some work focusing specifically on low-stress accessibility (Lowry, Furth et al. 2016, Imani, Miller et al. 2018, Kent and Karner 2018).

# 3 CASE AND DATA

## 3.1 Case: Edmonton

Edmonton is the capital city of Alberta, a Canadian prairie province. It is located above the 53rd parallel, with sub-zero average daily temperatures observed five months of the year and snowfall often recorded for eight months (Government of Canada 2018). Edmonton is self-described and promoted as a winter city.

Edmonton's growth as a city largely mirrors the development of the oil and gas industry in the province throughout the 20th century. Given that much of this development occurred after the Second World War, Edmonton's urban form largely follows typical mid-century American suburban form. The result is a low-density, car-oriented mid-sized city with relatively weak connectivity for all modes of transportation. Also like many cities, Edmonton developed around a water body; the Saskatchewan River separates the city in half running from the southwest to the northeast. A series of bridges connect the City, but in the central areas, only one bridge offers a connection across with limited change in elevation (22 meters).

This combination of weather, urban form and geography has resulted in very low utility cycling shares and a mostly absent cycling culture in the city. Indeed, census data shows a decreasing share of cycling for journeys to work between 2006 and 2016. While the working population increased by about 20%, the increase in cycling was limited to 5.2%. This equates to a decrease from 1.36% to 1.20% in cycling mode share for the ten-year period (Statistics Canada 2009, Statistics Canada 2017). No definitive data is available regarding city-wide cycling volumes for other trip purposes. Investment in cycling infrastructure continues to be a highly polarizing topic among residents.

Despite the above, the City of Edmonton Transportation Master Plan (City of Edmonton 2009) aims to increase active transportation to achieve health, livability and sustainability goals. The corresponding Bicycle Transportation Plan supports this overarching objective. As a step towards realizing this vision, the City implemented over 20 km of protected bicycle lanes in the core neighborhoods during the summer of 2017, 7.8 km of which are located in the central business district (CBD, see Figure 1). 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. Bicycle-specific signals were added to signalized intersections and bike turning boxes installed such that cyclists can enter or exit the network at key locations. A distinct feature of the project was its rapid implementation. All bike lanes were constructed and opened to the public within about 8 weeks, from mid-June to mid-August 2017. This departs from the typical incremental approach of adding protected bike lanes. Whereas bike lanes are often implemented one corridor at a time, the Edmonton network was constructed as a coordinated effort to connect important central destinations to existing trails and low-stress streets around the CBD (Figure 1).

In a car-centric city, the new infrastructure has sparked heated debate and polarized opinions. Therefore, an independent assessment of the effectiveness (or lack) of the protected bike lanes can help support the discussion.

### 3.2 Data

The Edmonton network geodatabase, including streets, alleys, trails, breezeways, park paths, and shared-use paths was constructed in a collaborative effort with the City of Edmonton. We assembled it from shapefiles provided by the City as part of a broader research project investigating the impacts of bike infrastructure in Edmonton, and is used with their permission. The integration of the different facilities is critical as cyclists are likely to travel on any of these facilities. The City maintains separate databases for these different types of infrastructure representations; hence, extensive manual corrections were required.

The resulting integrated network (Figure 1) contains 57,756 segments with the minimum attribute information required to assess level of traffic stress on each link, including segment type (street, trail, etc.), street functional class, bicycle infrastructure type, and speed limit.

To conduct the analyses, we chose seven significant destinations of interest (see Figure 2). The destinations were selected because of their high trip generation potential. Edmonton's central core, where cycling is more likely to happen, has traditionally been solidly anchored in government, as Edmonton is Alberta's capital city, and education, notably through the University of Alberta, the flagship institution for the province. 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 surrounded by other government offices, and Churchill Square, which is the public space in front of the Edmonton City Hall), and two centers of Edmonton's social life (Roger's Place Arena, and the Old Strathcona Farmer's Market). Note that Churchill Square is also a center of social life since it is the scene of several festivals and public activities throughout the year. Four of those destinations (the Legislature Building, MacEwan University, Rogers Place, and Churchill Square) are on the edges of the central business district where protected bike lanes were built.

Finally, potential origin points were generated from the centroids of Traffic Analysis Zones. Figure 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).

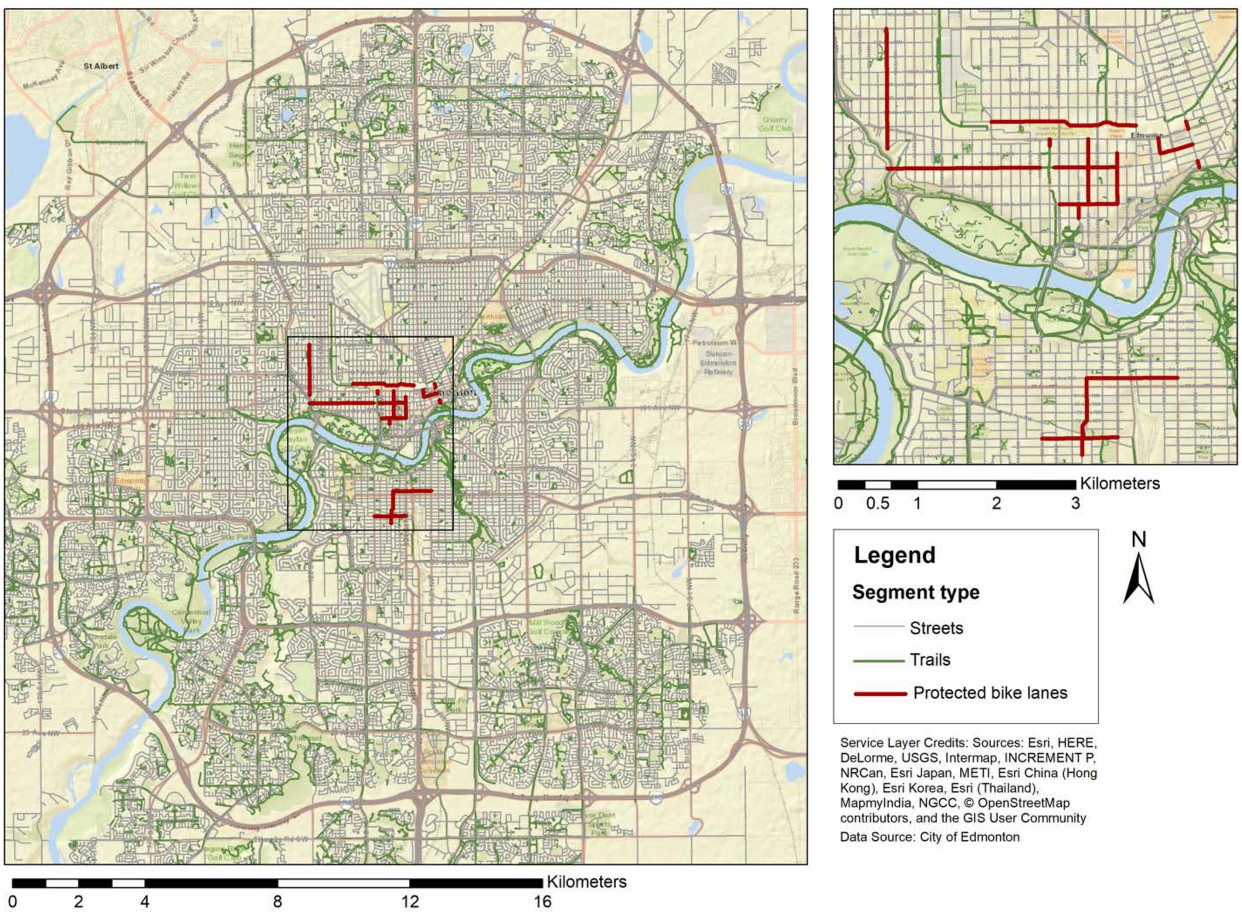


**Figure 1  Edmonton street and trail network and protected bike lane network.**

## 4 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). This level of stress was designed to be suitable for most of the adult population (see Table 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 through exclusively low-stress routes around important destinations (Figure 2). Second, we identified potential origin points and computed the number of origin-destination pairs connected. Finally, shortest path data was contrasted for all connected origin-destination pairs, before and after the build-out. 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.

### 4.1 Level of Traffic Stress Assignment

A segment’s LTS is determined mainly by its physical characteristics and speed limit, as outlined in Table 1 (Mekuria, Furth 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, Furth et al. (2012), use different tables and criteria depending on parking presence. Table 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. 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. Keeping them in the network representation would erroneously increase low-stress connectivity.

### 4.2 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.

#### *4.2.1 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 (Moritz 1997, Larsen and El-Geneidy 2011). This analysis is useful to visually identify improvements in connectivity, as well as barriers. The bikeshed area can also be used to measure area changes.

#### *4.2.2 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.

#### *4.2.3 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 2).

## 5 FINDINGS

Figure 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 2b and 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 and 2c).

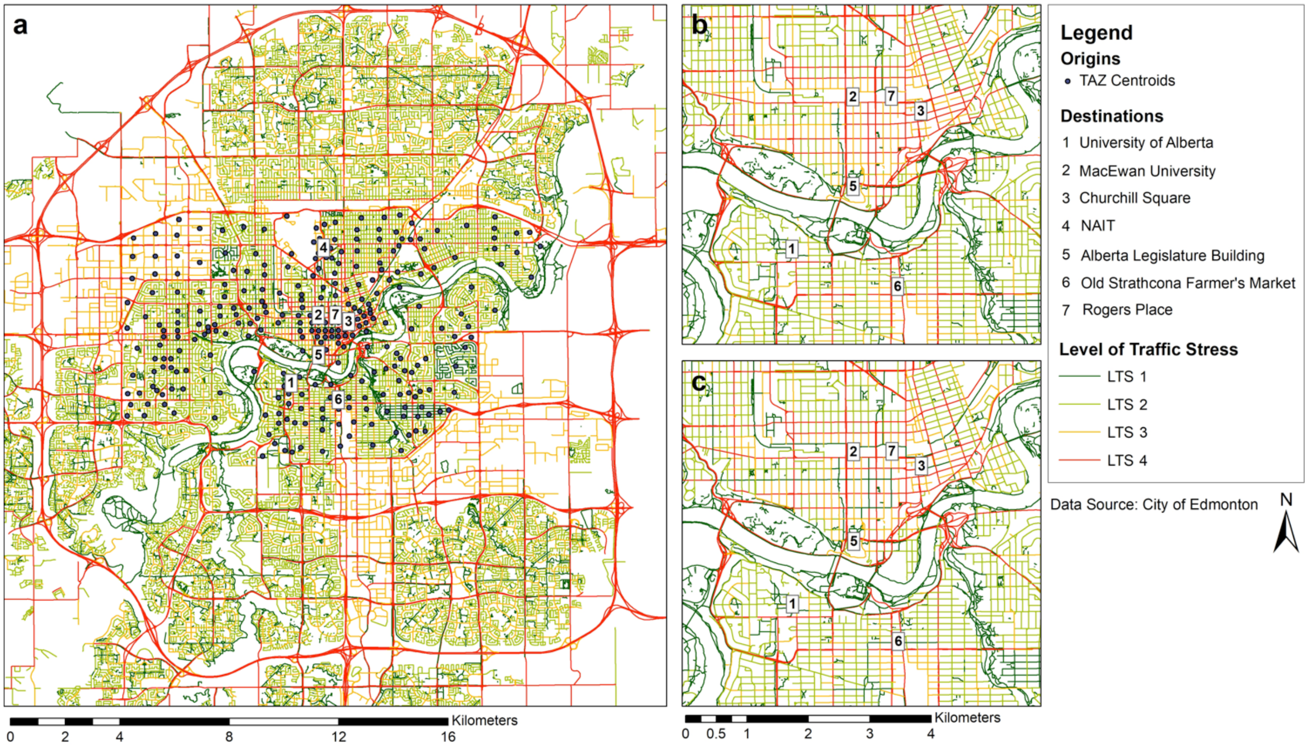


**Figure 2 LTS rating, origins and destinations. (a) Full network (b) Core area before implementation of protected bike lanes (c) Core area after implementation of protected bike lanes.**

## 5.1 Bikeshed analysis

Figure 3 and Figure 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.

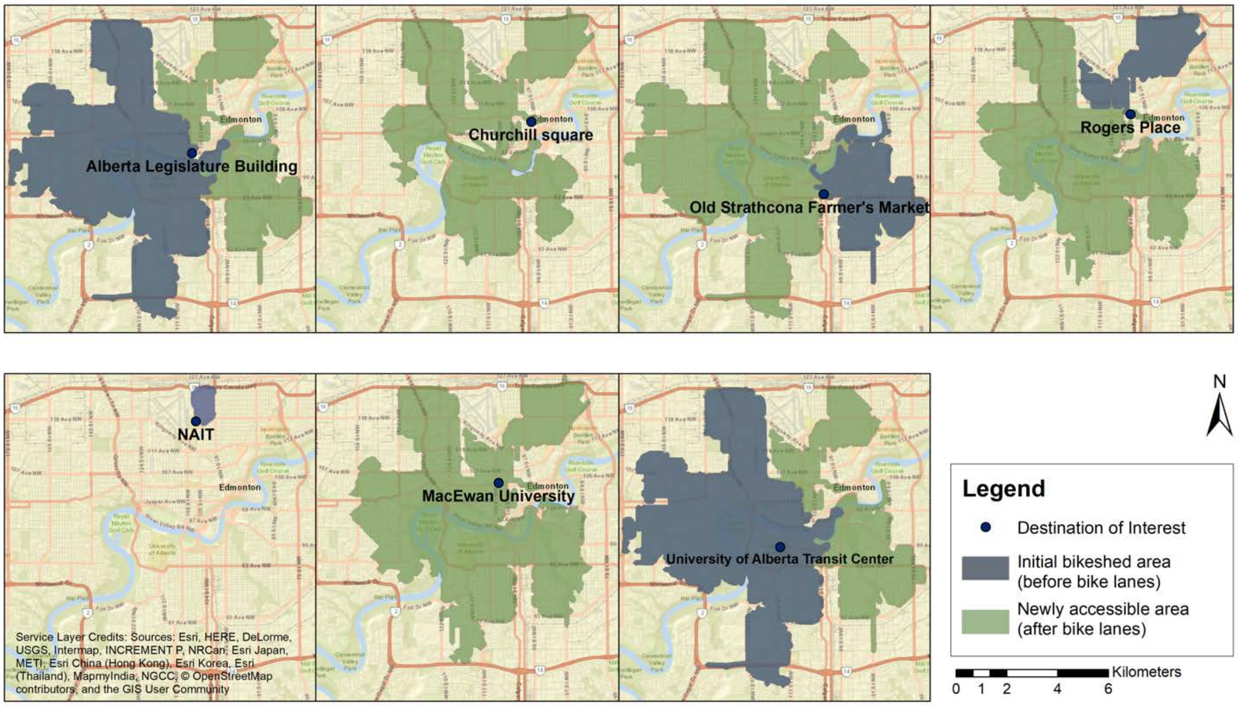


**Figure 3  Bikeshed area for each destination before and after protected bike network construction.**

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 2). This result was expected since no new infrastructure was constructed in the immediate vicinity of the institution. 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.

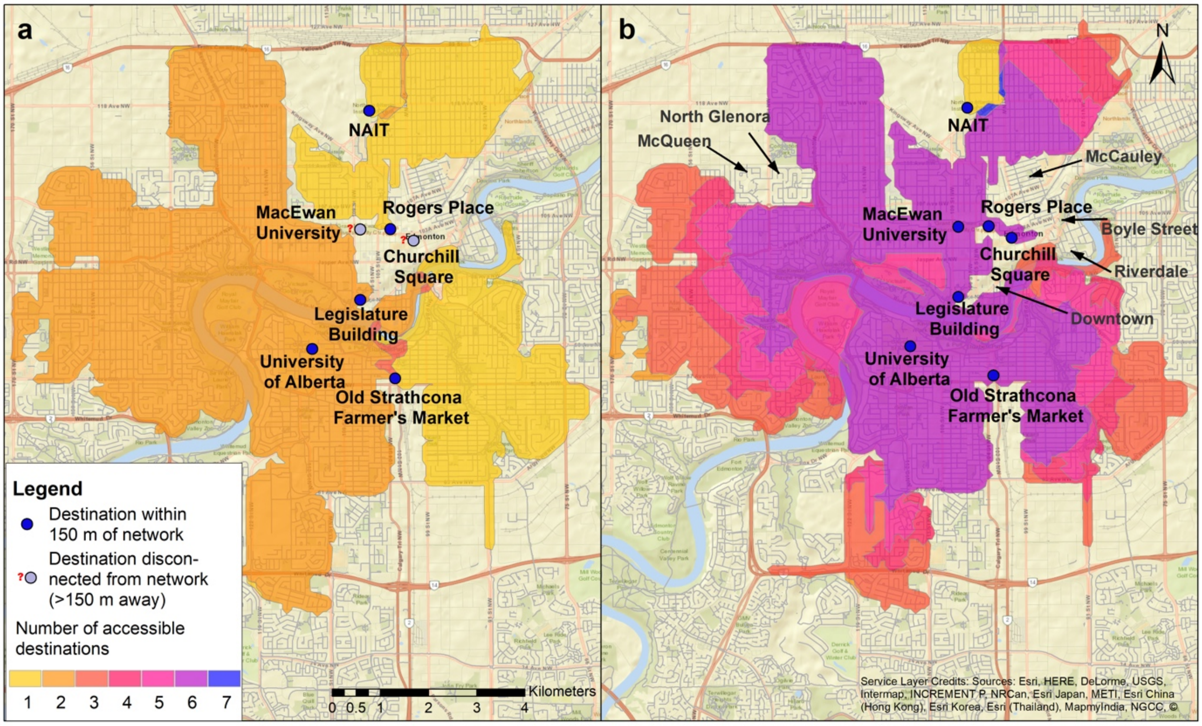


**Figure 4 Bikeshed area for all destinations combined, (a) before and (b) after protected bike network construction.**

Beyond bikeshed size, Figure 4 illustrates a better 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). A cyclist leaving from the west 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 4) can access six of the seven destinations; NAIT remains isolated. Table 2 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 4(a), 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 areas are still unreachable using the low-stress network. This is true of McQueen, North Glenora, Riverdale, Downtown, Boyle Street, and McCauley, as illustrated in Figure 4(b). Notably, the latter three neighborhoods are among the poorest in the city (Statistics Canada 2017). Some of the connectivity issues in these neighborhoods will likely be resolved once the Downtown portion of a new light rail train line is finalized and the protected bike lanes currently absent because of construction are completed.

### 5.2 Origin-destination Connectivity, Shortest Path, and Detour Factor

In addition to bikeshed areas, Table 2 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 made shorter through the addition of the bike lanes. The average change in trip length for these destinations is minimal (between 81-322 m), but is still statistically significant. 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 saw 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 (Winters, Teschke et al. 2010, Larsen and El-Geneidy 2011, Mekuria, Furth et al. 2012, Boisjoly and El-Geneidy 2016). 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 2 Comparisons 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 ($p > 0.05$).

## 6 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 2) 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, Teschke 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, Furth 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 4.1). 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.

## 7 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), greater bikeshed overlap (Figure 4) and number of connected origin-destination pairs (Table 2). 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 paper, 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 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.

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