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Cycle accessibility and level of traffic stress: A case study of Toronto

Ahmadreza Faghih Imani*, Eric J. Miller, Shoshanna Saxe

Department of Civil Engineering, University of Toronto, Canada

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ABSTRACT

This paper examines the level of traffic stress for cyclists on the street and path network in the City of Toronto. Link as well as intersection stress is calculated to develop a citywide network of cycling stress. The cumulative opportunities reachable at four levels of cycling stress are calculated for each dissemination area in the city. The results show a low level of cycling access (< 5000 jobs) across most of the city at low levels of stress (LTS ≤ 2). Only at level of stress three, where cyclists may be required to negotiate with vehicles and may be in proximity of high-speed traffic, does cycling accessibility rise above 15,000 jobs for a sizeable section of the city. The link between low-stress access to jobs and the decision to cycle from home is investigated using a binary logit model. The results indicate that the cycling accessibly measure has a significant effect on choosing cycling as the travel mode with larger effect for low-stress access. The low stress cycling accessibility to subway stations is calculated as an example of the practical applications of this method and illustrates the limited cycling access to many stations in the Toronto network. Further, a theoretical scenario analysis is undertaken comparing different bicycle network scenarios. Three scenarios are tested 1) removing all cycle tracks, 2) upgrading all bike lanes to cycle tracks, and 3) decreasing street speeds by 10 km/h on the road network entire network. Scenario 3 in particular drastically increases cycling access to jobs.

1. Introduction

This paper investigates the level of traffic stress (LTS) and associated cumulative opportunities at different LTS for bicyclists in the City of Toronto. Cities around the world are investing in cycling infrastructure and increased cycling has been shown to have positive impacts on health, mobility and the environment (Reynolds et al., 2010; Woodcock et al., 2009). As a result of pro-cycling policies and infrastructure investment, cycling has seen a rise in popularity in recent decades (Pucher et al., 2010). However, though growing, cycling infrastructure and cycling mode share in many Canadian cities continues to be low. In 2016, the City of Toronto had 16 km of separated cycling track and a cycling mode share for daily commute to work of 2.7%. The length of separated cycling track and cycling mode share for commuting to work numbers for other large cities in Canada are: Montreal, 72.4 km and 3.6%; Vancouver 23.0 km and 7.6%; Calgary 7.0 km and 1.5%; and Ottawa 5.1 km and 2.6% (Statistics Canada, 2016; Vijayakumar and Burda, 2015).

Accessibility is an established predictor of mode choice for other travel modes (e.g. automobile, public transit) and is defined as the ability to reach destinations where opportunities, activities and individuals are located (Ewing and Cervero, 2010; Geurs and van Wee, 2004; Handy, 2005). Isochrone area and cumulative opportunities calculations of accessibility are widely used in the literature in analyses of automobile and public transit travel (Farber and Marino, 2017; Geurs and van Wee, 2004; Owen and Levinson, 2015). Isochrones are lines of equal travel time from a point that create an area. Cumulative counting of the opportunities within that area generates a general measure of accessibility. However, similar calculations for cycling have rarely been carried out (Vale et al., 2015). This is in large part due to the tension between the legality of cycling on most urban roads and the reality of barriers to safe and comfortable cycling on those roads.

Most people find cycling near fast vehicular traffic or attempting to hold the right of the way on busy roads stressful and uncomfortable. In fact, earlier studies show that about 60% of people would consider cycling if a low-stress network existed for their daily trips (Dill and McNeil, 2013). Safety and comfort concerns have repeatedly been factors in studies examining cyclists' route choice preferences (Broach et al., 2012; Sener et al., 2009) and cycling mode share (Buehler and Pucher, 2012; Pucher and Dijkstra, 2000). Cyclists exhibit preference for streets that are perceived to be safe and make space for them (Larsen and El-Geneidy, 2011). This perception of space is influenced by, for example, the type of road, road speeds and presence of cycling-specific lanes. A residential street with a low speed limit provides a different

* Corresponding author.
E-mail addresses: a.faghihimani@utoronto.ca (A. Faghih Imani), miller@ecf.utoronto.ca (E.J. Miller), s.saxe@utoronto.ca (S. Saxe).

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cycling experience than a bike lane on a major arterial with a high speed limit. While cycling infrastructure is a critical step in achieving a low stress cycling experience high stresses related to road speed and traffic are still possible, especially for painted bike lanes. Similarly, many roads without a bike lane, namely narrow, low traffic, low speed, local roads are very comfortable to cycle on.

In this paper, adapting the approach proposed by Furth et al. (2016), we define the level of cycling stress for every link in Toronto's road network. Using this street stress network, we calculate the 30-minute cycling isochrone and associated cumulative opportunities to jobs and population for each dissemination area in the City of Toronto for cycling stress levels ≤ 1 to ≤ 4. We further examine the link between the calculated measure of cycle accessibility and bicycle mode choice decision making. As a case study, we look at the cycling accessibility to subway station entrances. Finally, we investigate the potential of three different road network policies on cycling LTS in Toronto: 1) removing all cycle tracks, 2) upgrading all bike lanes to cycle tracks, and 3) decreasing street speeds by 10 km/h on the road network entire network.

2. Research context

2.1. Bicycle network

There is a large body of literature examining the relationship between cycling and road infrastructure, especially cycling facilities (Buehler and Dill, 2016). A range of studies have showed that installing bicycle infrastructure, such as bike lanes or cycle tracks, increases the cycling mode share and frequency of cycling trips (Buehler and Pucher, 2012; Dill and Carr, 2003; Mitra et al., 2017). Buehler and Dill (2016) have completed a recent literature review on the relationship between cycling infrastructure and cycling mode choice (Buehler and Dill, 2016). Cycle infrastructure has different degrees of influence on the mode choices of different population segments; Several studies have investigated identifying clusters of cyclists within the entire population (Birk and Geller, 2006; Damant-Sirois et al., 2014; Dill and McNeil, 2013; Geller, 2006). These typology studies underscore the importance of cyclists' level of comfort on different infrastructure and road types. They show that having a network adapted to various cyclist types, highlighting flexibility and convenience, can be an effective intervention to attract more cyclists. Other studies emphasize the importance of the connectivity of the bicycle infrastructure in a city (Birk and Geller, 2006; Dill, 2009; Schoner and Levinson, 2014). Cyclists are highly sensitive to travel distance, express reluctance to adopt longer routes and want to minimize the number of detours on their travel path (Faghih-Imani and Eluru, 2015; Handy and Xing, 2011). Thus, for cities to attract more cyclists, a primary task is building a connected and low stress cycle network.

In addition to connectivity of the network, the safety and comfort of cyclists on the cycle network is an important factor for increasing the attractiveness of urban cycling. Several methods have been introduced in the past decades to assess the cycle suitability of a roadway section (for a detailed review, see Callister and Lowry, 2013 (Callister and Lowry, 2013)). A recent study developed a Level of Traffic Stress (LTS) metric which classifies street segments between LTS 1 (low stress) and LTS 4 (high stress), considering primary roadway attributes including: speed limit, number of vehicular lanes, bike lanes, parking and traffic signals (Furth et al., 2016). The four LTS classes are defined to have similarity to the popular four types of cyclists identified in earlier studies, i.e. "the strong and the fearless," "the enthused and confident," "the interested but concerned," and "no way, no how" (Dill and McNeil, 2013; Geller, 2006). Similarly, the employed LTS criteria has four classes: LTS 1, suitable for all cyclists including children; LTS 2, needs attention as some traffic stress may occur, demands more caution from children; LTS 3, cyclists may be required to negotiate with vehicular, and may be in proximity of, high speed traffic; LTS 4, cyclists must share the road with high-speed traffic, cyclists are regularly required to fight for the right of the way on a busy street with moderate-speed traffic, and/or cyclist must traverse dangerous crossings (Furth et al., 2016). The LTS framework has been used in several studies. These include examinations of cycling network connectivity to identify and prioritize locations for new cycling infrastructure investment (Lowry and Loh, 2017; Lowry et al., 2016) and an investigation of cycling equity (relationship between wealth and availability of low stress cycling) in two Brazilian cities (Tucker and Manaugh, 2018).

2.2. Accessibility

The literature on accessibility is more than half a century old; accessibility has long been identified as an important driver of mode choice (Hansen, 1959). Geurs and Van Wee (2004) summarized different ways accessibility is quantified, including, infrastructure-based measures, location-based measures, person-based measures, and utility-based measures (Geurs and van Wee, 2004). The cumulative opportunities counted within a set of travel time isochrones has been used in studies on the relationship between accessibility, mode choice, and land use outcomes (Farber et al., 2014; Farber and Marino, 2017; Miller, 1991; Owen and Levinson, 2015; Saxe et al., 2015). While there has been a large body of literature discussing accessibility by different modes of travel (e.g. automobile, rail), there are relatively few studies focusing on cycling accessibility (Iacono et al., 2010; Vale et al., 2015). McNeil (2011) considered a set of destinations and computed accessibility scores for residential parcels by aggregating the number of attractions within a 20-minute bicycle ride (McNeil, 2011). Saghapour et al. (2017) developed a cycling accessibility index using factors including the cycling catchment area and the travel distance between origins and destination and tested the index with the data from metropolitan Melbourne, Australia (Saghapour et al., 2017).

Several recent studies considered measures of safety, comfort and convenience on the street network in their analysis of cycle accessibility. For example, Sisson et al. (2006) investigated the cycle accessibility to elementary schools in a city in Arizona using a bikeability instrument which accounts for several factors including vehicular traffic and speed, number of lanes and bike lanes, and pavement attributes (Sisson et al., 2006). Another study calculated the Highway Capacity Manual Bicycle Level of Service (BLOS) for every bikeway and then computed bicycle accessibility for a community in Idaho based on a distance-based function weighted by BLOS (Lowry et al., 2012). Winters et al. (2013), proposed another bikeability index consisting of factors related to the connectivity of bicycle facilities, bicycle-friendly streets, topography, neighbourhood land use and then mapped their measure of bikeability at a 10 m grid-cell resolution for the City of Vancouver (Winters et al., 2013).

In this paper, we continue the research on bicycle accessibility by employing the level of traffic stress as the measure of bicycle suitability of the network accommodating the safety and comfort concerns of the cyclists. We compute the level of traffic stress for every road segment, intersection and bikeway in the City of Toronto. This provides the opportunity to assess bicycle accessibility based on the road links accessible at given threshold levels of LTS (a network with only links at LTS = 1, LTS ≤ 2, LTS ≤ 3, or, LTS ≤ 4). Further, we use the LTS framework to develop accessibility measures and then relate the generated measures to travel behaviour by modelling individual's decision to make a trip by bicycle. Finally, we present a scenario analysis demonstrating the potential application of cycling LTS accessibility measures as a quantitative approach to analysing the impact of different cycling interventions.

3. Toronto bicycle network

Toronto is the most populous city in Canada and the fourth largest city in North America. It has a fast-growing population; 2.7 million lived in Toronto in 2016 and 3.5 million residents are expected by 2031

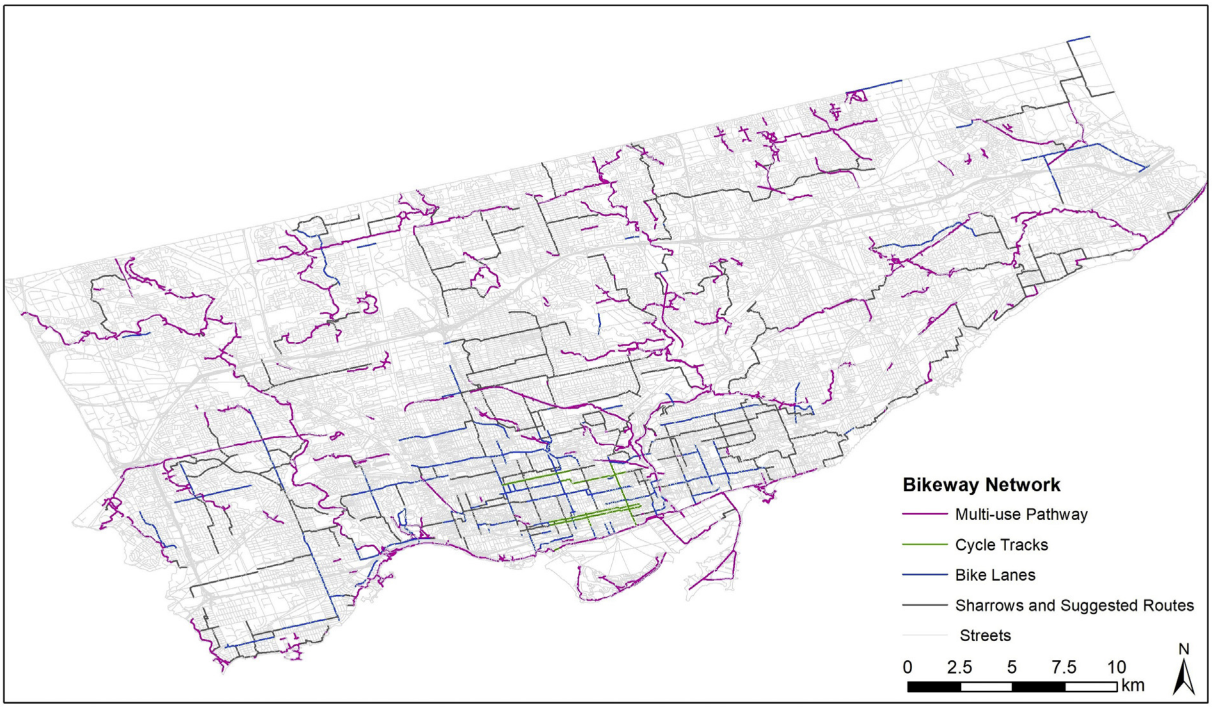

Fig. 1. City of Toronto bikeway network.

(Ontario Ministry of Finance, 2017). Fig. 1 depicts the City of Toronto bikeway network, highlighting the multi-use pathways around the city and higher concentration of cycle tracks and lanes in inner parts of the city. In Toronto, the cycling mode share has increased over the last 15 years, from 1.18% in 2001 to 2.74% in 2016 (Data Management Group, 2016). The largest growth is observed in the central business district and inner urban neighbourhoods. Although cycling mode share has been growing in Toronto since 2001, investments in cycling facilities and attentions towards cycling as an equitable, healthy and sustainable mode of transportation have been delayed. Toronto has the lowest length of cycling facilities per capita and highest rate of cycling crashes within major cities in Canada (Vijayakumar and Burda, 2015). Thus, it is not surprising that the cycling mode share in Toronto is still relatively low and that there remains significant potential for cycling growth in the city. A recent study showed that about one-third of all non-active trips in the Greater Toronto Area can be potentially taken by cycling (Mitra et al., 2016). Further, although the number of cyclable trips for women are higher than men, women currently make up < 30% of cyclists in Toronto (Mitra et al., 2016). While in many European cities with a more mature cycling infrastructure, women make the majority of the cyclists, the lower rate of female cyclists in Toronto may be due to the absence of a safe and low-stress bicycle network (Garrard et al., 2008; Mitra et al., 2016).

In our study, the road network consists of a high-resolution geospatial data set with attributes accumulated from several sources. The road geometry, bicycle facilities such as cycle tracks or bike lanes, road classification (local, collector, minor arterial, etc.), number of lanes, directions, stop signs and signalized intersections are obtained from the City of Toronto Open Data portal (City of Toronto, 2017). City of Toronto classifications were used to differentiate between bike lanes (painted) and cycle tracks (physical separation). Vehicular traffic speeds are from the GTAModel V4.0 for the morning peak period (Travel Modelling Group, 2015) which accounts for road volume and travelled (rather than posted) speeds. The dataset is further augmented with on-street parking data obtained from the City of Toronto. Using ArcGIS, the data were gathered as link attributes on one network. The network was also manually checked and edited to correct detected inconsistencies and to add a cycle track on Bloor Street installed in 2016. The final network has 56,156 links with a total length of 7530 km. The population data were from the 2011 Canadian Census and employment data were from the 2011 Transportation Tomorrow Survey (TTS) (Data Management Group, 2016).

4. Methods

4.1. Level of traffic stress

LTS criteria are defined separately for different street types - streets with mixed traffic including sharrows and signed routes, streets with bicycle lanes along a parking lane, and streets with bicycle lanes without parking lanes (for details, see (Furth et al., 2016)). In generating the LTS network for Toronto, highways and expressways were removed from the network: on these high-speed, high-volume roads cycling is forbidden. Physically separated cycle tracks, multi-used pathways, walkways in parks and trails are assigned the lowest level of traffic stress, LTS 1. For the remaining segments, the LTS criteria are primarily based on the segment's speed and the number of lanes as described by Furth et al. (2016). For example, a street with one lane per direction with speeds ≤40kmh is assigned LTS 1 for the local streets and LTS 2 for others. Data were not available on the width of cycle lane and tracks or the presence of medians as such, these attributes are not included in this assessment. Streets with cycle lanes that are painted rather than having a curb or other physical separation can have all four LTS levels depending on the segment speed, street width and presence/absence of parking lanes. Bicycle lanes on streets with speed ≥60 km/h have the highest LTS (LTS = 4) regardless of other criteria, save for physical separation as noted above. A descriptive summary of the Toronto network is presented in Table 1. The generated level of traffic stress is presented in Fig. 2.

The LTS for intersections was calculated based on the LTS of the links. Intersection LTS is important to capture given the impact of a high LTS street on intersecting low LTS links. For example, two road links of LTS 1 bisected by a road of LTS 4 will not be cycle-able for children or most adults. The LTS of intersections was calculated based

Table 1
Toronto network summary.

Attributes		Length (km)	% of Network
Bicycle infrastructure	Cycle track	16	0.2%
	Bicycle lane	148	2.0%
	Multi-use pathway	517	6.9%
	Mixed traffic including Sharrows and signed routes	6850	91.0%
Road type	Trails and walkways	1094	14.5%
	Local	3906	51.9%
	Minor arterial	1636	21.7%
	Major arterial	893	11.9%
Number of lanes per direction		5985	79.5%
	2	1335	17.7%
	3	≤1	2.1%
	4≥	50	0.7%
Speed (km/h)	≤40	4173	55.4%
	40–60	3200	42.5%
	60≥	157	2.1%
Level of traffic stress	LTS =1	2666	35.4%
	LTS =2	2424	32.2%
	LTS =3	1363	18.1%
	LTS =4	1077	14.3%

on the LTS of the crossing street and the presence of traffic lights and stop signs. In the absence of traffic signals, the highest LTS of the two intersecting segments dominates the intersection LTS. For example, if a cyclist on a local street with LTS 1 wants to cross an LTS 4 arterial without stop light, the crossing would have LTS 4. For simplicity, and due to the lack of data on turning restrictions, we do not differentiate between right turns, left turns and through movements. The model assumes cyclists follow the road directions for vehicles in compliance with local law except for contra-flow bike lanes. Intersections with stoplights were assigned the LTS of the street to be crossed minus one (crossing LTS 4 with a stoplight = LTS 3). Stop signs were considered relevant only for crossing streets of LTS 2 and in this case were assigned a level of LTS 1. Intersection LTS values were coded into the ArcGIS street network through the creation of “intersection links” extending 25 m from an intersection and coded with the higher of the LTS of the intersection or the link itself.

4.2. Isochrones and cumulative opportunities

Thirty-minute isochrones and cumulative opportunities were calculated for LTS1 to LTS4 for each dissemination area (DA) in the City of Toronto based on 2011 census geometry. Dissemination areas are the smallest of Canadian census agglomerations, with populations between 400 and 700 people. LTS accessibility was calculated for the 3685 DAs in the City of Toronto. The network analyst toolset within ArcGIS was used to calculate 30-minute service areas (isochrones) based on the available network links at each LTS level (LTS1, LTS ≤ 2, LTS ≤ 3, LTS ≤ 4). A consistent travel speed of 15 km/h is assumed similar to the existing literature (Hatzopoulou et al., 2013; Jensen et al., 2010; Saneinejad et al., 2012). A 30-minute isochrone is used as the observed 90 percentile travel time of cycling trips in household travel survey in Toronto is about 30 min (assuming an average speed of 15 km/h), indicating that most of the destinations for trips made by bicycle are within 30 min cycling. The cumulative counts of population and jobs were then calculated for each DA at each LTS. Both population and jobs were agglomerated to the DA level and counted as based at the centroid of their DA. The accessibility measures were calculated for each DA based on the 30-minute isochrones from the DA's centroid; a DA's jobs or population are considered inside the isochrone if its DA is inside the isochrone. Fig. 3 illustrates the different isochrones for a residential DA located near downtown Toronto at different LTS. The developed network was geographically limited to the City of Toronto, as such, DAs at the edge of the municipal boundary may have available opportunities outside the Toronto boundaries not captured here. Given the limited number of low LTS cycling links at the municipal boundary we expect the impact to be marginal.

5. Analysis and discussion

As illustrated by Fig. 2, road links outside of the historic City of Toronto tend to have higher stresses for cyclists than the streets in the inner sections of the city. This is due to wider streets, higher speeds and lack of cycling infrastructure outside the historic city. The current speed limit in Toronto, unless otherwise posted, is 50 km/h, which results in LTS 3 or 4 depending on the street width, unless cycle tracks physically separate cyclists from automobile traffic. The reduction in speed limit to 40 and 30 km/h on local roads, along with a denser and calmer road network with more bicycle facilities, creates a lower stress environment for cyclists in the inner sections of the city. Thus, it is not surprising that cycling mode share in some parts of the inner city is almost 5 times higher than the city's average (Data Management Group, 2016). Overall, most of the streets have low stress levels; only 32.4% of network links have a LTS of 3 or 4. However, the higher levels of stress (3 and 4) are found on most of the main streets in Toronto, creating isolated and disconnected islands of LTS 1 and 2.

LTS 1 and 2 isochrones are frequently limited by space rather than the cut off time; there are often not enough available links for a 30-minute low stress isochrone. Table 2 lists the mean travel time for isochrones at LTS 1, 2, 3 and 4. The mean possible time at LTS ≤ 2 is 8.4 min, only 28% of the 30-minute time threshold. The accessible area expands as the level of stress increases. Fig. 3 illustrates the isochrones for a sample DA at LTS ≤ 1, ≤ 2, ≤ 3 and ≤ 4. It highlights the importance of a connected network; the residents in this DA can cycle to the east and south on low stress streets and by using cycling infrastructure, but to cycle west they have to tolerate higher stress due to discontinuities in cycle tracks and bike lanes. For this DA, using the LTS 1 and 2 network, the cyclists can reach 5.4% (7.1%) of jobs (population) accessible by the LTS ≤ 4 network. The rate of accessible opportunities significantly increases to 73.7% (85.6%) at LTS ≤ 3.

Using this approach for accessibility analysis, even a short discontinuity in the network at the examined LTS limits the isochrone and the associated cumulative opportunities. Some people, however, may be willing to tolerate a higher LTS for a short period of time; this is an area for future investigation.

Fig. 4 maps the cycling accessibility to jobs in the City of Toronto for each LTS tolerance threshold. The maps highlight the limited access to jobs by cycling, especially in outer neighbourhoods and the eastern parts of the city. At LTS 1 nearly the entire city has access to fewer than 5000 jobs by cycling. At LTS ≤2 only a few neighbourhoods in the central city show job access between 15,000 and 60,000, with most of the city still able to access fewer than 5000 jobs. This finding is consistent with the low cycling commute share in Toronto of < 3% overall around the city but with higher share for some central neighbourhoods (Statistics Canada, 2016). By LTS ≤ 3 the downtown and much of the western part of the city have high accessibility to jobs. The LTS ≤ 4 analysis illustrates the potential accessibility if most roads were safe and comfortable for cyclists. In that case, most of the city would be within a 30-min cycle of > 60,000 jobs, at which point cycling accessibility becomes comparable to transit accessibility in Toronto (Saxe et al., 2017).

5.1. Low stress access and mode choice

To examine the link between the LTS measures and the cycling behaviour in Toronto, a binary logit model for cycling mode choice is developed (similar in approach used by (Manaugh and El-Geneidy, 2011) to examine walkability indices). The household travel survey in Toronto (TTS) collects detailed travel behaviour data from 5% of the

Fig. 2. Toronto network level of traffic stress, calculated for individual street segments.

households in the Toronto region (Data Management Group, 2016). In addition to the trip data, individual and household characteristics are gathered during data collection. For this analysis the 54,350 households residing in City of Toronto were selected from the dataset; households with incomplete and inconsistent attributes were excluded. The binary logit model analyses home based trips to investigate the relationship between LTS-based cycling accessibility at place of residence and cycling mode choice. The 54,350 households made 83,937 trips originating from home locations, these trips are the basis of this analysis.

A set of variables considered are extracted from TTS survey including the trip distance, age, gender, number of vehicles in the household, and household income. In addition, the distance from each household home location to the Toronto City Hall was computed as a measure to identify the impact of proximity to the central business district (CBD). Home location job accessibility measures using different LTS thresholds were included in the model to relate the LTS framework to cycle mode choice. The use of job accessibility as a key measure is well established and can be found in analysis of land value (Du and Mulley, 2012; Iacono and Levinson, 2017), commuting distance (Levinson, 1998; Manaugh et al., 2010), social equity (Foth et al., 2013; Manaugh and El-Geneidy, 2012) and mode share (Foth et al., 2014; Owen and Levinson, 2015). The LTS accessibility variables considered in our analysis defined as the additional jobs accessible by each level of stress. For example, "Accessible Jobs with LTS 3" variable shows the

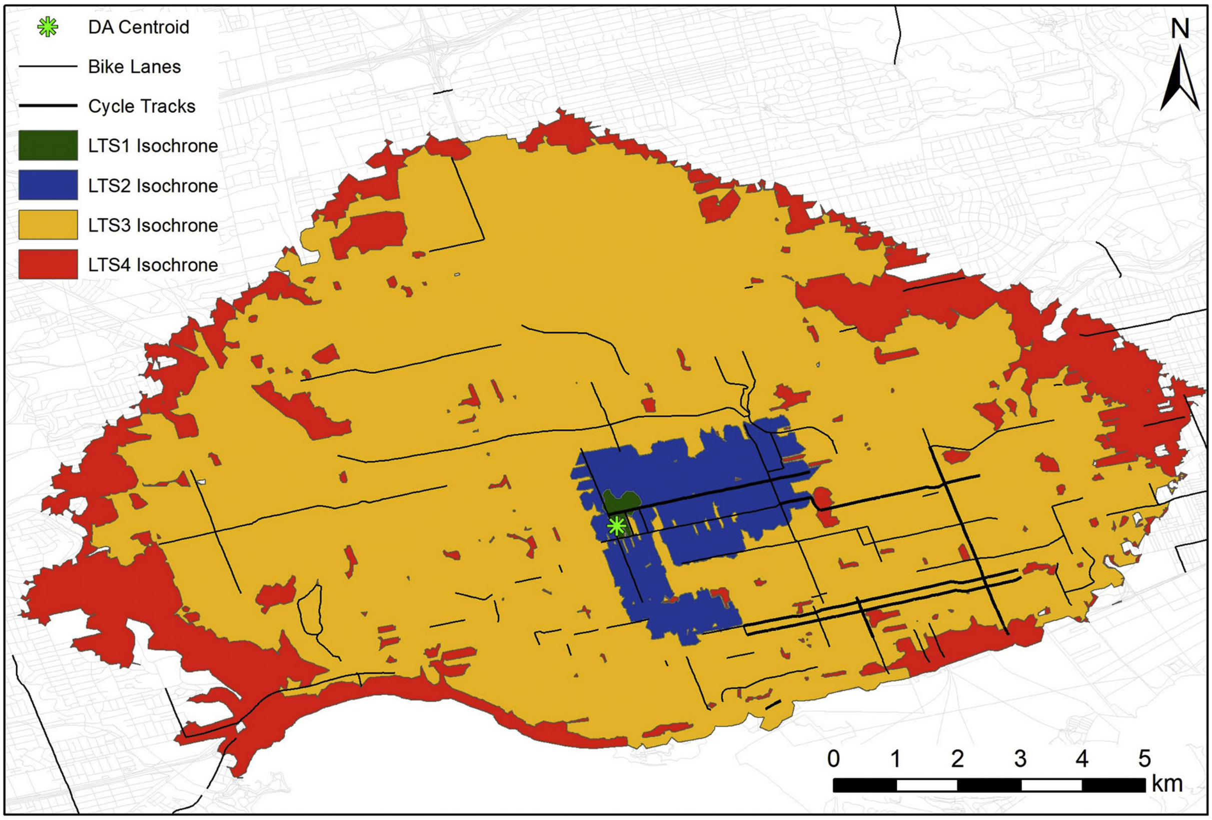

Fig. 3. LTS isochrones for a sample residential DA in Toronto.

Table 2
Cycling accessibility at different LTS for the 3685 DAs in the City of Toronto.

	LTS	1	≤2	≤3	≤4
Travel time isochrone (minutes)	Mean	2.9	8.4	26.7	30.0
	Standard deviation	3.5	8.8	8.3	0.5
	Max	22.2	30.0	30.0	30.0
Population access (# people)	Mean	1920	14,977	218,826	438,068
	Standard deviation	3116	30,709	212,677	178,049
	Max	20,616	160,003	747,855	818,874
Job access (# jobs)	Mean	568	5099	140,048	277,154
	Standard deviation	1352	11,416	182,486	226,599
	Max	30,018	52,584	554,573	753,648

effect of the additional reachable jobs from home by tolerating level of traffic stress 3 on the way. Table 3 presents a descriptive summary of sample characteristics.

Table 4 presents the binary logit model's estimation results. The parameters estimated for these variables are as expected. As expected, trip distance has negative impact on likelihood of choosing bicycle as the mode of travel. Individuals age variables are introduced as dummy variables, with the category of older than 60 years old being the base. The estimated coefficients for all the age categories are positive indicating that compared to the base, people younger than 60 years old are more likely to bike with larger effect for people age 20 to 40 years. The estimated results indicate that females are less likely to choose bicycle as their travel mode. Further, the more vehicles in the household and the farther the home location is to CBD, the less likely people are to cycle for trips (Table 4).

The sign and size of LTS accessibility coefficients indicate that the cycling accessibly measure has a significant effect on choosing cycling as the travel mode. The LTS 1 access variable was insignificant in the model as there were few locations with meaningful LTS 1 access across the city. All the three accessibility measures have positive coefficients indicating that the higher the access is, the more likely cycling is selected as the travel mode. The odds ratios for Additional Accessible Jobs with LTS 2, LTS 3 and LTS 4 are 1.41, 1.14, and 1.05, respectively. This indicates that adding 100 jobs in the locations accessible by lower stress links (LTS 2), increases the likelihood of cycling by about 41%, while adding similar jobs on higher stress links has a smaller effect, about 14% for LTS 3 and 5% for LTS 4. This indicates that the impact of 100 jobs within LTS 2 network is equal to 293 jobs within LTS 3 and 820 jobs within LTS 4 network. The analysis here indicates that in order to encourage people to cycle more and increase cycling mode share in Toronto, more opportunities should be added along the low-stress network and/or the level of stress of high-stress links near large opportunities should be decreased by improving the infrastructure.

5.2. Case study: bike access to the TTC

The LTS approach to cycle accessibility is useful for analysing and visualizing the areas of the city that can be accessed by bicycle as well as for a more detailed analysis of access to a particular service. As an example, Fig. 5 plots the LTS ≤ 2 bicycle accessibility to Toronto Transit Commission (TTC) subway station entrances. This illustrates the extent to which most adults would be comfortable cycling to access the subway. This example was chosen in part because the TTC has been making efforts to encourage cycling to its stations. These include the provision of bicycle parking at stations, installation of basic bicycle maintenance stops, and easier access gates for transit users with bicycles (TTC, 2017). Toronto has long discussed the potential for combining cycle-transit trips to compete with automobiles for mode share. As early as 2001, the City of Toronto identified improving cycle accessibility to stations as critical to increasing cycle-transit trips (City of Toronto, 2001). The provision of low stress access to the stations has

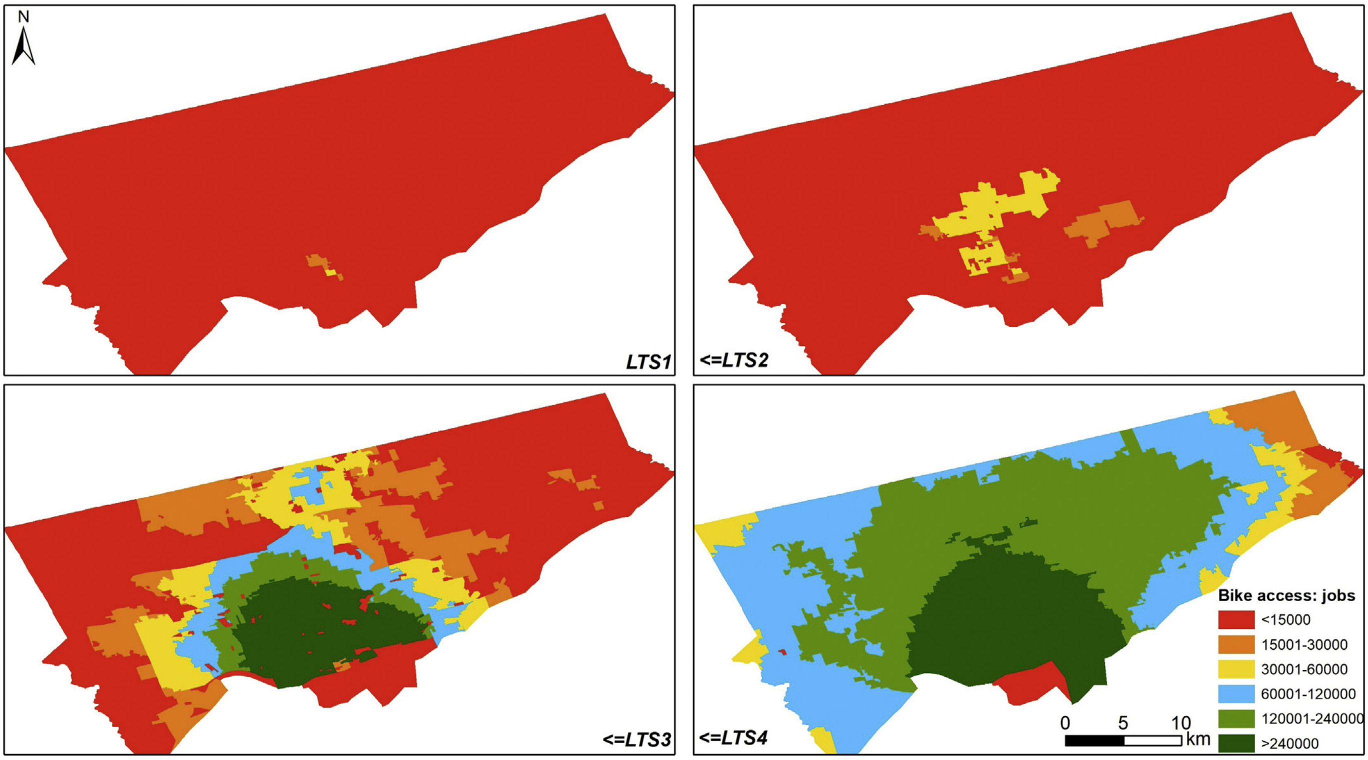

Fig. 4. Cycling accessibility to jobs in Toronto.

Table 3
Descriptive summary of sample characteristics.

Variables	Min	Max	Mean	Std. Dev.
Trip distance (km)	0	74.97	7.37	8.19
Age < 20	0	1	0.09	0.29
Age 20–40	0	1	0.31	0.46
Age 40–60	0	1	0.36	0.48
Age 60+ (Base)	0	1	0.23	0.42
Female	0	1	0.51	0.50
Number of Vehicle in HH	0	12	1.31	0.89
Income < $39,999 (Base)	0	1	0.17	0.38
Income = $40,000 to $59,999	0	1	0.15	0.36
Income = $60,000 to $99,999	0	1	0.25	0.43
Income = $100,000 to $124,999	0	1	0.13	0.34
Income ≥ $125,000	0	1	0.30	0.46
Home Distance to CBD (km)	0	26.77	10.74	6.02
Accessible Jobs with LTS 1 (×100) (Base)	0	0.30	0.01	0.02
Additional Accessible Jobs with LTS 2 (×100)	0	0.51	0.04	0.11
Additional Accessible Jobs with LTS 3 (×100)	0	5.53	1.42	1.83
Additional Accessible Jobs with LTS 4 (×100)	0	7.07	1.42	0.81

not yet become a priority.

The location of the station entrances was obtained from Open Street Map (OSM, 2017). The area of the LTS ≤ 2 isochrone around the station entrances varies significantly from station to station and entrance to entrance. In many instances the isochrones are limited by the LTS of most major roads in Toronto (often LTS 3 or 4) near which most subway station entrances are located. In most cases the limits of the accessible road segments governs the size of the isochrone rather than the 30-minute time cut off. Seven station entrances had no isochrone due to lack of access to LTS ≤ 2 streets or paths. Only five out of 188 analysed entrances achieved the full 30 min isochrone in at least one direction. On average, at LTS ≤ 2, it was possible to cycle for 5.32 min; the median time was even lower at 1.01 min. The largest isochrone catchment area is 22.1 km^2; the mean catchment area size is 1.34 km^2. Overall, LTS ≤ 2 accessibility provided access to or from a subway entrance to 518,801 people and 276,751 jobs, out of > 2.61 million

Table 4
Binary logit model results.

Variable	Estimate	z-stat	Odds ratio (OR)	95% Confidence Interval for OR	
				lower	upper
Constant	−2.843	−16.32	0.058		
Trip distance (km)	−0.102	−18.26	0.903	0.893	0.913
Age < 20	0.354	3.36	1.424	1.159	1.750
Age 20–40	0.803	11.36	2.231	1.943	2.563
Age 40–60	0.766	10.70	2.150	1.869	2.474
Age 60+ (Base)	–	–	–	–	–
Female	−0.663	−15.62	0.515	0.474	0.560
Number of vehicle in HH	−0.615	−18.46	0.540	0.506	0.577
Income < $39,999 (Base)	–	–	–	–	–
Income = $40,000 to $59,999	0.256	3.02	1.292	1.094	1.526
Income = $60,000 to $99,999	0.517	7.11	1.678	1.455	1.935
Income = $100,000 to $124,999	0.562	6.84	1.753	1.493	2.060
Income = $125,000 and above	0.619	8.31	1.857	1.605	2.148
Home distance to CBD (km)	−0.078	−7.90	0.925	0.907	0.943
Accessible jobs with LTS 1 (×100) (Base)	–	–	–	–	–
Additional accessible jobs with LTS 2 (×100)	0.341	2.23	1.407	1.042	1.899
Additional accessible jobs with LTS 3 (×100)	0.128	5.95	1.136	1.090	1.186
Additional accessible jobs with LTS 4 (×100)	0.048*	1.71	1.049	0.993	1.108
Final log likelihood	−9698.7				
Log likelihood at constant	−11,757.7				
Nagelkerke R square	0.196				
Number of observations	83,937				

* Estimate is significant at 90% level of confidence.

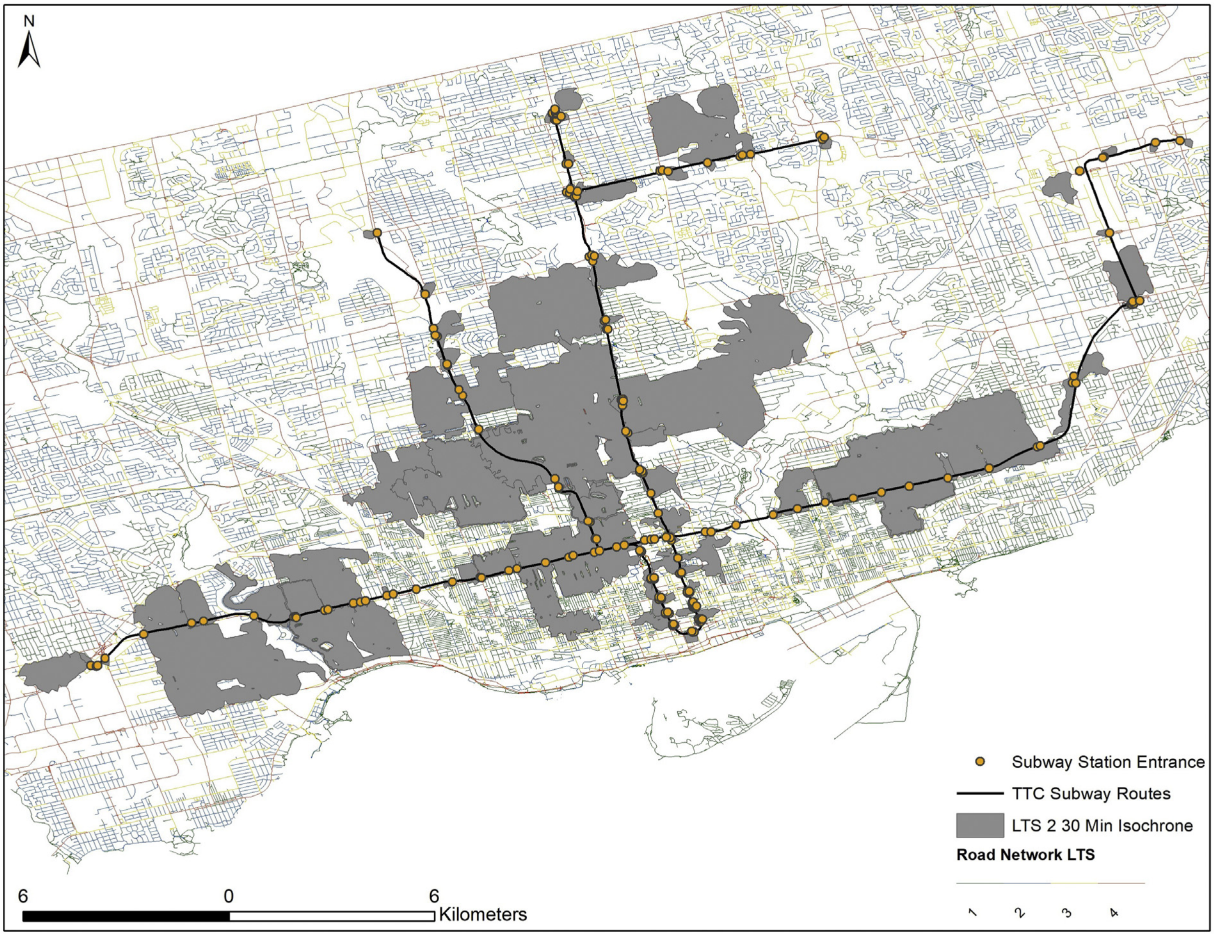

Fig. 5. LTS2 Cycle access to subway stations in Toronto.

Table 5
Scenario analysis results for LTS ≤2 isochrones.

		Base Case	Scenario 1	Scenario 2	Scenario 3
Travel time isochrone (minutes)	Mean*	8.4	8.1	10.2	28.6
	Std. Dev.	8.8	8.6	10.2	5.7
	Max	30	30	30	30
Population Access (# people)	Mean	14,977	14,157	24,315	316,900
	Std. Dev.	30,709	30,317	46,340	214,098
	Max	160,003	160,003	226,007	789,027
Job access (# jobs)	Mean	5099	4387	9314	211,063
	Std. Dev.	11,416	10,369	20,525	232,757
	Max	52,584	52,584	103,156	714,345

* The mean is the average maximum “reach” of the isochrones expressed in travel time terms for each scenario.

people and 1.47 million jobs in the study area.

This research illustrates that low stress access to stations in Toronto continues to be limited. While working towards a citywide network of cycle infrastructure, transit-oriented cycle routes could increase cycling by facilitating station access for cycle-transit trips, this could also provide new access in the suburbs where cycling LTS is high and rates are low. The impact this would have on cycle mode share and cycle safety is not within the scope of this paper.

5.3. Scenario analysis

Since 2011, Toronto has begun to make meaningful efforts towards increasing cycling facilities and safety, though many improvements are still needed (City of Toronto, 2016, 2011). Currently, the City of Toronto has the lowest cycling infrastructure per capita within major cities in Canada. To improve infrastructure connectivity and reach, the City has developed a 10-year cycling network plan which recommends 41 lane-km of additional cycling facilities (City of Toronto, 2016; Vijayakumar and Burda, 2015). To illustrate the impact of completed and proposed interventions we develop three scenarios and evaluate their impacts on cycling LTS. In the first scenario we examine the cycling LTS of Toronto without the existing cycle tracks, instead replacing them with painted bike lanes, as an approximation of the cycling network in 2011. This scenario illustrates the impact of the recent major improvements in cycling infrastructure in Toronto. It also can help in justification of installing future cycle tracks as they are still controversial in Toronto. The second scenario upgrades all bike lanes (148 km) to cycle tracks to highlight the impact of physical separations between vehicles and cyclists on road; cycle tracks are recognized to have a higher impact on improving safety for the cyclists than bike lanes (DiGioia et al., 2017). Finally, the third scenario decreases speeds by 10 km/h on the entire road network: a scenario with potential to improve safety for all people. This scenario results in a speed limit of 30 km/h on local roads which is in agreement with Vision Zero guideline that no vulnerable road users should be exposed to vehicles with speeds faster than 30 km/h (Johansson, 2009). City of Toronto's Vision Zero plans consider speed reduction by 10 km/h as one of the safety improvement measures (City of Toronto, 2017). It is well established that simply changing posted speeds is not sufficient to change driving speeds, and other interventions like street redesign are needed, we none the less include this scenario as an example of the scale of cycling LTS change that could be possible with lower driving speeds.

As above, we compute available opportunities for each DA in

Toronto at LTS ≤ 2 for the three scenarios. LTS ≤ 2 is used for this comparison since it is the LTS at which most people are comfortable biking. The impact of each scenario is compared to the current network as the base case. This exercise also again highlights the impact of high-stress arterial roads on cycling accessibility. The analysis results are presented in Table 5.

From scenario 1, we see that while there were improvements in cycling accessibility in Toronto relative to the base 2011 network, these improvements were modest. The improvements were 4%, 6% and 16% on average in terms of travel time isochrone, population and job access. The higher improvement in terms of job access is due to the concentration of cycle-tracks in the downtown area, near a large concentration of jobs. From scenario 2, we find that upgrading current bike lanes to cycle tracks can significantly improve the cycling accessibility (by 21%, 62% and 83% on average in terms of travel time isochrone, population and job access, relative to the 2011 base). This scenario illustrates how, by upgrading existing infrastructure to a safer alternative, it is possible to significantly improve the low-stress cycling accessibility in the city. Scenario 3 shows that reducing vehicle speed has a high impact on improving low-stress cycling accessibility; the impact would be city-wide and not limited to the segments that already have cycling infrastructure. We have examined the above three potential scenarios to demonstrate the potential use of cycling LTS accessibility as a quantitative measure to test the impact of different approaches to road and cycling infrastructure. Overall, the method presented in this paper shows a quantitative way to analyze the access implications of new cycling infrastructure and can be easily adapted to examine a variety of proposals.

6. Conclusion

The LTS method proposed by Furth et al. (2016) provides a useful way to calculate and visualize the varying suitability of cycling in the City of Toronto. While most of the city's streets and paths have low LTS, the high LTS arterials create islands limiting the area people can access without cycling on, or crossing, high stress streets. LTS ≤1 and ≤ 2 isochrones are frequently limited by space rather than the 30-minute cut off time. Cumulative accessibility analysis illustrates that outside the core of the city cycling accessibility to jobs and people is quite low at the lower levels of stress where most people would be comfortable cycling (LTS ≤ 2). For those that are willing to tolerate higher levels of stress (LTS ≤ 3) a large number of jobs (> 60,000) become available in much of the central city. At the periphery of the city, wider streets and higher speed limits are an impediment to achieving low street links or areas.

The paper further investigated the link between low-stress access to jobs and decision to cycle from home. The results indicate that the cycling accessibly measure has a significant effect on choosing cycling as the travel mode with larger effect for low-stress access (LTS ≤ 2). Applying the LTS-cumulative accessibility approach to TTC stations illustrates that most have limited low stress cycling access. Further, the scenario analysis shows how the method presented in this paper can be used as a tool to evaluate different scenarios' impact on cycling accessibility.

The analysis is not without limitations. A more accurate level of stress can be developed for crossings considering turning restrictions and the type of cycling facilities at intersections. Further, bike lane blockage and the number of private accesses and driveways such as parking entrances along a segment should be also taken into account. In addition, the LTS can be computed for different time periods, such as peak and off-peak, as some of the network characteristics (such as curbside parking) vary by time of day. However, the analysis illustrates the usefulness of an LTS approach to cycling combined with cumulative opportunities accessibility measure as a new quantitative tool for examining existing or proposed changes to the road network for cycling. The opportunities within the 30 min isochrones are considered the same in our analysis. Slope and distance travelled in the isochrones can be considered as factors in a decay function while calculating the cumulative opportunities. Future work will further investigate the use of cycling accessibility metrics, along with similar accessibility measures for other modes, in multivariable models of cycling mode share to better understand the impact of different levels of stress on mode choice.

As many cities struggle with the competing desires and priorities of pro and anti-cycle groups and the politicization of cycling infrastructure, the numerical metrics provided by the LTS and LTS accessibility approach can provide novel quantitative tools. These quantitative measures can provide objective analysis of the impact for cycling, mode choice, and accessibility of cycling infrastructure and other changes to street space.

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