Quantitative Spatial Bikeability Diagnosis for Commuting

with case studies for the City of Sherbrooke and Region of Peel

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Executive Summary

Increasing the proportion of work trips completed by bike is a worthwhile public well-being goal, with important and well-proven benefits in long-term health, carbon emissions reduction, motor vehicle traffic reduction, and many economic benefits. This study looks at biking from home to work, and not at recreational cycling. It is based on the cyclist having a predetermined place of origin and a goal (destination) in mind. We study how well these origins and destinations are connected in a city. In order to enable more commute and other utilitarian (shopping, etc.) cycling trips, we wish to ensure that the trip can be completed from beginning to end with good safety, that is, minimal interaction with motor traffic.

In this work, we validate a methodology for measuring how well workplaces can be reached from residences via biking along the road and path network. To do this, we find the fastest paths for the cyclist to take, as well as a longer, but safety-conscious path. The difference between these paths (measured by their duration ratio) measures the quality of the cycling network compared to what it could be. We can therefore find which parts of the city map are most deficient in utilitarian biking access, which could then be increased by improving the cycling infrastructure. The safety rating of a path is found using a well-established standard: Level of Traffic Stress (LTS).

We take two approaches: the first uses an origin-destination study; the second, the population density and workplace locations and counts. These two approaches are different, but yield similar results (about 70% correlation), indicating that origin-destination studies may not be needed, as long as the other two datasets are provided. The population density is fortunately available publicly from the national Census, while the workplace dataset is harder to obtain, but at least approximate data will hopefully be available from the City, as it has been in this case for the City of Sherbrooke and the Region of Peel.

Nomenclature

BNA	Bike Network Analysis – U.S. bikeability project
Conveyal R5	Free and open routing engine that implements a simplified version of LTS
DA	Dissemination area – smallest geographical subdivision in the Canadian Census
LTS	Level of Traffic Stress – standard for assigning one of four levels of safety to roads based on level of separation of cyclist from heavy traffic
O-D Pair	A pair of geographical coordinates, indicating the start (origin) and end (destination) of a route to be travelled. In our context, origin refers to a residence, and destination refers to a workplace.
OD Analysis	One-to-one bikeability analysis mode, where each residence is routed to exactly one workplace
O-D Survey	A population survey containing the locations of both a persons place of residence, and their usual place of work (and, optionally, their favoured mode of transport, hour and duration of travel, etc.).
OSM	OpenStreetMap
OSRM	Open Source Routing Machine – free routing engine, optimized for speed.
PCT	Propensity to Cycle Tool – U.K bikeability project
RW Analysis	All-to-all bikeability analysis mode, where each residence is routed to each workplace

Concepts

All-to-all	A bikeability study where each residence is matched to all workplaces.
Bikeability	A measure of how good a geographical region has good conditions for cycling. There may be many definitions of such a measure, depending on the geographical region taken, where the cyclists want to go, a cyclists ability, etc.
Cycling infrastructure	Any public infrastructure that has cycling in mind: includes painted lines and physical barriers, cycling and multi-use trails, protected intersections. More broadly, may include signage, repair stations, etc.
Cycling lane	A painted traffic lane alongside motor lanes, without physical separation.
Cycling network	The connected collection of all roads and paths where it is possible and legal to cycle, including lanes, tracks, multi-use trails, and most streets (except highways); also includes pedestrian trails (but the cyclist must dismount).
Cycling track	A dedicated path for cyclists with a physical barrier from motor traffic.
One-to-one	A bikeability study where each residence is matched to exactly one workplace – it requires an O-D survey as input data.
Routing engine	Software that takes a road network and an origin and destination point, and finds the optimal route to travel between both points via a given travel mode.

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I - Introduction

A **well-connected** network of **bike-safe** paths and roads is the primary requirement for enabling utilitarian urban cycling for the majority of the population. Indeed, the average cyclist needs a route from their residence to workplace (or other location of import) that minimizes sharing space with motor traffic, and that does not take too long to bike. A well-planned cycling network is expected to increase bike mode share to work, resulting in **long-term health benefits** (notably for metabolic disease and mental health), reductions in **traffic** congestion and urban **pollution,** and **economic** and **tourism** benefits. By **planning** bicycle infrastructure geographically across a city, one has a **very cost-effective** means of improving these many vital socio-economic factors.

The commuting bike mode share in Canada remains **below 2.5%** for most major Canadian cities [2016 Census]. The situation is better than in the U.S. (with less than 1% in all but four states [League of American Bicyclists 2016]), but worse than in many E.U. countries, several of which have a double-digit percentage of cycling to work – such active participation usually follows the institution of a **National Cycling Strategy** [Eurobar442a, 2014], which has also been proposed for Canada [Canada Bikes, 2016]. We propose that detailed methodologies for **measuring and planning of cycling networks** at the scale of the entire city is an essential component of such a strategy, with the final goal of increasing bike mode share to work and also for other utilitarian trips (shopping, entertainment, community events, etc.) - and thereby reaping the aforementioned important health, wellness, and economic benefits. While this study does not include biking to school, measuring and improving bikeability to schools has been shown to increase student participation [Stewart, 2018] and our methodology could be adapted to include students according to their specific requirements.

Quantifying bikeability is a multifaceted problem, and it is not simple to devise a single indicator that entirely captures the cycling connectivity situation. However, it is also essential to find a meaningful indicator of bikeability, which could inform cycling infrastructure planning decisions for maximum increase in biking at minimum construction cost. Towards this purpose, research has focused on three methods of measuring the cycling situation. At the most basic level, one can evaluate the bikeability of a given **road segment**, which indicates how safe (i.e., separated from fast motor traffic) the segment is – this results in a map of the road network, with different roads coloured according to a safety rating, and a visual inspection of the map can hint at what locations are the most in need of improvement. Secondly, one would like to consider not only the road segments individually but also how well they are **connected** to each other in a **network.** This method, however, is of limited use if we do not know where origins and destinations of trips are concentrated. Therefore, the most advanced approach is to consider also **population and workplace density** – one can then analyze where the majority of the cyclists need to go on the network. Such an analysis can show more accurately in which parts of the city people are thwarted from easily completing trips, and help **identify bottlenecks** in the network. It can also quantitatively show the increase in bikeability after the addition of particular improvements, thereby estimating which infrastructure additions will most increase the commute bike mode share.

Health Benefits

Biking to work is an effective and practical form of exercise, and is also extremely efficient in that it doubles as leisure and exercise and also commute time – bicycle commuting is therefore an important opportunity to reintegrate physical activity into the lives of Canadians, who may have limited time opportunity for it.

As mentioned earlier, the main obstacle to bike commuting outside winter is lack of protection from motor traffic on some of the road segments. We therefore see a **conflict** between **immediate safety** and **long-term health** as being the fundamental dilemma that thwarts efforts at promoting cycling to work. This can most effectively be addressed by building the **missing links** of a safe-enough cycling network, which must be planned at the city scale for best results, and such planning and infrastructure-building can thus be considered as an essential effort for long-term public health. Another health concern is inhaling vehicle fumes while cycling in the city.

In [de Hartog 2010], it was found that a shift from car to bike proved overwhelmingly beneficial to health, vastly compensating for increased risk from traffic accidents and air pollution inhalation. Similar conclusions are reached in [Teschke 2012], which shows results from Canada that confirm that the long-term health benefits of urban cycling far outweigh the harms, also indicating that traffic fatalities are lower for cyclists than for pedestrians and also motor vehicle drivers and passengers, and argues for better infrastructure (physically-separated bike tracks) as a primary preventative measure for collisions. The benefits of commute cycling for cardiovascular disease and cancer prevention are presented in [Celis-Morales 2017], and advocates for better cycling infrastructure, bike hire and purchase schemes, and bicycle access on transit.

To quantify the health benefits of cycling, a software tool, Impacts of Cycling Tool (ICT) [Woodcock, 2018] was developed to provide an open-source model for measuring both health impacts and traffic congestion relief due to an increase in the population's participation in cycling.

A **focused and well-planned** improvement to the cycling network can have a significant positive effect on utilitarian cycling frequency. Based on U.S. [Geller 2009, League of American Bicyclists 2016] and Canadian [Winters 2008] reporting, about 60% of the population would be willing to cycle in the city if the conditions were sufficiently safe. It is with an eye to this majority of the population that the improvements would best be directed.

Impact on Traffic and Urban Emissions

Because of the very high number of car commuters, and the very low bike mode share, it may be difficult to see how replacing a few motor vehicle trips will significantly help in reducing traffic and pollution. What needs to be taken into account is the effect of increased traffic on congestion, idling, and searching for parking spaces – therefore, removing even a small percentage of motor vehicles from the road at rush hours could result in **more than proportional gains** in reduced vehicle-hours on the road.

Similarly, the load on transit is reduced. It is also interesting that dedicated cycling paths rarely suffer from congestion, and are many times more efficient in transporting a given number of people per hour.

Economic Impact for Commerce

Placing a protected bike lane (perhaps in the place of parking or a traffic lane) on a major arterial road with commercial buildings may be posited as detrimental for commerce. [Rowe 2013] and others have argued with data that this fear is understandable but unnecessary and that the impact of replacing street parking or an additional motor lane is none-to-positive on the economic success of commerce on that street. The economic impact in many U.S. cities and for the province of Quebec is summarized in

[Flusche 2012], detailing not only the economic and job creation benefits of the cycling industry, but also the important **benefits to commerce with good cycling access**, with increased repeated trips and overall increased land desirability, and better access for delivery and cargo bikes.

Case Study Geographies

This work examines bikeability in the city of **Sherbrooke** in the region of Estrie, Quebec, Canada. The municipality counts 161,300 people [2016 Census] in a region that fits within a 25km x 25 km square. However, most of the population is concentrated within a much smaller centre. It is therefore expected that many utilitarian trips could be completed in the majority of the city within a reasonable time (which we will later assume to be 30 minutes). Sherbrooke represents an interesting case study of a semi-rural context, for a city which has both a focused city centre surrounded by suburbia, itself surrounded by a rural region. The city is not contiguous to any other major urban centre, signifying that it can be studied without having to consider cross-over effects with neighbouring urban centres. Sherbrooke is also interesting from the point of view of its waterways: three major river branches join near the city centre and divide the city into quarters – the resulting road and cycle path network thus only has a limited number of connections (bridges) between sectors.

The **Region of Peel** is an order of magnitude larger, with 1,382 million people [2016 Census] and an area of 1247 km^2, 48km wide by 56 km tall. It provides contrast and comparison in terms of geographical extent and spread, as well as connectivity of cycling and motor roadways, and finally population and workplace distribution - this increases our understanding of how robust the methodology is and provides comparison and contrast. It is a more populated Region with two large adjacent urban municipalities (Mississauga and Brampton) and one large rural (Caledon) municipality in the north, which itself contains a few small and geographically isolated municipalities. Compared to Sherbrooke, it has less of a focused and concentrated centre, and its road network has more interactions with neighbouring urban areas in Toronto and Oakville: the study therefore requires a surrounding buffer (9 km wide), to include commutes between neighbouring urban areas.

II – Measuring Bikeability

Bike mode share to work in Canada is usually around 1% to 6%, whereas it is estimated that, in North America, up to one third of the population would be willing to bike to work regularly (outside winter months) if the conditions were favourable, and only one third of the population is not interested at all. The target population of this study is thus not the strongest and experienced cyclists, who would be willing to bike far and alongside fast traffic to get to work. We are instead interested to see what are the cycling needs of ~60% of people [Geller, 2009], those with moderate ability and willingness to cycle to work.

Previous research has shown that most people are deterred from utilitarian cycling primarily due to having to interact with motor traffic on parts of the trip. It directly follows that having a connected network of safe-enough roads is the primary goal for urban planning – indeed, academic research and resulting online projects in the past few years have explored how to measure the quality of the connectivity of the road network.

Two projects that measure bikeability at a large geographical and population scale are:

1. Propensity to Cycle Tool (PCT), U.K.-based, covering all of England and Wales.
2. Bike Network Analysis (BNA), U.S.-based, covering over 300 major U.S. cities.

In this project, we use a methodology described in [Szyszkowicz, 2018] that draws important elements from both projects, as well as from the *Open Source Routing Machine* (OSRM), and varied recent cycling research.

In devising a spatial bikeability metric, it is desirable for the metric to have several characteristics:

1. *Sensitivity*: improvements in the most needed network segments (bottlenecks) which are expected to be most used should increase the metric the most.
2. *Robustness* to data error (stability): because GIS databases are prone to human error and obsolescence, the metric should not vary much due to erroneous or incomplete data on a small map feature.
3. Spatially *unbiased*: cities differ in size, density, spatial distribution, physical obstacles (rivers, large hills), residential and workplace locations, and large human-made features where no bike path may be built. A good bikeability metric would be one that can be improved and maximized by *only* improving the bikeable network.
4. Spatial *divisibility*: the metric could be applied to any geographical region, however small.

Level of Traffic Stress (LTS)

Previous research indicates that danger due to having to share the road with motor vehicles is the foremost barrier to utilitarian cycling in cities. The Level of Traffic Stress (**LTS**) is a **4-level** rating system that was developed [Mineta Institute, 2012] for measuring the level of this danger, based on criteria such as speed limit of motor traffic and physical separation between cyclists and motor vehicles. LTS4 is the highest level of peril and is recommended for experienced cyclists only, while levels LTS2 and LTS1 can be recommended for casual cyclists. One can also distinguish roads where cycling is illegal (freeways in Canada), as well as pedestrian paths (also rated LTS1) where the cyclist should dismount, and finally roads with special or poor surfaces for cycling, which are not considered within the LTS framework, but have to be taken into account in their own right.

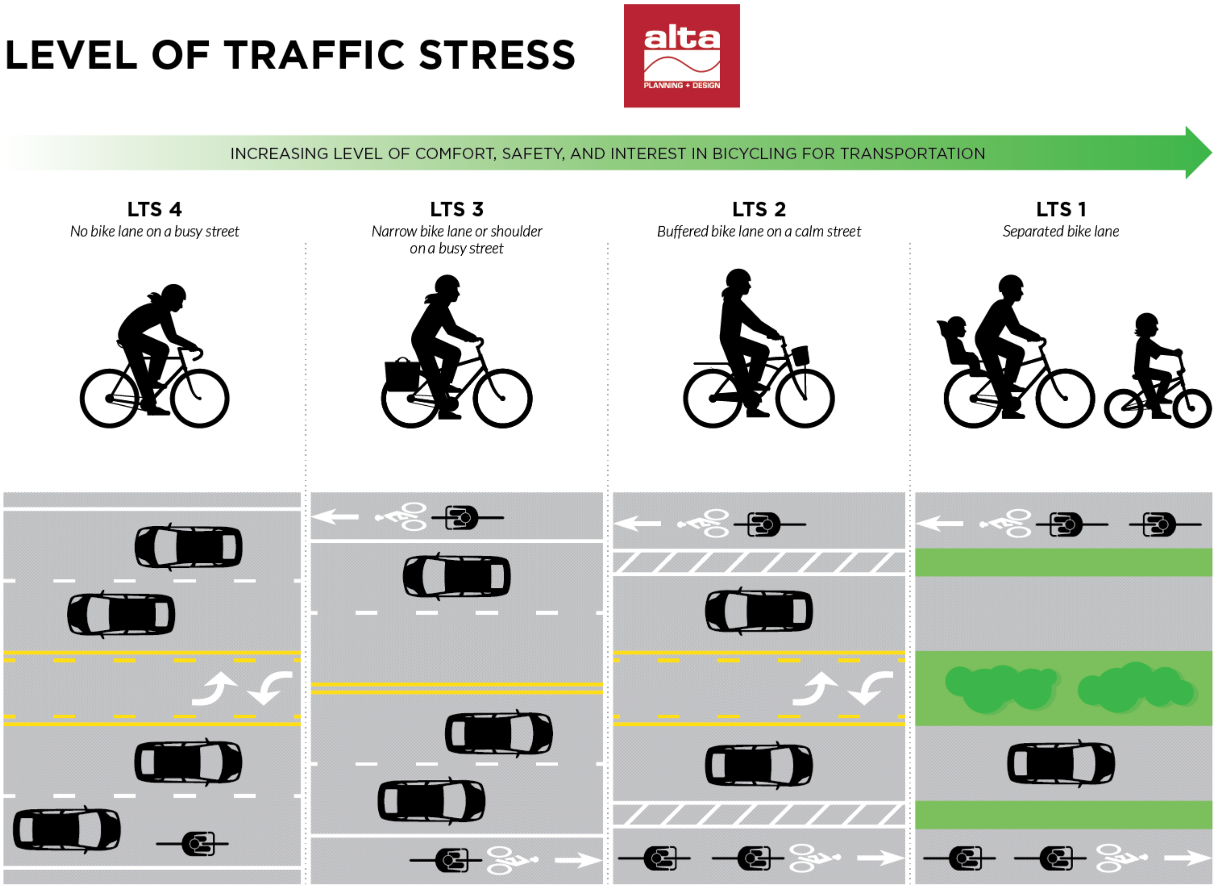

Figure 1: Infrastructure examples of the four categories of roads in the LTS framework [Alta Planning].

Examples of cycling conditions for each LTS rating are shown in Figure 1; however, many situations can occur, and a few general guidelines on how LTS operates are:

1. Conditions where there is minimal-to-no possibility of interaction with motor traffic are categorized LTS 1 – examples include a cycle track (alongside any road), bike paths and multi-use paths, and some quiet residential streets.
2. LTS 2 and 3 have the most complex rule boundary: we observe that most residential streets are LTS 2, while LTS 3 belongs to minor arterial roads.
3. LTS 4 corresponds to major arteries with many lanes or higher speed limits.
4. The LTS rating increases with: number of lanes, posted speed limit, presence of parking on the street, absence of bike lane, and non-residential street.

The LTS rating has gained popularity in various software projects and has been implemented based on OpenStreetMap tags in the BNA project, by *BikeOttawa.ca*, and in the *Conveyal R5* project.

Active Projects and Research for Measuring Bikeability in Cities

Quantifying bikeability is a challenging endeavour, partly due simply to the computational load and lack of data in the domain – problems that have been lessened in the last decade due to more powerful personal computers, and to opening of access to data by national and municipal agencies, and the emergence of a high-quality crowd-sourced database of the urban maps: OpenStreetMap.org (OSM).
The road safety rating used in our work is taken from the BNA project (found at *bna.peopleforbikes.org*), which has direct affiliation with the creators of the LTS standard, and indeed uses the standard to assess road safety, and, from there, bicycle network connectivity. The project considers LTS 3 and 4 to be unbikeable, and therefore studies the connectivity of the road network composed of LTS 1 and 2 streets and paths. We can contrast to this, e.g., work by [Cooper 2017], where roads with heavy traffic are instead penalized by slowing down the cyclist's speed (even by over 700%) - in which case, short segments with poor bikeability can still be travelled without breaking the connectivity of the routes in the network. The BNA project considers access from residences to various amenities, which is similar to an all-to-all approach.

The PCT project (described in [Lovelace 2017] and accessible at *pct.bike*) uses a large-scale national UK origin-destination survey (not available openly), combined with a routing engine configured with various cyclist profiles. Bikeability is measured by routing a performance cyclist, as well as an average cyclist, each along the fastest path that suits their comfort level. The paths are compared based on time, and the closer their trip times, the better the bikeability is said to be at the origin location. The origin-destination values are further weighed by the population density in each administrative region, based on open data from the national UK Census. The purpose of the project is to give a quantitative indicator of the priority of need of cycling infrastructure improvement, and is the closest project to our methodology: it uses a two-trip routing methodology, and a one-to-one (from the OD survey) correspondence between residences and workplaces.

Several research projects also explore various approaches in measuring bikeability as it varies spatially over the area of a city. In [Abad 2018], a similar approach to the BNA's is used, and the score is computed not only for the whole city, but on a hexagonal grid with a few hundred meter resolution. In [Necessary 2016], the importance of network connectivity is emphasized, and a formula for assigning different cycling speeds to varying types of roads is proposed (similarly as in the PCT project). Similarly, [Lowry 2017] uses an all-to-all methodology to measure cycling intensity along roads. [Cooper 2017] uses a similar methodology, and also uses the speed formula from [Broach 2012] for taking into account different road types and motor traffic intensities.

Both projects and the research papers all use OpenStreetMap as their data source for road geometry and typology.

Profiling the Typical Cyclist

The **maximum trip** for average-ability cyclists is given as a distance of six miles (9.7 km) in [Mineta Institute 2012], and a median value of 3.8 miles (6.1 km) in [Dill 2008] for commute trips. Based on [Necessary 2016], a maximum trip time of 30 min is expected for commuting. The maximum default cruising speed assumed in most open-source projects varies between 16-24 kph, but the consensus is around 18 kph [Szyszkowicz 2018], resulting in maximum possible range of 9 km. Also, based on [Necessary 2016], a maximum commute distance of 5 km is given. However, this may be far too short to give good connectivity results. Many trips will indeed be significantly shorter than 9 km due to sub-optimal infrastructure, but 5 km is not very far if one has a good bike path for most of the trip. Also, to keep with the idea of referring all dimensions onto time, we set the maximum trip at **30 min**, and the cruising speed to **18 kph**. These two numbers (maximum commute time, and maximum cruising speed) are part of what we call the **cyclist profile**.

To give more realism, and to incorporate road safety ratings into the model, we can profile the cyclist according to how they tolerate riding alongside traffic. The approach taken in [Broach 2012, Necessary 2016, Cooper 2017] is to increase the cost of a road segment by a factor based on the amount of motor traffic on a street. This means that the road is effectively considered longer (or, equivalently, the cyclist is considered slower) by that factor. The factors given in these works are [Broach 2012, Cooper 2017] 37%, 140%, and 716% for increasing levels of traffic. If we take the largest of these values, it gives an effective speed of only 18kph/(1+7.16) = 2.21 kph, a value much slower than walking – and a range of only 1.1 km. Conversely, in [Necessary 2016, Table 9], very poor cycling is given a factor of not much more than 100%, effectively a speed reduction down to about 8 kph.

Instead, we use the proposed percentages from [Broach 2012, Cooper 2017] divided by two, which results in an effective speed of 3.93 kph in the worst case (all roads having LTS4) and a range of almost 2km on these worst-case roads. We propose that this is reasonably equivalent to walking one's bicycle alongside a fast-moving street, and represents a reasonable compromise for assigning weights.

The resulting **effective speeds** on different road conditions are as follows:

1. Little to no interaction with motor traffic, go at full speed: 18 kph.
2. Pedestrian-only roads: cyclist must dismount: 6 kph.
3. Moderate interaction with slow traffic (residential streets): 15 kph.
4. Faster traffic, worse conditions: cycle carefully: 10 kph.
5. Dangerous roads: dismount and walk on the side of the road: 4 kph.
6. One-way street: if going the opposite way: speed as if dismount.
7. Special or poor road conditions: damaged roads, earth, cobblestones, stairs, etc. - a speed cap is added to the model, such that the resulting cyclist speed is the minimum of this cap and the speeds calculated above.

Thus, rather than forbidding cycling on more dangerous routes, we penalize them, allowing for short segments to be travelled on these roads – however, for longer stretches, it is likely that the routing engine will rather choose a detour with lower traffic stress. It can be seen from such a profile that the three dimensions of time, distance, and safety rating are now converted to the single dimension of time, and routes can be compared accordingly. Such a profile is for a typical likely cycling commuter, and can be contrasted with an avid ("super") cyclist, where the speed is 18 km/h for any amount of motor traffic, except in the dismount and special/poor road conditions.

Designing our Bikeability Metric: Two-Trip Routing Methodology

A bikeability measure can now be performed based on different routes from residence to work (origin to destination). We route one typical cyclist, and one avid cyclist, from the same origin to the same destination, and compare their travel times. In a perfect scenario (very safe travel), these should be identical (best bikeability). Otherwise, we measure the bikeability as a decreasing function of the gap (measured as a ratio) of the two routes, shown in Figure 2. By averaging these results over all routes, one can obtain a bikeability score for a given location.

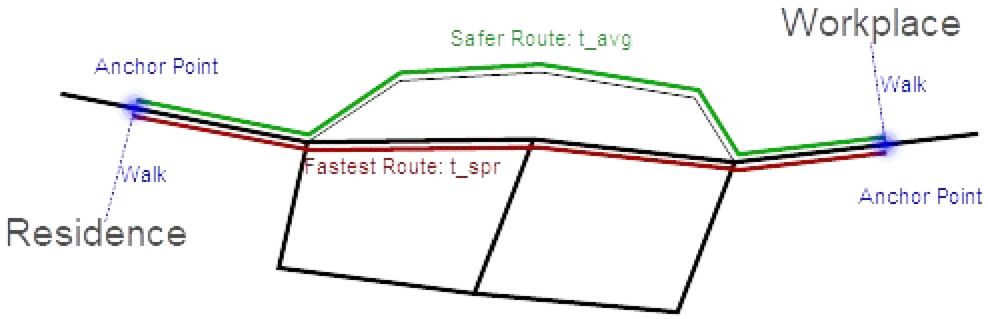

Figure 2: Two-trip routing methodology:

The two cyclist profiles are Super and Average, where the Super cyclist is one that is not significantly affected by riding directly alongside motor traffic, while the Average cyclist represents an individual from the population being studied: which is most likely to start or continue cycling to work if the infrastructure conditions and range are sufficient. The average cyclist has a maximum commute time range of **30 minutes** one way, and a maximum cruising speed of 18 kph (and thus a maximum commute distance range of 9 km). Cycling speed is determined by road type and condition as seen in Table 1.

Road type	**Super Cyclist (<2% population)**	**Average Cyclist (~60% population)**
LTS1	18 kph	18 kph
LTS2	18 kph	15 kph
LTS3	18 kph	10 kph
LTS4	18 kph	4 kph
Dismount condition	6 kph	
Poor roads, gravel, stairs, etc.	2-10 kph (formula obtained from OSRM project)	

Table 1: Profiling the speed of an average cyclist according to road type.

Based on this table, one can assign a speed to every road and path segment, and therefore find two fastest routes, one for each cyclist type, between the same points O and D. Their travel times can then be combined according to the delay percentage formula. This result is a measure of the quality of access by bicycle from each residential location to each employment location. It should be noted that these figures are best viewed alongside the density of residences or workplaces, to evaluate which regions cause concern. Indeed, it is expected that areas with low population or workplace density will have poorer infrastructure, and thus a higher delay percentage.

For a given pair of geo-located points O and D, the routing engine proceeds as follows:

1. For both O and D, find the nearest road and walk (6 kph) towards it by the shortest route, until reaching the "anchor point". This is necessary since the building locations are not, in general, placed exactly on the roads – and routing can only really be performed on the road network.
2. Find the best path in the road network between the two anchor points. The best path is the one that minimizes travel **time**. Two routes are found, one according to each profile (see Table below).
3. The travel time achieved by each cyclist is recorded as t_spr and t_avg, respectively. It includes the time walking to/from the anchor points.
4. The metric of interest is **biking delay** percentage, found from the ratio of trip time of the average cyclist over that of the super cyclist, given by the formula:

Biking Delay =
(t_avg/ t_spr – 1)*100%

This is the percentage of delay that the average user has to endure due to sub-optimal infrastructure, and is caused by a varied combination of two effects: some road difficult segments are avoided **(detour)**, while some difficult segments have no efficient detour and the cyclist must attempt to navigate alongside motor traffic **(slow down)**.

These results can be viewed in two ways:

1. By averaging the bikeability from a given residence to all reachable workplaces, one obtains a bikeability index for a residence.
2. By averaging the bikeability to a given workplace from all reachable residences, one obtains a bikeability index for a workplace.

Both these measures can thus be drawn on two separate city maps, with a heat-map colouring representing the values.

Obtaining and Matching Residences to Workplaces

Two main approaches can be taken according to the existing datasets:

1. From origin-destination surveys: one has a one-to-one correspondence between each origin and each destination, and one can straightforwardly perform routing accordingly. This approach is more representative of career jobs, where one has little choice of one's place of work, which can be only performed at a particular location.
2. From population density and workplace density map data: in this case, there are many more combinations of origin-destination pairs, since it is not known which populations travel in what proportions to what workplaces. We must thus route all possible pairs, and we no longer have a one-to-one correspondence, but a matrix (table) of each origin to each destination.

In both cases, results are further weighed by the corresponding population and workplace counts, to count each route a certain number of times in the overall weighted average that gives the bikeability score.

Residence-Workplace Methodology: All-to-All

In this methodology, residence and workplace coordinates are constructed from available data sources. Each residence is weighted by its population, and each workplace is weighed by the number of jobs available. Because all this data is not generally available in an exact form, we may use other data sources for estimating them. In this project, we find the required data as follows:

The number of residents is known for each dissemination area (DA) polygon [2016 Canadian Census], i.e., the smallest geographical census subdivision. For each DA polygon, the population could be represented as being concentrated at a point inside its polygon. However, the geometric centroid (a common definition of polygon centre) is not always inside the polygon (this can happen when the polygon is not convex); furthermore, some DA polygons are much larger than others, and it may be very inaccurate to reduce a large DA polygon onto one point. Instead, we distribute residences alongside all residential roads inside the DA polygon (at 50m intervals), dividing the population equally among all such points inside a particular DA polygon.

The locations of workplaces are obtained from a database of buildings [provided by the City of Sherbrooke], where buildings of a workplace nature (commercial, industrial, service, government, etc.) are selected. The number of jobs is either given or estimated by the area of the footprint of the building (it would be more accurate to multiply this by the number of floors – however, this information is often not available). Each building's location is represented by its geometric centroid, which is then connected to the nearest road via a direct walkable path (the speed on that path is assumed to be 6kph).

In this methodology, we have no way of knowing which residents travel to which workplace, and so we route *every* residence to *every* workplace (**all-to-all**); routes that are too far for an average cyclist are ignored. Each such route is weighed by the number of residents times the number of jobs calculated for those locations. The result of this simulation is thus as series of routes, each having a weight.

Origin-Destination Methodology: One-to-One.

This methodology differs from the first in that each origin is paired with a destination, resulting in a one-to-one correspondence. The data source for such information is not public but is a city-wide survey of a representative portion of the population.

The routing engine receives each O-D pair, one by one, and finds the duration of the trip for both cyclist profiles as described in the speed table. O-D pairs resulting in trips longer than 30 min for the average cyclist are rejected from the study.

The ratio of the two trip durations is computed and then aggregated (averaged) per geographical region of interest according to either origin or destination point. This averaging also helps to anonymize the O-D data in the output figure.

III – Data and Software Components

A bikeability simulation fundamentally requires five essential components:

1. a data source for identifying origin (residential) locations,
2. a data source for identifying destination (workplace) locations,
3. a map of the road and path network of the city, with each distinct road segment tagged with information about its characteristics relevant to cycling,
4. a formula for measuring the ease of cycling on a given road segment, based on its tags,
5. a routing engine, for finding the optimal (according to some metric) route between a given origin point and destination point.

Once we have these components, we may use the **routing engine** to find the optimal path between an **origin** and a **destination** location along the **network**, such that the **measure of cycling ease** is minimized along that path. Performing this operation over many origin-destination pairs is all the data input that is needed to calculate the bikeability metric in this work.

Residence and Workplace Density

The **population density** is open access from the Canadian National Census (2016). It can be visualized for the entire country on *CensusMapper.ca* – for example, Sherbrooke is visualized in Figure 3. The population is reported by "Dissemination Area" (DA), the smallest census **land parcel**. There are about 56,000 such parcels in the country, with a population of the order of a few hundred people per DA – each DA thus represents a small city neighbourhood, though in rural areas, DAs may be much larger, and thus the exact population distribution is harder to estimate as accurately in these locations.

The **workplace density** can be obtained either from a database of workplace building polygons (where the number of jobs can be estimated by the area of the building's footprint) or from a database of employment counts and locations. The data for workplace density is generally not available openly for cities in Canada, and therefore it is necessary to work with the Municipality to obtain this dataset.

Within the context of the Sherbrooke study, the city of Sherbrooke provided us with a (confidential) database of **geographical locations** of workplaces, alongside the **number of jobs** at each location.

In the RW (or "all-to-all") methodology, it is not necessary to know which residence is matched to which workplace, as they are all matched to each other for potential trips.

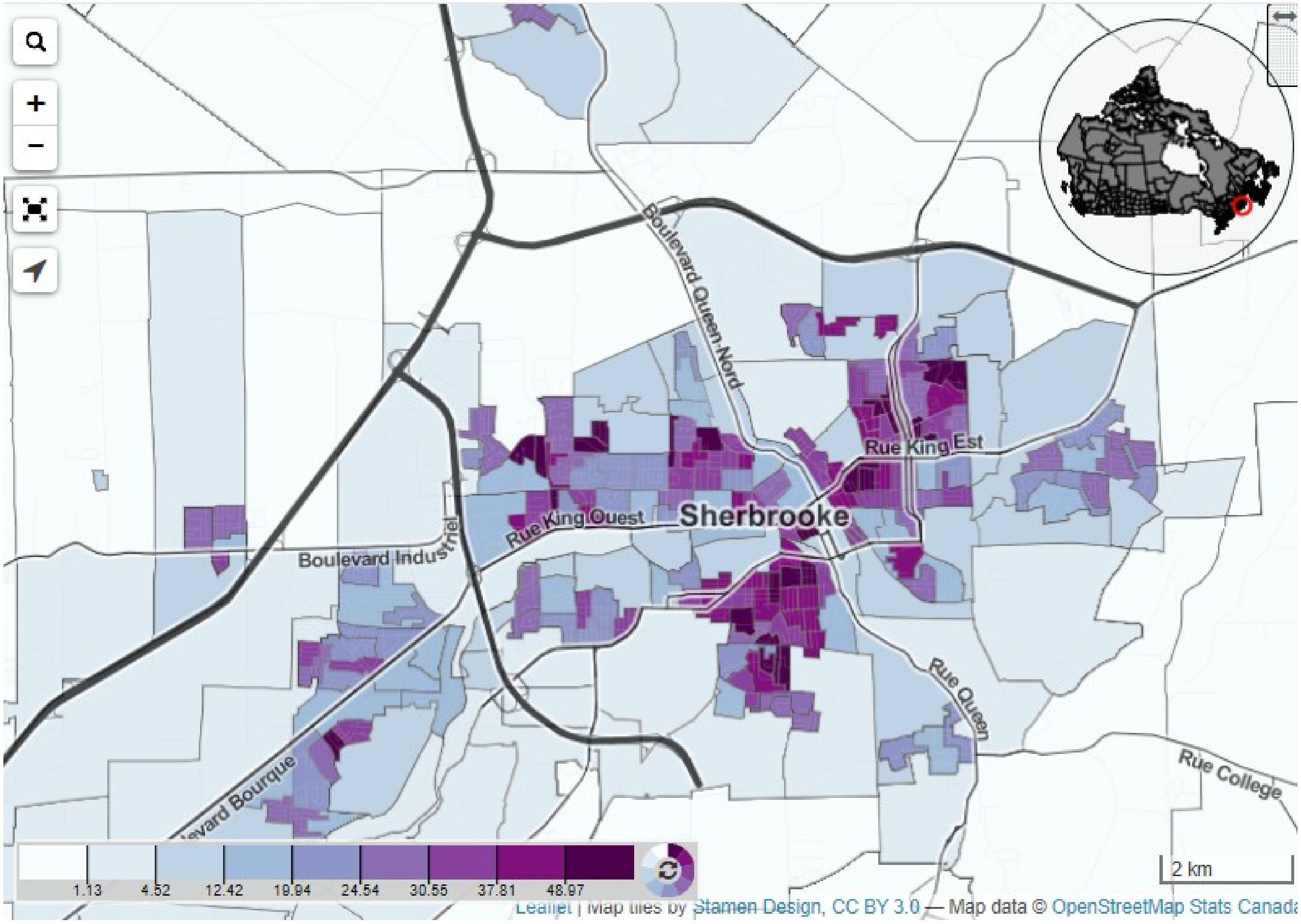

Figure 3: Population density [2011 Census] for the majority of the population spread of Sherbrooke, QC (visualized on censusmapper.ca). Values are given in people per hectare.

Origin-Destination Municipal Survey

The origin-destination ("OD") **survey** of a representative portion of the population reports the **locations** of both **residence** and **workplace** of a surveyed person, along with **mode** of transportation and a **weight** representing the multiplicity of this trip.

In an OD (or "one-to-one") methodology, every residence is matched to exactly one workplace, which represents sensitive information for the resident, and the survey data is **not publicly available**.

Road Network

The **road network** is provided by the free and open crowd-sourced OSM project, which provides the **geometry** of the roads, their **connectivity** to each other (graph topology), and informative **tags** (road size, speed limit, number of lanes, etc.) that can be used to evaluate their safety rating for biking.
Most roads and paths in the OSM database are each assigned a *highway* tag, which can take many values, and described the type of road, and its ranking in the road network hierarchy; some most

common values are: *motorway, motorway_link, trunk, trunk_link, primary, primary_link, secondary, tertiary, unclassified, road, residential, living_street, service, track, pedestrian, bus_guideway, path, cycleway, footway, bridleway, byway, steps, construction, ferry*. Additionally, each road can have many optional tags that further describe its properties. Some of the most pertinent to cycling are given in Table 2.

Road information	**OSM tag name(s)**	**Possible values**
Road has a cycling lane	*cycleway,* or *cycleway:left,* or *cycleway:right*	*lane, track, opposite_lane, opposite_track, opposite, shared, segregated, shared_lane, share_busway, opposite_share_busway.*
Buffered bike lane	*cycleway:buffer*	*yes, right, left, both*
Cycling status (useful for overriding default cycling behaviour on a *highway* type)	*bicycle*	*yes, no, designated, permissive, dismount, private, destination, use_sidepath*
Road shoulder	*shoulder:access:bicycle* or *paved_shoulder*	*yes, no*
Motor vehicle speed limit	*maxspeed*	value in kph or *national*
One way traffic or cycling	*oneway* or *oneway:bicycle*	*yes, no*

Table 2: A list of the road tags most pertinent to cycling in the OSM road network database.

For example, a single road might be described as:

highway	*residential*
maxspeed	40
cycleway	*lane*

This corresponds to a residential road with a 40 kph speed limit, and having a painted cycling lane (without a physical barrier – as opposed to a *track).*

Together with the type of *highway*, these tags can be used to evaluate the properties of a road, most importantly a safety rating, as has been done in several projects, most notably for the LTS rating.

Road Characteristics Formula

The LTS metric has been **implemented** in software for evaluating roads/paths according to **OpenStreetMap (OSM)** tags. At least three implementations exist:
1. *BikeOttawa.org* has implemented the most detailed version of LTS (about 50 rules).
2. The *Conveyal R5* project also implements a simpler version of the 4 levels of LTS (about 10 rules).
3. The *Bike Network Analysis* project (by *PeopleForBikes.org)* only distinguishes between low (LTS1 and 2), and high (LTS3 and 4). The rationale is that only LTS1 and LTS2 rated roads are cyclable. However, we found that this is too restrictive and that such a limitation results in large discrepancies between predicted (network analysis) and actual (survey mode share) cycling behaviour.

We use the first implementation for evaluating LTS based on OSM tags. Roads and paths can be visualized in Figure 4 according to the LTS rating, with the additional road type "pedestrian path" where a cyclist is very safe but must dismount. The proportion of each road type is shown in Table 3. The formulae for evaluating LTS ratings can be found in the Appendix.

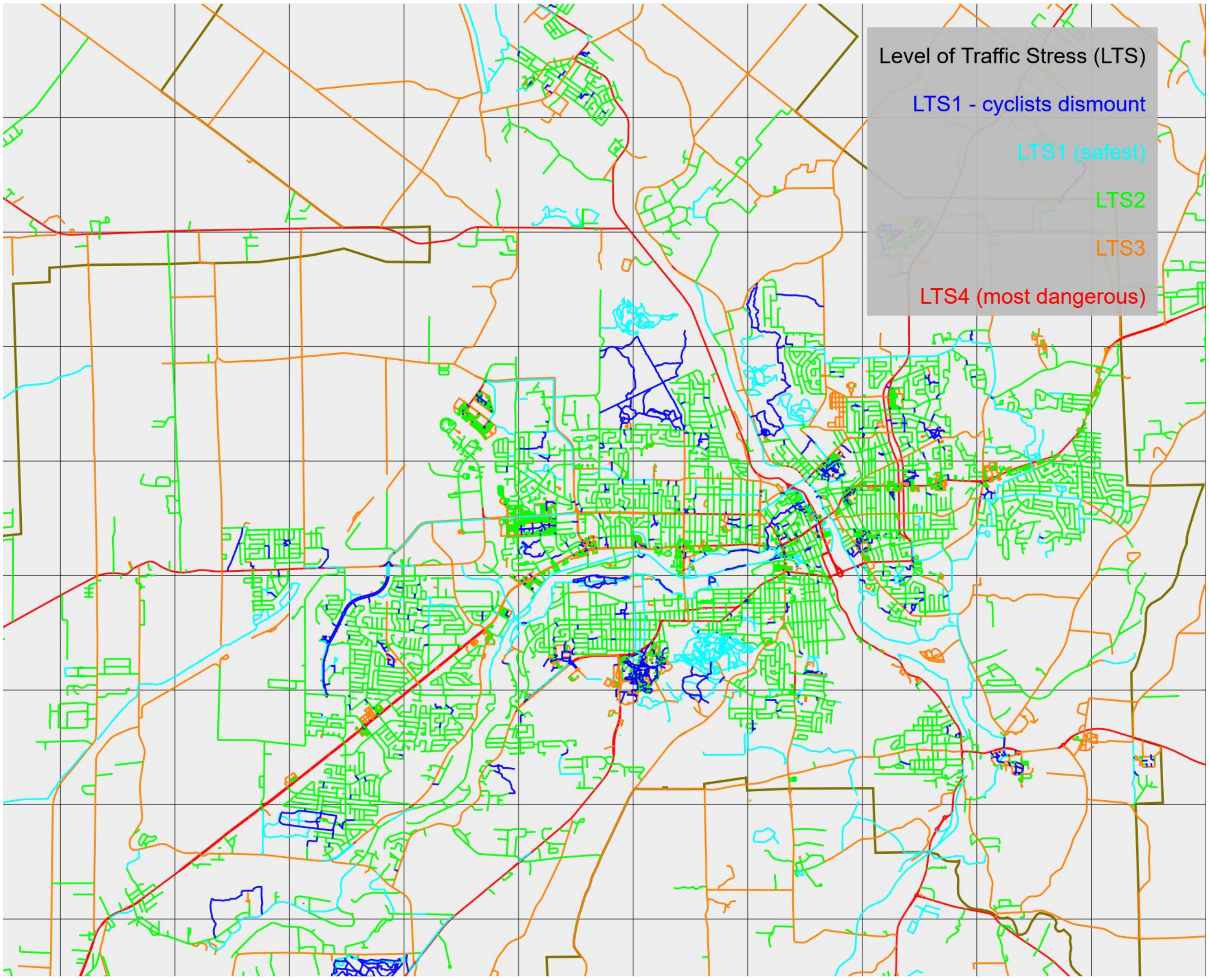

Figure 4: LTS road ratings implementation in Sherbrooke.

Modelling special and poor surface conditions is another consideration. A detailed model is given in the OSRM project, where a maximum speed is given for different road surfaces, irrespective of the road's safety rating. Thus the speed of cycling is given as the **minimum** of the one allowed by the LTS rating, and that allowed by the road condition. A table of possible surfaces and conditions is given in the Appendix, alongside the maximum speeds.

Road type	**Total km**	**Percentage**
pedestrian-only	155	3.61%
LTS1	604	14.08%
LTS2	1501	35.00%
LTS3	1499	34.95%
LTS4	529	12.34%

Table 3: Distribution of LTS road types in Sherbrooke and surrounding rural area.

Routing Engine

A routing engine is a piece of software for finding routes in a road network. The software receives:

1. a road network with tagged properties for each road,
2. a cyclist profile that interprets a road's properties into a measure (in our case, speed) for the cyclist,
3. an origin point,
4. a destination point.

The routing engine produces a route across the road network that minimizes some metric (in our case, travel time), and outputs travel statistics (in our case, the travel time is the statistic of interest). There are several routing engines available that are both free and open-source; all of them operate on the OpenStreetMap road network. The two criteria of selection for this work are:

1. Speed of execution: number of routes per second,
2. Configurability for a cyclist profile.

It should be noted the computational time for finding a route depends both on the route distance and the size of the city graph. An example route found via a routing engine is shown in Figure 5.

The choice of routing engine does not significantly affect results, as long as the road formula is encoded in an identical way. What is most affected is the time duration and memory requirements of the simulation, which will vary widely among the engines.

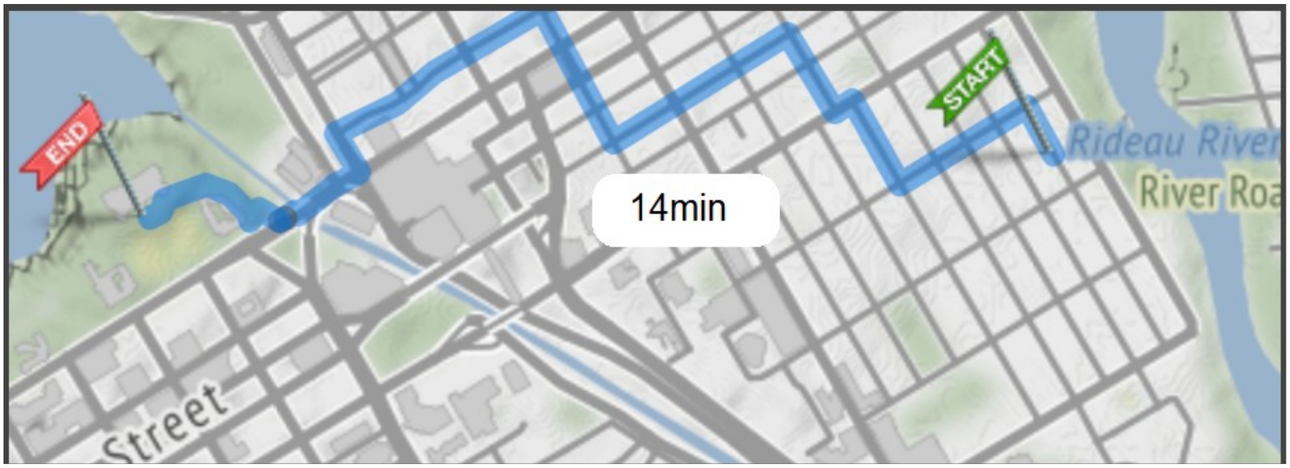

Figure 5: Example route found between two points using the OpenTripPlanner *routing engine, and corresponding trip duration.*

Computational Time Estimation

Considering a medium-size city, between 100,000 and 2,000,000 people, let us examine the speed required to perform simulations in reasonable time.

Our quantization method results in the order of one residential point per 10 people, while the number of workplaces is of the order of 1 per 100 people. Thus the number of routes to be calculated is approximately: 2 x $(\text{population})^2$ /1000, given that two routes (one for each profile) need to be calculated for each trip. Thus, for a city of 1,000,000 people, we need to route of the order of 2 billion routes in R-W simulations. In this case, we need a routing engine that can find over 23,000 routes per second in order to complete the simulation within one day. Few routing engines can achieve this speed.

For example, we have tested the *OpenTripPlanner* and obtained about 10 routes per second in our configuration, which is far too slow for R-W simulations. A related project, called *Conveyal R5* is based on the same code base, and may be a good candidate for such work, as it may have been optimized for speed – we have not tested it, however.

The ***Open-Source Routing Machine*** **(*OSRM*)** is specifically designed with speed in mind, and advertises routing across a continent in "milliseconds", as confirmed by [Ramm 2017]. The *OSRM* engine uses a pre-computation on the network graph that take some initial time once for a given map, but then greatly accelerates searching individual routes, an approach that is thus optimized for routing large numbers of routes. *OSRM* is written in the *C++* programming language (with speed in mind), and is configurable in the *Lua* scripting language (for configuring the profile). *OSRM* proved faster than five other routing engines (*Graphhopper*, *Mapzen Valhalla, Routino*, *Itinero*, *BRouter)* in a country-wide (Germany) set of tests [Ramm 2017], providing routing in a few milliseconds for routes hundreds of km long. For *OSRM*, it is expected that scaling down the routing requests to a single city, and proportionally reducing the distance also, will reduce the required time at least by a factor of the reduction in map size. Considering Germany, a country of about 80 million people vs. a city of about 1 million, we expect a reduction of a factor of at least 80 in speed over average simulation times of below 5ms – we can thus expect at least 16,000 routes per second with the OSRM – almost enough for completing an RW study in a day (this is our worst-case estimate).

Other active open-source routing engines include *CycleStreets.net* and *pgRouting*.

In this project, we designed our own routing engine, and were able to achieve in the range of hundreds of thousands of routes per second in the project's simulations, thus completing the R-W simulations inside a few hours on a regular personal computer. For development, we recommend using either *OSRM*, or possibly *Conveyal R5*, as the routing engine for performing RW simulations in reasonable time.

IV – Results and Discussion

Bikeability is measured as **delay percentage**, i.e., higher delay corresponds to **worse bikeability**. It can be measured either at the **residence location:** where the bikeability at a given point of the map tells how a resident at that location experiences biking to workplaces; or at the **workplace location**: where bikeability at a given point gives how good is biking from a workplace at that point towards residences.

Correlation between One-to-one and All-to-all Methodologies

We propose two methods for assigning residences to workplaces for computing trips, each based on different geographical data: the one-to-one methodology (using an OD survey), and the all-to-all methodology (using residence and workplace densities). The results from both methodologies are shown in Figure 6. We see an overall similarity between the two metrics. This being said, the one-to-one methodology shows a lot more spatial discontinuity.

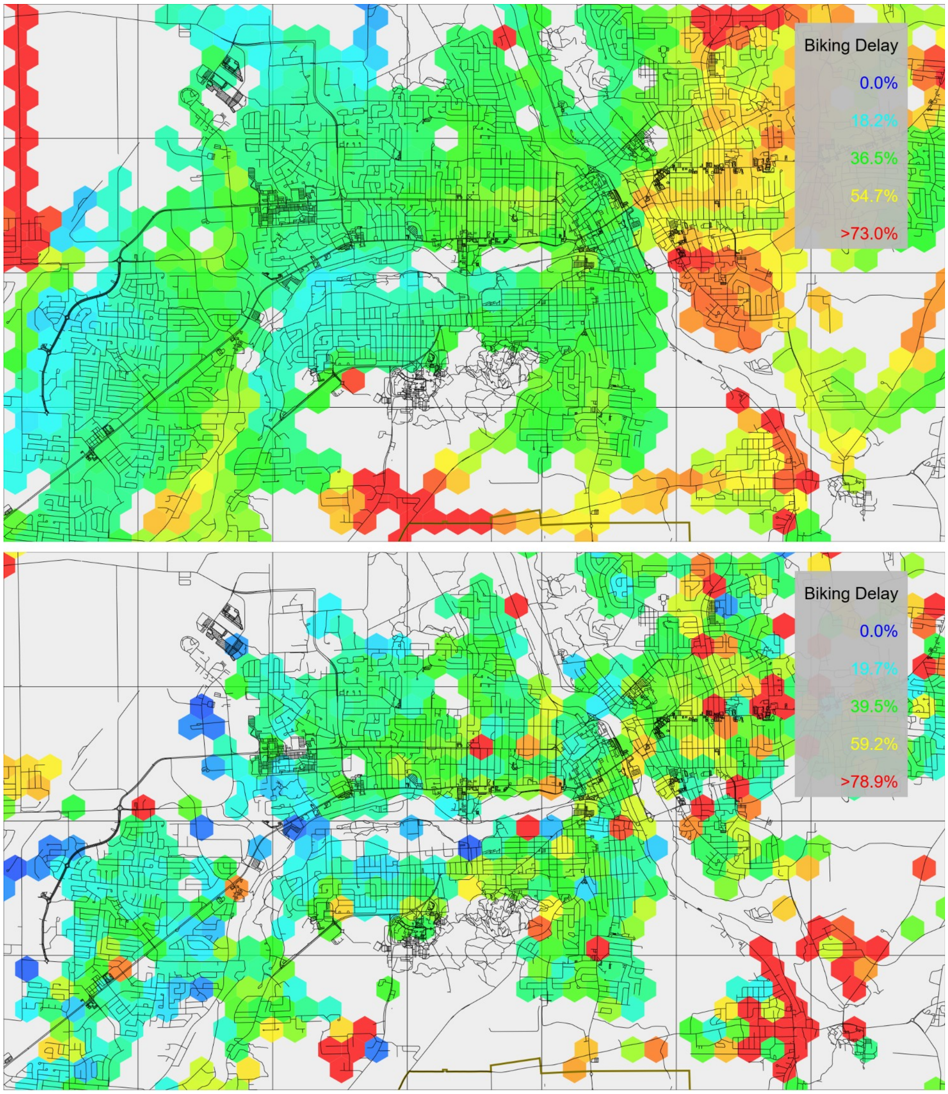

Figure 6: Comparison of Bikeability at Residences in Sherbrooke using all-to-all (top) and one-to-one (bottom) methodologies.

The two metrics are highly-correlated with each other, as summarized in Table 4: an estimated **74%** correlation in Region of Peel, and **67%** in Sherbrooke.

Region and Perspective	Correlation Coefficient	95% Confidence Interval on Corr. Coef.	99% Confidence Interval on Corr. Coef.
Sherbrooke - Residences	0.68	0.64	0.62
Sherbrooke - Workplaces	0.66	0.57	0.54
Region of Peel – Residences	0.73	0.68	0.66
Region of Peel - Workplaces	0.75	0.67	0.65

Table 4: Correlation analysis between one-to-one and all-to-all methodologies.

Correlation between Bikeability Metric and Bike Modes Share

The bikeability metric developed in this work is a function of both the road infrastructure and the building locations.

The Sherbrooke O-D survey is too small to obtain a meaningful estimation of the bike mode share for most of the city's geography. On the other hand, the Region of Peel O-D survey contains more than 134,000 entries, 745 of which represent trips by bike; this O-D survey does not give exact locations – rather it divides the geography into land parcels, and indicates parcels of origin and of destination. By looking at the origin parcels for trips, we can count what proportion of trips begin as cycling trips in a given residential area, obtaining an estimate of the **bike mode share** in a given land parcel. We expect that locations with a lower bike mode share to also experience higher biking delay, thus we expect a **negative correlation** between the two metrics, as can indeed be seen in Figure 7.

Based on 4391 values of the bikeability metric, when compared to the bike mode share The sample correlation coefficient is **-0.17**. The confidence intervals on this value are -0.14 with 95% confidence and -0.13 with 99% confidence. Thus, we are 99% certain that there is at least a 13% negative correlation between the bike mode share from the Region of Peel O-D survey and the biking delay devised in this work. In particular, from the scatterplot in Figure 7, we observe that very high biking delay is strongly associated with low (<1%) bike mode share.

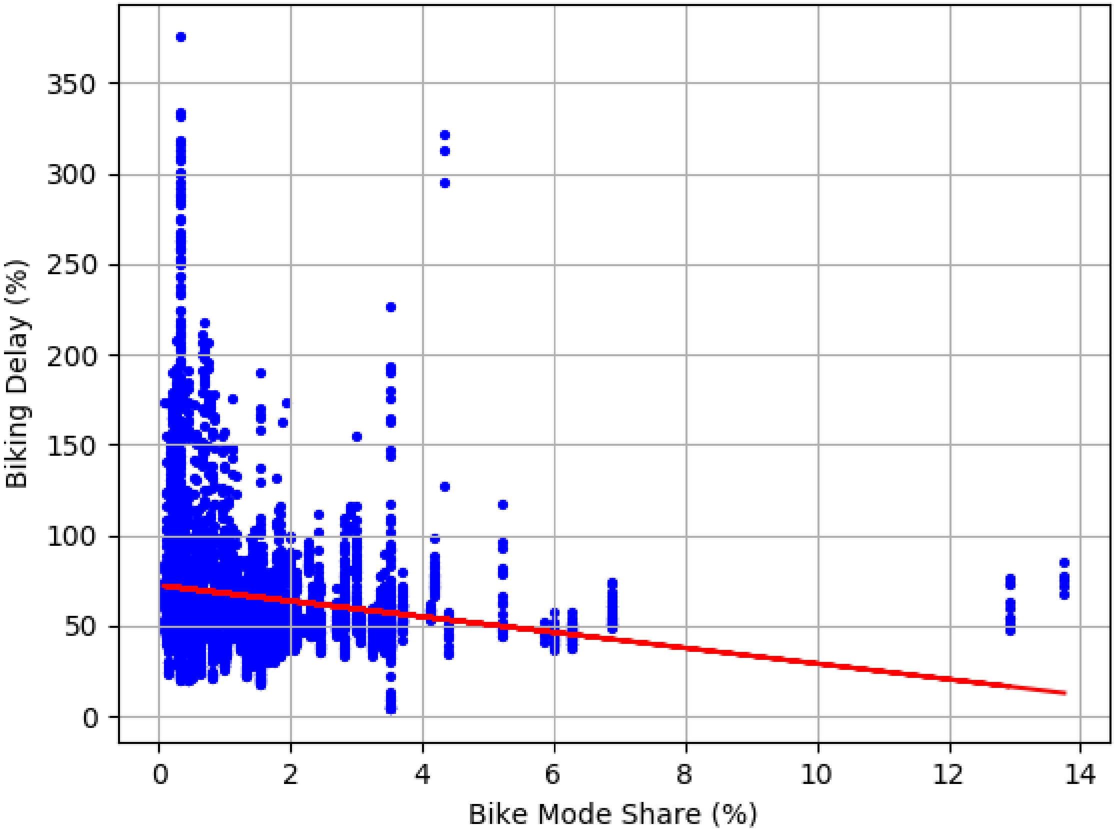

Figure 7: Scatterplot and linear regression fit showing negative correlation between bike mode share and biking

Sherbrooke Simulations

One-to-one study: Out of 6508 O-D pairs, 3921 (about 60%) are sufficiently close for an average cyclist to commute within 30 min according to our model. This value is broken down geographically by region (hexagonal cell) in the figures, both from the point of view of residences and from the point of view of workplaces.

All-to-All study: 727 workplace locations and 48486 residential points are considered in this simulation, resulting in over 32 million routes to compute. Again, the values are grouped and averaged geographically by hexagonal cells and can be viewed either from the point of view of residences or workplaces.

The results are also contained within an *ESRI Shapefile* (.shp) containing the data for all four figures, in their respective columns: RES_OD, WRK_OD, RES_RW, WRK_RW. The shapefile is composed of a hexagonal grid (200 m side length), with the bikeability values associated with each cell.

The urban region is more amenable to precise examination. Both the workplace and residence density datasets are much larger, and show a detailed and spatially varied picture of the city. An example is shown in Figure 8.

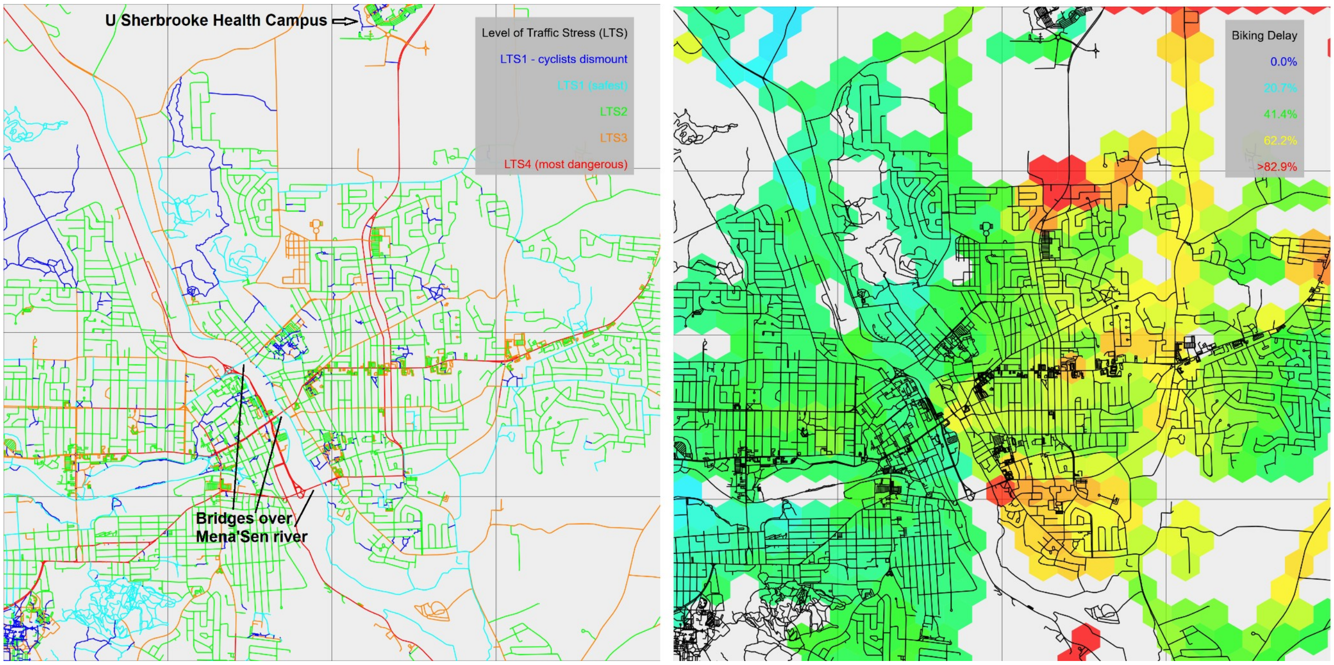

Figure 8: Bikeability from the point of view of residences (right) versus road LTS rating (left) in the east part of downtown Sherbrooke

The populated area of the municipality of Sherbrooke shows a series of contrasting regions. The most bikeable region is the western part, whereas we see several poorly-bikeable regions on the east bank of the Mena'sen river. The central and south-most bridge over the river are indeed rated LTS 4, and represent several minutes of delay as the cyclist has to effectively dismount and walk the bike, while avoiding pedestrians. Only the northmost bridge has a cycling path (LTS 1), which favours the neighbourhood adjacent to it. The situation is not quite symmetrical on both banks – the east side is smaller, and therefore more isolated from jobs and services than the larger west side of the city.

It is also interesting to observe the situation of travel between an urban and a rural region. On the north end of the eastern part of the city, we observe a cluster of poor bikeability, just south of the University of Sherbrooke Health Campus. Indeed, the only routes connecting the city to the campus are a direct LTS4 road, and a side LTS3 road, both inducing significant delay in our model. This same part of this city is also poorly-connected to the city centre – as such, in all directions, most travel to workplaces by bike incurs significant delay, resulting in a poor, but potentially very improvable situation.

In the rural zones, it is difficult to approximate the locations of residents, as it is not certain on which roads they reside. Because the Dissemination Areas are designed to cover approximately equal population groups (with counts in the hundreds), these areas are very large in rural regions, and therefore the error in approximating resident location can also be very large (hundreds of meters).

Looking at bikeability from the perspective of workplaces (shown in Figure 9), we generally observe poor bikeability in reaching the outer workplaces, which are indeed often connected only via roads that are designed for the car (and often rated LTS 3 or 4).

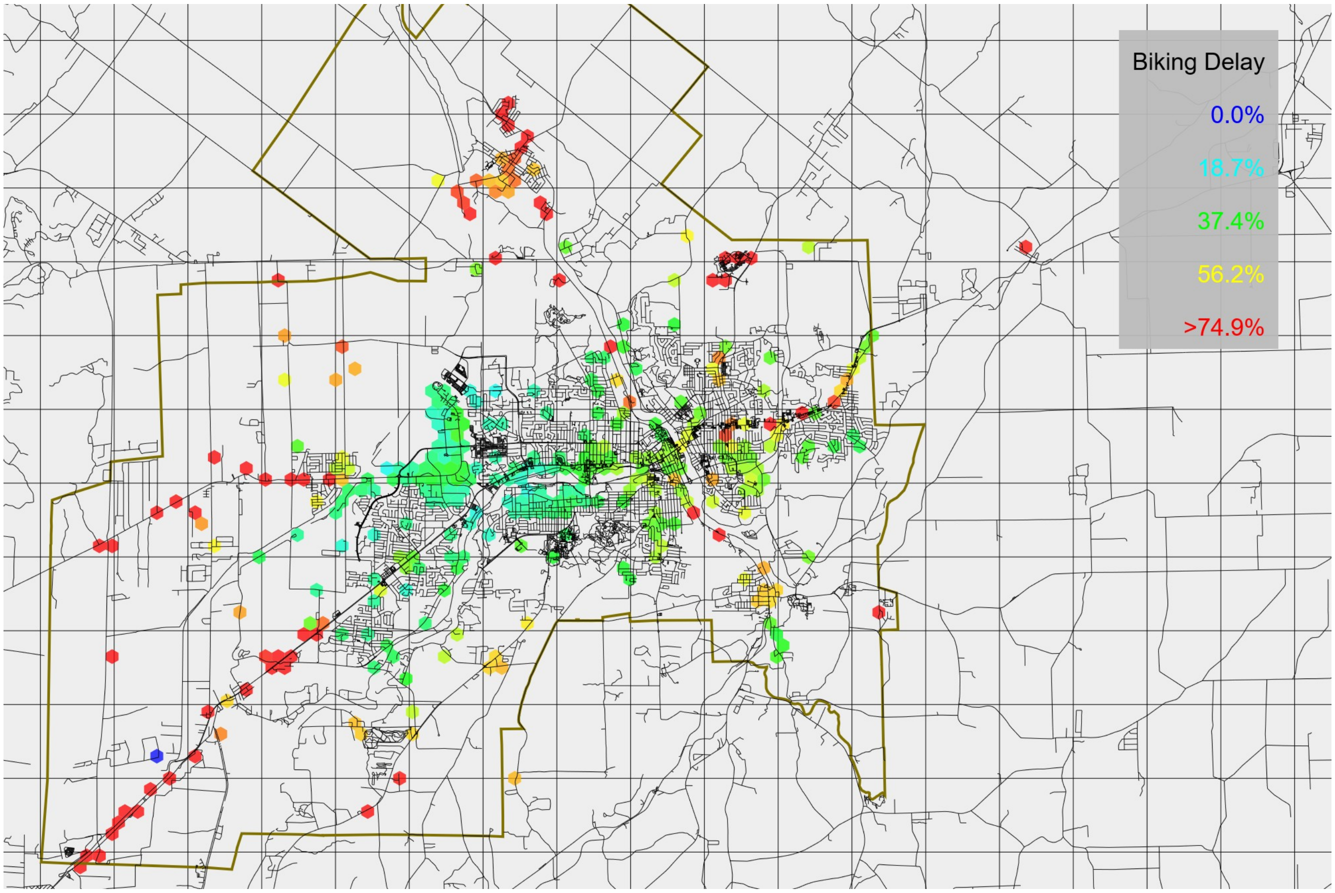

Figure 9: Bikeability from the point of view of workplaces in Sherbrooke

Region of Peel Simulations

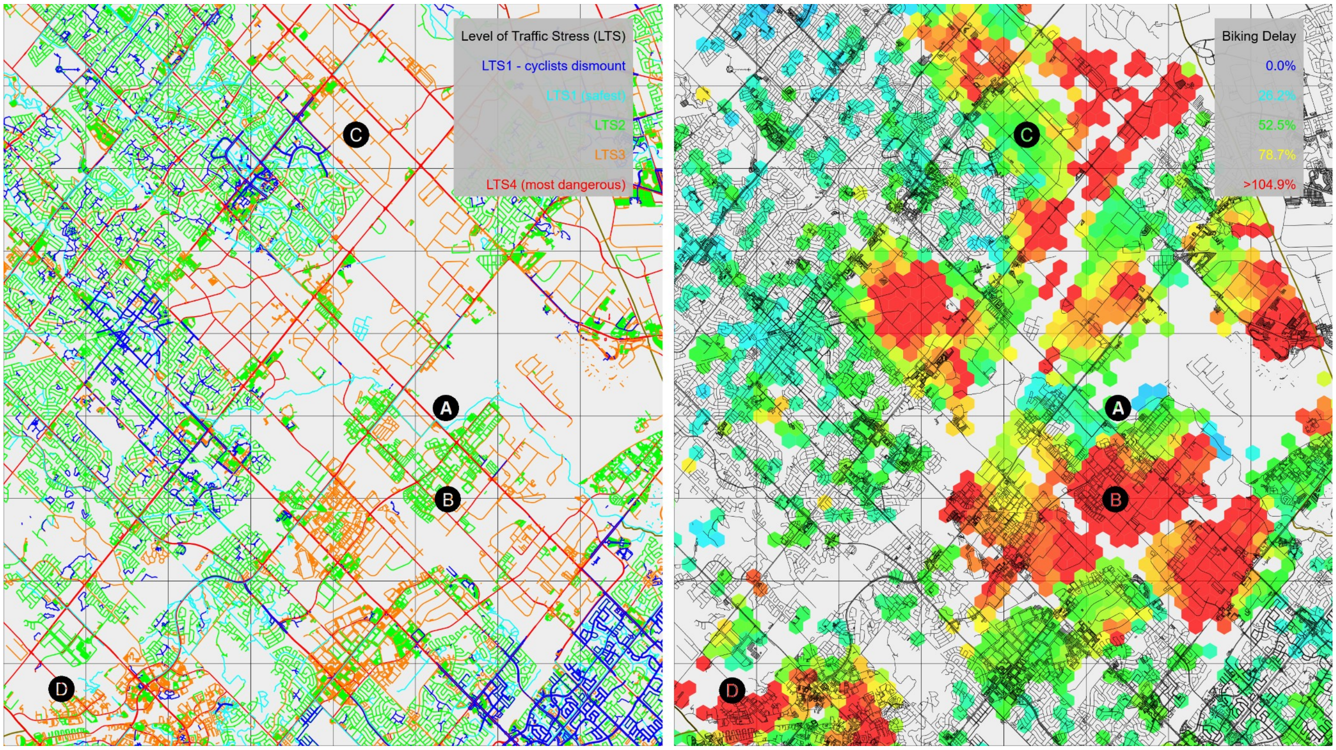

Figure 10: Bikeability at workplaces (right) and the corresponding roads with their LTS ratings (left) in part of the Region of Peel.

Figure 10 illustrates how bikeability measured at workplaces relates to the LTS rating of the surrounding roads. Several locations were marked as examples of different bikeability situations due to different surrounding road types and urban layouts:

A: The work area is well connected via an LTS1 path to residential areas within a few km, resulting in good bikeability.

B: Bikeability quickly degrades from region **A** moving south, where all major arteries are LTS3 and LTS4. The cyclist has no options to travel to most of the poor bikeability area around **B** by any LTS1 or LTS2 road.

C: Although only connected via LTS3 roads, this moderate bikeability region is still considered accessible in our model, being very close to a residential area which contains good bikeable LTS1 arteries connecting it to even more residences.

D: This work area is in a very poor cycling situation: all residential areas in the vicinity can only be reached by cycling on LTS4 roads. Also, this region has no good connection to the work area in the south-east, where bikeability to work is much better (this results in a discontinuity of the metric).

Overall, this scenario shows many situations where the outer regions of industrial and commercial regions are often accessible by bike, but cycling becomes rather harder once one enters the region, resulting in poor bikeability closer to the centres. This suggests that cycling infrastructure may need to be built deeper into the industrial and commercial zones to make biking a viable commute mode.

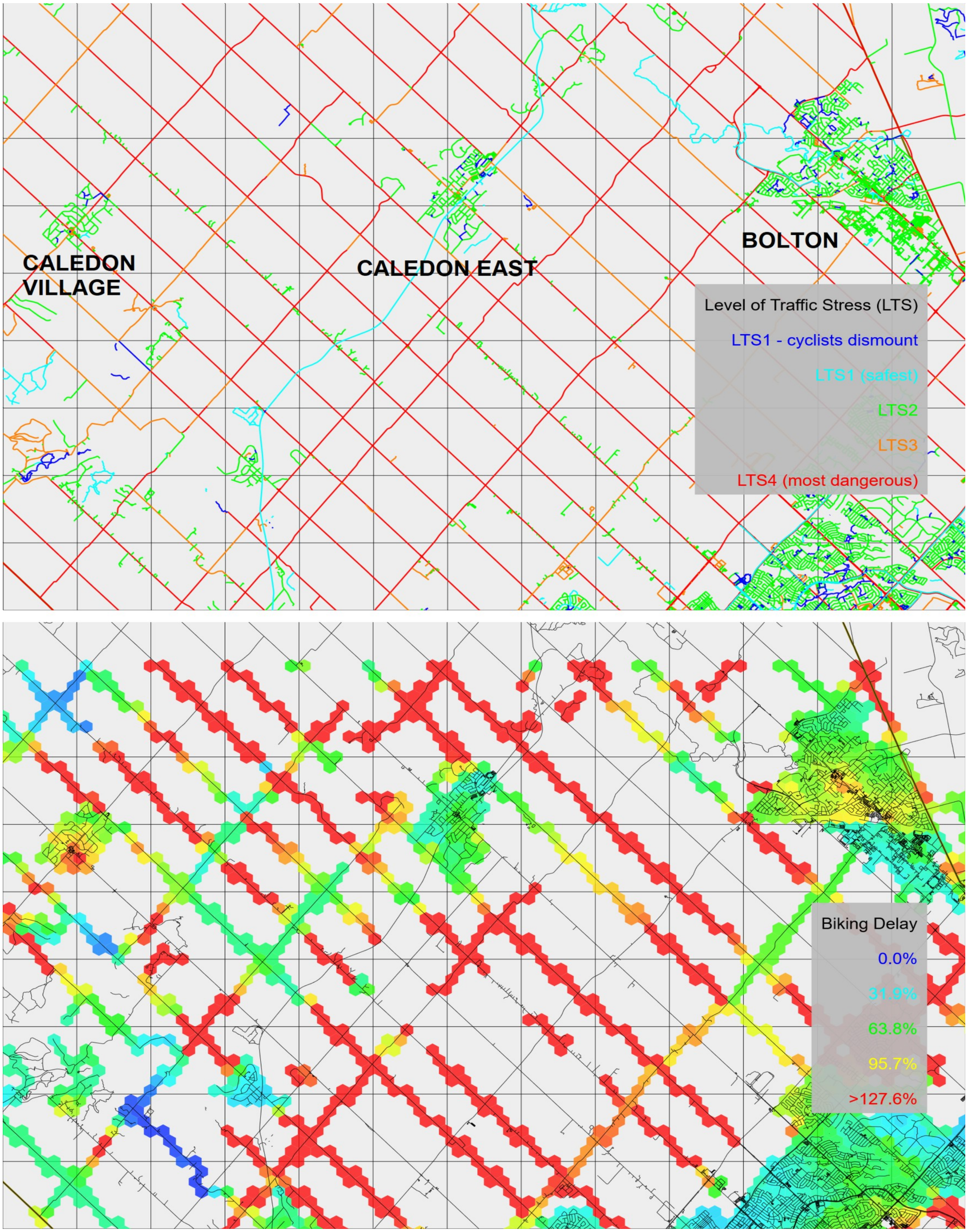

Figure 11: Road types (top) and bikeability at residences (bottom) in part of the Region of Peel (mainly in Caledon).

Figure 11 shows a significant part of the rural area of the Region of Peel, and maps out the bikeability metric as measured at residences.

First of all, we observe that the rural road grid is mainly composed of LTS4, and some LTS3 roads, rending biking very difficult. We generally observe better bikeability in the towns themselves:

Caledon Village suffers from geographical isolation, and is only connected to the outside via LTS4 type roads. To the extent that it has good bikeability, it is to workplaces within its small borders. In the north-east part of the town, we observe some pedestrian paths (LTS1+dismount) which nevertheless give a valuable detour around the LTS4 arterial connection, showing, in miniature, the potential benefits even of such small improvements.

Caledon East benefits from an LTS1 bike path running through it. Notably, this gives good bike access to workplaces (not shown) located a few km north-east of the town.

Bolton: Because this map does not give us information about workplace locations, we observe that it is not obvious how to explain the much better bikeability from residences in the south of this town. In fact, the dataset indicates that most workplaces are located in this southern part of the town. We can observe a rift in the road network between this part and the rest of the town, which is only bridged by LTS4 roads, making access from northern residences to southern workplaces difficult.

Summary

We found a very high correlation between the two approaches of one-to-one and all-to-all bike routing. There is also significant correlation between our bikeability metric and the bike mode share in a major urban area. Indeed, we found that poor bikeability in particular locations can largely be explained by poor connectivity via bike-friendly roads – indeed, this is what the biking delay is designed to measure. Poor bikeability at workplaces is often due to workplaces that are geographically isolated and mainly accessible by cars, or locations inside industrial parks, where there might be less provision for cycling.

The contrast between urban and rural work locations presents a conundrum of whether to first improve bike access to outlying rural work campuses, or to improve infrastructure inside the city core, which already has better, but very non-uniform, bikeability. To a certain extent, this question cannot be answered by an engineering analysis, since it may be reflective of the values that a city wants to prioritize. Nevertheless, our future work in cycling network analysis will hopefully make possible a quantitative comparison of the relative value of various options in cycling infrastructure improvements. Meanwhile, we want to emphasize that making infrastructure improvements is probably most beneficial where a large number of residences becomes linked to a large number of workplaces via a route that can be reasonably completed by a moderate-ability cyclist (as described in the cyclist profile). The bikeability metrics can help identify whether such a condition is achieved.

The urban context presents a variety of scenarios. The best way to view the bikeability metrics is side-by-side with the road quality rating (here, LTS), so that one can see the connectivity of the nearby areas. The bikeability metrics are usually spatially continuous, but not always; discontinuities arise from particular road network situations: usually a poor cycling road next to otherwise good biking conditions. The rural context often has a few concentrated clusters of population, as well as a few workplace clusters. Connecting residential clusters to workplace clusters is a worthwhile endeavour, as long as the trip can be completed within the criteria described in the cyclist profile: notably, adding bike paths may not be of much use if the commute trips are much longer than 9km door-to-door.

V – Conclusion and Future Directions

Because typical trips are expected to be in the range of 5-10 km, and their location is affected by residence, workplace, and road/path location, it is necessary to take a large-scale urban planning view at the network level, on a scale of at least 10 km, and ideally of the whole city. Indeed, recent research in cycling includes an emphasis in cycling network analysis, as well as several open-source projects (and using mostly open data), with the purpose of studying such networks at the level of routes and end-to-end connectivity. Important projects are the Propensity to Cycle Tool (PCT) in the U.K., and the Bike Network Analysis (BNA) project by PeopleForBikes in the U.S., as well as the commercial project WalkScore.com (which includes a BikeScore component), as well as several routing engines with bicycle profiles that can be used to find the fastest end-to-end bike route in a given urban network. Many of these projects are designed to use mainly or exclusively the open and crowd-sourced database OpenStreetMap.org (OSM), which contains the network of roads and paths, each tagged with information that can help quantify their suitability for safe cycling.

The methodology designed in [Szyszkowicz 2018] and refined in this paper uses the Level of Traffic Stress [Mineta Institute 2012] (LTS) standard to measure the safety of individual bike segments – this is found based on the road tags in OSM and a combination of existing software implementations by BikeOttawa.org, from the BNA project, and from the Open Source Routing Machine (OSRM).

Methodologies Devised

The spatial metric we have devised measures of how good bikeability is in a given location **compared to what it could be if cycling infrastructure was improved**. Thus, some locations may have good measured bikeability, yet have access to few locations, simply because of its geographical isolation – such a situation cannot be remedied by improving the infrastructure alone, and is therefore not evaluated negatively in our methodology.

The two methodologies, *one-to-one* (OD) and *all-to-all* (RW), reveal similar overall results about bikeability for most locations. The first methodology requires an O-D survey, which is costly to perform and is the more sensitive dataset, whereas the second methodology only requires the less-sensitive set of locations of workplaces. While it is more accurate to pair up origins and destinations, the OD approach shows a much more thinly sampled set of points on the map. The RW is also predictive of all other possible utilitarian trips one might take, and is appropriate for analyzing access to jobs such as in retail or service, where there may be the possibility of choice of work location.

Feasibility and Challenges

In our developed methodology, **most of the components are freely and openly available online**. What is missing is the **locations of workplaces** (and their relative importance), information that can be obtained or estimated based on datasets held by the City.

Currently, if the number of jobs is not known in a workplace location dataset, we use the area of the building's footprint as a proportional estimate of the number of jobs – this is the case for the Region of Peel simulations. This estimation can be quite inaccurate: in the case of warehouses, it will greatly overestimate the number of jobs, while it will do just the opposite in the case of office towers. It remains the case that this is the most accurate method of estimating job density we were able to find.

Illustrating the results on a map is a challenge, particularly for larger regions. To fully illustrate the bikeability situation of a certain area, one needs to show three layers: the rating of the roads, the bikeability at residences, and the bikeability at workplaces. In fact, population density and workplace density would also be pertinent.

An essential consideration for scaling the methodology is computational time and memory, which is strongly tied to the routing engine used. A city of around one million people is expected to require several billion routes to be calculated, with the corresponding time and memory requirements – such a simulation may still be feasible on a modern personal computer. Larger cities are expected to have quadratically-increasing requirements, and more work and care is required in the software design to be able to scale to large metropolitan areas – this is however inherently possible and is not an absolute limitation.

Future Directions

In this work, we measured bikeability at endpoints: residences and workplaces. It is also possible to measure bikeability flow along all roads [Lowry 2017], in order to identify the most important roads (for cycling) and to plan improvements accordingly:

1. **Analysis of the road network**: up to now, we have observed bikeability from the point of view of the trip endpoints. We can also measure bikeability based on the probable bike traffic on each road segment. We could obtain a map of the road network, with the most important (for cycling) roads highlighted. This would be a next step in obtaining a more accurate picture of where infrastructure interventions should be prioritized.

2. **Speeding-up simulations**: Ongoing software development efforts demonstrate that it should be possible to find millions of routes per second in a medium-sized city. Such technology could enable trying out very many combinations of infrastructure improvements, and making a cost-benefit analysis of both the **most useful infrastructure additions**, and their **prioritization in time** – effectively finding which improvements would have the most benefit first.

3. **Road improvement planning**: Improving the simulation software to be able to **identify** parts of the network that most need improvement, as well as **suggesting** a **prioritization order** in which infrastructure improvements could be made to maximize utility at every step. The goal is to enable the maximum number of average-ability cyclists to have access to the maximum number of safe-enough trips for utilitarian purposes.

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Appendix: Road Rating Implementations Based on OSM Tags

LTS Implementation in Conveyal R5

Pseudocode [blog.conveyal.com/better-measures-of-bike-accessibility-d875ae5ed831]:

```
Does not allow cars: LTS 1
Is a service road: Unknown LTS
Is residential or living street: LTS 1
Has 3 or fewer lanes and max speed 25 mph or less: LTS 2
Has 3 or fewer lanes and unknown max speed: LTS 2
Is tertiary or smaller road:
        Has unknown lanes and max speed 25 mph or less: LTS 2
        Has bike lane: LTS 2
        Otherwise: LTS 3
Is larger than tertiary road
        Has bike lane: LTS 3
        Otherwise: LTS 4
```

Note: tertiary road is one step above residential and living street in the hierarchy of street size. Larger roads are tagged: *secondary, primary,* and *motorway*.

LTS Implementation by BikeOttawa.org

BINARY QUESTIONS:
- Has cycling lane: painted separation.
- Has cycling track: physical barrier
- Is residential street: tagged as *residential* or *living street*
- Has on-street parking
- Has a separating median (*)

NUMERICAL VALUES:
- Biking space width (*)
- MS: speed limit (of motor vehicles)
- PS: perceived speed = MS + 10kph if there is on street parking.
- NL: total number of car lanes (in both directions).

(*) Not implemented, as the data is usually not available in OpenStreetMap

ROADS UNDER CONSTRUCTION:
Are assumed finished and take the rating that the finished road will have.

CYCLING FORBIDDEN is chosen under the following conditions:
- freeway or on-ramp
- *private* road
- *no* cycling
- road under *construction* of unspecified type.

DISMOUNT is chosen under the following conditions:
- Is a *pedestrian*, *footway*, *steps*, or *elevator*.
- *dismount* tag present.

LTS1 is chosen under the following conditions:
- *motor_vehicle* is *no*.
- Has a *cycle_track*.
- *bicycle* is *designated*.
- Is a *cycleway*, *path*, *track*, or *rest_area*.
- Has a cycle *lane*, is a residential street, and PS<=40kph.

LTS4 is chosen under the following conditions:
- *bicycle* on a *forbidden* road is *yes*, *permissive*, or *destination*.
- There is a cycle *lane* and PS > 65kph.
- There is no cycle *lane* and:
    - NL>5   OR
    - NL>3 and MS<=50kph   OR
    - MS>50kph.

LTS3 is chosen under the following conditions:
- if there is a cycling *lane*:
    - NL>2   OR
    - not a residential street   OR
    - MS>50kph;
- if there is no cycling *lane* (i.e., mixed traffic condition):
    - if MS<=50:
        - if it is not a service road OR
        - is not residential OR
        - NL>2.

LTS2 is chosen otherwise.

OSRM *Implementation of Special and Poor Road Conditions*

Condition	**Maximum speed**
If road is *steps*	2 kph
If road is a *parking* lot	10 kph
If road is a *pier*	6 kph
If road *surface* is: cobblestone:flattened, paving_stones, compacted, sett	10 kph
If road *surface* is: cobblestone, unpaved, fine_gravel, gravel, pebblestone, ground, dirt, earth, grass	6 kph
If road *surface* is: mud, sand	3 kph

The resulting travel speed will be set to the **minimum** speed of all applicable conditions, regardless of the LTS rating. These conditions are not very frequent, and mostly concern short road segments.