“Bikeability for Commuting”

Report prepared for Public Health Agency of Canada

by

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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 motor 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 Study	One-to-one bikeability analysis mode, where each residence is routed to exactly one workplace
OSM	OpenStreetMap
OSRM	Open Source Routing Machine – free and open routing engine, optimized for speed.
PCT	Propensity to Cycle Tool – U.K bikeability project
RW Study	All-to-all bikeability analysis mode, where each residence is routed to each workplace

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 location across a city, one has a **very cost-effective** means of improving these many vital socio-economic factors.

While 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 strong participation is usually follows having instituted 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 school and also for other utilitarian trips (shopping, entertainment, community events, etc.) - and thereby reaping the aforementioned important health, wellness, and economic benefits.

Quantifying bikeability is a multifaceted problem, and it is not simple do 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, 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, 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

It is difficult to put a price of health, yet necessary to do so for planning purposes: while it is outside the scope of this work to quantify the health improvement from improved cycling infrastructure, we can begin by making the argument that a **focused and well-planned** improvement to the cycling network can have a significant positive effect on utilitarian cycling frequency.

Biking to work is among the most effective and practical forms of exercise available, and is also extremely efficient in that it doubles as leisure and exercise and also commute time – 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 and school.

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.

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.

It is 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 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.

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 [Lowry 2017, Winters 2016, Lovelace 2017, Aldred 2017].

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.

Active Projects 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, 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 PCT project uses a large-scale national UK origin-destination survey (not available openly), combined with a router 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 given a quantitative indicator of the priority of need of cycling infrastructure improvement, and is the closest project to our methodology.

Both projects 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 even more realism, and to incorporate safety rating into the model, we can break down the cruising speeds as follows:
1. LTS1: Little to no interaction with motor traffic, go at full speed: 18 kph.
2. LTS1 (pedestrian): same safety rating, but cyclist must dismount: 6 kph.
3. LTS2: Moderate interaction with slow traffic (residential streets): 15 kph.
4. LTS3: Faster traffic and/or street parking: cycle carefully: 10 kph.
5. LTS4: Dangerous conditions: 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 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 router will rather choose a detour with lower average LTS. 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 cyclist, where the speed is 18 km/h for any LTS type, except in the dismount and 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). By averaging these results over all routes, one can obtain a bikeability score for a given location.

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".
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 **delay percentage:**

$$\boxed{\mathbf{(t\_avg/\ t\_spr - 1)*100\%}}$$

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)**.

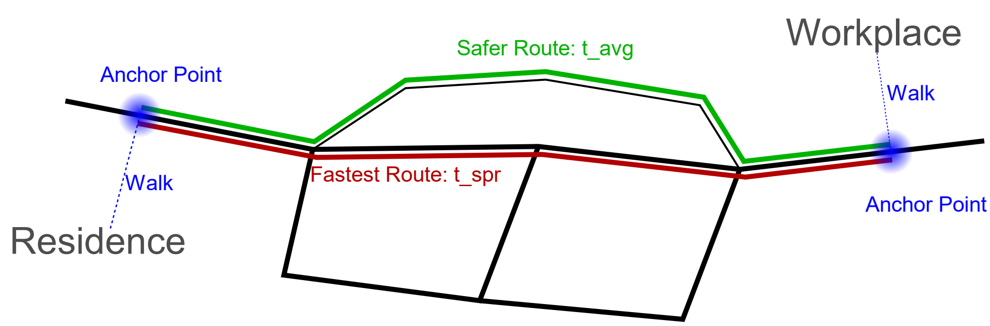

Illustration 1: Two-trip routing methodology

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 this table:

Road type	Super Cyclist (<2% pop.)	Average Cyclist (~60% pop.)
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)	

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 O and D points. 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.

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. The aggregate statistics for the city can also be summarized in a histogram.

Obtaining and Matching Residences to Workplaces

Two main approaches can be taken according to the existing data-sets:
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 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 as proxies 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 Census], i.e., the smallest geographical census subdivision. For each DA, the population could be represented as being concentrated at a point inside its polygon: however, the geometric centroid is not always inside the polygon; furthermore, some DA polygons being much larger than others, and significant inaccuracy may result from reducing a DA to 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.

The locations of workplaces are obtained from a database of buildings [provided by the municipality], 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 in excess of the reach of an average cyclist are ignored. Each such route is weighed by the number of residents times the number of jobs calculated for those locations.

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.

Within this framework, there are several possible options and alternative methodologies.

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 therefore not publicly available.

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* . 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 density is not estimated as accurately in these locations.

The **workplace density** can be obtained either from a database of workplace building polygons (where the number of workers is estimated by the area of the building's footprint) or from a database of employment counts with geo-coded addresses. 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. 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.

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.

Each road and path in the OSM database is 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 the following table:

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*
One way traffic or cycling	*oneway* or *oneway:bicycle*	*yes, no*

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

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 [Mineta Institute, 2012] that was developed 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 poor surfaces for cycling, which are not considered within the LTS framework, but have to be taken into account in their own right.

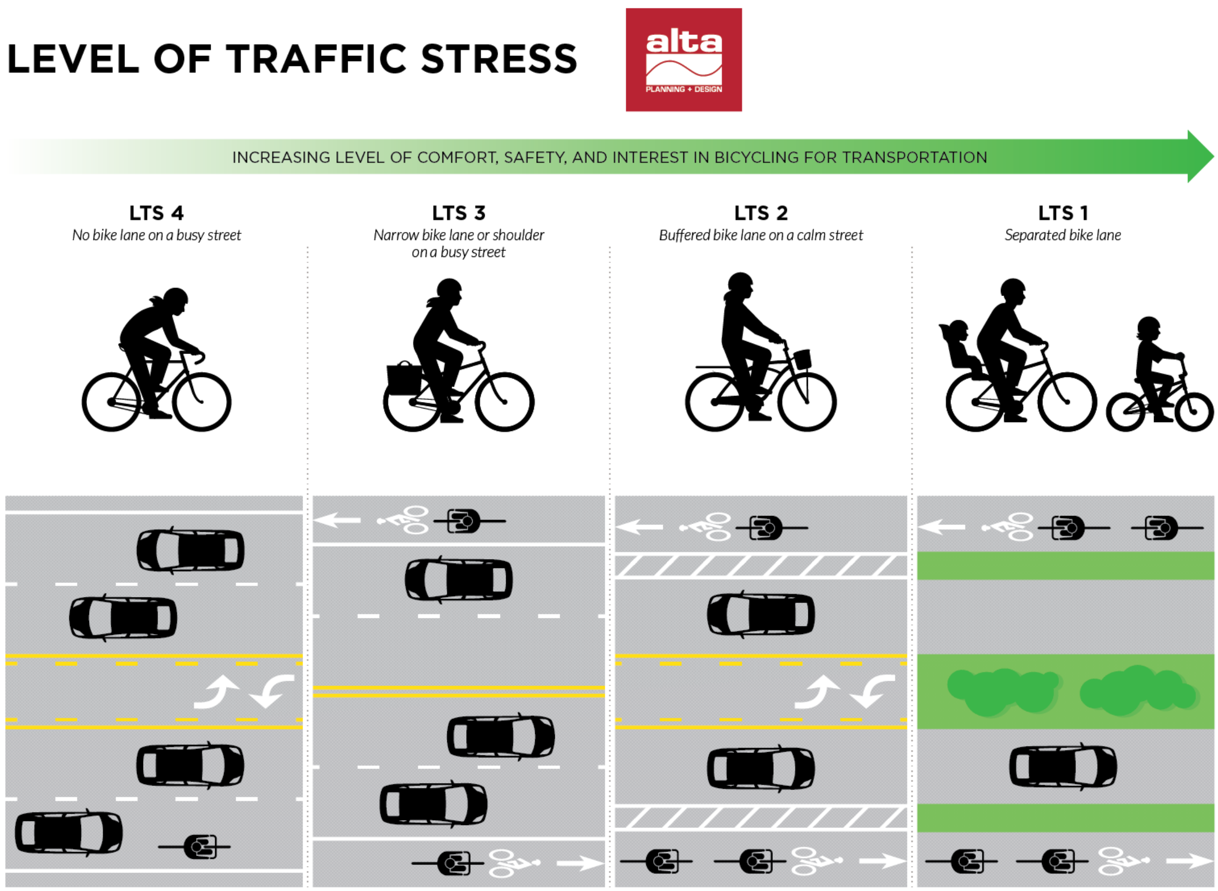

Illustration 2: The four categories of roads in the LTS framework [Alta Planning]

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 1 according to the LTS rating, with the additional road type "pedestrian path" where a cyclist is very safe but must dismount. The formulae for evaluating LTS ratings can be found in the Appendix.

Modelling 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.

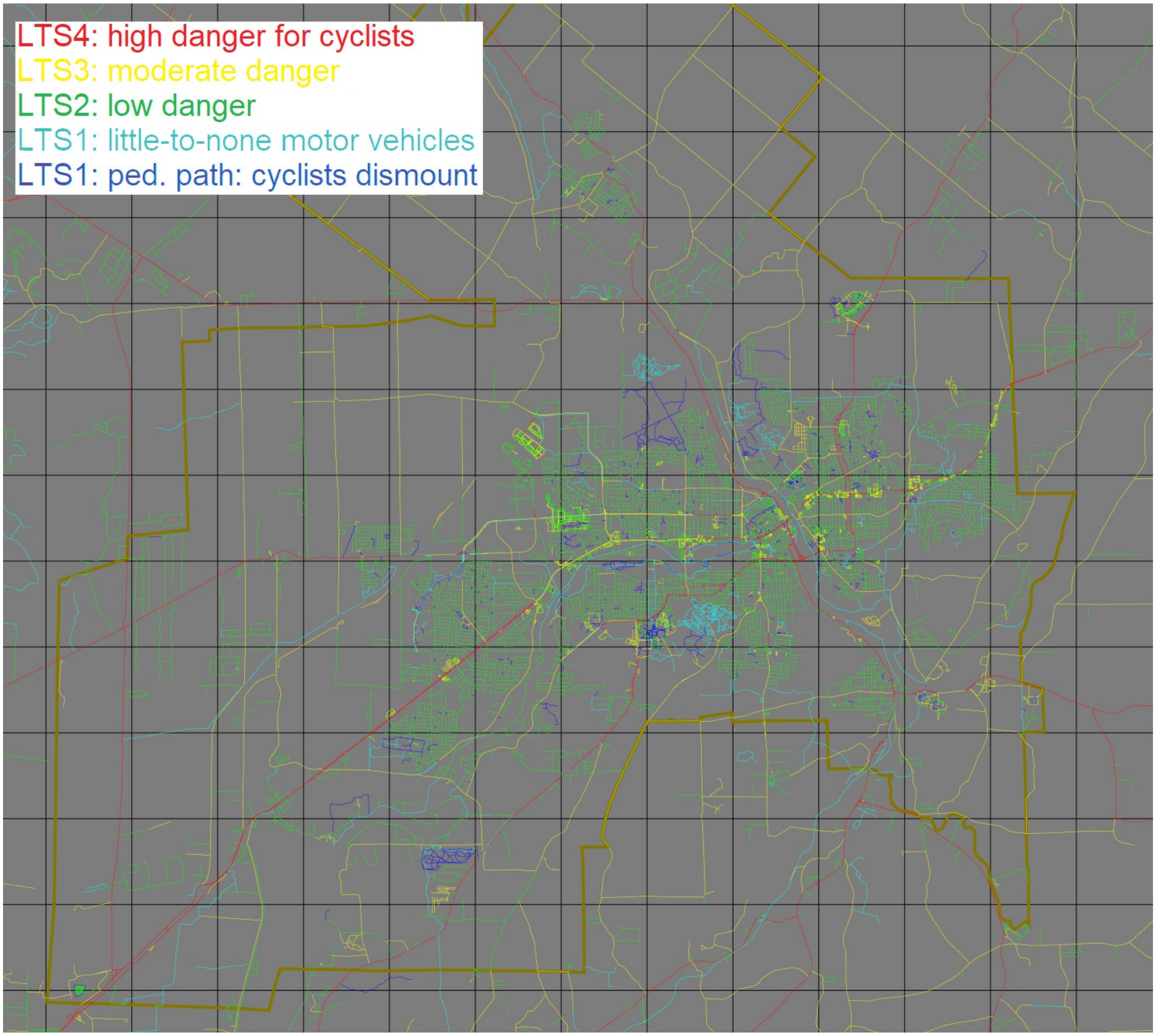

Illustration 3: LTS road ratings implementation in Sherbrooke

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.

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.

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 router that can find over 23,000 routes per second in order to complete the simulation within one day. Few routers 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

Sherbrooke Simulations

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.

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: 458 workplace locations and 48486 residential points are considered in this simulation, resulting in over 22 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.

Interpretation of Results

Urban Regions

The urban region is more amenable to precise analysis. 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 below.

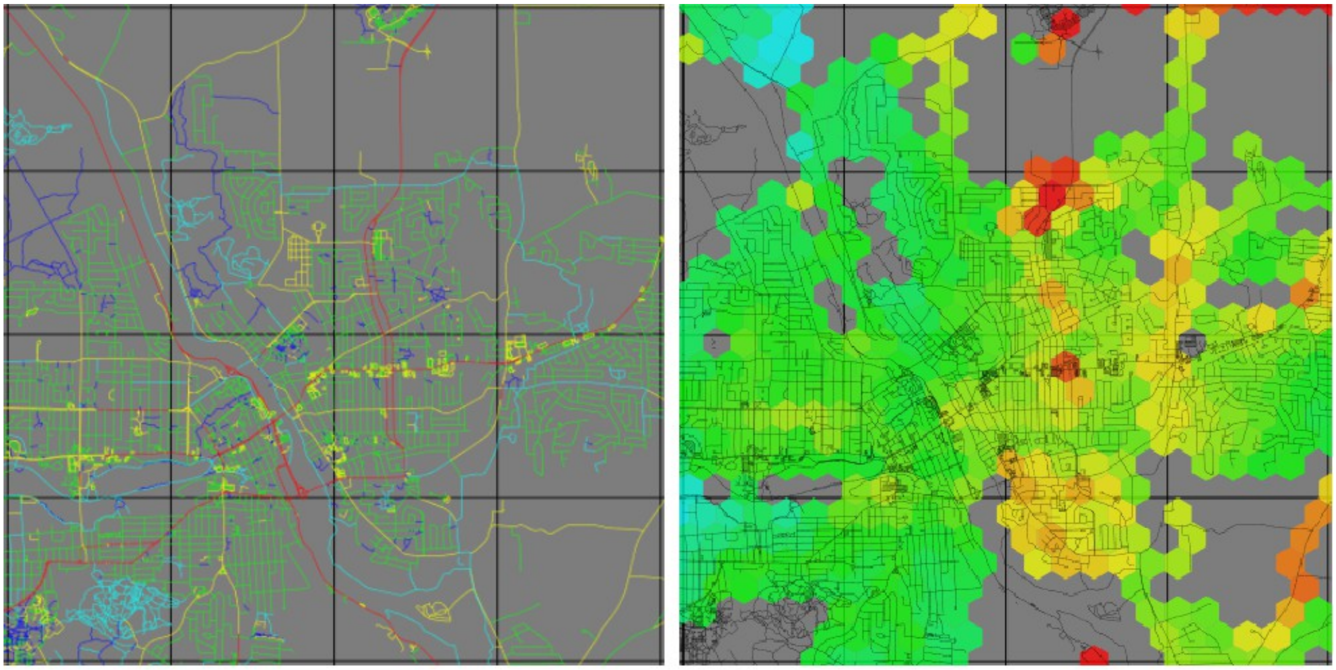

Illustration 4: Bikeability from the point of view of residences (right) versus road LTS rating (left) in the east part of downtown Sherbrooke

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 river Mena'sen. The central and south-most bridge over the river are indeed rated as LTS 4, and represent several minutes of delay as the cyclist has to effectively dismount and walk the bike, while avoiding pedestrians. Only the north-most 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.

Rural Regions

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).

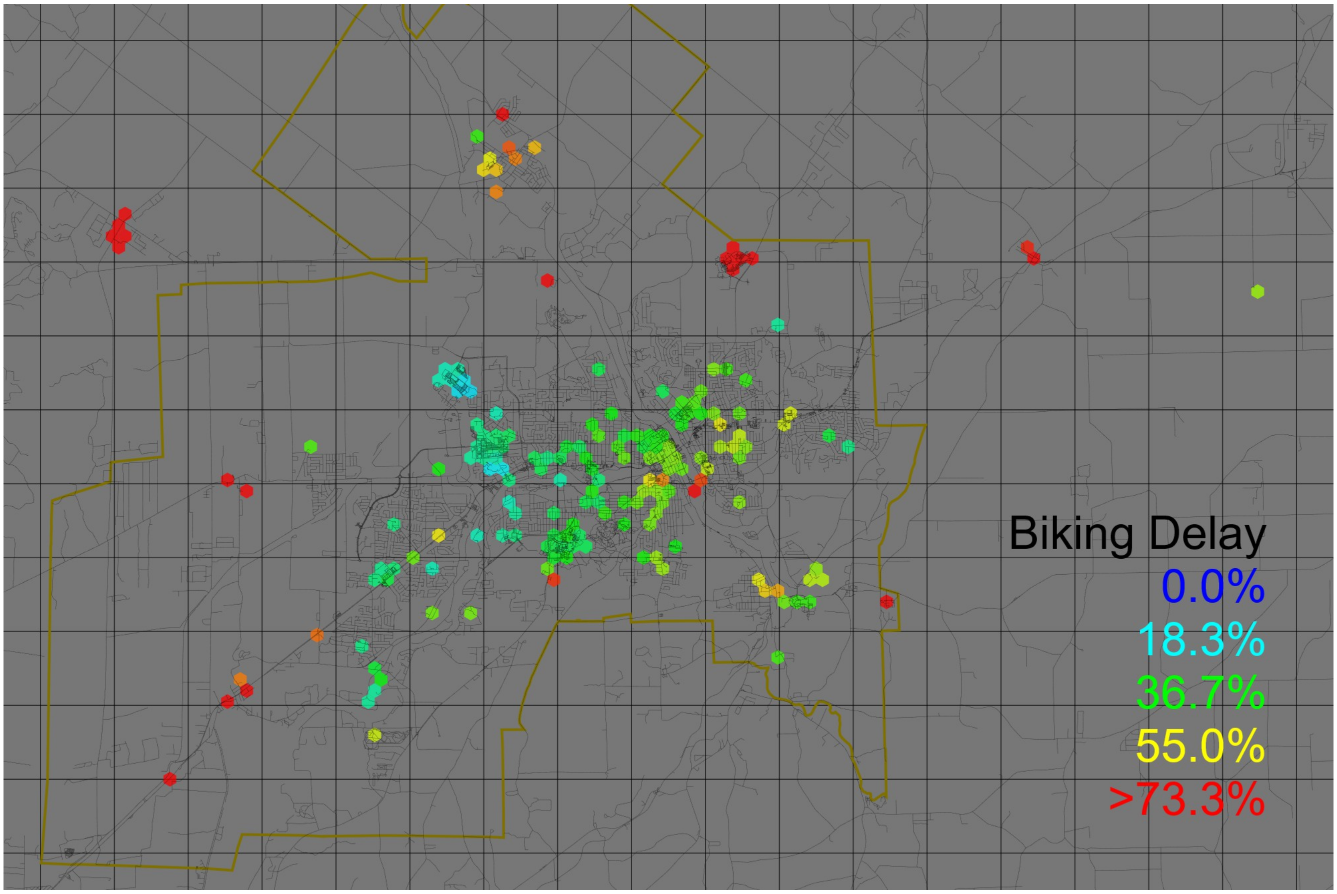

Illustration 5: Bikeability from the point of view of workplaces in Sherbrooke

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

Summary

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.

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 now 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 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

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.

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 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

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 a 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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Time 29:50 – Conclusion: OSRM is the fastest for long (inter-city) routes.

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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' is 'yes','permissive','destination' on a 'forbidden' road.
- 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):
    - if MS<=50:
        - if it is not a service road OR
        - is not residential OR
        - NL>2

LTS2 is chosen otherwise.

OSRM *Implementation of 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. It should be noted that the above conditions are not very frequent, and mostly concern short segments of the network.