Prioritizing Cycling Infrastructure Improvements on Urban Maps using Open Data

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Overview

The purpose of this document is to describe the functioning and results of a **simulation software** developed by us with the goal of identifying **optimal locations for cycling network improvements**, principally physical-barrier-protected bike lanes (i.e., tracks) along mixed-traffic roads. The placement of the proposed bike tracks is based on connecting the maximum number of residents with places of work and thus repents a "**utilitarian**" cycling scenario, representing, most importantly, cycling **commute**, as well as cycling to **shopping** locations, **community** centres, etc.

The methodology of this work is quantitative, and therefore this simulation project combines various existing **quantitative knowledge** about cycling modeling along with various **open data** sources into a coherent whole. The results of these simulations are maps describing cycling at a **per-road level**. In particular, each road segment is rated by its **ease of cycling** (according to safety, material condition, one-way streets, and slope) and, after a **routing simulation** (finding best routes between residences and places of work), the simulator evaluates which road segments are in most need of safety improvements.

Guide to Figures and the Shapefile

The **image maps** associated with this document are very large (of the order of 10000 pixels per side) and must be zoomed in to be useful. It is thus difficult to place a legend on the figure, and we give the interpretation of the maps here:

- The **LTS rating** for each road is colour-coded as follows: blue, green, yellow, and red for LTS levels 1 through 4, respectively; violet for roads with forbidden cycling; grey-light-blue for the dismount condition; blue-green for boat ferry routes; and black for unknown LTS.
- The **priority rating for infrastructure improvement** is given both for a *2D* (no slopes) scenario and a *3D* (with topography) scenario. The road segments chosen for *priority* improvement are rated yellow (least urgent), orange, or red (most critical). The rating is given on a logarithm-base-10 scale; thus each priority range is ten times higher than the previous range.
- The **priority difference rating** (*Priority_Diff*) gives the difference between the 2D and the 3D results, showing in red those roads that only appear prioritized in one of the two maps, whereas roads in yellow are prioritized in both maps, but at different priority levels.

The ***Shapefile*** associated with the report gives all the information from the figures in a GIS-ready format that can be used for further processing. The ***LTS* rating** is given as a value of 1 to 4, whereas a 5 indicates forbidden cycling, 0 indicates a dismount condition, and -1 corresponds to a road segment for which there was not enough information to rate the LTS (this is defaulted to LTS = 3 in our simulations). Now the ***priority* rating** is given as 5, 6, or 7 (highest) for both the 2D and the 3D simulation, whereas lower priority roads are marked with 0.

Various Approaches to Cycling Network Analysis

In order to obtain network-level knowledge of where people are cycling and where infrastructure could be improved, several approaches exist:

- Using the density of **GPS traces** [Broach2012, Garber2019] of biking trips. This approach has several drawbacks: it is **biased** towards the route choices of more avid cyclists as well as those willing to share their travel routes online; it only indicates where cyclists **actually travel**, without suggesting where they **might travel** if cycling infrastructure were improved; there is a **high cost** of obtaining such traces for every city under consideration.
- Using **origin-destination pairs** (obtained via phone interviews) of locations of residence paired with the person's workplace. The cycled route is not known, but an optimal route is derived using a **routing engine**, i.e., a piece of software that finds the best path (according to some preset criteria) between two points on the bikeable network. The disadvantages of this approach are: again, the **high cost and time** required to perform the phone survey for each city, and forcibly a **small sample** with respect to the general population; this approach is only indicative of where people **already cycle**, not of where they could cycle given better infrastructure; there is also the problem of **data privacy**, as the dataset reveals the workplaces of residents at particular locations.
- The "**all-to-all**" approach, where each residence is paired with each workplace in range, and a round-trip route is found for all residence-workplace pairs. The main disadvantage of this approach is the **very large number of trips** to be routed. In [Szyszkowicz2019], we showed results of the all-to-all method correlating well (70%) with those of origin-destination pair routing for two urban areas.

We take this last approach in this work, which has the advantage of being **based solely on publicly available non-private data**. The simulation work requires a **routing engine**, several of which are available for **free** and are **open-source** [Szyszkowicz2018]. We use our own routing engine optimized for simulation speed.

Cycling Network Infrastructure Improvements

Each cycling trip on the **bikeable network** is composed of travel on a **sequence of surfaces**, each falling into one of three categories:

- **On-road cycling-specific infrastructure**, such as painted bike lanes alongside a road with motor traffic. A physical barrier separating from traffic may or may not be present;
- **Mixed-traffic** condition, where the cyclist shares the same road surface with motorized traffic;
- **Off-street** condition, where there are no motor vehicles, and cycling is either allowed (multi-use trails, etc.), or a dismount is legally required.

Cycling **infrastructure improvements** that can potentially increase the ease of cycling along a particular segment of the network are [Buehler2016]:

- Unprotected paint-only **bike lanes;**
- Allowing cycling (**no** need to **dismount**) on pedestrian off-street paths;
- **Bike tracks**, i.e., lanes with a physical barrier separating them from motor traffic, offering the best safety for cycling alongside a street [Schepers2015, Winters2017, Marqués2017, TAC2020].

The purpose of our **simulation** work is to identify the **locations** of such improvements on the city map.

Cyclist Profile

The simulation aims to model commute trips for moderately-capable cyclists [Geller2006]. All trip parameters (cycling safety, slope, travel distance and speed) are converted to a common dimension:

time (total one-way trip duration), with a **minimum of 10 min and maximum of 30 min** for the commute (shorter trips can be considered candidates for walking instead). The top speed is **18 kph**, which results in a maximum commute distance of 9 km. However, the travel speed is reduced according to formulas based on safety rating, slope, and surface material, all resulting in potentially lower maximal trip distances.

Data Sources

The following databases are used as input to our routing software.

Database	Data Type	Purpose
OpenStreetMap (OSM) roads	Connected polyline geometries and associated road properties	Routable street and path network
OSM buildings	Polygons + height information	Approximate workplace density
Canadian Census	Census “dissemination area” polygons and their population count	Approximate population density
Natural Resources Canada (NRCan) digital elevation model	Raster maps: 1201x1201 grid for every 0.25°x0.25°of land area	Estimates road and path slope

Algorithms

Calculating the Safety Rating of Each Road and Path

The LTS standard developed by [Mekuria2012] is used to classify each road and path according to one of four safety levels for cycling, LTS 1 being the safest. See Appendix A for a detailed formula. The calculation of the LTS rating is well-adapted to OSM road tags [Abad2019].

Additionally, we define: **forbidden** roads for cycling (freeways, private), pedestrian paths that require the cyclist to **dismount**, and roads for which there is **insufficient information** to determine the LTS rating.

Calculating Cycling Speed on the Road Graph

In order to perform lowest-cost (fastest) routing on the road graph, we need to specify a speed for both directions of every segment of the network. Then, given the length of that segment, its travel duration in each direction can be evaluated.

The **final speed** is evaluated as follows: the cycling speed on a piece of road is evaluated as the top speed (18 kph) reduced by the penalty from the **worst** of the effects (safety, one-way, material, and slope) – the effects are not applied cumulatively.

The effect of the LTS **safety rating** on speed is modeled according to the following table, the rationale being to add impedance to travel on higher LTS roads, which encourages the routing engine to select lower-LTS detours rather than a direct route on a high danger road. This is in contrast to the approach of entirely forbidding cycling on more dangerous routes (LTS 3 and 4), as done in the BNA project [Abad2019] (bna.peopleforbikes.org).

LTS rating	Modeled Speed
1	18 kph
2	15 kph
3	10 kph
4	4 kph

If the LTS value is unknown, it is set to LTS 3, the same as that of service roads.

The **one-way** street condition is modeled as cycling at top speed (18 kph) with the direction of traffic, and a dismount condition (6 kph) otherwise.

Road quality and **material** is indicated for some roads and paths based on corresponding OSM tags, and its effect on speed is given in a table in the Appendix.

The effect of **slope** on speed is evaluated according to a table for climbing slope values [Broach2012, Lowry2016], whereas a descending slope gives neither penalty nor bonus for the cyclist. However, a slope of more than 10% [Abad2019] in either direction results in a dismount condition and is made comparable to climbing stairs (at 2 kph). The cycling speeds for various slope ranges are as follows:

Climbing Slope	Cyclist Speed (based on a 18 kph maximum speed)
< -10%	2 kph
-10% – +2%	18 kph
2–4%	13.14 kph
4–6%	8.18 kph
6–10%	4.29 kph
>10%	2 kph

Finding Cycling Traffic Density on the Road Graph

Given all the data sources previously mentioned, and having formulas for quantifying network segments according to a common dimension (speed), it is now possible to simulate travel between all residences and all workplaces and superimpose these routes to obtain a **metric of relative importance** of each segment in the bikeable network.

In order to find the **residential** locations, all roads of types compatible with residential buildings are sampled every 50 meters. Then all sampled locations are assigned to their census dissemination area (DA) polygon, and each sampled point is given a **weight** equal to the total population of this DA divided by the number of sampled points in that DA.

Finding the **workplace** locations is based on OSM building polygon footprints. All buildings of a commercial or workplace type are considered as a workplace location with an assigned **weight** proportional to the building's volume (area of its polygon times height). A height of one storey is assumed for buildings without height information.

The **all-to-all** approach consists of using the **routing engine** to find a path from each residential point to each workplace point in bikeable range, and also a path back again (these paths may be different, due to conditions like one-way streets and slope). Each generated path is assigned a weight given by the equation:

$$w_P = w_R * w_W,$$

where w_R and w_W are the weights of the endpoints of the trip. All trips in this calculation are within the bikeable range (10 to 30 minutes trips).

By **superimposing** all the routed paths onto the network map with their calculated weights w_P, we obtain a total **network usage map** – akin to a **betweenness centrality** [Daniel2021] metric – giving the **predicted bike traffic** for each segment of the bikeable network. We thus have a ranking of all parts of the bikeable network according to relative importance of use.

Identifying Road Network Segments in Most Need of Improvement

The final result of our simulations shows a map of road segments that have priority in needing to be improved. This map is obtained by superimposing the network usage map (described in the previous section), with the LTS rating map. Two cases are highlighted as having **priority** for infrastructure intervention:

- roads with high LTS (3 or 4) where a **protected cycle track** would bring the LTS down to 1;
- paths where cyclists are required to **dismount** and where that condition could be lifted by appropriate infrastructure intervention.

Because we do not forbid cycling on dangerous (LTS 3 or 4) road segments (as done, e.g., in the BNA project [Abad2019]), more dangerous (or otherwise difficult) roads will be **avoided** if there is a short-enough **detour** in the network. On the other hand, sometimes there is no such detour, and the routing engine chooses cycling across a difficult road segment – if this happens enough times, the popular but difficult road segment will be highlighted for **improvement**: meaning that there should be new cycling infrastructure built either on that segment, or somewhere close to it (to offer a reasonable detour). Thus our approach still requires human decision-making to find how best to solve such situations of popular but difficult segments: there can be freedom of **alternatives** in handling each case.

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Appendix

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.

Project-osrm.org *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