Bikeability as an Indicator of Urban Mobility

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Executive Summary

Transport Canada is developing a set of indicators for both freight and passenger mobility. Already, it has developed 6 indicators through working with a Federal/Provincial/Territorial Task Force on Capacity Monitoring and Performance Measurement. However, urban mobility presents a complex challenge to measure due to a mix of both motorized and non-motorized travel. Attention is already given to the level of vehicle congestion on main arteries, however in the context of reducing carbon emissions it is clear that the movement of people using non-motorized modes such as bicycles is both growing and critical to environment and transportation policy. In this context, there is a demand to understand how non-motorized mobility and accessibility in urban areas can be captured and then measured.

This report examines the feasibility of measuring the connectivity of the cycling infrastructure, in particular for enabling commuting by bicycle. The considered approaches are based on GIS road databases and network analysis software tools. The goal is to identify the available digital resources that could be used to construct a meaningful *bikeability indicator* that measures how well the infrastructure is placed for enabling cycling as a desirable option for mode of commute.

The single most important consideration that emerges from individual surveys, academic research, and is built into major software analysis projects, is *safety* of travel. Predominantly, safety can be observed as the degree of physical separation (distance and barriers) from fast and heavy motor traffic, as well as *space* to cycle away from parked cars and bad road conditions (e.g., potholes). Safety also includes not being isolated on a dark and lonely road segment, as well as having secure bike storage available.

The desire for a continuous safe path from origin to destination is the primary consideration and/or roadblock for the decision to undertake a utilitarian (notably, commute) bike trip, and therefore also an influential factor to impact the bike mode share of a municipality's population. The next deciding factors are the trip duration, the trip distance, and finally pleasure of experience.

Fortunately, quantifying the safety of bikeable roads is already a well-studied topic and, what this report attempts to show, can be used as an essential component of an indicator that is *not biased* by the size and geographical layout of the municipality under consideration.

Because shortening trip distance is a goal that is sharply limited by many physical and urban planning considerations that have little to do with the cycling infrastructure itself, the best and most achievable goal is instead to provide the city with a well-connected network of bike-safe paths and roads, focusing on enabling the majority of desirable origin-destination trips (that is from residential areas to work, service, community, leisure, etc.). This report argues that an indicator that measures the level of connectivity of safe cycling infrastructure is feasible with current data, knowledge, and software techniques, and shows a road map for constructing such an indicator, by combining municipal origin-destination commuter surveys with openly available physical data and open-source software tools.

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Acronyms and Abbreviations

API	Application Programming Interface (software term)
BNA	Bicycle Network Analysis (software tool)
GIS	Geographic Information System
GPS	Global Positioning System (technology)
GTFS	General Transit Feed Specification (data format)
LTS	Level of Traffic Stress (standard)
NCR	National Capital Region (geographical region)
NCS	National Cycling Strategy
O-D	Origin-Destination
OSM	OpenStreetMap (project)
OTP	OpenTripPlanner (software tool)
XML	Extensible Markup Language (data format)

1 Introduction

The value of a good cycling infrastructure and its effect on promoting cycling mode share is difficult to overstate: from the potential benefits to health and quality of life, to the reduction of carbon emissions and traffic congestion, as well as boosting the economy and tourism. Improving the cycling network has been argued to be one of the most cost-effective interventions to improve these essential individual and societal needs (Canada Bikes, 2016).

In this report, we investigate methods for assessing the connectivity of the urban infrastructure specifically for *commute* cycling (residence to main place of work or post-secondary education), although this can be similar to studying other forms of *utilitarian* cycling, such as shopping and service access, or reaching community and entertainment events.

Because of the difficulty of improving what one cannot measure, it is desirable to construct a numerical *indicator* (index, metric) of the quality of the cycling network, such that the indicator increases with the proportion of the population for whom cycling becomes a *realistic* and *desirable* commute mode, in particular in preference to individual motor vehicles. A good indicator would have the double benefit of providing an indication of the current state of cycling ease in different geographical regions and could help prioritize interventions in cycling infrastructure improvement to the neediest regions. Additionally, a useful indicator could measure proposed future improvements to the cycling network, thus allowing cost-benefit comparisons of different infrastructure improvement plans for the same region.

The *cycling network* can be said to consist primarily of the dedicated and designated bike paths, all the paths shareable with pedestrians, legally bikeable roads shared with motor traffic (therefore excluding freeways, in Canada), as well as intersections with roads that allow motor traffic. Additionally, the *cycling infrastructure* includes bicycle parking (and its security), lighting and signage on bike paths, and finally services such as road maintenance and seasonal snow removal.

The quality and quantity of these infrastructure elements, their degree of connectivity into a spatially-continuous network, and the degree to which most desirable origin-destination trips can effectively be made, are increasingly-accurate ways of measuring the quality of the cycling network.

The sharp increase in literature on urban cycling in recent years is contemporary with the rising interest in the search for ways to limit urban air pollution, traffic congestion, and carbon emissions due to motorized personal vehicles. The last decade has also seen the rapidly increasing open availability of municipal infrastructure data and user-generated open data (notably by the OpenStreetMap project). All these factors make *quantitative* research in urban cycling infrastructure both *timely* and *feasible.*

1.1 *What Is Being Measured in Urban Bikeability*

Bike mode share measurements according to census data provide a measure of the success of a cycling strategy:
- Census, national or municipal, asks about principal commute mode, and can be multi-modal (an important example is bike plus transit).
- European Union: Special Eurobarometer 422a Quality of transport (Eurobar422a, 2014) . It reports on the percentage of people who answered "cycling" to the question: "On a typical day, which mode of transport do you use most often?"

As much as possible, one would want a bikeability indicator to be predictive of the bike mode share, and the match between the two should provide a bridge and mutual validation between reported cycling behaviour and GIS-based cycling network analysis. The different approaches in

attempting to measure the quality of the cyclable network fall broadly into three categories, each building on the previous one:

The **first level of measurement** is at the level of *individual roads or points*. There has been substantial research and standardization of metrics for quantifying the level of safety for cyclists on different road types, according to very many physical criteria, and with varying levels of granularity of distinction. The abundance of these *safety ratings*, notably in the U.S., points to the importance of measuring the safety of sharing the road with motor traffic in car-centric cities. There is less information overall on how the safety of an *intersection* could be measured, which may be due to the difficulty of modelling or lack of detailed infrastructure data.

Once the level of safety has been quantified for each road and path segment (and perhaps, each intersection), it is easy to measure the proportion, or total length, or area density of each safety level type, along with the density of other cycling infrastructure features. Because of the network nature of transportation, this is usually insufficient, or perhaps only an initial estimate.

Therefore, the **second level of measurement** is a *network connectivity metric* of the bikeable network, as it considers how the bikeable road segments connect to each other. The bikeable network is then a graph, and various metrics based on mathematical graph theory and adapted to transportation problems can be used. We will not focus much on this type of measurement, as it does not, by itself, indicate which roads will be most significant for cycling commute trips (this may not, in fact, be straightforwardly intuitive just from looking at a city map). Instead, this report will examine approaches that go beyond simple graph connectivity to include the essential question of where do utilitarian cycling trips begin and end.

Indeed, the zoned nature of North American cities will dictate that large areas of the city can be categorized as either mainly residential or not. Therefore, most utilitarian trips will begin in a residential zone, but not terminate in one, and a good cycling connection between two residential areas is of limited use for utilitarian cycling.

The **third level of measurement** considers not only the shape and nature of the cycling network in itself, but also where are cyclists beginning, pursuing, and ending their trips. This approach requires additional types of data beyond the road network itself: one needs some data indicative of *origin and destination locations* of potential and actual trips. A different approach is to measure the relative importance of network segment use via counting methods (bike counters or GPS traces).

A prominent example of the synthesis of these approaches is the Propensity to Cycle Tool (PCT) developed by Lovelace et al. (2017), a U.K.-based project that uses most of the data sources, measurements, and concepts described above. The measurements are presented in an interactive map of the entire country, subdivided into census regions, and allows a geographically-detailed interactive examination of the cycling mode share and trip distance and safety, with the purpose of influencing the national cycling strategy and focusing national and local infrastructure improvements efforts.

1.2 Goal: Desired Characteristics of a Bikeability Indicator

The purpose of a numerical bikeability indicator is to measure the current quality of the existing bike network, track the improvement of the bike network over time, compare different municipalities and regions among themselves (if applicable), and finally to compare various infrastructure improvement proposals for cost-benefit analysis. In order to achieve these ambitious goals, the indicator should, as much as possible, fulfill these criteria:

- *Sensitivity*: it can be intuitively understood that improving the cycling infrastructure at certain key locations will be most beneficial to most commuters. Thus, improvements in the most needed network segments (bottlenecks) which are expected to be most used should increase the indicator the most.

- *Robustness* to data error (stability): because GIS databases are prone to human error and obsolescence, the indicator should not vary much due to erroneous or incomplete data on a small map feature. It would also be valuable if the methodology for measuring the indicator also has a side effect of being able to identify which parts of the infrastructure need most careful examination and double-checking.

- 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 indicator would not be swayed by these highly-varying and uncontrollable characteristics, but would be one that can be improved and maximized by *only* improving the bikeable network.

- Spatial *divisibility*: the indicator would not only provide a single meaningful numerical measure of an entire city, but could also be applied to any smaller geographical region.

- *Predictive* power: as the infrastructure is improved in a given region, only the future will tell whether a constructed bikeability indicator will increase along with the reported bike mode share in that region.

The final goal of the bikeability index and associated research is to make it easier for more of the population to cycle for utilitarian purposes. Because so many factors combine into what makes a city bike-friendly, the bikeability indicator should serve as an accurate thermometer of current and future biking situations, as well as a compass for directing efforts in improving bike mode share.

1.3 The International Situation and the Canadian Context

Canada is considered to have low cycling mode share (less than 5%), which shows ample room for growth, when compared with many European Union countries, with the Netherlands, Denmark, Hungary, and Sweden all above 16% mode share according to two measures (Eurobar442a, 2014). The ample spread in cycling mode share among European countries does not seem to strongly follow any obvious physical characteristic (climate, topography, city size and type), though such effects may also worthy of study. What emerges instead is that European Union countries with moderate-to-high mode share all have or had a national cycling strategy (NCS), while all those that do not have a NCS report at most a 7% mode share. The Netherlands lead the pack (36%) and no longer have an NCS, and perhaps represent a plateau.

Darkness during commute hours for about 4 months and the harsh Canadian winter (with biking in sub-zero temperatures and on snow and ice, as well as irregular snow removal) make seasonality a particular concern that is little-addressed in research and software projects based in Europe (where much research is focused in the U.K., Netherlands, Denmark, and Germany), and the U.S.. However, the high bike mode share in European countries with similar climate: Sweden (17%), Finland (14%), Denmark (23%), gives hope that there is much room for improvement in the Canadian climate.

In the U.S., while the cycling mode share is very low – less than 2% in all states, and less than 1% in all but four (League of American Bicyclists, 2016), it has been successfully and dramatically increased in certain cities via a purposeful and coordinated municipal strategy and well-planned infrastructure improvements, notably in Portland, Oregon (Alta Planning, 2012; McLean, 2012), and is in the range 5-17% in 12 cities (across 5 states).

Notwithstanding the difficult Canadian winter and the car-centric nature of many of our cities,

examples from other countries and cities with similar characteristics show that there is room to increase bicycle mode share (notably for commutes) many times over. Towards this goal, Canada Bikes (2016) has made a case for a National Cycling Strategy for Canada. A NCS could include measuring cycling usage and demand, setting cycling targets and allocating funding based on cost-benefit analyses, ensuring that investment and funding is strategically allocated to the most needed infrastructure, policy development and planning, fostering research and knowledge transfer, establishing standards for infrastructure design quality, defining roles of different levels of government for cycling, and coordinating on issues related to cycling: health, economy, environment, transit, recreation, tourism, smart cities and strong communities, land-use planning, rural and northern communities, road safety, education on cycling, children's and accessible mobility, and the bicycle industry.

1.4 Report Organization

Chapter 2 is an examination of **literature**, describing both qualitative and quantitative factors that affect urban cycling from the point of view of the cyclist, the urban planner, and policymaker.

Chapter 3 examines the availability and contents of **data sources** that could be used as components (some essential and some optional) for measuring a bikeability indicator. The principle data sources are: user-generated open-source data, several agencies of the Government of Canada, the City of Ottawa, and the City of Gatineau.

Chapter 4 examines existing **software projects** that could be used as components in building software that can measure a bikeability indicator: notably, they allow for routing bike trips on a GIS road map of the city, and implement formulas for calculating path safety and travel speed. In

Chapter 5, we report on an **experimental setup** for validating the practical feasibility of measuring bikeability using some of the data and software resources found, with a case study in downtown Ottawa-Gatineau, and propose a generic design of a software system for measuring commute bikeability.

Chapter 6 summarizes the findings and observations from the literature, data sources, software projects, and experimental setups proposed in this report. **Observations and ideas** are summarized on what is currently possible for constructing a reasonable and useful bikeability indicator, and suggests interesting venues for focusing further study.

Chapter 7 **concludes** the report and proposes tasks for moving foward with measuring bikeability in Canada.

2 Utilitarian Urban Cycling Topics in Literature

Research in urban cycling takes several forms, the most prevalent and pertinent to our topic being:

Qualitative surveys (Hughes, 2013) of the population (cyclists: actual and potential) – from large scale municipal surveys of pre-specified questions with limited or numerical answer sets, to in-depth questionnaires of small numbers of avid individuals (which also include an open-ended dimension, e.g., asking "what *other* (unmentioned) factors affect your cycling behaviour or decision to cycle"). Studies of cycling behaviours (Geller, 2009) and grouping cyclist into categories *(profiles). Meta-analysis studies* of surveys for identifying universal cycling behaviour trends (Aldred, 2017).

Guides for forming a *municipal biking strategy*, building a biking culture, and improving the cycling network, including plans for including timescales, funding, and communication between experts from many fields, local agencies, and the affected population (Alta Planning, 2012; McLean, 2012; Melia, 2012; Mineta Transportation Institute, May 2012).

Road biking safety through statistics, road quality metrics, behaviours and infrastructure that promote it (Mineta Transportation Institute, Feb. 2012; Necessary, 2016; Philips, 2003; Sprinkle Consulting Inc., 2007; Gutierrez, 2017).

Reports written by *advocacy groups* (Canada Bikes, 2016; Bike Ottawa, 2018) indicate a strong grassroots interest in improving cycling infrastructure and culture, and offer a perspective of the manifold social and experiential issues tied to cycling as experienced by the citizen. They help bring attention to overlooked issues and successful practices from other countries, and coordinate multi-disciplinary discussions on how to enable more people to cycle.

Software projects that are usually of an open-source and academia-led nature, and run primarily on the freely available and globally ubiquitous OpenStreetMap road data set. The projects usually including a routing engine, road quality formula, and cyclist profiles.

Approaches for *measuring the connectivity of biking networks (*Gupta, 2014; Hartanto, 2017; Krismer, 2016; Lovelace, 2017; Lowry, 2012; Thistle, 2016; Winters, 2016).

Assessments of available *infrastructure data* (Barrington-Leigh, 2017).

2.1 Benefits of Increasing Urban Cycling

Making the city more bikeable, and walkable (Ghenadenik, 2018), is increasingly being shown to offer significant benefits (Alta Planning, 2012, Canada Bikes, 2016), both to the individuals who cycle and walk, and to the entire urban population – so much so, that we can talk of a *biking culture* that can emerge and become self-sustaining.

Personal benefits of cycling include: health benefits, reduced costs, time saving (particularly if one factors in leisure/exercise time), and perceived quality of life. The society as a whole also benefits from increased biking infrastructure and each bike on the road in: reduced traffic and load on transit (Phillips, 2003), lower emissions and noise, more walkable neighbourhoods, benefits to the economy (e.g, cycling industry) and tourism, as well as a more resilient multi-modal transportation network (Philips, 2014).

Many North American cities are designed primarily around motor vehicles, and we may also talk of the car as a symbol of freedom, independence, and responsibility – we have (to a certain extent) a *car-centric* culture. Beyond transportation planning, climatic, and distance issues, it is important to think how we can foster a *bike-friendly* (if not bike-centric) culture, modelled after countries (Netherlands, Denmark) and cities (Portland, Oregon), which have high bike mode share. The value of a bike culture is that it may become self-sustaining and self-propelling, and can give valuable

feedback on unforeseen issues.

The presence of biking advocacy groups at the national (Canada Bikes) and local (e.g., Bike Ottawa) levels, along with volunteer projects for mapping the road network (the OpenStreetMap community) indicate a robust grass-root interest and dynamism in promoting cycling and its infrastructure analysis and development.

The cyclist is in a unique and challenging transportation category: *fragile* like a pedestrian in a collision, yet can moves several times *faster* than one – as such, motorists may not be paying attention to cyclists in areas where they are rarely seen. This calls for a greater awareness of rules of the road mutually between drivers and cyclists, education of the population, and school programs. As a biking culture takes root and the bike mode share increases, a snowballing effect of increased biking popularity can lead to more safety on isolated roads, with drivers paying more attention to the possibility of oncoming cyclists.

2.2 Desirable Infrastructure Features Based on Cyclist Surveys

Aldred (2017) conducted a systematic review of 54 studies, investigating how cycling infrastructure preferences varied by gender and age; of these studies, 44 (including 4 in Canada) concerned separation from motor traffic, by far the most common infrastructural characteristic discussed. Other topics that were less studied include: winter maintenance; lighting of track and being seen; protection at road crossings; direct routes; avoiding hills; need to carry cargo; widening cycling lanes; cycling infrastructure for 3-wheeled cycles carrying children or cargo. Women were more concerned about: personal safety from crime, winter conditions, carrying items, and hilliness.

In countries with low cycling mode share (defined as less than 5%, which includes Canada), cycling is more demographically unequal, and women report a stronger preference for greater separation from motor traffic. In high mode share countries, the situation is more demographically equal. Women in Canada (and on average around the world) generally show a stronger concern for safety. The age situation is less consistent: older people may be more risk-averse, but also have more experience in navigating traffic. Children and elderly also have a strong preference for better infrastructure, but more studies are needed. There is a difficulty in performing meta-analysis over age categories, as there is no consistent or natural way of selecting age intervals.

There are several differences in methodology of how surveys are performed. They vary in the specificity: how many different types of cycle lane are considered (in Figure 2.1, one sees 7 degrees of separation from motor traffic, but studies may include far fewer). The populations surveyed also varied in composition, notably, what percentage of those surveyed are non-cyclists. Finally, the elicitation method could have a differing emotional effect on the respondents' perception of cycling safety, differing by whether the scenario was described via text only, reference to existing infrastructure, images, or video.

In low cycling mode share countries, it is important to include non-cyclists in surveys, as active cyclists may represent the preferences of the majority. The idea is to study how to encourage non-cyclists and find what is blocking most of them from cycling to work in the city.

Winters (2008) summarizes focus group discussions on what qualitative factors affect the decision to bike for "utilitarian purposes" (not only commuting, but also shopping, etc.), which factors are the most important, and how this ranking is affected by the cyclist's level of experience. We summarize their findings here; most of the factors described could be measured using features from GIS databases. A few factors (e.g., building aesthetics) are harder to correlate with available GIS information and are omitted.

In this report, less confident cyclists said they would be encouraged to cycle (more) for transport purposes based on these factors:
- Cycle paths through parks, or residential streets;
- If along traffic, a physical barrier;
- Aesthetics of surrounding environment (beautiful architecture, panoramas, nature) – improves the *perception* of safety;
- Residential streets also give the *perception* of safety (traffic judged as slower than it really is) – perhaps better visibility, more manoeuvre space, and lower traffic volume do indeed make residential streets safer, even when vehicular speed is the same;
- Commute distance within about **5km**, and time within about **30 min** (time being more important). See also, Necessary (2016).

Whereas, the following factors discourage or even prohibit cycling for these users:
- Pollution, noise, and heavy traffic (trucks, diesel buses);
- Alongside fast traffic;
- Forced to cycle very close to parked cars (fear of opened doors or sudden departures), or in tight spaces between moving traffic and parked vehicles;
- Bad road shoulder when moving alongside traffic (garbage, gravel, or potholes);
- Poor signage on bike routes (may cause getting lost on first trips);
- Lots of hilly topography;
- Highways, bridges, and tunnels (unless they are made very easy to navigate);
- Fear being attacked in industrial zones (due to isolation).

The three most important factors were: presence of **bike routes**, co-existence with **vehicular traffic**, and the **connectivity** of the street network.

Taken together, all these qualitative factors strongly point to the existence of a **connected route without heavy traffic** as being the single most desirable trait that encourages switching to biking commute. This single criterion lends itself well to a quantitative GIS analysis based on road types and graph connectivity.

More confident cyclists differentiate themselves by several characteristics. They are more willing to cycle alongside traffic if necessary. They will cycle longer and are more tolerant of hills, some viewing them as a desirable challenge. More confident cyclists prefer fewer stops, and therefore longer blocks and fewer intersections so that cycling momentum may be developed and not wasted.

Other factors affecting willingness to cycle include: lack of end-of-trip facilities (secure parking, showers) (Alta Planning, 2012), and unwillingness to ride in winter (Malatest & Associates Ltd., 2013), and accessibility by bike to transit hubs (Hartanto, 2017), particularly when the commute is too long to be completed by bike alone (Mayor of London, 2017). On this last point, Veryard (2018) argues that cycling can be seen "as a component of the public transport system", extending its range and completing missing links, and argues for providing "adequate bike parking areas at stations and stops".

2.3 Profiling the Urban Cyclist and Measuring Road Quality for Cycling

Profiling the urban cyclist is essential for calibrating cycling routing engines (Krismer, 2016; Lovelace, 2017) and this practice groups cyclists into discrete categories according to:
- How far (time and distance) is the potential cyclist willing to commute each day?
- What is their cruising speed and delays at intersections?
- How much hill slope are they willing to climb?

- How much detour (percentage trip length, or absolute increase) is the cyclist willing to tolerate in order to cycle within their desired level of safety in comparison with the most direct route?
- What minimum level of road *safety* does the cyclist need? Most classifications include 3 or 4 categories (or the 4th category is implied: "will never cycle").

The two extremes for safety categories of cyclists are: 1) will cycle in any legal conditions and take the fastest route (about 1% of the population) and 2) has no interest in cycling. In both cases, variation in infrastructure are unlikely to have much effect, and it is the middle categories (confident and hesitant cyclists) whose cycling behaviour is most likely to increase with improved infrastructure.

Concerning road types, the cycling network for less confident cyclists consists of:
- Bike paths and occasional footpaths; (away from roads, in parks, etc.)
- Residential streets; (with low traffic volume and speed)
- Bike lanes with physical barriers protecting them from traffic.
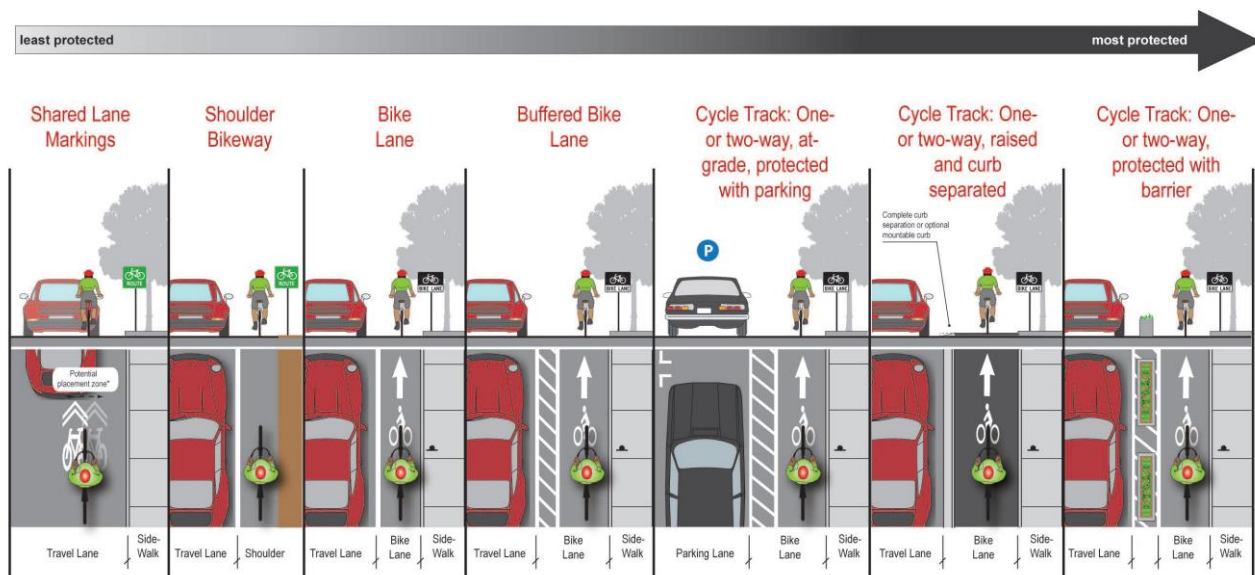
Figure 2.1 Levels of physical separation from motor traffic (Alta Planning, 2012).

Such road conditions also strongly correlate with other desirable factors: aesthetics and immersion in nature, low exposure to traffic fumes and noise, and having room to manoeuvre away from parked and moving vehicles and around potholes. Thus, for inexperienced/potential cyclists, the experience of commuting by bike should be a pleasant one – and this is almost always concurrent with safe conditions.

The level of physical separation from traffic correlates with the decrease in cycling fatalities (Buehler, 2017). It can be graded into many levels (Figure 2.1), and may not always be sufficiently differentiated in surveys and standards. For example, painted shared lanes ("sharrows") may not be considered to have much safety value (Bike Ottawa, 2018). Reports by McLean (2012), Alta Planning (2012), and Mineta Transportation Institute (Feb. 2012) detail some infrastructure improvements that can make cycling along traffic safer, notably:
- Physical separation from traffic on the road using a barrier, or at least a curb.
- Intersections adapted for bicycles: automatic bicycle detection, cyclist-specific signalling, painted bike "boxes" for waiting at stoplights, etc.
- Traffic calming methods: speed bumps, street narrowing, etc.

The problem of classifying roads according to cycling safety is tightly related to profiling the cyclist as to their *road safety tolerance*. The Federal Highway Administration (FHWA) in the U.S. gives three categories of cyclists (Mineta Transportation Institute, May 2012):

"A = Advanced cyclists whose greater skill enables them to share roads with motor traffic. Moreover, they are unwilling to sacrifice speed for separation from traffic stress.

B = Basic adult cyclists, who lack the "skill" to confidently integrate with fast or heavy traffic.

C = Children cyclists, less capable than class B at negotiating with traffic and more prone to irrational and sudden movements.

Categories A and B have very different preferences. Category A desires getting to the destination as fast as possible and is willing to share the road with vehicular traffic. Category B (and C) desires to get to the destination safely, and will be deterred from cycling by even short sections where it must share the road with heavy traffic."

Work by Roger Geller (2009), Portland's (U.S.) bicycle coordinator, classifies the city's population into four categories:

- Less than 1%: The "strong and fearless" respond well to riding in almost any traffic conditions and correspond to the class A riders of the FHWA scheme;
- About 7%: The "enthused and confident" don't show that same tolerance for mixing with fast, turbulent traffic, but respond well to riding in bike lanes along arterial streets and to sharing smaller roads with traffic.
- About 60%: The "interested but concerned" find situations in which they have to negotiate with traffic streams uncomfortable, but respond well to standalone paths and streets with little and slow traffic.
- About 33%: The "No Way No How" group is not interested in riding a bicycle at all.

In Ottawa (Malatest & Associates, Ltd., 2013), the population was surveyed for their cycling behaviour and preferences. The respondents classified themselves within these categories:

- Don't cycle now and not interested in starting: 33%.
- Interested in cycling more but concerned about traffic and safety, waiting for more bike lanes or off-road paths: 33%,
- Comfortable in traffic but prefer bike lanes and like using segregated facilities: 26%
- Comfortable cycling with traffic; roads fine as they are and somewhat dislike segregated facilities: 9%.

Road Safety Standards

Several standards exist for evaluating the safety of the road for cyclists, each based on a large number of physical road characteristics (Lowry, 2012; Gutierrez, 2017; Sprinkle Consulting Ltd., 2007). The Level of Traffic Stress (LTS) proposed by the Mineta Transportation Institute (May 2012) has received research interest (Thistle, 2016; Gutierrez, 2017) and is the only standard that we have found implemented in software: in the BNA project by PeopleForBikes.org, in the Conveyal R5 project, and by BikeOttawa.org . The LTS is based on Dutch cycling road design standards, and defines four levels of traffic stress for cyclists:

- Level of traffic stress 1 (LTS 1) is meant to be a level that most children can tolerate;
- LTS 2, the level that will be tolerated by the mainstream adult population;
- LTS 3, the level tolerated by American cyclists who are "enthused and confident" but still prefer having their own dedicated space for riding;
- and LTS 4, a level tolerated only by those characterized as "strong and fearless."

Cyclist's Speed and Measuring Trip Length

After safety rating, it is desirable to measure both the linear length and time duration of a route. This requires an estimate of the cyclist's speed. We define *cruising* speed as the one assumed over long uninterrupted stretches of road (these are an input to the cycling model), and *average* speed: the total trip distance over total trip time (this is an output of a simulation).

Determining cruising cycling speed: most software projects assume a constant biking speed for their cyclist, in the range 16-18 kph, sometimes up to 24 kph. However, the resulting average speed will change based on the following circumstances:
- There is a model for adding delay for each intersection.
- For paths that are walkable but not bikeable, it may be assumed that the cyclist will walk their bike (resulting in a cruising speed of about 6 kph) – this is important not to break the connectivity of the bikeable network.
- In some models, there are different cruising speed ratings for different road types.

2.4 Assessing the Bikeable Network

In developing a bikeability indicator of an urban area, two primary considerations predominantly emerge from the literature and existing bikeability projects:
- How **fast** may one commute to work? (Time is generally seen as more important than distance)
- Regardless of the time or distance, how **safe** is the commute? (Safety being primarily affected by having to share the road with vehicular traffic.)

The more experienced a cyclist, the more they are concerned with the first factor (time), while less experienced (as well as hesitant but potential) cyclists are more concerned about the second factor (safety). Thus, the main obstacle to increasing bike mode share appears to be **safety**, i.e., ensuring that there exists a continuous route between residence and workplace that has little to no overlap with heavy traffic. On the other hand, getting to work as fast as possible appears to be the main goal of experienced cyclists, and cycling along major traffic routes (particularly during rush hour), has generally been rated feasible only for them. Because most of the population is considered less experienced (particularly the population that is not cycling to work but could potentially be doing so), it may be most valuable to focus primarily on improving the safety of existing roads for cycling, to improve the bike mode share. Also, road safety is the most controllable variable, whereas trip duration/distance are heavily influenced by city layout factors that cannot be changed easily, if at all.

Network Connectivity
Several works (Lowry, 2012) have considered the connectivity of the cyclable network to measure the network's quality. Mere connectivity does not convey the entire picture of which infrastructure segments are the most significant, and an Origin-Destination (O-D) approach is useful to determine likely routes taken by cyclists (Lovelace, 2017; Winters, 2016; Thistle 2016; Necessary 2016; Gupta, 2014). This will be explored in detail in Chapter 4, which contrasts projects that take these two approaches, and argues for the use of an O-D routing approach for more accurate bicycle network analysis.

Safety Models
We will distinguish the *relative* safety of a route: a weighted average (according to some formula) of the safety on each segment; and its *absolute* safety: the safety of a path is given by its worst-case segment, however short. The *relative* safety model assumes that a given route is acceptable if a properly weighted average of the safety along all the route is above a certain threshold, and thus allows for short rides alongside traffic. The *absolute* safety model says that if any part of the commute is below the safety comfort level of the individual, they will certainly decline to cycle to

work. Both safety models require one to establish a quantitative measure (rating) of safety:

- For each road, a safety rating (number) for cycling based on the road's characteristics.
- Similarly, a safety rating for each intersection. (In simplified models or due to lack of data, this is simply inherited from the road's safety rating.)
- In the absolute model: what is the lowest safety rating that the average cyclist will tolerate?
- In the relative model, a weighing formula needs to be established to quantify the tolerance of the average cyclist to different lengths of unsafe roads over a route that is safe in its majority.

At this stage of reasoning, it is difficult to choose between the relative and absolute safety approaches, but a partial comparison can be made according to their relative advantages:

Advantages of measuring *relative safety*:

- A very safe route with very short dangerous segments will not be disqualified, only penalized. This approach is thus more tolerant to inaccurate road data, making the analysis more stable, as short errors in road type will not have an overriding effect on the final result.
- Several projects for cycling routing take the approach of trying to maximize relative safety.

Advantages of measuring *absolute safety*:

- The simplicity of describing the cyclist by only one number, i.e., their minimal safety tolerance, rather than a more complicated weighing formula.
- Routing software engines also allow for forbidding cycling on a certain category of streets (in our context, those below the allowed safety rating), though this is usually not the default way they are set up.

3 Available Data Sources

In this Chapter, we examine data sources that are pertinent to cycling and that can be part of a quantitative and GIS methodology for measuring indicators of bikeability. The types of data that we examine fall into several categories: essential to any transportation network connectivity is the geometry and topology of roads and paths, as well as qualitative information about the nature of its segments and nodes (intersections); however, this in itself is generally insufficient in telling us which network segments are most critical to connect people to where they want to go, and therefore we also examine datasets that can give an idea of where people are expected to begin and end their trips (i.e, residences and workplaces for commute analysis). We also discuss the avaialbility of data sources that measure the geographical locations of actual cyclists. Finally, we examine environmental data that can be helpful in studying cycling as it varies according to season.

3.1 Data Source Agencies

Various sources of data pertinent to bikeability exist, both at the federal and municipal levels (open data), as well as from commercial sources (usually available for purchase) and open crowd-sourced projects. The nature of the source can affect the cost of the data as well as its reliability and completeness.

3.1.1 Government of Canada

Several federal agencies offer various data pertinent to cycling in an open manner. In particular:

National Resources Canada (NRCan) provides topographical (elevation) models of the entire country (open.canada.ca), which are very valuable if one wants to include the slope of cycling paths in road speed and difficulty modelling.

The National Research Council (NRC) of Canada provides digital cartography product know as CanVec, which includes polygonal regions of land use according to different building types. This data may be helpful in identifying residential and workplace districts for analyzing commuting behaviour. The NRC also provides a sunrise/sunset calculator, which can help with studying periods of darkness during commute hours by season.

Statistics Canada provides reported bike mode share by census division every five years (most recently, 2016), as well as the geographical polygons of these divisions.

Environment Canada provides historical weather data (climate.weather.ca) that can be used for studying seasonality.

3.1.2 Municipal (City of Ottawa & City of Gatineau)

The cities of Ottawa and Gatineau are here taken as test cases of what type of data could be available at in a typical city, and which ones will be most essential to measuring cycling.

- The City of Ottawa offers open data at data.ottawa.ca and several datasets can be visualized at maps.ottawa.ca. Data includes road networks, cycle lanes and paths, and winter scheduled snow removal. The City of Gatineau provides open data of a similar nature at gatineau.ca/donneesouvertes/donnees_ouvertes_en.aspx .

- In private communication, the City of Ottawa commented on the lack of information on end of trip facilities such as showers at places of work. The City of Ottawa provides the 2011 Origin-Destination Survey, which contains anonymized commute statistics for approximately 25,000 households.

- The Ottawa Police Service and Ottawa Traffic Services (obtained via Carleton University

library) provides collision statistics, notably their locations, severity, and which ones included cyclists.

3.1.3 Corporations

Google LLC is the owner of the largest GIS database of the entire world, as one of its mandates is to map the entire world via satellite and ground-level imagery and road network and feature databases. A rendered visualization of its urban data can be interactively and freely explored via maps.google.ca in Canada. However, the data is proprietary and not openly available, and the potential of using *Google's* road data for research and automated analysis appears to be limited: while it is possible to access *Google*'s API to perform O-D routing for various modes (including cycling), it does not appear to be possible to access the full underlying mechanics of the routing engine, nor the road database itself. Neither do we find any cycling analysis project that uses this, or any other commercial road network. There is far more understanding and control in having a fully open road dataset and routing engine.

Strava Inc. is a company that collects GPS trip traces from sports enthusiasts, notably cyclists.

- *Strava mobile application:* allows the user to track their travel according to GPS location and time, as well as store these trip traces and obtain trip statistics. It is aimed at sports enthusiasts (cycling, skiing, water-sports), and has a strong cyclist base.

- *Metro Strava*, which sells anonymized and aggregated data obtained from the GPS traces from the mobile applications: specifically, approximate origin-destination pairs, and travel counts for each road segment and intersection – the data is separated by mode, and specifies whether a trip is a commute (this is perhaps detected automatically, based on travel patterns).

- *Strava Labs* is its research branch: notably, it has developed technology that snaps noisy GPS traces to linear road segments, which provides "cleaned-up" usable cycling counts on the urban road network via *Metro Strava*.

Time and Date AS is a private, limited liability Norwegian Company that operates timeanddate.com since 1998, and specializes in providing astronomical time data, notably information related to time zones and the apparent position of the sun in the sky.

3.1.4 Crowd-Sourced

OpenStreetMap (OSM) is a world-wide project, similar in philosophy, approach, and magnitude to Wikipedia, whose purpose is to map the entire world as vector data entered by volunteers. It includes the data-set itself, an online tile map renderer (OpenStreetMap.org), an interface for signing up as a user and modifying the data-set (with a user guide to in wiki format, maintained by an active worldwide community), and may open-source software tools for viewing, analyzing, and modifying the OSM data-set.

The OSM database has been a great boon for the research and non-profit communities in general, and for cycling in particular. In the next Chapter, we examine a dozen projects whose purpose is to analyze cycling connectivity, and all these projects use the OSM database as their primary or only source of road data. The OSM data can be visualized online in several ways; the OpenCycleMap.org project emphasizes drawing cycling lanes and paths.

OSM serves as a fully-accessible and open-source alternative to commercial map sources such as *Google*. Maps are encoded in a human-readable XML-compatible format (.osm) or compressed in a custom binary format (.pbf). Particular features may also be extracted in a GeoJSON or Shapefile formats via free software tools. The XML-based format is mainly composed of a list of these features:

- A *node* is a geo-located point *(lat,lon),* identified by a world-unique integer (*id*).

- A *way* is an ordered list of nodes (specified by *id*), forming either a linear curve (path) or closed polygon, along with key-value pairs specifying its nature and any number of properties. Any geographical feature not located at a single point is represented by one (or more) *way*s: these can represent roads, paths, building shapes ("footprints"), land-use, and natural features (green areas, bodies of water), etc.

- A *relation* sometimes combines several *way*s into a logical whole, e.g., multi-part buildings, or multiple segments of a road.

Portions of the world's map may be downloaded directly from OSM. Larger map portions are more efficiently downloaded as regional extracts via intermediary websites such as:

- All of Canada or individual provinces: geofabrik.de;

- Major metro regions, including 7 in Canada; mapzen.com's "metro extracts".

Canada has a very well-populated OSM road network by international standards according to Barrington-Leigh (2017), and the data-set is actively being improved by volunteer organizations at the national level (osmcanada.ca − which coordinates mapping efforts and identifies data gaps) as well as groups at the city level (e.g., OSM mapping meet-ups in Ottawa) and private individuals.

The OSM data-set and format has been adopted worldwide for much academic research and open-source projects (notably for finding routes on a road network, for cycling and other modes as will be seen in Chapter 4).

Another project of interest is **Mapillary.org**, which aggregates geo-tagged user photos at street level, and serves as an open alternative to *Google*'s *Street View.* Mapillary also includes open-source image detection (artificial intelligence) for street signs and other features.

3.2 Transportation Network

As argued in the research literature and throughout this report, bikeability measuring bikeability means, in a large part, studying the connectivity of roads and paths that are cyclable, and determining to what extent there are safe and direct paths between desired origins and destinations, i.e., between residences and workplaces in the case of commuting.

As such, two essential pieces of information are needed from GIS network information:

1) Road geometry and topology: how are the roads and paths spatially laid out, and where do they connect with each other.

2) Road tagging: information about the nature of a road and its various attributes as relates to travelling along them in various modes (motor, cycle, walking, wheelchair access).

For this purpose, there exist alternative data sources: both open-source and government (national and municipal) data.

3.2.1 Road and Cycle Path Network

Open-Source Data

The road network given by OpenStreetMap consists of ways with the tag *highway* or *cycleway,* and includes paths not open for motor vehicles. The type of road is indicated by the value of the highway tag (e.g., *highway=footpath*). Table 4.2 in the next Chapter lists these road types and gives one project's interpretation of how these road categories can be mapped to cycling safety. Additionally, a *highway* can have any number of optional tags, of which several are pertinent to cycling, as detailed in Table 3.1.

Table 3.1 OpenStreetMap road tags most pertinent to cycling.

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*
Artificial lighting above road	*lit*	*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, described in Chapter 4.

Information about whether there is artificial lighting on the path (using the *lit* tag) can be used to assess the safety of isolated bike paths, particularly during regular commute hours in the fall and winter months.

Other useful cycle-relevant road tags can be found, with more descriptive detail and photographic illustrations, in the OSM online documentation.

The OSM format has the advantage of being the primary format used by all routing software we identified (see Chapter 4), probably due to its easy, open, availability, good coverage of much of the earth (Barrington-Leigh, 2017), and the fact that it has road network connectivity built into its format: i.e., if a node belongs to two roads (e.g., an intersection), it will have the same identifier.

Municipal Data

The City of Ottawa provides a vector database of the cycling network. It includes linear path data and a type for each path. The 7 types are as follows: 'Cycle Track', 'Advisory Bike Lanes', 'Path', 'Segregated Bike Lane', 'Paved Shoulder', 'Bike Lane', 'Suggested Route' – this last type does not correspond to any physical infrastructure. The City of Gatineau provides a similar database; however, path types are only specified as numbers: 1 to 7.

Data Representation and Its Consequences on Automated Routing

Roads obtained from municipal open data are found to be in formats such as Shapefile or GeoJSON, which encode a road geometry as a sequence of (latitude, longitude) coordinates. While this gives the shape of individual roads, the connectivity among the roads, and the connectivity between roads and cycle lanes and paths is not straightforward to derive, nor is it easy to represent roads that overlap (in two dimensions) but do not connect. The connectivity between roads is represented in a different database.

Conversely, in the OSM database, each road or path is represented as a sequence of *node id*s

(unique integers), whose coordinates can be looked up. The consequence on road network representation is that if two roads connect or intersect then they have a node *id* in common. In the case that the roads overlap but do not intersect (e.g., a bridge or overpass), there is no common node at the overlap point, and furthermore, both roads are given a different *layer* value. Such a representation of the road and path network is called *topological* and is very convenient for routing software or analysis of the road network as a graph.

3.2.2 Street-Level Imagery

Because there may exist errors, or more often, gaps in both government and open-source road network databases, it may be necessary to verify particular segments of the network manually to assess the conditions on the ground. While satellite and aerial imagery may be of some help, it may not be accurate enough to evaluate the exact nature and safety of the cycling infrastructure; we therefore suggest the use of street-level imagery for verifying particular road segments. Because a city contains many thousands such segments, it is unrealistic to verify them all. What we suggest instead is that cycling network analysis via routing can identify the most important routes in the cycling network, and the most popular roads or anomalous results can be verified on a per-case basis to identify the most significant data gaps and errors.

Google's *Street View* enables a photographic visualization of the details of a road, thereby allowing checking a particular road's characteristics without going into the field. The data can be accessed via a browser (maps.google.ca), or via the free *Google Earth* desktop application.

Alternatively, **Mapillary.org** provides a user-driven geo-tagged database of street-level images. Visual inspection of the NCR map shows very high coverage (with photos often taken even every few meters), with photos of most of the region's roads and paths (less so in the Orleans sector and in the Quebec province). Indeed, in the NCR, we find that there is some complementarity in the gaps of the photographed roads between Mapillary and Google, hence the value of having both resources.

In the cycling context, it is conceivable that Mapillary's images could be used to assess the quality of the cycling infrastructure: not only by humans but perhaps also automatically in the future, as the Mapillary project also has street-level image recognition technology for extracting road infrastructure features.

3.2.3 Transit Routes and Schedules

Cycling and transit (bus, light rail, etc.) are an important mode combination that can extend the travel connectivity and range well beyond one of these networks' alone (Veryard, 2017). The OTP tool has the property, along with individual modes, to analyze transit+cycling or transit+walking trips; for this, it requires a transit route database in the GTFS format, which it uses together with the OSM road network to perform transit-only or transit+cycling routing.

The GTFS (General Transit Feed Specification) format was designed by *Google* as a universal standard for encoding transit stop locations, transit routes, and their schedules (and other optional information, such as accessibility).

The GTFS format has received broad adoption in North America, with network schedules for most major cities aggregated for download on dedicated websites. Table 3.2 lists free sources for GTFS data for many cities, as well as sources detailing the GTFS data format. The NCR is served by OCTranspo in Ottawa and the STO in Gatineau (with some geographical overlap between the two).

Table 3.2 Transit schedules (GTFS) data sources and documentation.

GTFS Transit Schedule Region	Website
Ottawa	octranspo.com/developers
Gatineau	sto.ca/index.php?id=596&L=en (STO: Developer Space – Open Data)
Worldwide, including about 40 Canadian cities.	transitfeeds.com
Worldwide	transit.land/feed-registry
(Format Specifications)	developers.google.com/transit/gtfs gtfs.org

3.2.4 Planned Snow Removal on Bike Lanes

The City of Ottawa provides an online visualization of the portions of the bicycle paths and lanes scheduled for snow removal. Thus, the cyclable network in winter can be seen as a reduced one, but its connectivity can be studied by the same methods as the complete one.

However, this approach has not been taken in any software project that we are aware of, and requires further study and thinking to implement properly.

3.2.5 Topography

NRCan provides the Canadian Digital Elevation Model (CDEM): topographical data as an elevation raster (in GeoTiff format) image with about 20m horizontal resolution, and a vertical accuracy of 4m to 27m.. All of Canada is mapped and divided into a geographical grid, with the NCR falling in Regions 031F and 031G.

It should not to be confused with the Canadian Digital Surface Model (a similar resource), which would follow, for example, the top of trees and would be inappropriate, e.g, for a cycle path overshadowed by a tree canopy.

3.3 Locating Commute Trip Endpoints

For the purpose of establishing the endpoints of biking trips, most notably for commutes (residence to place of work or study), we found two main data-based approaches:

1) Identifying a spatial density of the population's residences, as well as the spatial density of work and study locations.

2) Obtain a set of origin (residences) locations for bike commute trips, and, for each origin point, a corresponding destination (work) location.

We think that the first is more appropriate for retail and service jobs that are interchangeable in nature, and where proximity to the workplace may be the main factor in job choice. In this case, we can measure both the access to local job opportunities, as well as other forms of *utilitarian* cycling (for purposes of shopping, entertainment,...).

Conversely, the second approach may be appropriate for those with specialized careers and post-secondary students, whose occupations can only be performed at a very specific location. It also suffers from the issue of personal privacy, as individuals may not want to divulge where they work; this problem can be mitigated by giving only approximate locations.

In both cases, the origins and destinations are specified as a geo-located point, which will usually not be exactly on a road. The simplest (though not always entirely accurate) method, is to project each point onto its geometrically nearest road (this is the approach taken, e.g., by the OpenTripPlanner routing engine) – in general, the relatively long commute trips, combined with a large number of trips aggregated for statistical purposes, could justify the approximate nature of placement of origin and destination points.

3.3.1 Building Locations and Types

Building Representation in OpenStreetMap

Building footprints are represented as *way*s, with a *building* tag. The building's area can be derived from its footprint polygon. Its height, or number of floors, if given, can be used to estimate volume, and thus the relative importance of a building (number of residents or jobs therein). The building type is not always specified (in which case, we have *building=yes*); otherwise, the building's function is given by a qualitative tag (e..g, *building=residential*) – the types of buildings can be grouped into categories for classifying their purpose in an origin-destination simulation setup.

Data Completeness

Visual inspection shows (possibly) complete coverage of buildings in Ottawa-Gatineau, Vancouver, and most of Edmonton, but only small portions (around 20%) in the greater Toronto and Montreal areas. Furthermore, not all buildings have their type indicated (residential, etc.) - notably, there are important gaps in Ottawa's downtown building types (this part of the city was historically mapped first).

There is an initiative to map all of Canada's buildings by 2020: *Building Canada 2020 initiative (BC2020i)*. Its webpage states that currently "there is no comprehensive, open database on buildings in Canada". This project reports that about 2 million of the estimated 10-15 million of Canada's buildings are currently on OSM. The project details software tools and methodologies for importing these buildings, and proposes governance structures, progress metrics, funding opportunities, and tagging standardization efforts towards this goal. It takes inspiration from various similar initiatives in several European countries and U.S. cities.

Data Sources

The set of buildings for the NCR comes from several specified sources.

About 206,000 of the NCR's over 306,000 buildings are specified to be obtained from *source=City of Ottawa*. This comprises most of the buildings in Ottawa. It's probable source is the City of Ottawa's open data of its buildings, which contains 293,698 entries.

A few thousand buildings in the OSM database are also specified to be obtained from CanVec. CanVec is a digital cartography product by Natural Resources Canada (NRCan).

3.3.2 Residential Land Use Areas

The OSM documentation describes basic format and tool information for importing (more) CanVec data into the OSM data-set. NRCan supports the Canadian Openstreetmap Community by providing its data in the OSM format.

CanVec provides locations of individual service buildings, but not of individual residential buildings. Rather, it provides polygons that encompass residential areas. Such land use polygons can be found in the OSM database of as *way*s of type *landuse=residential.*

CanVec data could be used to qualify some of those buildings whose type is unknown (*building=yes*). It can also serve as an approximation of residential density via polygonal areas.

3.3.3 Origin-Destination Pairs

Municipal Census: Sensitive Personal Data

The City of Ottawa provided us with the 2011 Origin-Destination Pair Survey, which includes:

- Commute distance (as the crow flies),

- Commute duration (based on departure and arrival times),

- Modes of transportation, including: car, walking, bike, transit (bus); can be multi-modal,

- Demographic profile (age, gender,...).

The geographical locations of origin and destination, however, are considered *personal data*, and were not divulged. We will see later in this report how this personal information can be used in a confidential manner to obtain important statistics towards measuring a bikeability index.

Commercial Data

The company *Strava* sells origin-destination pairs based on cyclists' GPS routes as tracked by their mobile app. To protect user privacy, the origin and destination locations are given as approximate (with a few hundred meters). O-D pairs are also classified as to whether they represent a commute.

The free sample data-set given by *Strava* for the City of Toronto gives an average commute distance of about 8km (as the crow flies), which is far in excess of the 5km trip specified in surveys for less confident cyclists. Because *Starva* is aimed at sports enthusiasts, it may be heavily biased towards much more experienced cyclists.

3.4 Cycling Behaviour

In this section, we describe different types of data reflective of where people actually bike.

3.4.1 Mode Share by Census Division

The national census reports the percentage of residences in each district that use biking as their main mode of commuting. The 2016 census data, and GIS census region polygons, can be found at Statistics Canada.

It reports data on "Main Mode of Commuting (10), Commuting Duration (6), Distance from Home to Work (12) and Time Leaving for Work (7) for the Employed Labour Force Aged 15 Years and Over Having a Usual Place of Work, in Private Households of Canada, Provinces and Territories, Census Divisions and Census Subdivisions".

The main mode of commuting gives the reported bike mode share.

3.4.2 GPS Traces

The company *Strava* sells data on cycling activity on road segments and intersections based on its users' GPS traces. As such, it serves as a virtual bike counter on each road, but only for cyclists actively using the S*trava* mobile app, and suffers from the same problem of being biased towards its users: it is likely that avid cyclists are willing to take road segments that average cyclists would not be comfortable taking. The users' GPS traces are mapped onto the OSM road network, and road segments are conveniently mapped to OSM road *id*s, making it straightforward to create a correspondence between the two data-sets.

User privacy is maintained, since counts are made on each road and intersection, but individual routes cannot, in general, be reconstructed.

3.4.3 Automatic Bike Counters

The City of Ottawa maintains counters in 12 locations on important cyclable paths and bridges. Counter data is available since 2016. There are several difficulties with the accuracy and completeness of this data, for various reasons:

- Other modes (most large wheeled strollers, wheelchairs, mobility scooters, occasionally skateboards and roller-blades) will be usually be counted as bikes;
- On the other hand, it often possible for a cyclist to bypass the counter via a path segment not part of the main designated bike route;
- Only some counters are operated in the winter: those where there is regular scheduled snow removal.

The counter data can be used to study the effect of seasonality on the average amount of cycling in the city, which could be used to estimate how cycle mode share varies by season. However, the small number of counters probably makes it an ineffective and cost prohibitive approach to obtain a detailed image of cycling connectivity in a city.

3.4.4 Cyclist Collisions

The Ottawa Police Service provides open bicycle collision data since at least 2004, specifying, among others: locations, gravity (including fatal), people and vehicles involved (bicycles have code "36") , time and day, weather conditions, etc. The data-set "Ottawa_Accidents_Collisions_2004-2015" was obtained from the Carleton University library. A similar dataset can be viewed in an interactive map produced by BikeOttawa.org .

Vehicle-on-cyclist collision density can be indicative of dangerous segments of the cyclable network. It can also be used to study the effect of different bike infrastructure types on cyclist safety. Finally, points of particularly high collision density can be considered as good candidates for placing protected bike lanes and crossings or constructing reasonable detours.

3.5 Environmental Data for Seasonality

Environmental data could be used for studying seasonal cycling behaviour. In particular, the City of Ottawa 2011 Origin-Destination Survey covers commute trips from late September to early December and specifies the day and time for each commute trip. Thus, it is possible to find the weather and lighting conditions for each trip. The survey covers three distinct seasonal periods:
- Early Fall: there is daylight during most regular commute hours;

- Late Fall: there is no longer daylight during most regular commute hours;

- Early onset of snowfall.

These three periods can be used to distinguish cycling behaviour with respect to seasonality.

3.5.1 Daylight

Daylight times for each day at a particular location can be obtained from online sources such as timeanddate.com

In particular, *civil twilight* is probably the most useful time for "artificial lighting is generally not required in clear weather conditions to carry out most outdoor activities."

Also, the National Research Council (NRC) provides a "sunrise/sunset calculator" for particular dates. It specifies that: "The NRC does not collect or maintain records of solar phenomena such as observed times of sunrise, sunset and twilight. Since the relevant data can be computed for past or

future dates to sufficient accuracy, such observations are not routinely made."

Daylight calculations are most interesting for the late Fall, where the seasonal impediment may be darkness during the majority of commute hours rather than temperature and snowfall. This is particularly pertinent for long isolated stretches of the cycle path, such as through parks or industrial zones.

3.5.2 Weather

Historical weather data for weather stations are provided by Environment Canada at. Weather data can indicate temperature and precipitation (rain, snow) on an hourly basis for any date. Meanwhile, the municipal O-D survey contains times and dates of commute trips taken. Thus, it is possible to identify the weather conditions during which each trip was taken, as well as estimate the amount of snow on the ground based on the precipitation in previous days. Such an analysis could be useful for extracting information about the effect of seasonality and weather on cycling behaviour, though significant work would be needed to develop a proper methodology.

3.5.3 Data Sources Summary

Of all data source types, the most critical and widely available is the **road and path network** GIS database, along with tagging information on how easy it is to cycle along the various parts of the network. Secondly, various data that locates places of residence and workplace and, even better, pairs them exists, though not yet completely in every Canadian city. These together form the most critical components for a GIS methodology for measuring the effect of cycling network connectivity on bikeability.

While government datasets are openly available, and corporations such as *Google* offer some access to cycling routing, it is crowd-sourced data that is by most used for studying cycling network connectivity. We will see in the next Chapter 4 how the **OpenStreetMap** road database has been extensively used by the research and not-for-profit communities, and even a government initiative in the U.K., for developing quite sophisticated cycling network analysis tools along an open-source philosophy.

While there also exists data pertaining to locating **actual cyclists travelling within the city**, this data does not appear to be of sufficient density to properly reflect the overall cycling behaviour, and such detailed surveillance poses serious difficulties in terms of cost, and personal privacy. The GIS methodologies surveyed in Chapter 4, and our own described in Chapter 5 do not require such data. Furthermore, the most interesting data is actually not about where people are already cycling (which is heavily biased towards more confident cyclists), but rather **where there is greatest potential in encouraging new cyclists**, and this is what the methodologies of interest attempt to study.

Finally, pertaining to **seasonality**, historical weather and sunlight conditions can be matched to cycling trips in population surveys (which may contain exact times and dates of travel) to analyze the effect of weather, sunlight, and seasonality on cycling behaviour. However, this require much additional work in creating a good methodology, and we do not do so here.

Data Completeness and Gaps

Based on discussion with the City of Ottawa and the City of Gatineau, we see a data gap as in end of trip facilities at businesses: **secure bike storage and showers**.

As for **locations of businesses** themselves, there is good information on business location both from OpenStreetMap and the federal resource CanVec, but the data is not yet complete or in most major cities. What would be of great value is a spatial density of job counts across the city map, as well as places of **residence**, even if the locations are approximate/low-resolution. Even better are

O-D surveys that give paired locations of residence-workplaces; and while this data exists, its personal nature makes it only available to the municipality. We propose that by grouping locations by proximity, the data could be effectively **anonymized**, while still having enough resolution to be useful in cycling network analysis.

Even though the residence and workplace densities and O-D information datasets may not at this time be fully available and complete in every city, it is our recommendation that it is high to time go ahead with network analysis approaches of the nature described in Chapter 4 and 5. Work on network routing and analysis should give a more detailed picture of what exact data is most needed for measuring bikeability, and can feed back into informing federal and municipal governments, as well as corporations and not-for-profit crowd-sourcing organizations, on where to focus time and resources in data collection.

4 Software Projects

In this Chapter, we present an overview of several cycling research projects that have developed software tools to analyze the bikeable roads from the perspectives of safety and network connectivity. We compare these projects according to their relative advantages and capabilities and suggest the most applicable elements of each project that can be applied to a Canadian context.

Two important components of such projects are a formula for assigning a **safety rating** to roads and intersections (as well as speeds to roads and delays to intersections) and a **routing engin**e for finding optimal routes between O-D pairs.

The projects also require a road network to analyze, and the **OSM road network** is usually used for this purpose; its free and easy availability makes it a boon for researchers, and its format is conducive to network analysis and routing as we have observed in the previous Chapter. We examine three important projects that are currently active and give numerical results on cycling for different cities or administrative regions.

4.1 Measurement of Cycling Quality over Geographical Regions

There have already been efforts to measure the quality of the cycling network over an entire region (city or census region). Two important research projects with differing approaches are the Bike Network Analysis (BNA) project for U.S. cities, and the Propensity to Cycle Tool (PCT) by Lovelace at al. (2017) that has been used to analyze the U.K.'s entire surface. Both projects have websites where the results can be examined by region. Additionally, the company WalkScore provides a "*BikeScore*" that measures access to bike infrastructure froma given point, and can be visualized over an urban map ot averaged as a score for the entire city.

4.1.1 Propensity to Cycle Tool (PCT)

The Propensity to Cycle Tool (PCT) is a project that comprehensively measures the quality of the cycling infrastructure thoughout the U.K., and includes an interactive website for visualizing the results on the national map. A comparable project could be constructed for Canada.

The PCT project uses the following components:
Data:
- **Road network from OpenStreetMap**,
- **Mode share and administrative region polygons**: percentage of commuters cycling to work per administrative region (2011 national U.K. census),
- Reported commuting by bike **origin-destination pairs** (2011 national U.K. census).

Software functions:
- **Routing engine: CycleStreets.net is used** to find routes between origin-destination pairs,
- **Core** software that combines all data and software and produces statistics,
- **Data Visualization**: an interactive website: www.pct.bike .

Formulae:
- Converting OpenStreetMap **road type** tags to numerical values (encoding: **speed**, **safety**, and **intersection delay**) – given as a table within the CycleStreets.net project,
- **Cyclist profiles**: - given by the CycleStreets.net project, which gives three profiles "fastest", "most quiet" (safest), and "balanced".

Each of these components of the U.K. project can be copied in the Canadian context. Some remarks

on how to do this:
- All projects that we have examined draw their road network data ultimately from OpenStreetMap – this road network data is recognized to be well-populated for Canada (Barrington-Leigh, 2017).
- Mode share percentages and administrative region polygons are readily available.
- **Origin-destination** pairs are held by the City of Ottawa (2011 census). They are deemed *personal data* and are therefore not readily available to outsiders, but can be analyzed by the City.
- **Routing engine**: there are several options avaialble.

In order to do statistical research on O-D pairs, and ultimately obtain indicator values, it is essential to have access to a routing engine that can construct routes for each O-D pair in an automated (batch) fashion.

4.1.2 Bike Network Analysis (BNA)

The Bike Network Analysis (BNA) tool has been developed by the advocacy group PeopleforBikes.org for the purpose of measuring the connectivity of the cycling network of a city. The project has been used to give a score for over 300 U.S. cities. The software code is available in its entirety, and the software can potentially be run for any city in the world to measure its BNA score. Results can be viewed online for many U.S. cities, The project uses the following components:

Data:
- **Road network from OpenStreetMap**,
- **Mode share and administrative region polygons**: U.S census data by census block.

Formula:
- Converting OpenStreetMap **road type** tags to a **safety rating** calculated according to a formula based on the LTS standard. The cycling safety is *absolute*: roads that qualify as LTS1 or LTS2 are said to be cyclable, all others (LTS3 and LTS4) are absolutely forbidden.

Software functions:
- **Connectivity:** a graph connectivity algorithm is needed to evaluate whether two administrative region are connected by a safely bikeable road. Two points are deemed connected if they can be reached by a safe (LTS 1 or 2) route that does not exceed 25% detour from a direct (any LTS) route. According to this rating and detour definition, the connectivity between administrative districts is assessed (yes/no).
- **Core** software that combines all data and software and produces the BNA score.

The output of the BNA project is a numerical rating (out of 100) for each analyzed city. As we will see in Table 4.3, the BNA score is not always a good predictor of bike mode share. The BNA tool uses *absolute* safety connectivity, meaning that a route containing even a short segment (or intersection) that does not meet the calculated safety rating is considered not cyclable. In practice, one could, e.g., dismount for a brief period and walk the bike across the problematic segment, while still completing a pleasant trip overall. As such, the decision of whether two regions are connected may be too strict in some cases. Conversely, a poorly connected network may still be rated well if there exists a single low-stress connection between census blocks. Connectivity based on absolute safety is also sensitive to potential errors, or gaps, in the road tagging information, which might result in computing a higher LTS rating than is warranted in reality.

For this reason, the BNA score may not be a good measure of the bikeability in Canadian cities, as it has produced results for major U.S. cities that are widely inconsistent (both over- and under-estimating) the bike mode share in those cities. The BNA project remains interesting in particular as a case study of implementing the LTS rating based on OSM road tags.

4.1.3 BikeScore

BikeScore is one of the metrics produced by the company *WalkScore.com,* giving a measure of bikeability for a particular location (with about a 1km resolution), based on four equally-weighed factors:

- Presence of bike lanes (a density count),
- Hilliness,
- "Destination and road connectivity" which is based on WalkScore's methodology that measures access to important amenities via routing on the road network,
- Cycle mode share data taken from the U.S. census.

BikeScore is proprietary software and therefore its code is not available and its methodology is based on patented technology. WalkScore.com currently operates on maps in the U.S., Canada, and Australia. Winters (2016) examined the correlation between the *BikeScore* and cycle mode share for 9 Canadian and 15 U.S. cities, and concluded: "Given the demonstrated significant and meaningful association across neighborhoods in diverse US and Canadian cities, Bike Score may be a valuable tool to aid with research and with planning for bicycle infrastructure and increasing bicycle mode in large studies."

4.2 Cycling Routing Engines

We have found that it is possible to have access both to real user O-D location pairs for commute trips, and to a good GIS representation of the road network. However, it does not appear to be realistic to trace real cyclists' routes from origin to destination: such data would be both private in nature and heavily biased towards the small sample of volunteer users. Instead, one can use a *routing engine* (router) to estimate the most optimal route one would take, where optimality can be tuned according to safety tolerance. The routing engine is the key software component that makes O-D data useful. Many routers are currently available (Table 4.1), many of them free and modifiable. All routers (except *Google*'s) use the OSM road network as their primary database.

Table 4.1 Software Projects with Cycling Routing Capabilities.

Project	Status	Source code	Notes
CycleStreets.net	Online router	Planned future release	Biking-only; plans individual O-D requests entered manually (via interactive online map), or online via API.
CycloPath.org	Offline, no longer maintained	Available, open source	Depends on GraphServer for obtaining the road network.
GraphServer	Offline, No longer maintained	Available, open source	Superceded by OpenTripPlanner.
OpenTripPlanner	Active, Desktop Download	Available, open source	Multimodal (e.g., bike+transit trips). Transit data in GTFS format. Topography in GeoTIFF format.
OTP Analyst	Active, Desktop Download	Available, open source	Branch of OpenTripPlanner. Data visualization capabilities.
Conveyal R5	Active	Available,	Grew out of the OpenTripPlanner project.

		open source	Implements a version of LTS.
GraphHopper	Active	No (commerical), some components open-source	Commercial product with API. Can be licensed, pricing by number of O-D requests.
OpenSourceRouting Machine	Active, Online router	Available, open source	Unimodal. Modes: car, bike or walk.
Mapzen Valhalla	Uncertain	Available, open source	Multimodal (including transit). Includes safety and hilliness for cycling.
pgRouting	Active	Available, open source	Bare-bones graph routing.
Bike Network Analysis (BNA)	Active	Available, open source	Project includes a biking router and safety rating formula based on LTS.
BikeOttawa.org	Active	No.	Ottawa-Gatineau only. Map of LTS ratings for all roads, and interactive router with choice of maximum LTS rating.
Google Directions	Active	No (commercial)	Unimodal: drive, walk, bike or transit.

We have identified **OpenTripPlanner (OTP)** as being a very good candidate for a routing engine for analyzing urban cycling commutes, due to these many factors:

- Freely available (downloadable) and modifiable (open-source),
- Runs on the desktop, allowing for data privacy,
- Has multi-modal abilities, including scheduled transit (in GTFS format),
- Includes topography (in GeoTIFF format),
- Active development community, good documentation, actively discussed online,
- Successfully tested and used in this report as described in Chapter 5,
- Has a web front-end, and can therefore be deployed as a website for individual route planning. It has been successfully deployed in about 15 important metropolitan areas as route planner (primarily for transit), and is therefore well-tested in real-world conditions.

The **Conveyal R5** ("Rapid Realistic Routing on Real-world and Reimagined networks") project has branched from the OTP project, and is created for *analytical* purposes, i.e., analysis of the type we are attempting in this report. However, routing can equally-well be performed in the OTP project. The R5 project has the important difference of implementing a version of the LTS standard. Because we only identified this project towards the end of creating this report, the simulations in Chapter 5 are created using OTP. However, the R5 project should be examined as a possible replacement.

The other project that can boast comparably strong features is **Mapzen's *Valhalla*** project. Mapzen was an open-source research lab (funded by Samsung), which closed down in January 2018. The existing *Valhalla* code is available for download, but is perhaps no longer supported nor developed.

The **OTP router** has all features necessary for performing O-D analysis. The main features of the router are as follows:

Given the data:

- A list of O-D locations;
- An OSM map file of the city;

- A GTFS transit schedule (optional);
- A GeoTIFF raster elevation map (optional).

And with parameter choices:
- Continuous trade-off setting between A) safest, B) fastest, and C) topographically flattest route.
- 11 different modes of travel, including: bicycle only and bicycle+transit;
- Almost all aspects of the router can be customized via configuration files.

One can compute:
- Length and duration of trips;
- Street-by-street directions, transit transfers, etc.

One can also visualize individual routes on a map viewer for purposes of debugging and sanity checks.

4.3 Formulae for Computing a Road Safety Rating

Generally, each project with a cycling router also has its own formula for computing the safety rating (as well as path speed and intersection delay) of each road. We give here a series of representative examples that should give insight into how OSM tags can be translated into a safety rating.

Cyclestreets.net offers an example of how one might the qualitative OSM road types to numerical rating. A safety rating of X indicates that the road is not accessible for cyclists and pedestrians (based on U.K. road laws). Additionally, optional road information in the table (not shown) may modify the quietness and, in particular, cycle lanes may increase the quietness rating to 100%.

Table 4.2 OpenStreetMap road type conversion table in the CycleSteet.net routing engine.

highway type	"Quietness" (Safety rating)	Speed (km/h)	Pause (seconds)		*highway* type	"Quietness" (Safety rating)	Speed (km/h)	Pause (seconds)
motorway	X	24	0		service	60	20	0
motorway_link	1	24	0		track	50	6	10
trunk	20	24	0		pedestrian	70	6	3
trunk_link	20	24	0		bus_guideway	X	24	0
primary	25	24	0		path	50	6	0
primary_link	25	24	0		cycleway	100	24	0
secondary	50	24	0		footway	50	6	0
tertiary	60	24	0		bridleway	64	6	10
unclassified	70	24	0		byway	80	16	0
road	50	24	0		steps	25	1	15
residential	80	24	0		construction	20	6	0
living_street	95	24	0		ferry	50	12	1800

Figure 4.1 shows the level of safety as evaluated by CycleStreets.net according to this formula for downtown Ottawa (warmer colours correspond to safer roads).
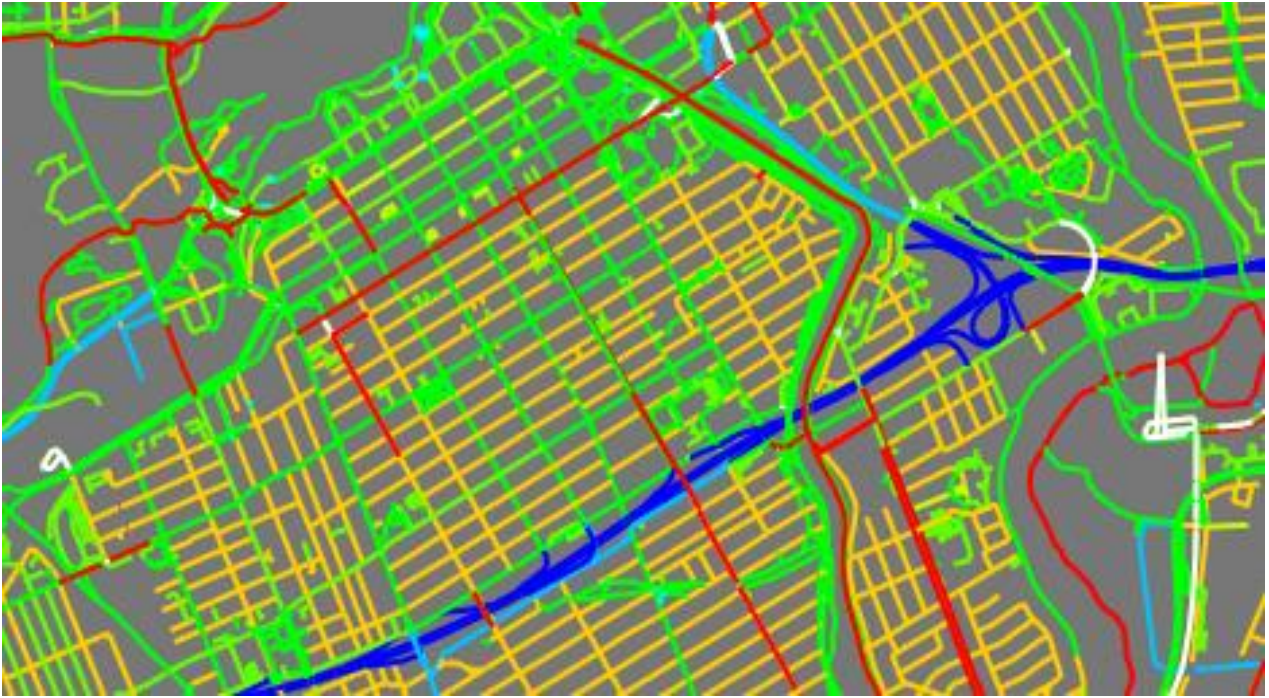
Figure 4.1 Example safety ("quietness") rating map based on CycleStreets.net table for downtown Ottawa.
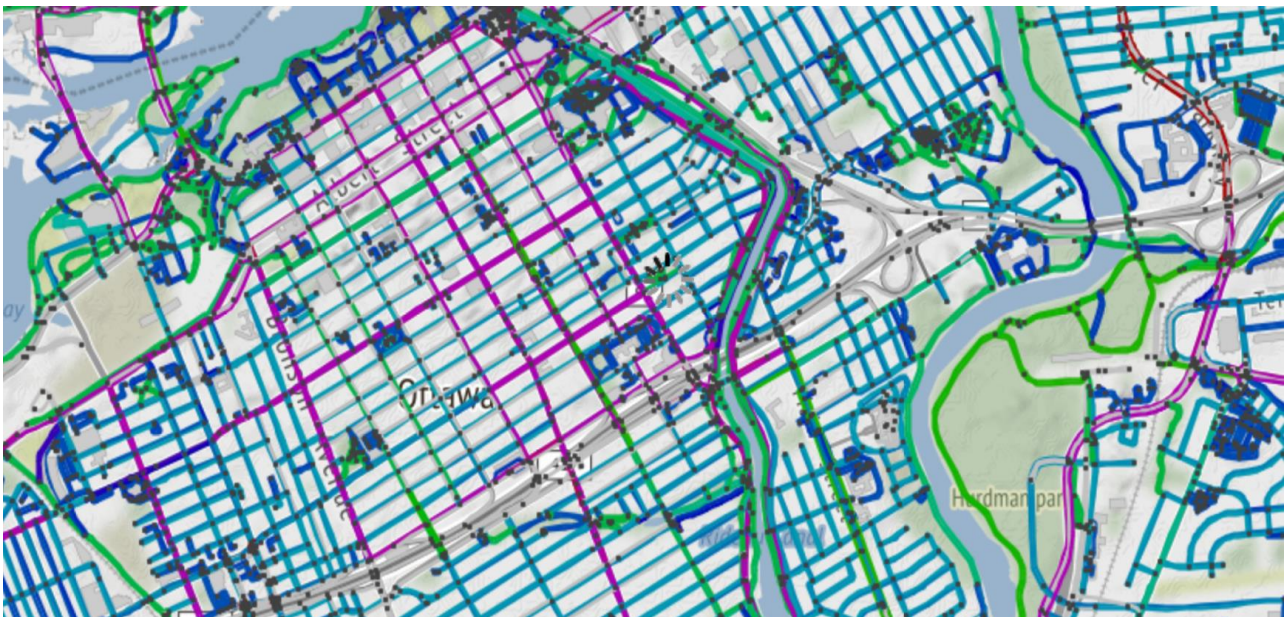
Figure 4.2 Example safety rating map by OpenTripPlanner for downtown Ottawa.

OpenTripPlanner incorporates an interactive map visualization of its computed safety ratings. This is useful for a visual assessment of the city's network safety and OSM database accuracy. Safety rating is classified by numerical value and grouped by colour: green (safest), blue, purple, red. Note that a bike lane right next to a busy street may not always be visible due to overlap.

BikeOttawa.org has implemented the 4 levels of LTS, and has evaluated it for every road and path in Ottawa-Gatineau, which can be visualized on an interactive map, as illustrated in Figure 4.3. The ratings are: LTS1 (blue), LTS2 (green), LTS3 (yellow), LTS4 (red).
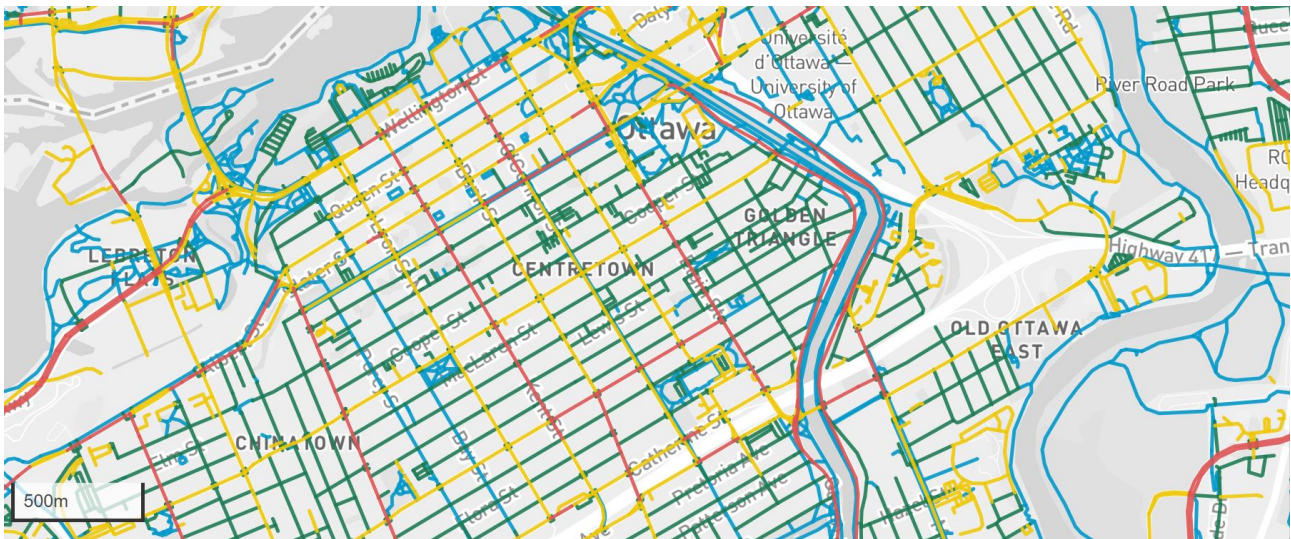
Figure 4.3 Example LTS rating map by Bike Ottawa for downtown Ottawa.

The **Conveyal R5** is a project that has branched out from OTP, and is designed for analytical purposes (such as the analysis we are attempting), rather than as on online routing tool. It differs from OTP notably in its safety formula calculation, which is an approximate LTS rating (Fig 4.4).

Pseudocode:
```
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
```
Source: blog.conveyal.com/better-measures-of-bike-accessibility-d875ae5ed831

Figure 4.4 Simplified formula for conversion of OSM road tags to LTS ratings in the Conveyal R5 project.

The BNA project uses its own interpretation of the LTS safety rating based on OSM road tags. Each road is classified as one of two levels: either "low" or "high" stress, where "low stress" corresponds to an LTS rating of 1 or 2, because the BNA algorithm is only interested in the connectivity of these low-stress roads, and does not weigh the relative merits of cycling on different levels of road safety. The project's source code includes a formula for discerning between LTS1-2 and LTS3-4, as a function of the following characteristics:

- Motor vehicle speed limit.
- Number of lanes for motor traffic.
- Presence of parking on the side of the road.

- Width of bike lane.
- Type of street or bike path: residential, cycle track, bike lane (including buffered), combined bike-parking lane, shared lane.

4.4 Projects Summary

At the current stage of technology, measuring bikeability in Canada will most likely require three essential components: a **routing engine** that can find probable routes taken by a cyclist between two points (O-D), a **safety rating formula** (e.g., based on a standard such as LTS) for roads and intersections, and origin-destination information, either taken from of O-D surveys or based on locations of residences and places of interest (notably, workplaces). Additionally, some **visualization** software is very desirable for analyzing the results of the road network and for potential infrastructure improvement planning. Because of the personal data sensitivity of O-D pairs from census data, it is of primary importance that the routing engine can be used on a local machine. Additionally, open-source source software is desirable for its ability to be inspected and modified at will and for its community support.

All research projects use OSM as their primary source and format for the road network. Each project implements its own measure of safety according to OSM road tags. The only road safety standard that we have found implemented was LTS, and this in three projects (BNA, Conveyal R5, and BikeOttawa). As the project websites themselves explain, the implementation of LTS based on OSM road tags cannot be exact, due to missing information in OSM road tags, most notably lane widths. Nevertheless, these represent the important attempts at a software implementation of an exisiting bike road safety rating.

Pertaining to projects whose aim is to score the bikeability of a city or area, we have identified: BNA, PCT, and *BikeScore*. The approach taken by the BNA project suffers from some difficulties, which discourages us from pursuing its approach:
- Conceptually, it only studies connectivity of the cycling network, without considering the nature of the locations being linked. Thus, it is heavily biased towards measuring the connectivity between various residential areas, which is of less importance to utilitarian cycling, while the other two projects focus on measuring connectivity to desirable locations.
- It enforces an *absolute* safety routing, where even short unsafe sections result in a failed trip; as such the methodology may be too sensitive to erroneous or ambiguous road type entries. The other two projects consider relative safety routing, where riding on roads with lower safety is allowed but penalized by the routing engine.
- BNA gives a surprisingly low score for several U.S. cities that boast some of the highest mode shares (see Table 4.3).

The PCT project and *BikeScore* take an approach that goes beyond cycle network connectivity to consider where the routes are heading, based either on reported actual O-D location pairs (PCT), or connectivity to places of interest (*BikeScore*). *BikeScore* consistently gives high scores to the U.S. cities with the highest cycle commute mode share, while the BNA project gives surprisingly low score to many of these same cities as observed in Table 4.3, whereas many cities with low cycle mode share obtain a score above 80/100.

Table 4.3 Cities in U.S. that have a commute bike mode share above 5%, and how they are rated in the BNA project, and by WalkScore.com's BikeScore.

U.S. City	Census mode share (League of American Bicyclists, 2016)	BNA score (/100)	WalkScore.com's *BikeScore* (/100)
Davis CA	16.60%	72	89
Boulder CO	9.00%	66	86
Berkeley CA	9.00%	N/A	89
Palo Alto CA	7.80%	42	N/A
Chico CA	7.70%	N/A	N/A
Missoula MT	7.20%	30	69
Somerville MA	6.60%	13	N/A
Portland OR	6.30%	35	98
Eugene OR	6.20%	25	74
Cambridge MA	6.10%	32	93
Mountain View CA	5.70%	N/A	N/A
Fort Collins CO	5.30%	56	80

Apart from the safety rating, cycling speed and delay at intersections are important routing parameters. Cycling cruising speed on bicycle paths is generally assumed to be in the range 17-19 kph, and average speed results in the city core (that is, with intersection delay) is around 15 kph. This is roughly consistent with tests using *Google* Directions (which also calibrates its timing with real GPS traces, when avaialble), while the cycling speed of 24 kph proposed by CycleStreets.net for most street types is uniquely high.

The next Chapter demonstrates some capabilities of the OpenTripPlanner router on an OSM map of the National Capital Region, with case-studies demonstrating the feasibility of an O-D methodology. Along with OTP, the related project Conveyal R5 may be an effective router for bikeability analysis, as well as Mapbox's *Valhalla.*

5 System Design of Bikeability Measurement with Case Study in the NCR

Having identified data sources and routing software available for cycling analysis, we propose a generic simulator design that can be used to evaluate probable cycling commute trips, from which meaningful statistics can be extracted towards the construction of an indicator of the connectivity for commuting purposes of the cyclable network.

We first propose a generic design, with various choices of components possible. We then test this design for a particular implementation, using the OTP project as the routing engine and road safety formula, and OSM building locations for O-D location data. Due to time constraints, we were not able to examine the Conveyal R5 project (which branched out from OTP) and may be more suited for this type of analysis.

5.1 System Design
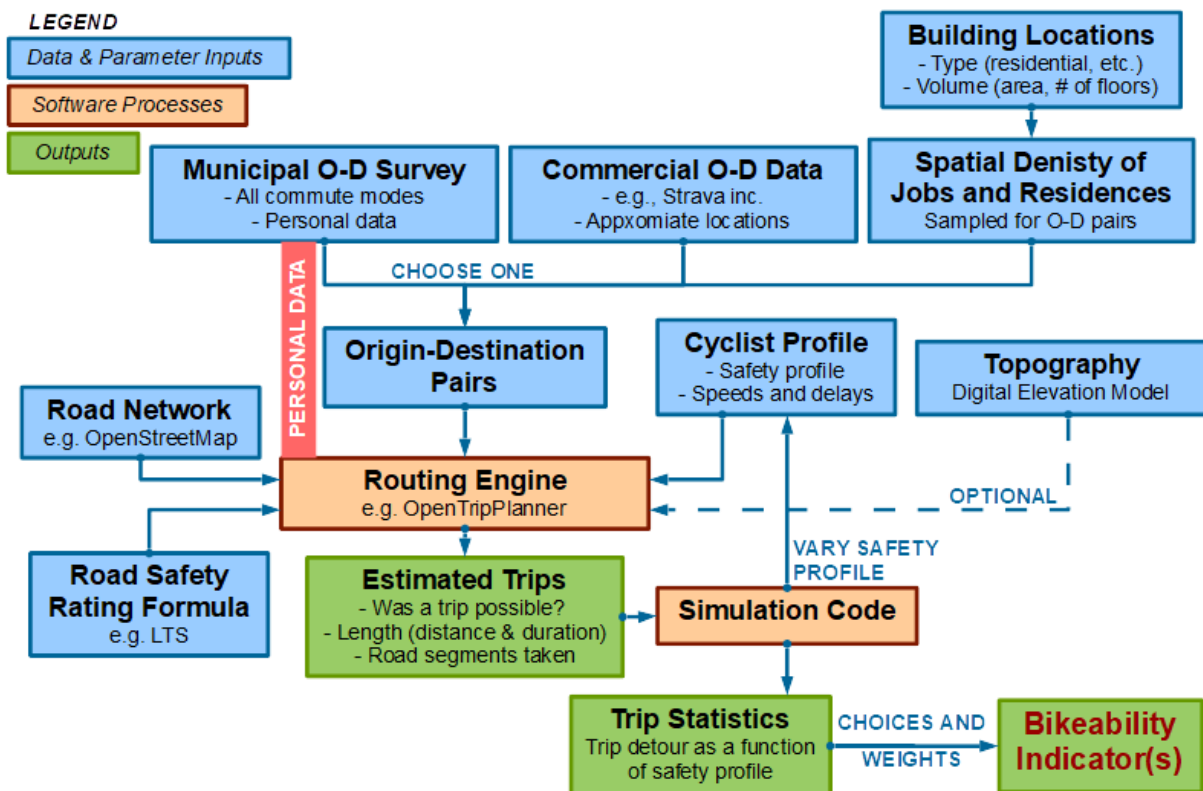
Figure 5.1 Generic software design for measuring a bikeability indicator based on weighted connectivity.

Figure 5.1 illustrates the proposed generic design of a simulator for identifying probable cycle commute trips and measuring the effect on trip statistics of varying the cyclist's safety tolerance. A simplified algorithm can be expressed as follows:

1) Load O-D pairs data.
2) Load road network data for city/region under analysis.
3) * Choose cyclist safety profile.
4) Run the routing engine software with all information from previous steps.

5) Obtain results about trip trajectories found (length, duration, worst-case safety, average safety).
6) * Aggregate results according to a formula in order to obtain meaningful statistics.
7) Display results (numerical table, graph, online, etc.).

The steps marked * indicate a choice between various options. If many such option combinations are desired, automating the whole process via software and running all experiments in a loop becomes desirable.

Origin-Destination pairs from a municipal commuting survey may be held by the municipality and analyzed by a routing engine without the need of sending data over a network, so as to preserve data privacy. In this case, we can use both cycling and non-cycling commutes for analyzing the quality of the cycling network for commute purposes.

Survey Data: Actual Cyclist Behaviour
Only a small portion of commute trips from the municipal survey is expected to be by bicycle. We may consider this O-D sample as biased towards more experienced cyclists. Questions that could be answered by such a simulation include:
1) By how much (time, distance) must a commuter increase their cycling trip if they change their safety tolerance?
2) Given a safety tolerance, what is the average safety ratings for all trajectories taken? (this is more-or-less a measure of overall trip "stress").

Survey Data: Potential Cyclists
One could also study how difficult it would be for commuters using other modes to switch to cycling. While most O-D pairs in the municipal survey are expected to be non-cycling, we can still derive meaningful information form this much larger sample. Notably, we might be able to estimate what proportion of non-cyclists are close to a threshold where they would be willing to switch to cycling mode. Questions that could be answered:
3) How much additional time would the commute take if switching to bike mode? Do this for each cyclist safety profile.
4) For each safety tolerance, is a cyclable commute feasible within a specified (time, distance) pair – do this for various (time, distance) limits. The result is a percentage of possible bike commutes for each (time, distance, safety tolerance) combination.

Alternative to Survey Data: Building Locations and Types
In the case that actual commute O-D location pairs are not accessible, one can perform a similar analysis based on building locations and types – in particular, these can be taken from the OSM database for those cities where the building database is close to complete (e.g., Ottawa-Gatineau). In the next section, we demonstrate this approach in a localized case study.

5.2 Case-Study: Access to Parliament Buildings from Residences in Ottawa-Gatineau

In order to test the OTP router and make a minimal proof-of-concept demonstration of our methodology, we perform a study of likely routes from the Parliament Hill to nearby residences, as routed for different safety profiles, and observe how the simulation results can be used towards calculating a bikeability indicator. The simulation is set up as follows:

Destination

For simplicity, we only consider one point on Parliament Hill (75.6995ºW, 45.4247ºN). This single point is meant to approximate a very concentrated region of high-rise office buildings, and thus a

major employment centre, notably for federal government workers.

Origins

1000 residence buildings were chosen randomly from the OSM database in a 5km straight-line radius around the destination. Buildings are considered residential if their OSM *building* tag is one of the following: *apartments, dormitory, residential, terrace, house, detached, semi-detached, static_caravan, cabin, bungalow,* or *block.* Note that these were all the tags that pertained to residential-type buildings in the Ottawa OSM database. Other cities might have additional *building* types that could qualify as residential.

Cyclist Profile

The OTP router allows a continuous setting of the trade-off between optimizing routes for safety and for shortest duration (there is a third dimension also: finding the topographically flattest route, which we do not consider here). We consider the two extreme settings on this continuum: the "fastest route", whose meaning is unambiguous as it effectively ignores road safety ratings; and the "safer route", where additional weight is given to less-safe segments in the routing choice, but nevertheless these segments will occasionally be taken if the detour around them is too great. This corresponds to a *relative* safety regime, and signifies that most cycling trips can, in fact, be completed (indeed, all trips are routed successfully in this case-study).

Figure 5.2 Example of the fastest and safer route found by the OTP router for a given O-D pair.

Results

An example route from a residential location to the Parliament Buildings is shown in Figure 5.2, with both the fastest and safer routes found by the OTP routing engine. The average results over

1000 residence choices are summarized in Table 5.1. Note that change can be calculated both as mean-of-ratios or ratio-of-means; both approaches give similar results in this numerical regime.

Table 5.1 Summary of case-study simulation trip results.

Average value	Safer Route	Fastest Route	Change
Trip length (m)	4961	4724	~5%
Trip duration (min)	23.94	21.18	~13%
Average speed (kph)	12.4	13.4	~7.5%

We can make some **basic observations** from this downtown cycle data:

- The change of safety profile has a stronger effect on trip duration than on its length. Duration may thus be the more sensitive parameter, and a better one to measure bikeability. Duration also includes the effect of intersection delay and tends to penalize routes with frequent stops.
- The average trip is within the 5000m and 30min commute bounds proposed in the literature for an average cyclist.
- Given that the cruising speed of the simulator is set at 17.7 kph, we can remark that delays at intersections result in a significant reduction in the average trip speed.

The increase in trip length and duration between the two safety regimes is a testimony to the existence of less-safe segments on the most direct routes. In the ideal case of all roads being improved for maximum bike safety, the fastest and safest routes should overlap, with the amount of *change* being zero. More realistically, as more safe-enough segments are added to shortcut the most common detours caused by less-safe parts of the network, the *change* should decrease correspondingly. As such, the *change* value of trip duration or length can be seen as an inverse indicator of cycling infrastructure quality for an average cyclist for the purpose of commuting to the Parliament Buildings and surrounding office buildings. This indicator can be calculated for any place of work, and then spatially grouped and averaged as desired.

The simple simulation setup could be **further enhanced** in several ways, including:
- Trips could be strictly limited to a maximum distance and duration, and *change* statistics calculated only from those selected trips. Also, trips could be given a minimum distance, below which the trip would be considered a candidate for walking.
- The residence locations were chosen at random with equal weight given to every building recognized as residential. However, some buildings (apartments, residences) house hundreds of inhabitants: the population of these buildings could be estimated from their building footprint area and number of floors (obtainable from the OSM database).
- The safety regime could be changed from *relative* to *absolute,* signifying that roads below a certain safety threshold would be strictly forbidden: this would result in a greater *change* in trip length between *fastest* and *safer*, but also in a certain proportion of trips that cannot be completed safely – this proportion would be a second value that would be included in a bikeability indicator formula.

- There is room for experimenting with improving the formula for route safety rating. The OTP router could be replaced by the similar Conveyal R5 project (with which it shares code) or use the formula implemented in the BNA project: unlike OTP, both of these projects attempt to implement the LTS standard for evaluating cycling road safety.

Additional work is required to properly calibrate the different parameters to obtain a more accurate bikeability indicator. Nevertheless, we have demonstrated that a cycling router is a key enabling technology, which can be combined with route information and O-D data to obtain probable bike trip routes for different cyclist safety profiles.

Tracking actual cycle trips (e.g., via GPS traces) suffers from user privacy concerns, cost of acquiring commercial data, and bias towards the section of the population willing to report their trip traces (i.e., probably the more avid cyclists). A good cycling routing engine fed with reliable O-D data is therefore probably the most effective method at this point for estimating where cycling trips take place and where they are being delayed or prevented by incomplete infrastructure, which makes this *O-D routing* approach very useful both for measuring a bikeability indicator and also for cycle network planning. We think that the approach described here is the most significant part of the computational work required to produce a meaningful bikeability indicator, though other weighing factors, such as presence of good end-of-trip facilities, could certainly be included.

6 Observations

In this report, we have examined the feasibility of composing a bikeability indicator for measuring the quality of the cycling infrastructure for facilitating commutes by bike. We have seen that the problem is being examined in literature, that many good enabling data sources exist, that several good software projects (mostly free and open-source) exist for routing and safety evaluation of the road network. Furthermore, there is keen interest in the scientific literature and from community organizations to improve the cycling infrastructure, making the development of a bikeability indicator a timely and pertinent endeavour.

We were able to connect these components into a working generic simulator and show a case-study example for the National Capital Region. It appears that designing a quantitative software methodology is essentially feasible at this point, even though there exist partial gaps in the data and models – the methodology can be refined in time as the quality of the existing resources improves.

Our main observation on how to measure bikeability based on existing literature and projects is that it requires at minimum these three essential components: a safety rating for each road and path, as well as a database of origin-destination pairs (e.g., for commutes), and to have access to a routing engine that can make educated guesses on the most likely routes. Thus, simply studying the connectivity of the bikeable road graph is not very interesting: the connectivity between two residential areas is not of prime importance (for utilitarian trips), and the O-D routing approach is technically feasible and gives a more accurate picture of which infrastructure is the most important (i.e., which are the main cycling arteries).

Also, we have found that measuring bikeability via an O-D routing approach is strongly tied with two other issues: improving the quality of the GIS database (road safety qualifiers) and placing new cycling infrastructure (bike lanes, protected intersections) for maximum benefit. Indeed, routing based on O-D pairs automatically identifies the most probable popular routes (which can then be vetted to ensure they are described accurately in the database), and excessive detours in certain regions may indicate the need for a cycling improvement to shorten these routes.

The final issue to address, and one we will not attempt to resolve here, is how to weigh and select among the existing options to calculate a final indicator value. The main choices to make are:

- Which road safety model to use (LTS, BLOS, etc.), and how exactly to implement it in software (or which existing implementation to use).

- How exactly to define the amount of detour and how to treat unsafe segments (whether to enforce absolute or relative safety).

- How to profile the typical user: what are their road safety tolerance, maximum commute time (and distance), and their cruising speed. While some estimate of these values can be agreed upon based on literature, exact values still need refining.

These options are technically simple to implement and to modify if necessary.

6.1 Key Enabling Components for an Urban Bikeability Indicator

6.1.1 Road Safety: Urban Cycling Bottleneck and Essential Parameter for Measurement and Design

From both the literature and software projects, the safety rating of the road as experienced by the cyclist (mainly based on physical separation from traffic) is of primary concern for determining whether a cycle trip will be taken, followed by time and distance.

Furthermore, the safety of the infrastructure can always be increased, whereas the length of the trip

is subject to the urban layout and physical constraints (e.g., a river). Constructing the bikeability indicator based on safety and detour makes its value depend primarily on the safety of the network, and much less on the specific geographical layout of the city or region in question – therefore, the indicator becomes primarily a measure of the quality of the existing infrastructure to support the most needed trips, and should improve to as the most useful cycle paths and lanes are added.

The road safety ratings assign a value to each road segment in a network. In the *absolute* connectivity approach (notably, in the BNA project), all routes below a safety rating are strictly forbidden; one can then measure the following quantities:

1) What percentage of O-D trips can be completed via roads within the desired safety rating?

2) For trips that can be completed, how much (absolute or percentage) detour must one make to complete a trip on the safe-enough network?

On the other hand, the *relative* connectivity approach (as in the PCT project) proposes to assign a much heavier weight for all roads with a low safety rating. For very low safety rating, this may be roughly equivalent to having the rider dismount and advance at walking speed. This relative approach has the advantage of ensuring connectivity for most trips while significantly penalizing dangerous road conditions. Thus, in general, most trips (unless they require the freeway) can be completed, and delay due to safety can be used as a measure.

Another matter is defining the amount of detour caused by having to take a safer route, as there are several ways to define the direct route to which one is comparing the following scenarios.

1) Travel in a direct line (assuming maximum cruising bike speed).

2) Travel in a physically possible line, which may be same or different to the first scenario, depending if there is a physical obstacle in the direct path, such as a river or large hill.

3) Travel by bike assuming an experienced cyclist profile (i.e, ignoring safety concerns).

4) Travel by car. May be of significantly different distance from #3 if freeways are taken.

6.1.2 Origin-Destination Surveys – Highly Desirable Population Feedback Data

The O-D location surveys are the only data source that we could identify for establishing probable existing and potential cycling commute routes. The U.K.-wide cycling analysis project Propensity to Cycle Tool uses a similar national survey, with the same O-D pair compared according to different cycling safety profiles and comparing their delays.

In the Ottawa 2011 survey, the vast majority (98%) of reported commutes were non-biking – it is these O-D pairs that represent the population that could be made to switch mode, and are thus of particular interest. Using a routing engine, it is possible to study what percentage of these commutes are within reasonable distance but are prevented due to unsafe road segments.

O-D pairs constitute sensitive personal data and are suitable for studies done by the municipality. Routing based on O-D surveys can be used to measure the quality of access to current job locations and is thus particularly suited for career jobs of a permanent nature, or for post-secondary education, as these occupations usually require the person to commute to a particular fixed location.

Alternatively, locations of buildings, along with their classification (residential, commercial, office) allows studying the cycling access to work opportunities, in particular jobs of a retail and service nature. Additionally, such data can be used to assess the potential for other "utilitarian" cycling trips (shopping, entertainment, community services, etc.), which are not reported in the O-D survey.

6.1.3 Advantages of OpenStreetMap's Network Data

All the open source projects that we have examined in Chapter 4 use OSM as their preferred or only source of road network data – the use cases and deployments have been tested over many regions in Europe and the U.S.. There are several notable advantages of the OSM urban database:

- The road connectivity is explicit in the format (unlike in data found on the municipal website, in formats such as Shapefile or GeoJSON, where this is difficult or impossible) making it much easier to do routing properly.

- All city information (road layout, road properties, buildings, etc.) can be stored in a single file, human-readable, and parseable in the well-adopted XML format.

- The global ubiquity and uniformity of the data and format results in an urban database that is most easily usable by researchers and enthusiasts, who have adopted OSM, making it a very accessible standard

- The active community of OSM volunteers (at the international, national, and local level) and hundreds of related open-source software projects, form a culture where the database and software tools are continually being reassessed and improved. There are several well-functioning projects oriented on visualization of the cycle network or routing for bicycles alone.

6.1.4 Data Security and Integrity Considerations

Two important caveats should be mentioned regarding the proposed software methodology:

Using online routers, such as CycleStreets.net or Google's Directions API, requires sending O-D pairs over the Internet and to a remote entity. However, other routers, such as OpenTripPlanner, can be run on a local computer. Thus, it is possible to preserve the confidentiality of personal data, most notably residence-workplace location pairing used in the O-D method.

As for urban data from the OSM database, we observed that the data is usually correct, but may be incomplete: while the road locations are the most accurate (and usually the first, or only, feature of the city to be mapped), only 3 major cities in Canada appear to have a complete set of buildings, and the coverage is usually patchy (can be less than 20%). Furthermore, some OSM roads lack important optional tags that pertain specifically to cycling safety (and streets are described more with tags that relate to their ability to accommodate motor traffic), and many buildings lack information that can categorize them as residential or commercial. Some of this missing information could be imported from municipal databases or national sources such as CanVec. Conversely, a local (clean and safe) version of the OSM city database could be maintained at the municipal level, owing to the many advantages of this format.

6.2 Interesting Venues of Research Going Forward

6.2.1 Identifying Most Important Segments in the Bikeable Network

We have identified examples where the safety rating of a road was far better than the physical conditions would suggest (where, in fact, biking proved dangerous) – this was due to insufficient information tagged on to the OSM entry for said roads, and could be due to thinking of roads as primarily for motor vehicles, even in cases where there is no alternative cycle lane.

The principal arteries for utilitarian urban cycling might be non-obvious (often, they may consist of short-cuts across residential areas or pedestrian paths), and inspection of the many thousands of roads and paths that make up a city is a daunting task. The advantage of an O-D approach combined with a router is that it can easily identify the likely most taken roads and paths, or (under a router

setting that allows for low-safety cycling), the parts of the road network that, if made safer for cycling, would benefit the most commuters.

O-D routing allows focusing efforts on the paths that will likely be used the most: both for improving the database and for infrastructure planning. As both the database and the infrastructure are developed, the new network can be reassessed in the O-D methodology: thus, with the proposed approach, measuring the bikeability indicator, improving the database quality, and improving the infrastructure (with most necessary segments prioritized) form a self-improving feedback loop.

6.2.2 Standardizing Road and Intersection Safety Rating for Cycling

While there exist several standards for numerically rating road safety for cyclists, they are based on very many physical characteristics (Gutierrez, 2017), not all of which can always be found in a GIS database, and represent a significant amount of work to implement in software. The only standard that we have found implemented (and this in several projects), was the 4-level LTS rating proposed by the Mineta Transportation Institute (May 2012) as a function of road quality information as specified by the OpenStreetMap set of road properties. Even within the LTS specification there is room for interpretation when mapping its properties to a specific database (e.g., OSM), and there may also be missing information, most notably lane width.

Another difficulty in studying the quality of the cyclable network is the proper modelling and characterization of intersections (their safety rating and crossing delay), and this for two reasons:

1) Intersections are more difficult to model than roads, as they require modelling of lanes and possibly crossing the road. Proper safety and delay assessment of intersections is challenging to implement, and not all routing engines handle this in an accurate way.

2) Databases such as OSM or the municipal data-sets contain more qualitative information pertinent to road safety than to intersection safety. The only information, if any, found for most intersections is the presence/absence of traffic lights.

An important scenario is where it may be faster to take a cycle path detour around a built-up area, rather than a direct route with many intersection stops. It is desirable that the routing engine recognizes this properly.

6.2.3 Seasonality and Isolation

The high bike mode share in several Nordic countries indicates a **large potential for growth in utilitarian urban cycling, even in winter**. The presence of time and day information in an O-D commute survey covering several distinct seasonal ranges, combined with weather and lighting information, as well as information about bike path snow plowing schedules. Such an analysis would require further work, however, since the existing projects were mainly developed and tested in countries with limited snowfall, and this effect has not been specifically taken into account.

Apart from snowfall, another important issue is **darkness on isolated paths**. From our research, the primary safety concern for most cyclists is physical separation from motor traffic. However, there is an advantage when cycling in traffic-heavy areas, in that one is (in most cases) well-seen by others should a personal attack or medical emergency occur. Conversely, locations that are the most separated from traffic (bike paths, industrial areas), may have segments that are very isolated, and thus represent an additional safety concern and a potential impediment to cycling.

This problem is related to seasonality: in the late Fall period, while there is as yet hardly any snow, the regular commute hours occur mostly during darkness. We saw that the OSM data has optional lighting information for roads and paths, but it was found to be haphazardly completed. Identifying these isolated locations in a systematic (computational) manner is a problem that we have not seen addressed in the literature. As biking increases and a biking culture grows, this may reduce the

problem of isolation, as important cycling network arteries will become better frequented.

6.2.4 Multi-modal Commuting: Biking + Transit

A basic difficulty in assessing commute bikeability in a large spread-out city such as Ottawa is that there are entire regions, notably the suburban regions of Barrhaven, Kanata, and Orleans, which are mostly residential (Kanata additionally has a significant high-tech office sector), and have few corresponding commercial buildings (with the main exception being retail) – most jobs are located more than 10km away (in a straight line). As such, bike-only commuting becomes prohibitive for most people, regardless of infrastructure quality. In this case, since most commutes cannot reasonably be completed by bike alone, an indicator of the infrastructure quality for biking may become meaningless when taken in isolation from the transit situation.

In this case, the large residential area will probably have one or more major transit hubs, and the principle options for getting to work in another part of the city are:

1) Local bus, followed by transfer at main transit hub, then take main transit line to work.

2) Bike (or walk) to main transit hub, then take main transit line to work.

3) Drive to main transit hub, then take main transit line to work. ("park-and-ride")

4) Drive to work.

By encouraging the second option as much as possible, one alleviates the load on local transit, while including cycling in commutes. If the transit hub can be cycled to by a safe-enough and direct-enough route, and if the hub has safe bike parking, option #2 may be for many a more cost-effective (healthier, more pleasant, possibly faster) commute than driving to work.

To alleviate the load on local buses and reduce car traffic, cycling infrastructure from residences to the main transit hub(s) would be of primary concern. With and O-D approach that allows for transit segments, this becomes readily visible: by using a router in a multi-modal fashion, one might observe cases where the router chooses option #2 – from this, one can derive an indicator that increases as the safety of biking links to the transit hub(s) increases.

As for technical feasibility, while Google Directions (and its API) offers routing for individual modes (driving, walking, cycling, transit), there is no option for planning multi-modal trips at this time; many open-source routers do not have a multi-modal feature either. However, several free open-source tools have just such a feature: OpenTripPlanner and the related Conveyal R5 as well as Mapzen's Valhalla. They easily allow importing transit routes and schedules based on the widely adopted and freely available GTFS format databases. The OTP router has been deployed as an interactive route planning website in tens of cities across the world by the municipal governments as a tool for obtaining directions. Though most deployments have focused on finding scheduled transit routes, the router is inherently multi-modal and multi-segment and can support multiple cycling and transit route segments within one trip.

Even without the use of a multi-modal router, one can plan cycling networks from residential areas towards main transit hubs, and provide safe bike storage at transit hubs, thus integrating both networks (Alta Planning, 2012; Veryard, 2018).

6.2.5 Community Involvement in Cycling Analysis

The **OpenStreetMap** open-source GIS database has proven to be of primary importance in most quantitative research projects and is a popular resource for finding bike routes throughout the world. OSM's easily accessible and editable open data, its large community, and data format make it a pole of attraction for volunteer activity for data and product creation. Efforts are coordinated at the national level (osmcanada.ca) as well as the local level (OSM Ottawa meetups).

Importing GIS data into the OSM database can be said to consist broadly of two tasks: placing geo-located features (roads, buildings, etc.) and tagging them according to their properties. The first task is largely complete as pertaining to roads. For buildings, this is only the case in some Canadian cities, and there exist ongoing efforts to import building locations (e.g., from CanVec).

Tagging may be said to be the easier of the two tasks, particularly given the availability of online photos for reference: a road may be tagged with very many optional parameters that may be pertinent to cycling safety and speed. There is, therefore, value in encouraging efforts towards a complete tagging of OSM roads with cycling-pertinent information. However, this tagging is based on physical features only, and is sometimes limited in options (notably in lane width information) - the OSM documentation does not indicate a way of marking safety for cycling in a direct way, as this may be considered subjective, or can be the result of a complex interaction of physical features.

Cycling advocacy agencies (CanadaBikes.org, BikeOttawa.ca) provide an alternative perspective on cycling. At the national level, there is a desire (Canada Bikes, 2016) for a National Cycling Strategy such as exists in many European countries where bike mode share is significant as measured by the Eurobar422a (2014); an improved cycling strategy and infrastructure is seen as an excellent investment that touches and improves upon a vast variety of human needs: health, clean air, recreation, economy, tourism, taking the load off traffic and transit, etc.

Local advocacy groups can give useful feedback on specific needs of a city, which can be combined with quantitative analysis of O-D routing to identify priority cycling infrastructure locations. Local groups also "want to see federal leadership on cycling for all of Canada" (Bike Ottawa, 2018).

6.2.6 Emerging Urban Cycling Modalities

Although the bicycle is an old mode of transportation that precedes motor vehicles, it is currently experiencing a renewal on several fronts: improvement of the vehicle itself, a strong advocacy for urban cycling (to reduce pollution and traffic, improve health, save individual and municipal money, etc.), and in cycling route analysis and planning. A convergence of efforts from many fronts (government, research, cyclists, and volunteers) has created a momentum of creativity in new ways of using this old technology.

The emergence of bike sharing companies and municipal initiatives is an important part of the re-emergence of interest in cycling and an opportunity to "try before you buy" for those hesitant to invest in a bicycle and may be an important mechanism to encourage the demographics most likely to switch to cycling for some of their utilitarian transportation needs. According to Veryard (2018), "bike-share has greatly facilitated the use of cycling to complete trips on public transport as well".

The resurgence and improvement of electric bicycles (e-bikes) may significantly increase the distances people are willing to cycle and may become an attractive commute mode for people with longer commutes.

The renewed interest in cargo bikes (for mail package delivery, food distribution, etc.) may introduce new human-powered vehicle types on the cycling network, which may require reassessing safety and lane width assumptions. Balm (2017) summarizes the potential and challenges of light electric freight vehicles (LEFVs), and see opportunities for their expanded use in the Netherlands if improvements are made in policy, infrastructure, and the LEFVs themselves. According to the European Cyclists' Federation (2012), 25% of all urban cargo (and even 50% for light cargo) could be moved by cargo bikes; with an average speed not much lower than that of trucks when moving in the city centre, a cargo bike in France is delivering over 50 packages per day, with a payload of up to 250 kg; cargo bikes are proving to be cost efficient when compared to delivery trucks, and have the potential to reduce both the very high rate of fatal collisions due to delivery trucks and also traffic congestion in the urban core.

7 Conclusion

What is bikeability and how can it be measured? In a perfectly bikeable city, each citizen would be able to cycle via a direct and flat route that is always well-buffered from motor traffic towards their destination of work, where safe bike storage and showers await them. While this is an impossible ideal in any large city, it remains a clear goal towards which one can aim, and a quantifiable one for which progress can be measured via one or more numerical indicators. This report presented a methodology that combines available GIS software tools and datasets to measure the effect of road safety on detour for cyclists who are not very comfortable sharing the road with heavy motor traffic (i.e., most of the population, and the target one to be encouraged to cycle to work). There appears to be a data gap as concerning bike storage and showers at workplaces. Also, an additional analysis can be made to include combined cycling and transit to work, by studying cycling access to major transit hubs and using multi-modal cycling+transit routing. In final analysis, these different factors could be combined according to some weights in order to obtain a single indicator of bikeability. It is expected that a well-designed indicator would be a predictor of commute bike mode share.

Bike mode share in Canada remains far below that of many countries in the European Union that have adopted a **national cycling strategy (NCS)**. Canadian advocacy groups have been asking for an NCS, which appears to be the deciding factor of which European countries have large bike mode share, rather than physical characteristics such as climate, topography, or geographical spread. Even nordic countries with comparable climates to ours have the potential for high bike mode share (e.g., Sweden and Finland, at 17% and 14% respectively).

Commute origin-destination pairs in both cycling and non-cycling modes can be obtianed at the municipal level, but this personal data is not available for public research. **Sensitive personal** origin-destination commute **data could be anonymised** by giving only approximate locations (e.g., grouping all households in a neighbourhood together), while remaining very valuable for giving a sufficiently good estimate of where most people need to cycle to work.

There are good example of open-source projects that can be used as "off the shelf" components and sources of information and inspiration for developping cycling network analysis tools for Canada. An essential component of cycling network analysis is a router for cycling trips. Several working and well-maintained open-source projects exist for this purpose. Together with the router, one needs a formula for evaluating the **safety of roads for cycling**, since the degree to which one needs to share the road alongside heavy motor traffic is the primary impediment for taking on cycling for utilitarian purposes.

Three significant projects give different approaches to measuring bikability in a city or administrative region. The Propensity to Cycle Tool combines open-source software developed by the University of Leeds with national O-D survey data of the entire U.K. to map cycling behaviour and potential in the entire country. The results can be viewed online on an interactive map and can be used to examine cycling behaviour by region and can be used to prioritise cycling infrastructure interventions. The PCT serves as an excellent example of how the best of current data sources and technologies can be integrated to study actual and potential cycling behaviour, and set infrastructure imporvement goals while predicting bike mode share increase. The BNA project rates over 300 cities in the U.S. by the connectivity of its administrative regions. However, we found the BNA score to correlate poorly with bike mode share in cycling-friendly cities (those above 5% bike mode share). *BikeScore,* produced by the private company WalkScore, appears to correlate well with bike mode share, based on 24 cities in Winters (2016) and 12 cities in this document. These three projects and all other software projects found use the crowd-sourced OpenStreetMap road database for both road network topology, and road and intersection typing.

Based on analysis of existing projects and research and our own reasoning, we found that in order to be predicitive of bike mode share a bikeability measure needs to be aware not only of the road network and the safety rating of its components, but also needs to be aware of where people tend to begin or end their trips. For this purpose, **O-D commute surveys (both cycling and non-cycling) are most desireable**, while the geographical denisty of residences and job locations may be a suitable replacement.

Identifying where exactly people cycle is problematic due to the **high cost** (of placing many bike counters or buying GPS trace data from a commerical source) and **potential privacy concerns**, as well as a heavy bias towards much more experienced bikers willing to share their GPS location via smartphone apps aimed at sports enthusiasts. Furthermore, if one wants to increase bike mode share, it is more interesting to study not only those who are already cycling (the most resilient will cycle in almost any conditions), but perhaps more importantly those who would be willing to switch to cycling commutes if their cycling route had some infrastructure impovements. Indeed, all our findings point towards cycling mode share having the most potential to increase if efforts are focused on the needs of a large portion of the population (perhaps 33%) which can be considered "enthusiastic but concerned". For this reason, a routing engine, combined with a safety rating formula and origin-destination data, appears to be the most feasible approach at this time for evaluating both current and potential cyling behvaiour, as well as for planning cycling infrastructure improvements.

Cycling should also be seen as a **complimentary mode with transit**, integrating both modes to complete a commute trip, and studying cycling accessibility to major transit nodes is both very useful and technically feasible, thanks to existing routers that can combine biking routing with transit routes and schedules in freely-available GTFS format. The literature stresses the importance of planning a good cycle network towards principle transit hubs, and providing these with ample and secure bike storage facilities.

Finally, **bike sharing, electric bicycles, and cargo bikes (notably for e-commerce**) are important new cycling modalities that are expanding the potential of cycling for non-recreational uses and increasing the importance of a safe and well-connected cycling network.

As next steps, the experiment developed in Chapter 5 as a **proof of concept** for measuring bikeability could be **put into practice** using practical examples for a few cities across Canada. The results of this practical test would allow for a **repeatable** evaluation of a bikeability indicator that measures the **weighed connectivity** of the cyclable network.

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