CYCLING SAFETY

A GUIDE FOR NORTH AMERICAN CITIES

Supervised Research Project
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Executive Summary

Concerns over cycling safety are a major barrier to the uptake of cycling as a viable travel mode. This cycling safety guide aims to inform planners, engineers, and decision-makers how to plan to minimize cyclist risks. It provides the most recent information regarding what contributes towards cyclist risk, how networks can be evaluated for safety, and which measures are effective at mitigating cyclist risk. A focus will be paid to environmental risk factors as these are more effectively addressed with planning interventions. Key risk factors identified include:

- Motor vehicle speed and volume
- Direction of traffic flow
- Lane width
- Number of network junctions
- Intersection configuration
- Cycling facility type and degree of separation
- Interactions with heavy vehicles
- The presence of on-street and off-street parking
- Land use density and mix
- Network surface and topography
- Noise and air pollution
- Lighting
- Weather

Rather than strictly relying on accident data as an indicator of safety, knowledge of these factors and their impacts on cycling risk allow cities to evaluate and improve the safety of their networks in a preventative, rather than reactive, manner. This guide provides an evaluation method that considers the multiple factors that contribute towards cyclist risk to identify high-risk network segments. This tool can be used to signal to decision-makers which areas are in need of new or improved cycling infrastructure, route alternatives, and/or would benefit from further risk analysis. This method was applied to Montreal’s cycling network and tested against accident data and intersections perceived as dangerous for accuracy. However, due to a lack of publicly available data, it is recommended that standards be developed to ensure that cities collect the necessary information to be able to perform this type of analysis. A brief overview of the current types of cycling facilities and treatment designs and where they are best suited is provided to inform of potential planning interventions.

1. Introduction

Cycling is known to positively impact the environment, public health, reduce traffic congestion, improve equity, and reduce overall costs for users and cities (Wegman, Zhang, & Dijkstra, 2012; National Association of City Transportation Officials [NACTO], 2017; Useche, Montoro, Sanmartin, & Alonso, 2019; DiGioia et al., 2017). It can be done for either recreational or utilitarian purposes and, compared to walking, allows for greater distances to be covered (Wegman et al., 2012; Van Cauwenberg et al., 2018) and is considered a good alternative to driving for short trips under 7.5 kilometres (Schepers & Heinen, 2013). Further, given the current circumstances surrounding the COVID-19 pandemic making public transit a less safe and appealing travel option for the current and near future, it is critical that cities promote a shift towards more sustainable travel modes in order to deter the public from shifting towards personal vehicles. In Canada, cycling is a feasible travel alternative, with over 60 percent of Canadians having access to a bicycle and more than 80 percent of people living within eight kilometres of a regular destination (Bíl, Bílová, & Müller, 2010).

However, cycling can be a dangerous travel option (Wegman et al., 2012; Allen-Munley, Daniel, & Dhar, 2004; DiGioia et al., 2017) and cyclist safety has not improved as much as driver safety in the past few decades (Dozza & Werneke, 2014). Cycling is eight times riskier than driving per kilometre and the chances of injury or death in the event of a collision are 40 times higher (Short & Caulfield, 2014). This is largely due to transportation systems being designed around motor vehicles, with cyclists often seen as intruders and incompatible within current transportation systems. Cyclists are also more vulnerable and unstable than other road users (Reynolds et al., 2009), with falls being common and brain damage being a serious and frequent injury (Wegman et al., 2012). While fatal and serious injuries in the event of collision are more costly than minor and non-injury incidents, the latter occur more frequently and still result in productivity and leisure time loss as well as impact perceptions of cycling safety (Winters & Branion-Calles, 2017).

In Canada, only one to two percent of all trips taken are by bicycle (Boss, Nelson, & Winters, 2018; Harris et al., 2011). Concerns over cycling safety are the primary barrier toward a modal shift from motor vehicles to bicycles (Schepers & Heinen, 2013; Boss et al., 2018; Yiannakoulias, Bennet, & Scott, 2012; Asadi-Shekari, Moeinaddini, & Zaly Shah, 2015; Conway, A., Cheng, J., Peters, D., & Lownes, 2013; Reynolds et al., 2009; Rybarczyk & Wu, 2010). Canadian cyclists are two to six times more likely to be killed while cycling than Danish and Dutch cyclists (Harris et al., 2013). Improving cycling safety would reduce the number and severity of incidents and would also encourage those who are more risk averse to adopt cycling as a viable mode (Jacobsen & Rutter, 2012).

Cyclist safety is the responsibility of both the cyclist and other road users as well as the planners and engineers that design cycling networks (DiGioia et al., 2017). To create a safer cycling environment, planners and decision-makers need to understand where, when, and why cycling accidents happen (Vanparijs, Int Panis, Meeusen, & de Geus, 2015) so that measures can be taken to improve safety (Allen-Munley et al., 2004).

This cycling safety guide is to provide cities with the most up-to-date information concerning which factors have the greatest impact on cyclist safety, how cycling safety is modeled and networks are evaluated, which planning interventions are best suited to mitigate cyclist safety risks, and how planners can identify where interventions should be prioritized within a network. It will propose a method for cities to identify high risk areas using publicly available data from Montreal, Canada, and make recommendations for future data collection and network planning and design.

2. Literature Review

This section provides a review of factors identified in the literature as contributing towards cyclist risk as well as how researchers are modeling cyclist risk and evaluating cycling networks. The objective is to inform planners and decision-makers of which factors are incompatible with safe cycling so that measures can be taken to reduce their impacts and determine how these factors should be weighted when evaluating a network.

Cyclist Risk Factors

Cycling is not inherently dangerous, and most studies show that the health benefits of cycling greatly outweigh the risks (Jacobsen & Rutter, 2012; Dozza & Werneke, 2014). However, cyclists account for a greater proportion of road user fatalities at seven percent, with a majority of fatalities (82 percent) and injuries (87 percent) a result of collisions with motor vehicles (Manton et al., 2016). In Canada, the cycling collision rate with motor vehicles is between three and eight collisions per 100,000 kilometres travelled (Yiannakoulias et al., 2012). However, it should be noted that 70 percent of cycling incidents do not involve other road users. This is because cyclist stability is prone to sudden changes in the event of an unexpected situation or as a result of distraction (Dozza & Werneke, 2014).

The decision to bike is made based on the potential benefits and risks, with actual and perceived safety risks being major deterrents (Useche et al., 2019). Cycling risk can be defined as the probability that an incident will occur while accounting for cyclist exposure during a specific time period. Cycling risk factors are the independent variables that are associated with an increased likelihood of a cycling incident (Vandenbulcke, Thomas, & Int Panis, 2014). In reality, cycling accidents often result from a combination of interacting variables, with outcomes dependent on the number of potential conflict points and how well road users respond to the conflict (Schepers et al., 2014b). These factors do not necessarily contribute equally towards incidents, with different risk factors having a different level of impact (Rahman Shaon et al., 2019). These factors are also not necessarily causal but can be modified through planning interventions aimed at improving cyclist safety (Vandenbulcke et al., 2014).

Multiple studies have been conducted in order to identify which factors affect cycling network safety. A majority of which utilize either accident or survey data to assess actual or perceived safety risk factors at intersections or along road segments. There are several categories of factors that need to be considered when evaluating and improving cyclist safety. The first category are demographic factors such as cyclist age, gender, and socioeconomic status. The second category are behavioural factors like wearing a helmet, cyclist speed, listening to music, and obeying traffic laws (Vanparijs et al., 2015). Vehicle factors such as the size and speed of bicycle or motor vehicle also need to be considered (Vandenbulcke et al., 2014). Finally, there are environmental factors which include infrastructure and traffic flows as well as natural conditions, like weather and lighting, make up the final category (Vanparijs et al., 2015). This guide will focus on environmental factors as these can be changed through planning interventions.

Demographic Factors

Safer cycling conditions have been shown to increase cycling rates among children, seniors, and women (Buehler & Pucher, 2017). This is because women and the elderly are more sensitive to traffic danger and many parents prevent their children from cycling due to safety concerns (Pucher & Buehler, 2008).

Multiple studies show that children and seniors are more vulnerable to cycling injuries and fatalities (Buehler & Pucher, 2017; Bíl et al., 2010; Boufous, Senserrick, & Ivers, 2012; Engbers et al., 2017). Children are smaller and less visible to drivers and they often lack the ability to detect and respond appropriately to risks. Those over 65 years old typically ride more slowly and have relatively poor vision and response time. They are also the fastest growing demographic and are increasingly becoming car-free (NACTO, 2017).

While men are more likely to be involved in a fatal collision (Bíl et al., 2010), women are currently underrepresented in cycling as they are more concerned about personal safety and traffic stress (NACTO, 2017; Pucher, Buehler, & Seinen, 2011). In 2006, only 29 percent of daily cycling commuters in Canada were women, with a maximum of 37 percent in Vancouver (Pucher et al., 2011). Women, along with seniors and inexperienced cyclists, are more likely to ride where there are designated cycling facilities present (NACTO, 2017; Manton et al., 2016; Cushing, Hooshmand, Pomares, & Hotz, 2016; Pucher et al., 2011).

Those with disabilities are also at higher risk as they are more likely to ride slowly and are sometimes less visible and require more space as a result of using adaptive bicycles. Low-income groups and minorities face disproportionate risk when it comes to cycling as there is a lack of investment in infrastructure for these populations. Those with low incomes are also more often reliant on bicycles for their commutes, increasing their safety risk due to exposure (NACTO, 2017).

Behavioural Factors

Cyclists have been found to be less likely to comply with traffic laws when on local roads, for example, by riding the wrong way down a one-way street (Yiannakoulias et al., 2012). The most serious injuries are often the result of collisions at intersections where cyclists fail to give right of way. However, a driver is still more likely to be responsible for a fatal collision (Bíl et al., 2010). Alcohol use by both drivers and cyclists has been found to have a negative impact on safety by increasing the likelihood of a collision (Schepers et al., 2017). Fear of crime when cycling is also a major safety concern and deterrent for cyclists, particularly when cycling for recreational purposes (Rybarczyk & Wu, 2010).

Differing abilities and the physical effort required also have an impact on overall cyclist safety (Wegman et al., 2012). Higher vehicle kilometres travelled was associated with a slight increase in cyclist risk (Dumbaugh, Li, & Joh, 2013). What a cyclist is wearing may also have an impact on their visibility and safety risk, where fluorescent clothing was found to reduce the likelihood of collision (Bíl et al., 2010).

While cars and heavy vehicles can be designed with crash-friendly fronts and side-underrun protection can be added to trucks, the only personal protective equipment available for cyclists is the helmet (Wegman et al., 2012). While helmets do provide protection against head, face, and neck injuries (Schepers et al., 2017; Boufous et al., 2012), with soft-shell and hard-shell helmets reducing up to 41 percent and 64 percent of head injuries, respectively, it is argued that they do not improve safety at the societal level (Culver, 2018). They also do not protect other parts of the body and do not prevent collisions from occurring in the first place (Reynolds et al., 2009).

Wearing a helmet is also likely to have an impact on individual behaviour. Those who choose to wear helmets may be more cautious riders in general (Jacobsen & Rutter, 2012). Alternatively, it is possible that some cyclists and drivers may perform more risky maneuvers as they feel the helmet provides adequate protection (Jacobsen & Rutter, 2012; Culver, 2018; Pucher & Buehler, 2008). It also redistributes blame on cyclists who choose to forgo a helmet in the event of injury or death as a result of an accident (Culver, 2018).

Most bicycle-friendly countries have achieved high rates of safe cycling through the provision of cycling infrastructure as opposed to the widespread adoption of helmets (Culver, 2018). However, North American cities continue to promote their use (Culver, 2018; Reynolds et al., 2009; Pucher & Buehler, 2008). This may instead give the false impression that cycling is a risky activity and lead to an increase in risk as potential cyclists are deterred by mandatory helmet laws (Jacobsen & Rutter, 2012; Culver, 2018; Reynolds et al., 2009; Pucher & Buehler, 2008) which make cycling less convenient, comfortable, and fashionable (Pucher & Buehler, 2008). Cyclists in the U.S. are more likely to wear helmets yet are more likely to be killed or injured than cyclists in the Netherlands, where helmet use is rare (Culver, 2018; Pucher & Buehler, 2008).

A paper by Culver (2018) argues that this fixation on helmet adoption hinders legitimate efforts at improving cyclist safety and is a result of auto-centric culture. They claim that there is strong evidence that cycling infrastructure, reduced vehicle speeds, and regulations that hold drivers more accountable are more effective ways of improving safety conditions for cyclists.

Vehicle Factors

The type of vehicle involved in cyclist collisions is also likely to have an impact on safety risk and outcomes. Vehicle condition is equally important. For example, proper lighting equipment is necessary to ensure cyclist visibility (Bíl et al., 2010).

The adoption of electrically assisted bicycles is rapidly increasing. Reaching up to 25 km/h, a study by Schepers et al. (2014) compared the likelihood of crash and injury on electric bicycles to traditional bicycles in the Netherlands. The results suggested that electric bicycle users are more likely to be involved in an accident where treatment in an emergency department is needed, while collisions with electric bicycles were about as severe as with traditional bicycles. Previous studies have also found that collisions are more likely among electric bicycle users and that accidents tend to be more severe. Electric bicycle accidents are also more often single-bicycle accidents and are most likely to occur when mounting and dismounting, going around curves, or while overtaking. However, it should be noted that statistical significance could not be proven with the dataset that was used.

It is thought that the higher speed, heavier weight, and acceleration through the front wheel of electric bicycles could contribute to their relative safety risk. However, it should be noted that the average cruising speed of electric bicycles in the Netherlands is only 1-3 km/h higher than the average cruising speed of a traditional bike. It is also suggested that the behaviour and characteristics of electric bicycle users could increase risk as they tend to be older and, therefore, are more likely to be injured. Additionally, users are more likely to perform overtaking measures that they would otherwise avoid on a traditional bicycle. It is recommended that the width of current cycling paths be widened in order to accommodate the speed and safe passing of electric bicycles (Schepers et al., 2014).

Cars account for the majority of collisions with cyclists, however, trucks, buses, vans, and other heavy vehicles are more likely to be involved in a serious (Allen-Munley et al., 2004) or fatal collision (Vandenbulcke et al., 2014; Bíl et al., 2010). Heavy vehicles have a greater mass, resulting in collisions that are often more severe than those with other vehicles (Allen-Munley et al., 2004; Jacobsen & Rutter, 2012). They also have large blind spots and are prone to side-swipe and right-hook collisions. Increased noise and exhaust also impact health risk (NACTO, 2017). Road segments with heavy bus or truck presence decrease cyclist safety and comfort due to their often having to share the right lane, making unpredictable movements (NACTO, 2017), taking up more space, making wider turns, and reducing visibility for all road users (Bíl et al., 2010; Allen-Munley et al., 2004).

Buses in particular often share the same high demand routes as cyclists and encroach in bike lanes to access stops. They also travel at similar, yet inconsistent, speeds which often results in cyclists having to make higher risk maneuvers (NACTO, 2017). The likelihood of conflicts with trucks increases in commercial areas (Conway et al., 2013) where there is frequent freight loading/unloading adjacent to the curb (NACTO, 2017).

Lastly, the increased prevalence of hybrid and electric vehicles has led to concerns over the lack of auditory signals for cyclists. Traffic sound allows for the detection and localization of vehicles and other road users when they are outside one’s field of view. Vehicle quietness at low speeds was found to be a safety issue, particularly when cyclists used other auditory devices like headphones. Drivers were also found to be unlikely to compensate for lower sound levels by driving more carefully when using hybrid or electric vehicles. However, it is not clear to what extent auditory cues impact cyclist safety (Stelling, Hagenzieker, & van Wee, 2015).

Environmental Factors

Environmental factors include traffic conditions (e.g. vehicle speed and volume), infrastructure (e.g. cycling facilities), land use (e.g. zoning), and the natural environment (e.g. topography). Studying the design and conditions of the built environment often requires extensive fieldwork and an understanding of road design and operations (Jacobsen & Rutter, 2012).

Vehicle speed and volume are the two biggest sources of actual and perceived cyclist risk and they are often compounded by each other (NACTO, 2017). Higher vehicle speeds reduce visibility, increase stopping distance (NACTO, 2017; Dumbaugh et al., 2013; City of Vancouver, 2017), and increase injury severity and chance of fatality in the event of a collision (NACTO, 2017; Bíl et al., 2010; City of Vancouver, 2017). This is because injury severity is related to the kinetic energy involved, where outcomes are often the result of differences in speed and mass compatibility between road users (Schepers et al., 2014b; Reynolds et al., 2009).

Speeds below 30 km/h were found to be safest for cyclists, with injury and fatality risk increasing at higher speeds (Jacobsen & Rutter, 2012; Schepers et al., 2014b; Vandenbulcke et al., 2014; Harris et al., 2013; Bíl et al., 2010). Most people are not comfortable sharing the road with motor vehicles traveling over 40 km/h (NACTO, 2017; City of Vancouver, 2017) and safe cycling is not possible where vehicle speeds exceed 50 km/h (NACTO, 2017). However, these speeds do not apply to truck routes where far lower speeds can still result in fatalities as cyclists can pass under the wheels (Schepers et al., 2014b).

Cyclist speed is also thought to have an impact on risk. For example, Operational speeds between 18 and 26 km/h are common in Canada. Dutch cyclists travel at slower speeds between 16 and 18 km/h (19 km/h on electric bikes) and have better safety rates. Lower cycling speeds give drivers and cyclists more time to react and avoid collisions (Schepers et al., 2017).

Higher motor vehicle volumes are associated with increased risk (Harris et al., 2013) as it increases the likelihood of vehicle interaction and passing events. Traffic congestion also results in inconsistent speeds and more aggressive behaviour (NACTO, 2017). As traffic volumes exceed 1000 vehicles per day (or 50 vehicles per hour during peak hours), most cyclists are only comfortable with vehicle speeds below 30 km/h (NACTO, 2017; City of Vancouver, 2017).

Intersections with traffic volumes above 75 vehicles per hour were associated with increased injury risk (Harris et al., 2013) due to increased chances of conflict (Dumbaugh et al., 2013).

It is also important to consider changes in vehicle traffic volume at different time periods. During peak hours, traffic congestion can increase the likelihood of lane encroachment and hostile interactions, whereas high vehicle speeds during off-peak hours are more likely to result in serious or fatal cycling accidents (NACTO, 2017; Vandenbulcke et al., 2014). However, Allen-Munley et al. (2004) found that the severity of injury in the event of a collision decreased with traffic congestion since, as roads approach capacity, operating speeds decrease. The frequency of passing events may be a more useful indicator of risk along a roadway than speed or volume alone (NACTO, 2017).

By proxy, road hierarchy has an impact on cycling safety (Allen-Munley et al., 2004). Local roads tend to have lower speeds than collector and arterial roads in order to provide access while discouraging through traffic. Previous research shows that more cycling accidents occur along collector and arterial roads (Schepers et al., 2014b; Dumbaugh et al., 2013; Harris et al., 2013; Reynolds et al., 2009) where the purpose is to distribute traffic from local roads and facilitate traffic flow at higher speeds (Schepers et al., 2017; Dumbaugh et al., 2013). This can be seen in the Netherlands where it was found that collector and arterial roads have the highest share of fatal collisions with motor vehicles, with 80% of fatal and severe collisions occurring on collectors (Schepers et al., 2017).

In terms of infrastructure, roads with multiple lanes of traffic pose a safety risk as lane changes, passing, and more visual stimulation make them less predictable than one-ways or those with one lane in each direction (NACTO, 2017; Harris et al., 2013). However, one-ways were also surprisingly associated with an increased safety risk, possibly due to providing a false sense of security (Allen-Munley et al., 2004). Curved sections of road were also linked to increased risk of severe injury in the event of collision (Boufous et al., 2012).

Wider streets were generally found to be less safe for cyclists. This is thought to be due to higher operating speeds and an increased likelihood of passing. This supports the theory behind traffic calming (Allen-Munley et al., 2004). On the other hand, Pulugurtha & Thakur (2015) found that wider right-hand lanes decreased the number of cycling collisions as it provided more space for cyclists.

Shared streets are less secure for cyclists, particularly shared bus-bike lanes, and, while paved shoulders can provide space for cyclists to ride separately from vehicle traffic, they do not prevent vehicles from using that space (Jolicœur & Komorowski, 2019).

Most cycling accidents occur at junctions, with 20 percent occurring near driveways (Allen-Munley et al., 2004) and around half of all accidents (Allen-Munley et al., 2004; Schepers et al., 2017) and 35 percent of fatal accidents occurring at intersections (Manton et al., 2016). Pulugurtha & Thakur (2015) found that the number of signalized intersections per mile was associated with an increase in the number of cycling collisions. This is likely because frequent starts and stops increase cyclist instability and left turns are particularly risky for cyclists if they need to cross multiple lanes and merge with traffic (NACTO, 2017).

However, intersection configuration, the speed of vehicles, and the amount and direction of cyclist travel were related to injury risk (Harris et al., 2013). Complex intersections and intersections with cycling facilities had a statistically significant impact on cyclist risk (Vandenbulcke et al., 2014). Intersections with four or more legs have been linked to higher collision risk than three-legged intersections (Dumbaugh et al., 2013) and intersections between local roads were found to be one-fifth the risk of intersections between arterials. However, roundabouts were found to increase risk on local roads (Harris et al., 2013).

Roundabouts or traffic circles pose a risk for cyclists in particular (Vandenbulcke et al., 2014) as they increase the amount of time for cyclists to clear an intersection (Jolicœur & Komorowski, 2019) and vehicles are more likely to pass cyclists and travel at higher speeds (NACTO, 2014). Unless cycle tracks are included in their design, roundabouts were found to increase risk significantly (Reynolds et al., 2009).

Bridges and tunnels are thought to increase risk for cyclists as they reduce visibility and may lead to sudden changes in terms of infrastructure and road condition. The presence of on-street tram tracks and public transit stops are also thought to increase cyclist risk as there is more pedestrian activity in these areas (Vandenbulcke et al., 2014).

Poorly lit roads increase the risk of severe injury (Boufous et al., 2012) and fatality (Bíl et al., 2010) in the event of collision. Meanwhile, reliable and consistent lighting was found to improve the safety and comfort of cyclists (Reynolds et al., 2009), particularly at night and during the winter season (City of Vancouver, 2017) as it allows drivers to more easily detect cyclists and increases sight distance (Bíl et al., 2010).

Riding surface was found to have a significant impact on injury severity (Allen-Munley et al.,2004), including for single-bicycle accidents (Schepers et al., 2014b). Paved surfaces are associated with lower cycling risk (Reynolds et al., 2009).

Cycling infrastructure has been found to have an impact on both the rate and severity of cycling collisions (Reynolds et al., 2009). Pulugurtha & Thakur (2015) found that cyclists were three to four times more likely to have a collision on roads without a bike lane than roads with a bike lane and Reynolds et al. (2009) found that they reduced the risk of injury and collision by half compared to normal roadways. Wider bike lanes in particular were associated with reduced collision risk (Pulugurtha & Thakur, 2015). However, whether bike lanes reduce collision risk remains inconclusive as some studies have found a slight increase in the number of accidents. No studies exist for buffered bike lanes (DiGioia et al., 2017) while sharrows were found to have no impact on safety (Harris et al., 2013).

Cycles tracks have been found to reduce crash rates (DiGioia et al., 2017) and unidirectional tracks are safer than bidirectional tracks (DiGioia et al., 2017), particularly at intersections (Vandenbulcke et al., 2014). It is thought that bidirectional facilities make a cycling route more attractive as cyclists are not forced to cross the road as frequently. However, they are found to increase accident risk by up to four to six times (Methorst et al., 2017) as drivers fail to anticipate cyclists from the opposing direction (Schepers et al., 2014b). They also increase the complexity of roundabouts and unsignalized intersections and have been found to increase the likelihood of frontal crashes. This is likely due to motor vehicles turning right not scanning for cyclists approaching from the right (Methorst et al., 2017; Schepers et al., 2017).

While bidirectional facilities are common in bicycle-friendly countries like the Netherlands, they still have a relatively poor safety record compared to unidirectional facilities (Methorst et al., 2017). Bidirectional facilities were found to have 75 percent elevated risk of collision at intersections compared to unidirectional facilities. However, it should be noted that bidirectional facilities provide a net safety benefit compared to having no cycling facilities (Schepers et al., 2017).

Contraflow cycling was found to improve safety. This is thought to be because cyclists and drivers can better see each other and drivers may be more cautious due to perceived risk (Vandenbulcke et al., 2014). However, contraflow cycling at intersections was found to increase risk (Harris et al., 2013).

While bicycle-specific facilities are generally associated with lower risk of injury, there is evidence that sidewalks and multi-purpose trails are associated with higher risk (Harris et al., 2013; Reynolds et al., 2009). Shared-use pathways are perceived as safer and can encourage more cycling, however, the risk of collision is in fact higher than on bike-only paths (City of Vancouver, 2017). This is due to having to share the space with other traffic (DiGioia et al., 2017). Research has shown that it is safer to bike on the road than on fully segregated cycling facilities (Vandenbulcke et al., 2014).

Intersections with cycling safety treatments have been shown to reduce accidents and injuries in high traffic areas (Vandenbulcke et al., 2014). The safety impact of bike boxes varies between studies, with some finding a reduction in conflicts, little change, or an increase in right-hook collisions. No studies have been done to assess the safety impact of two-stage turn queue boxes (DiGioia et al., 2017).

Traffic calming has been found to improve safety by reducing vehicle speeds (Pucher & Buehler, 2008). However, traffic calming measures like curb extensions and speed bumps were not found to have a significant impact on traffic safety (Harris et al., 2013) and there is lack of literature on the safety impacts of other traffic calming measures (Reynolds et al., 2009).

Land use and infrastructure characteristics also influence the number of cyclist kilometres travelled, with higher densities and mixed land uses having a positive impact on cycling levels (Schepers et al., 2014b). Therefore, higher density areas also increase risk as there are more chances for interaction between road users (Allen-Munley et al., 2004). By proxy, city size may also have an impact on cyclist safety due to higher traffic volumes and greater exposure to noise and air pollution (Pucher et al., 2011).

Commercial and retail land uses have been associated with clusters of cycling accidents. This is likely a result of multiple driveways along arterial roads creating multiple conflict zones. However, the type and configuration of commercial and retail space has an influence, where strip malls and big boxes stores pose more risk than pedestrian-oriented mainstreets, which experience fewer accidents than traditional arterial roads (Dumbaugh et al., 2013).

On-street parking and off-street commercial parking entrances/exits are also thought to pose a risk to cyclists. Parked vehicles on-street restrict sight distances and areas with high turnover increase conflict with pedestrians (Vandenbulcke et al., 2014), during parking maneuvers, and with car doors (DiGioia et al., 2017; NACTO, 2017; Boufous et al., 2012). Parking entrances/exits are also often unexpected conflict points between cyclists and motor vehicles (Vandenbulcke et al., 2014).

Regarding the natural environment, studies show that flat topography encourages cycling and that cyclists avoid steep gradients (Pucher et al., 2011). Flat topography is associated with low cycling risk (Reynolds et al., 2009) while steep gradients were found to increase cyclist risk at intersections and non-intersections. This is likely due to faster speeds on the downslope increasing the force upon impact (Harris et al., 2013; Allen-Munley et al., 2004) and maneuvering and sight-distance issues on the upslope (Allen-Munley et al., 2004).

Most people can only maintain their balance on grades of four percent or less, and less than three percent for longer distances. Many people have to dismount at grades above 8 percent. Steep gradients are particularly challenging for children, seniors, those with disabilities, and inexperienced cyclists (City of Vancouver, 2017).

Ice and snow were found to be a major deterrents for cyclists (Winters, Davidson, Kao, & Teschke, 2011) as slippery road surfaces contribute to single-bicycle crashes (Schepers et al., 2014b). Cyclists also prefer routes away from noise and air pollution (Winters et al., 2011). Exposure to traffic exhaust has been found to have an adverse effect on cyclist health (Vandenbulcke et al., 2014). Motor vehicles release air pollutants such as carbon monoxide, nitrogen oxides, volatile organic compounds, and particulate matter or various sizes and composition (Terh & Cao, 2018; Bigazzi & Figliozzi, 2014). Concentrations of these pollutants are particularly high near roadways and cyclists have respiration rates two to five times higher than drivers as a result of higher exertion levels (Bigazzi & Figliozzi, 2014). This and longer travel distances increase cyclist intake and uptake rates of air pollutants when compared to drivers. While cyclists are sometimes less exposed to these pollutants on pathways separated from traffic, they are more exposed when having to share the road (Bigazzi & Figliozzi, 2014; Int Panis et al., 2010). It should be noted, however, that concentrations vary depending on weather, location, and time of day. The long- and short-term health impacts of inhaling more air pollutants are also less clear, although studies indicate an increased risk of developing asthma, reduced lung function, increased blood pressure, and cardiac and pulmonary mortality for urban populations. However, multiple studies have also shown that the health benefits from physical activity from cycling outweigh the costs of collision and air pollution risks (Bigazzi & Figliozzi, 2014).

Perceived Risk

Cycling is generally perceived as less safe than walking, driving, or taking public transit – particularly by non-cyclists (Schepers et al., 2014b). Negative perceptions of safety are a major barrier towards an increase in cycling. Perceived risk affects an individual's decision to bike at all, their route choice, and their riding behaviour (e.g. lane positioning) (Bigazzi & Gehrke, 2018; Manton et al., 2016; Useche et al., 2019; Pucher & Buehler, 2008). Further, perceived risk has been found to be poorly correlated to actual risk (Schepers et al., 2014b).

A descriptive study on the encouraging and discouraging factors for riding a bicycle (Useche et al., 2019) used hierarchical response categorization to find that perceived crash risk, adverse weather conditions, difficult road topography, and a lack of proper infrastructure were the most discouraging factors when it came to choosing whether or not to bike. A similar study by Winters et al. (2011) on the travel behaviour intent of individuals who had access to a bicycle and were willing to ride found that, along with unsafe surfaces, interactions with motor vehicles, particularly in areas with high traffic volumes and/or speeds, was one of the strongest cycling deterrents.

A study by Van Cauwenberg et al. (2018) used bike-along interviews to obtain information on the environmental factors influencing the perceptions and experiences of cyclists. Cyclists were most concerned with traffic safety, cycling infrastructure, road design and maintenance, connectivity, aesthetics, hilliness, and weather – with traffic safety being most important. Traffic safety was found to be influenced primarily by cycling infrastructure as well as road design and maintenance. Intersections and high traffic volumes, particularly along narrow streets without designated cycling space, were often perceived as dangerous. Opinions on roundabouts were mixed and vehicles entering the street from parking lots or side streets were also seen as a risk.

Manton et al. (2016) found that the top three perceived safety concerns for cyclists were the number of trucks passing, speed of traffic, and traffic volume. The maximum traffic speed that a majority of participants were comfortable with was under 50 km/h. Infrastructure was less of a concern, with the presence of roundabouts, road lane width, and on-street parking identified as the most concerning. Arterial roads with shared lanes were perceived as the most dangerous type of bikeway, while off-road, shared-use pathways were perceived as the safest. Cycle tracks were perceived as safer than bike lanes and shared lanes. Areas that had low density and single land uses were also perceived as higher risk.

Harkey, Reinfurt, & Knuiman (1998) measured cyclist perceived risk by having participants view numerous road segments on videotape and rate them based on how comfortable they would be cycling under various conditions. Variables that were thought to have a negative impact on cyclist stress levels included curb lane width, motor vehicle speed, traffic volume, large trucks or buses presence, vehicles turning right into driveways, and vehicles pulling in or out of on-street parking spaces. An increase in traffic volume or speed and on-street parking at more than 30 percent capacity resulted in a lower level of comfort for cyclists. It was found that cyclist level of comfort increased with the presence of a bicycle lane or paved shoulder; a wider bicycle lane, paved shoulder, or curb lane; and adjacent residential development.

It should be noted that these studies and other research that has looked at perceived cycling risk introduce subjectivity error as cyclists have been known to misjudge the safety of routes (Allen-Munley et. al., 2004). It is thought that highly visible changes in infrastructure are more likely to have an impact on perceived safety than measures that are more difficult to notice. Actual cycling incidents also have an influence on perceived risk and more than a third of single-bicycle crash victims' bike less after an accident (Schepers et al., 2014b).

Safety in Numbers

Few papers have analysed whether an increase in cycling results in and increase of cycling fatalities (Short & Caulfield, 2014). Some argue that as the number of cyclists increases, the number of fatalities may also increase due to greater exposure depending on local conditions (Wegman et al., 2012). Others argue that a shift from car to bicycle trips would lead to constant or reduced accident numbers. Shifting to cycling makes individuals less hazardous to other users as they expel less kinetic energy in the event of a crash (Schepers & Heinen, 2013). In Ireland, it was found that the number of cycling fatalities had decreased significantly with an increase in cycling rates, on the other hand, the number of collisions and injuries had increased (Short & Caulfield, 2014).

The prevailing theory is that an increase in cycling rates is thought to improve road safety through the 'safety in numbers' effect (Manton et al., 2016; Schepers et al., 2014b; Harris et al., 2011; Reynolds et al., 2009) as drivers change their behaviour when expecting to encounter cyclists (Jacobsen, 2003; Schepers & Heinen, 2013; Schepers et al., 2014b). This was first observed by Jacobsen (2003) and, according to this theory, individual cyclist risk decreases nonlinearly related to the amount of cycling as, while the absolute number of accidents may increase, they occur at a lower rate (Jacobsen & Rutter, 2012; Elvik & Bjørnskau, 2017). It was observed that the probability of collision decreases by -0.6 the power of cycling levels, so a 20 percent increase in the number of people cycling results in 10 percent decrease in risk (Jacobsen, 2003).

A systemic review by Elvik & Bjørnskau (2017) confirmed this theory by looking at the relationship between the number of accidents involving motor vehicles, cyclists, and pedestrians and the volume of motor vehicles, cyclists, and pedestrians. The studies reviewed consisted of multivariate accident prediction models and regression coefficients. It was found that the 'safety in numbers' effect exists, although it is unclear if the effect is causal and, if so, which factors would contribute to the effect. For example, it is possible that there is an increase in more cautious cyclists as the number of cyclists increases. Those who bike more are also less prone to collisions (Useche et al., 2019). Drivers may be more likely to expect and predict cyclist movements and adjust their behaviour accordingly (Reynolds et al., 2009). It is possible that an increase or improvement to cycling infrastructure provided could be what contributes to improved safety (Elvik & Bjørnskau, 2017; Schepers et al., 2014b). Further, a larger cycling population also means stronger lobbying power for cycling facilities (Reynolds et al., 2009). However, another study controlling for infrastructure factors observed the same 'safety in numbers' effect (Schepers et al., 2017).

Plans and policies aimed at increasing cycling rates are likely to result in an increase in overall cycling safety (Jacobsen, 2003). There is debate as to whether it is better to provide facilities that improve safety directly or facilities that people want to use (DiGioia et al., 2017). Finally, it should be noted that it is possible that there is a limit or turning point when it comes to this effect for cyclists (Elvik & Bjørnskau, 2017).

Safety Modeling and Evaluation

To ensure that a cycling network is safe, methods are needed for safety modeling and evaluation (Asadi-Shekari et al., 2015). Systematically investigating the environmental risk factors that influence cyclist safety allows planners and decision-makers to make informed decisions about cycling network expansion and design to make cycling safer and more appealing (Harris et al., 2011). However, there are currently no standards when it comes to the appropriate data sources and measures to use when evaluating cycling network safety (DiGioia et al., 2017). Ideally, the three dimensions of cyclist safety would be considered: exposure, risk, and consequence (Wegman et al., 2012).

Safety models, regression analysis, and point systems are the most common ways to evaluate safety (Asadi-Shekari et al., 2015). These models are typically based on the premise that safe routes produce fewer accidents then unsafe routes and that a route that has caused severe accidents is more dangerous than a route with the same number of minor accidents (Allen-Munley et al., 2004). They can be used to identify risk factors, rate the safety of particular road segments, highlight areas in need of improvement, and/or map safer routes for cyclists (Manton et al., 2016).

Incident and Exposure Data

Cyclist safety is often evaluated based on the frequency or severity of cycling incidents within a network (Vandenbulcke et al., 2014; Conway et al., 2013). Incidents are typically defined as either a collision or a fall. Conflicts or 'near-misses' are also sometimes considered (Reynolds et al., 2009). Cycling safety evaluation often relies on accident data such as police, hospital (Short & Caulfield, 2014), and/or insurance records (Winters & Branion-Calles, 2017). Ideally, accident data would also include information about the date, location, accident type, severity, and proximity to an intersection (DiGioia et al., 2017). However, this data is more often incomplete as reporting practices vary by location (Winters & Branion-Calles, 2017; Reynolds et al., 2009; Jacobsen, 2003), by personnel (Allen-Munley et al., 2004), and policy. Across 12 countries, the proportion of cycling accidents captured by police data varied from 7-66 percent. Hospital data misses' incidents that do not require medical attention, and insurance claim data only captures incidents with motor vehicles where a claim is made (Winters & Branion-Calles, 2017). Therefore, minor accidents, single-bicycle accidents, and accidents with other road users are often underreported (Wegman et al., 2012; Winters & Branion-Calles, 2017; Reynolds et al., 2009; Allen-Munley et al., 2004). In addition, as accident data is most often collected along roads, risk is often underestimated for certain facility types (e.g. off-street paths) (Winters & Branion-Calles, 2017; Buehler & Pucher, 2017).

A study in Vancouver, Canada, compared insurance claim cycling accident data to a population survey to assess the degree of underreporting. According to the survey, only 12.2 percent (1 in 8) of cycling incidents were reported for insurance claims. The most common self-reported incidents were as a result of a maneuver to avoid a collision (48.8 percent) and collisions with motor vehicles (31.7 percent) (Winters & Branion-Calles, 2017). Regarding police reports, Short & Caulfield (2014) argued that it would be beneficial for better quality information to be collected about cycling collisions and for there to be international standards on the definition and measurement of what qualifies as a serious injury. While hospital data can provide clinical data on the type of injury, no personal identification or location data can be collected. The same authors found that both data sources do not currently accurately reflect the number of cycling accidents due to the discrepancies between police and hospital records.

Multiple studies also recommend differentiating between cycling accident severity when conducting risk analysis. They argue that including minor accidents overestimates the risk of popular routes (Allen-Munley et al., 2004) and underestimates cycling benefits (Thomas & DeRobertis, 2013). However, it is important to consider that the outcome of an accident is often a result of chance and, therefore, all conflict types would need to be considered in order to eliminate accident risk entirely.

In addition, the current lack of reliable exposure data in bicycle safety analysis is a limitation in a majority of studies as it prevents meaningful analysis and the comparison of results (Vanparijs et al., 2015; Yiannakoulias et al., 2012; Schepers et al., 2014b; Thomas & DeRobertis, 2013; Dumbaugh et al., 2013; Reynolds et al., 2009; Allen-Munley et al., 2004; DiGioia et al., 2017). Risk is often measured using accident counts or rates per capita (Yiannakoulias et al., 2012), which alone do not provide a complete picture as the demand for cycling in a given area and over time is not taken into account. This can leave the impression that cyclist risk increases as rates increase when the relationship between risk and exposure is often non-linear due to the 'safety in numbers' effect mentioned earlier. Incorporating exposure data also allows for the evaluation of safety trends over time (Vanparijs et al., 2015; Yiannakoulias et al., 2012) or before and after cycling interventions (Thomas & DeRobertis, 2013). Ideally, both types of data are used for analysis, with the exposure parameter as the denominator and incident data as the numerator in order to identify the relative risk for a given area. Units of exposure can be cycling distance, time, and/or number of trips (Vanparijs et al., 2015; Yiannakoulias et al., 2012). A consistent counting database of cycling demand is needed to collect this information at a regional level (Vandenbulcke et al., 2014). However, collecting this level of data for every location along a network is impractical for many municipalities (Yiannakoulias et al., 2012) and varies by time of day and season (Harris et al., 2011; Conway et al., 2013). This information, therefore, has its limitations and often simply does not exist (Yiannakoulias et al., 2012). Strauss, Miranda-Moreno, & Morency, (2015) used a combination of GPS and count data in order to estimate cycling volumes, however, this data is often not readily and/or publicly available. Attempts have also been made to estimate exposure through the use of modified gravity-based accessibility models (Vandenbulcke et al., 2014), however, the accuracy of this method has not been tested. Otherwise, manual bicycle counts can be conducted for particular locations of interest (Conway et al., 2013).

Alternatively, Dozza & Werneke (2014) argue that using naturalistic data is best when trying to understand and analyze road user behaviour and assess traffic safety. This is because the events leading up to a collision can be observed and help better explain accident causation. Video, direct observation, and questionnaires are common methods to collect this type of data (Asadi-Shekari et al., 2015).

Network and Infrastructure Data

Infrastructure data can be collected by conducting infrastructure inventories manually in the field, using Google Street View (Conway et al., 2013), and or available open data. However, it should be noted that infrastructure is subject to frequent changes and, therefore, gathering and maintaining an accurate inventory can be a challenge. Current research on cycling safety lacks studies covering the full range of cycling infrastructure available (Reynolds et al., 2009). Instead, analysis is often done using observable proxy variables, such as facility type (Bigazzi & Gehrke, 2018) and road classification.

It is typical in transportation planning for analysis to be done at the city, census tract, or traffic analysis zone (TAZ) level. However, when evaluating cycling networks, it is more beneficial to use line segments of the road and/or existing cycling network. Analysis at the network level allows planners to identify priority segments that require safety interventions (Rybarczyk & Wu, 2010).

Geographic Information Systems

Advances in Geographic Information Systems (GIS) have facilitated transportation modeling and analysis at both the local and regional scale, with the simplest method to assess cyclist risk being to map the locations of cyclist collisions. It is important to map the risk of collision along a cycling network in order to understand causal factors and make informed planning decisions (Yiannakoulias et al., 2012).

GIS also allows for the visualization and analysis of multiple open data sets including cycling and road network data, origin-destination data, etc. (Conway et al., 2013). Information can also be calculated, including segment lengths, lane widths, the number and proximity of network features, etc. (Pulugurtha & Thakur, 2015). For example, Yiannakoulias et al. (2012) used publicly available origin-destination data for cyclist commutes and road network data in order to model shortest-path cycling routes. They then estimated cyclist collision risk at the neighbourhood level using the number of collisions divided by the total number of kilometres travelled by bicycle in each census tract.

GIS can be used to assess the spatial patterns of cycling facilities and identify inadequacies or gaps within a network (Rybarczyk & Wu, 2010). It can also aid in communicating where improvements need to be made to stakeholders and decision-makers using maps.

Regression Models

Regression models are often used to identify road design characteristics and other factors that contribute towards actual and perceived cyclist safety risk. However, it is important to remember that these models do not explain causation (Dumbaugh et al., 2013). Simple univariate and bivariate regression models have been used to predict the likelihood of collisions (Wier et al., 2009), however, multivariate crash frequency models have been empirically proven to be more accurate when it comes to modeling crash counts. This is because they consider that multiple factors likely contribute to collisions and can accommodate the correlation between these factors (Rahman Shaon et al., 2019; Wier et al., 2009; Chang, 2017). It is also argued that ordinary least squares regression methods are ill-suited for safety evaluation as model parameters cannot be combined unless they are all continuous. Logistic regression using maximum likelihood estimation is recommended instead as the model can be fitted so that predictions most accurately match observations (Allen-Munley et al., 2004). Poisson models, negative binomial models, and their variations are most often used to model accident frequency along roadways and intersections (Rahman Shaon et al., 2019; Dong et al., 2014; Chang, 2017).

Bíl et al. (2010) used univariate models to identify regression variables to include into a final multivariate logistic regression model identifying critical factors influencing fatal and serious cycling accidents with motor vehicles. While these multivariate linear regression models are commonly used to model cyclist risk (Boufous et al., 2012) or evaluate route safety (Allen-Munley et al., 2004), exponential regression models, like Poisson or negative binomial models, are often preferred as they more accurately represent accident count distribution (Schepers et al., 2011). It is not uncommon for all three types of models to be tested for goodness of fit when making prediction models (Pulugurtha & Thakur, 2015). The model is selected by first removing factors that are highly correlated (Pearson correlation coefficient above 0.5) using a correlation matrix (Rahman Shaon et al., 2019) and then eliminating model parametres with a p-value below 0.1 (Harkey et al., 1998; Wier et al., 2009) in an iterative process, with the final model complete once all insignificant variables were eliminated. The regression model of best fit would then be chosen based on an R^2 closer to one and/or a lower AIC value (Harkey et al., 1998).

Schepers & Heinen (2013) used a negative binomial accident prediction model (APM) to estimate the road safety effects of a modal shift from driving to cycling. It was found that the effect on the number of deaths for all road users was very small, but that the number of serious road injuries increased with modal shifts of 10, 30, and 50 percent. This was largely due to an increase in single vehicle crashes where no motor vehicle is present. A similar study by Dumbaugh et al. (2013) used multivariate analysis to identify built environment factors that might influence the likelihood of severe and fatal pedestrian and cycling collisions. They used negative binomial regression to analyze pedestrian and cyclist collision data against block groups, median household income, population aged 5-17, population over 65, vehicle miles travelled, net population density, intersection counts, arterial mileage, big box stores, strip malls, and pedestrian-scale retail uses in order to identify which factors contribute and to what degree towards an increase in collision rates.

It should be noted that all of the previously mentioned models are limited by their inability to account for excess zero counts, and it is common for road segments or intersections to experience zero accidents during a given study period (Dong et al., 2014; Chang, 2017). Dong et al. (2014) recommend using random-parameter models when studying vehicle accident frequencies and associated variables as they can consider the correlation between different accident types and account for unobserved heterogeneity from one area to another. Their study uses a multivariate random parametres zero-inflated negative binomial regression model.

Research using regression models is prone to such methodological issues (Vandenbulcke et al., 2014), including controlling for confounding risk factors and identifying denominators for risk calculations (Harris et al., 2011). Multivariate regression also requires a large dataset in order to properly evaluate the statistical significance of each cycling risk factor (Conway et al., 2013), with most studies using at least 150 observations of cycling incidents (Reynolds et al., 2009).

Other Evaluation Methods

Exploratory methods such as descriptive statistics, odds ratios, or other spatial approaches are often used to do an initial assessment of cycling safety prior to using explanatory methods such as regression above (Vandenbulcke et al., 2014).

Conway et al. (2013) developed a method to evaluate the frequency of conflicts between cyclists and other road users and identify the factors that contribute to the frequency of conflict. They performed bivariate correlation analysis between conflict types and the time of day, lane configuration, curb regulation, and land use variables. They collected this data through direct observation and data mining and performed statistical tests to identify which factors could be used to predict multimodal crash frequency.

Before and after studies are another simple option to compare safety before and after implementing new infrastructure, however, they do not account for cyclist exposure (DiGioia et al., 2017) and can be time consuming to conduct. This is why there have been few studies evaluating changes in safety following investments in cycling infrastructure.

Case-control studies are another option as they use control sites along the same network where an accident occurred in order to provide a baseline to compare risk factors. Vandenbulcke et al. (2014) used a spatial Bayesian model to predict cycling risk based on road infrastructure for an entire network in Brussels, Belgium. They used a case-control approach where control sites were sampled along the bikeable network. Autocorrelation and multicollinearity between variables was controlled for and the model selection was based on goodness-of-fit and other statistical tests.

Even more robust are case-crossover studies as they control for confounding factors (Reynolds et al., 2009). Harris et al. (2013) used a case-crossover study to compare infrastructure between injury and control sites within the same trips in Vancouver and Toronto, Canada. This allows researchers to control for personal or other factors (e.g. weather) that have an impact on cycling safety. They conducted an inventory of the presence of cycling facilities, the presence and type of intersection, streetcar tracks, slope, sight distance, motorized and non-motorized traffic volume, average vehicle speed, and street lighting. Conditional logistic regression was used to compare infrastructure characteristics between control and injury sites. A limitation of case-crossover studies is that they are often limited by small sample sizes (DiGioia et al., 2017).

Multi-Criteria Analysis

Comprehensive, long-term plans that guide incremental changes are necessary when planning a cycling network (Pucher et al., 2011). A method is needed that can assess route safety and provide planners and decision-makers the information needed to identify the safest routes and where improvements are needed (Allen-Munley et al., 2004) and should be prioritized.

In an effort to assess the conditions of cycling networks, several studies have created models that produce an index value for a particular road segment or intersection (Harkey et al., 1998). This value is often based on a number of factors (Allen-Munley et al., 2004), however, many models used for assessing the suitability of cycling routes fail to take safety into consideration, prioritizing cost, supply, and/or demand (Allen-Munley et al., 2004). Additional factors that should be considered when planning a cycling network include safety, ease of cycling, pleasant route conditions, connectivity, and integration with transit – with safety being the most important concern (Terh & Cao, 2018).

There are several index models to assess bicycle facilities, the two most common are the Bicycle Level of Service (BLOS) and the bicycle compatibility index (BCI). They are both regression models that consider multiple factors and require a large amount of data (Asadi-Shekari et al., 2015).

Harkey et al. (1998) developed the Bicycle Compatibility Index (BCI) based off of perceived risk criteria. However, it is argued that objective safety data must also be considered when rating route safety (Allen-Munley et al., 2004). The Bicycle Level of Service (BLOS) index is common method of evaluating the comfort level of a cycling network (Rybarczyk & Wu, 2010). It was developed by the Transportation Research Board and considers factors like street width, traffic volume, road surface conditions, and vehicle speeds (Terh & Cao, 2018; Rybarczyk & Wu, 2010). The resulting score represents the comfort or safety level of that section of the network (Rybarczyk & Wu, 2010).

Similarly, Asadi-Shekari et al. (2015) developed a Bicycle Safety Index (BSI) based on different safety guideline standards:

$$BSI = \sum_{i=1}^{n} c_i BI_i$$

Where *i* is a given safety variable, *c* is the weight determined by the regression coefficient, and *BI* is the variable score between 0 and 1 depending on agreement with the combined standards. The coefficient is representative of the importance of a particular variable according to different guidelines. The resulting BSI is letter grade based on a scale from 0 to 100 (Asadi-Shekari et al., 2015).

Planning cycling networks based on one set of criteria or perspective is insufficient to meet the diverse needs of the public and stakeholders. Some studies have used multi-criteria analysis (MCA) and/or GIS in the evaluation or planning of transportation networks. MCA is derived from multi-attribute utility theory and can combine multiple factors into an aggregate measure of risk. In other words:

$$R = \sum_{j=1}^{n} w_j y_j$$

Where y_j is the expected risk of a given factor *j* and w_j is a weighting factor, expressing its relative impact on total risk (Fischoff et al., 1984). MCA allows for the consideration of multiple stakeholder preferences and encourages engagement and transparency in bicycle network planning (Terh & Cao, 2018). Point systems like MCA also allow for easy interpretation and can include multiple risk factors (Asadi-Shekari et al., 2015). This type of analysis can be used to incorporate the planning objectives of multiple stakeholders, including government agencies, planners, and cyclists (Rybarczyk & Wu, 2010). While objective analysis is the goal, conducting risk analyses requires value judgements as what is considered risky varies from person to person (Fischoff et al., 1984). However, subjectivity and uncertainty can be minimized through regression analysis and/or sensitivity analysis to calibrate factor weights (Fischoff et al., 1984).

Hsu and Lin (2011) developed a MCA model using GIS to assess the feasibility of designing a bicycle route based on existing road characteristics. They used an expert opinion survey and the fuzzy analytical hierarchy process to determine criteria weights. A similar paper by Terh and Cao (2018) used a GIS based multi-criteria decision analysis (MCDA) framework to determine where to build cycling facilities in Singapore. They used this framework in addition to questionnaires to incorporate different stakeholder preferences to support a collaborative and transparent planning process. A paper by Zuo and Wei (2019) also used MCDA to incorporate different stakeholder opinions when identifying where to make cycling infrastructure investments, but in an effort to reduce conflict between different road users (cyclists, drivers, public transit riders, etc.) instead.

Previous research has also incorporated the quality of supply and demand when bicycle facility planning using GIS and MCA. A paper by Rybarczyk & Wu (2010) performed a multi-criteria evaluation (MCE) on the cycling network of Milwaukee City, Wisconsin and looked at bicycle traffic demand and crime risk associated with the current bicycle network supply. A demand potential index was then calculated for each road segment using the weighted summation of the normalized factor values, with higher values being associated with higher cycling demand. Cycling network planning research by Grisé and El-Geneidy (2018) used a GIS-based grid cell model and a multi-criteria approach to identify priority areas for cycling investment in Quebec City, Canada, considering equity, safety, demand, and connectivity of the network in their analysis. A weighting scheme based on the stated preferences of cyclists was used for analysis.

Another study by Fuller, Williamson, Jeffe, & James (2003) used MCE in a raster GIS to evaluate driver risk along several paved road segments on the Hopi Reservation in Arizona. The criteria used to assess vehicle risk included proximity to intersections, steepness of slope, proximity to washes, and road curvature. In order to perform the analysis, they used IDRISI in order to rasterize vector data, create fuzzy sets, and generate composite maps with variable factor weightings. They then tested their resulting maps against vehicle crash site data.

While previous studies have used MCA and GIS to evaluate and plan cycling infrastructure, none have incorporated individual risk factors within their analyses. Instead, they rely on accident data or intersections identified as dangerous (Grisé & El-Geneidy, 2018), which are outcomes not indicators of cyclist risk. Similar to Fuller et al. (2003), this guide will propose a method that considers these risk factors to identify areas in need of intervention prior to an accident occurring. The objective is to produce composite index maps similar to Hsu and Lin (2011) and Rybarczyk and Wu (2010) evaluating Montreal's cycling network based on cyclist safety risk. This is to serve as an example of what other North American cities can do with the data they have available.

3. Data Collection

The island of Montreal was chosen as the study area to facilitate site visits. In order to perform a MCA of Montreal's cycling network, data first needed to be collected regarding current infrastructure, risk factors, and outcomes. Open data was used in order to demonstrate what kind of analysis can be done with limited resources and publicly available data.

Open Data

Local collision data for 2018 was obtained for the City of Montreal from Montreal Police Service (SPVM) open data (see Figure 1). As previously noted, most cycling accidents do not result in serious injury, property damage, or death and are, therefore, underreported. Using collision counts also has its limitations as it does not reflect ridership intensity for a given area. However, accurate cyclist VKT data needed to calculate accident rates is currently unavailable for the City of Montreal. The number of severe accidents is often used instead as it is independent from demand (Allen-Munley et al., 2004; Rahman Shaon et al., 2019), however, the number of severe accidents was low in 2018 (see Table 1). Further, accident outcomes are often a result of chance. Therefore, to eliminate risk one should consider all types of conflict.

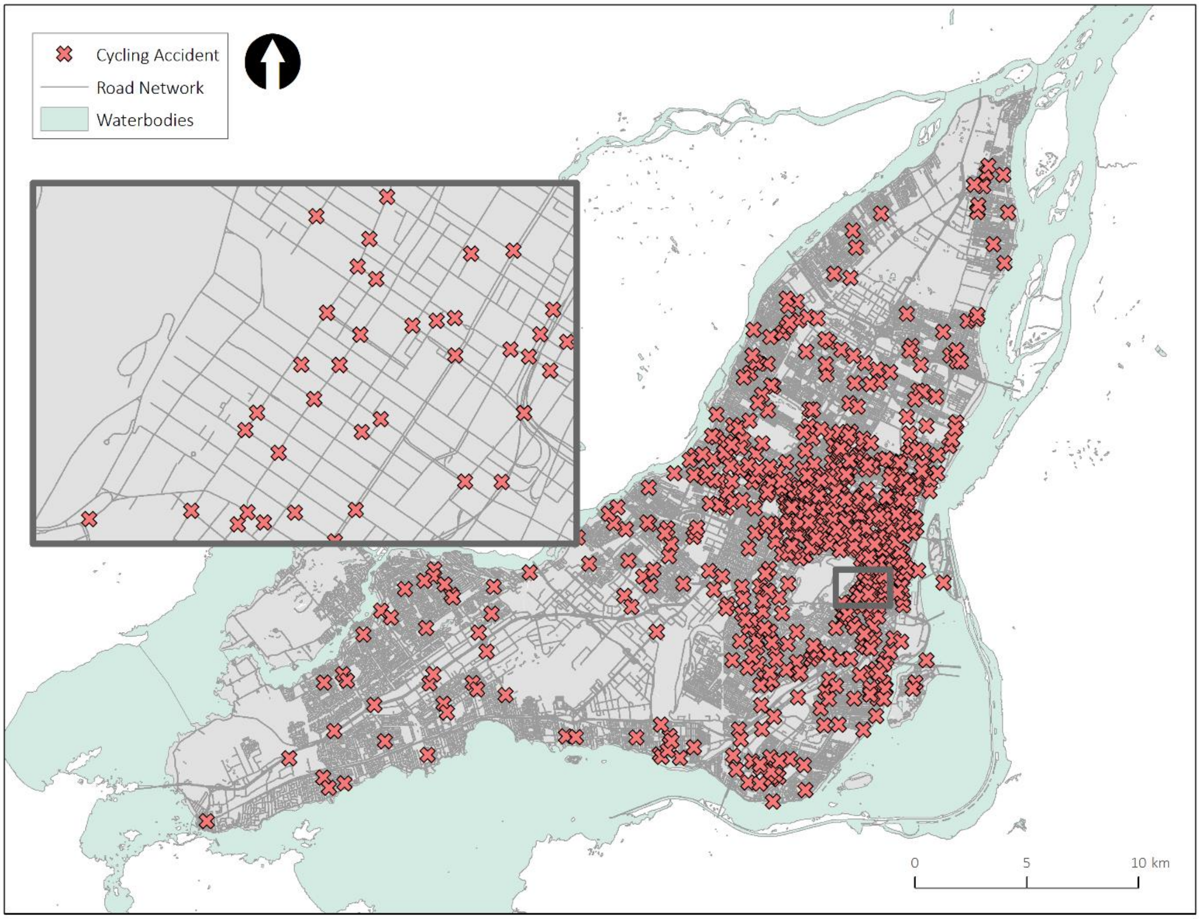

Figure 1. Reported accidents involving a cyclist, 2018. Source: SPVM

Perceived risk also needs to be addressed in order to convince the public to start cycling (Useche et al., 2019). Data concerning perceived accident risk was obtained from a cycling survey conducted by the Transportation Research Group at McGill in 2018 (see Figure 2). Respondents were asked to identify which intersection in Montreal they considered to be the most dangerous for cyclists.

Table 1. Descriptive statistics of cycling accidents on the island of Montreal for 2018. Source: SPVM

Number of Cycling Accidents	Number of Cyclists Injured	Number of Cyclists Severely Injured	Number of Fatal Accidents
797	602	20	3

Geospatial data about Montreal's road, cycling, and public transit networks as well as truck routes was also retrieved from the City of Montreal. The City of Montreal's road network also serves as a spatial representation of the potential cycling network and includes attribute data regarding road classification and direction (e.g. one-ways). The cycling network data contains information regarding the type of cycling facility and whether it is bidirectional or unidirectional.

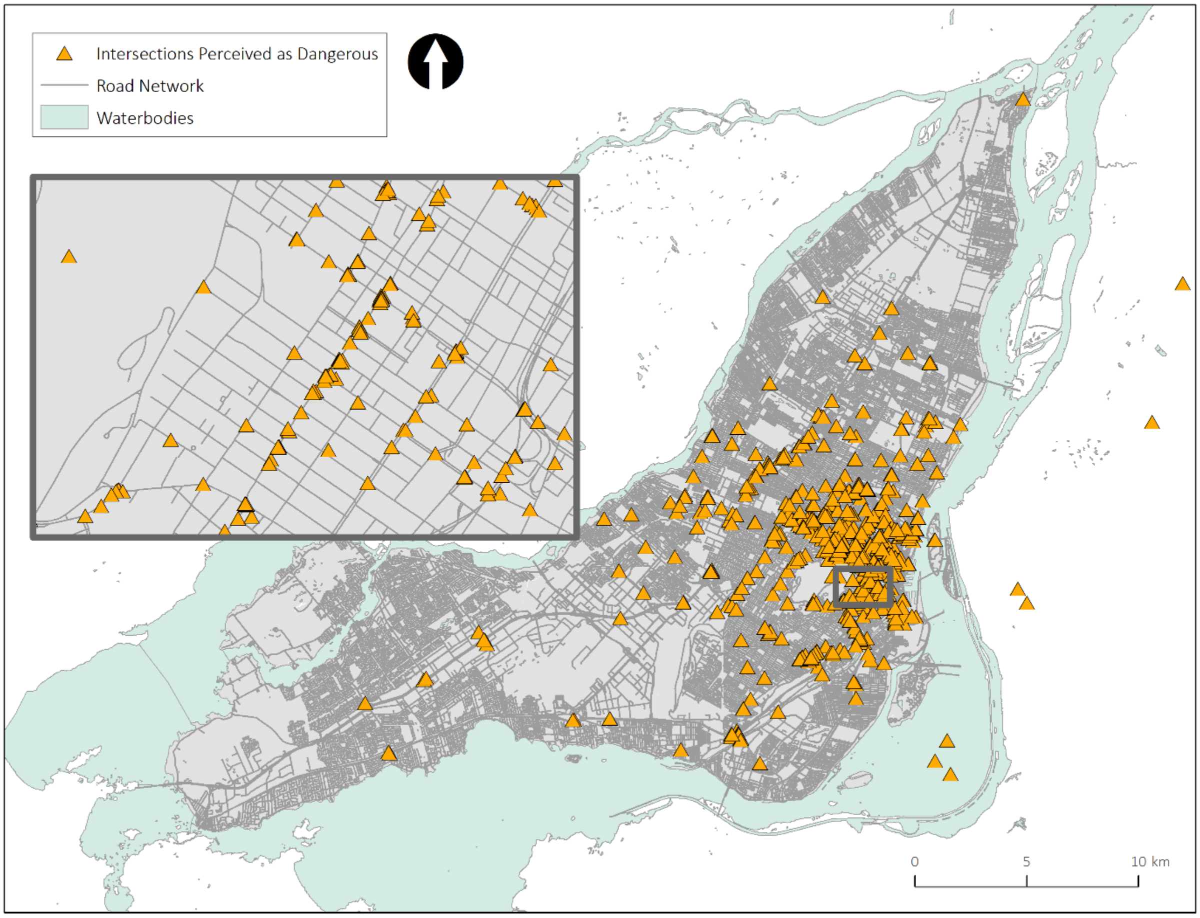

Figure 2. Intersections perceived as dangerous, 2018. Source: N. Chaloux, TRAM

Lastly, Montreal LiDAR data was retrieved in order to be able to calculate road segment slope. All metadata can be found in the appendix.

Infrastructure Inventory

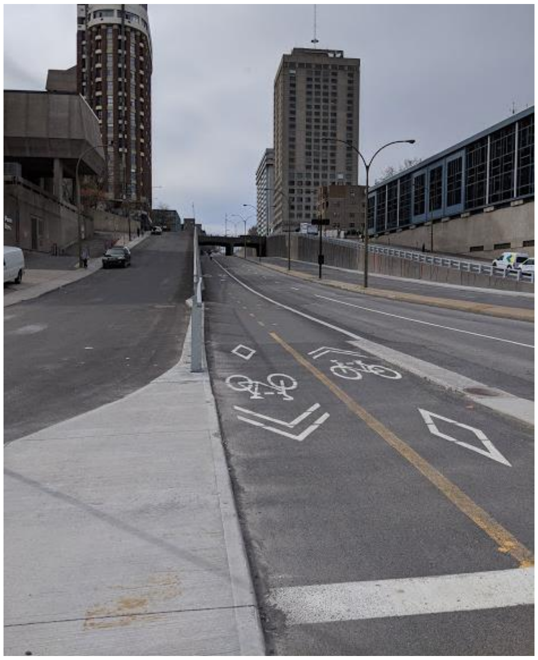

Figure 3. Site visit. Photo taken May 2, 2020

The top 20 road segments with the most collisions within 25 metres or those most frequently perceived as dangerous were selected to conduct an inventory of the built environment to objectively identify potential risk and perceived risk factors. This involved conducting site visits (see Figure 3) and desk studies using Google Streetview to record the presence or lack of certain features. The inventory questionnaire and road segments studied can be found in the appendix.

4. Methodology

The theory behind this method is that cycling accidents are not risk factors but are instead the outcome of risk. Therefore, they can be used to indicate areas where risk is high and identify the common features that contribute towards risk. MCA results are typically prone to subjectivity as factor weighting often relies on personal opinion. Ideally, more objective methods would be used when evaluating the safety of a cycling network. The following proposed method can be used to determine which factors contribute towards cyclist risk and to what degree based on the characteristics of the physical environment. High risk segments can then be identified based on these factors so that planners can apply the appropriate interventions to mitigate risk.

Descriptive Statistics

The descriptive statistics of the infrastructure inventory results for all accidents and areas perceived as dangerous were first calculated. This was to identify discrepancies and overlap between actual and perceived risk factors and later inform risk factor weights as part of the MCA. The results can be found in section 5.

Geographic Information Systems

The road, cycling, and transit network data along with truck routes were added in ArcMap. Road segments were categorized by their class and type of cycling infrastructure available, and Boolean values were assigned to segments depending on whether or not there were buses or trucks present, they were a one-way, or cycling facilities were bidirectional. A digital elevation model (DEM) was created using the LiDAR ground data for the island of Montreal (see Appendix). The average slope or percent grade was calculated for each road segment using the Add Surface Information tool.

In order to analyse the data, risk values were first assigned to each factor criteria and then to each road segment. Values were determined based on the degree to which each criterion contributed or mitigated cyclist risk. The final factor risk values can be seen in Table 2.

Table 2. Risk factor criteria values

Risk Factor	Criteria	Risk Value
Bus Presence	No	0
	Yes	1
Truck Presence	No	0
	Yes	1
Direction of Cycle Facility	Unidirectional	0
	Bidirectional	1
Cycling Facility Type	Designated Route/Bike Boulevard/Bus-Bike Lane	0
	Paved Shoulder/Bike Lane	-0.25
	On-Street Cycle Track	-0.5
	Separated/Raised Cycle Track	-0.75
	Multipurpose Trail	-1
Road Classification	Local	0.25
	Collector	0.5
	Secondary Arterial	0.75
	Primary Arterial	1
Direction of Vehicle Traffic	Two-way	0
	One-way	1
Percent Grade	<3%	0
	3-6%	0.5
	>8%	1

Multi-Criteria Analysis

To be able to perform the MCA, each risk factor had to be ranked based on its influence on cyclist risk. The literature review and results of the descriptive statistics informed the risk factor weights of the MCA and these values were then normalized to achieve a maximum sum of one. The final factor weights can be seen in Table 3.

With these factor risk values and their normalized weights, a risk index for each road segment was calculated using the following equation:

$$R = \sum_{i=1}^{n} v_i w_i$$

Where *R* is the risk index for a road segment, v_i is the risk value for criteria *i* for that segment, and w_i is the normalized weight for factor *i*. The equation calculates the weighted summation of normalized criteria values. These index values were then tested for accuracy against the collision and perceived risk data (see Appendix). The result is a composite index map measuring cycling network safety based on risk factors.

Table 3. Risk factor ranking and normalized weighting

Risk Factor	Rank	Normalized Weight
Bus Presence	1	7/28
Truck Presence	2	6/28
Direction of Cycling Facilities	3	5/28
Cycling Facility Type	4	4/28
Road Classification	5	3/28
Direction of Traffic	6	2/28
Percent Grade	7	1/28

5. Results and Discussion

Descriptive Statistics

The following descriptive statistics were used to inform risk factor criteria weights. Looking at the results of the infrastructure inventory, the findings both correlate and contradict what is observed in the literature and between areas of actual and perceived risk (see Table 4).

Table 4. Descriptive statistics of infrastructure at locations of actual and perceived risk

<table>
<tr><th rowspan="2"></th><th colspan="12">Actual</th><th colspan="12">Perceived</th></tr>
<tr><th colspan="6">Y</th><th colspan="6">N</th><th colspan="6">Y</th><th colspan="6">N</th></tr>
<tr><td>Is the segment one-way?</td><td colspan="6">45%</td><td colspan="6">55%</td><td colspan="6">25%</td><td colspan="6">75%</td></tr>
<tr><td>Are opposing directions physically separated?</td><td colspan="6">18%</td><td colspan="6">82%</td><td colspan="6">27%</td><td colspan="6">73%</td></tr>
<tr><td>Does the road profile have a perceptible grade?</td><td colspan="6">15%</td><td colspan="6">85%</td><td colspan="6">45%</td><td colspan="6">55%</td></tr>
<tr><td>Does the road have a perceptible curve?</td><td colspan="6">0%</td><td colspan="6">100%</td><td colspan="6">10%</td><td colspan="6">90%</td></tr>
<tr><td>Is parking permitted?</td><td colspan="6">95%</td><td colspan="6">5%</td><td colspan="6">45%</td><td colspan="6">55%</td></tr>
<tr><td>Is the road a bus route?</td><td colspan="6">65%</td><td colspan="6">35%</td><td colspan="6">95%</td><td colspan="6">5%</td></tr>
<tr><td>Is the road a truck route?</td><td colspan="6">45%</td><td colspan="6">55%</td><td colspan="6">90%</td><td colspan="6">10%</td></tr>
<tr><td>Did the accident occur at an intersection?</td><td colspan="6">95%</td><td colspan="6">5%</td><td colspan="12">NA</td></tr>
<tr><td>Does the segment have adequate lighting?</td><td colspan="6">85%</td><td colspan="6">15%</td><td colspan="6">80%</td><td colspan="6">20%</td></tr>
<tr><td rowspan="2">What is the segment surface condition?</td><td colspan="4">Good</td><td colspan="4">Fair</td><td colspan="4">Poor</td><td colspan="4">Good</td><td colspan="4">Fair</td><td colspan="4">Poor</td></tr>
<tr><td colspan="4">50%</td><td colspan="4">50%</td><td colspan="4">0%</td><td colspan="4">40%</td><td colspan="4">55%</td><td colspan="4">5%</td></tr>
<tr><td rowspan="2">What is the road segment classification?</td><td colspan="3">Local</td><td colspan="3">Collector</td><td colspan="3">Secondary Arterial</td><td colspan="3">Primary Arterial</td><td colspan="3">Local</td><td colspan="3">Collector</td><td colspan="3">Secondary Arterial</td><td colspan="3">Primary Arterial</td></tr>
<tr><td colspan="3">30%</td><td colspan="3">25%</td><td colspan="3">30%</td><td colspan="3">15%</td><td colspan="3">0%</td><td colspan="3">25%</td><td colspan="3">60%</td><td colspan="3">15%</td></tr>
<tr><td rowspan="2">Type of cycling facilities?</td><td colspan="2">None</td><td colspan="2">Sharrow</td><td colspan="2">Paved Shoulder</td><td colspan="2">Bike Lane</td><td colspan="2">Cycle Track</td><td colspan="2">Bike Path</td><td colspan="2">None</td><td colspan="2">Sharrow</td><td colspan="2">Paved Shoulder</td><td colspan="2">Bike Lane</td><td colspan="2">Cycle Track</td><td colspan="2">Bike Path</td></tr>
<tr><td colspan="2">65%</td><td colspan="2">0%</td><td colspan="2">0%</td><td colspan="2">20%</td><td colspan="2">15%</td><td colspan="2">0%</td><td colspan="2">35%</td><td colspan="2">5%</td><td colspan="2">0%</td><td colspan="2">20%</td><td colspan="2">40%</td><td colspan="2">0%</td></tr>
</table>

Are cycling facilities bidirectional?	Y		N	Y		N
	57%		43%	69%		31%
	Mean	Median	Mode	Mean	Median	Mode
Posted speed limit (km/h)	38.8	40	30	38.3	40	40
Lane width (m)	3.2	3	3	3.2	3	3
Bicycle lane width (m)	1.6	1.5	1.5	1.5	1.5	1.5
Number of lanes	2.44	2	2	2.5	2	2
Number of junctions (per km)	28.1	21.5	0	23.1	14.8	0

Similar to previous research, one-ways seem to be perceived as less risky, however, their impact on actual cyclist risk is less clear. Having a physical barrier where there are opposing directions of traffic also does not appear to have an impact on risk. Contrary to previous research, the percent grade and curvature of the segment do not seem to have much of an impact on actual risk, and have only a slightly greater impact on perceived risk. Adequate lighting also did not appear to have much of an impact on risk, however, this may be due to most recorded accidents happening during the day.

The presence of on-street parking seems to have negative impact on actual risk, although is not perceived as particularly high risk. This may be due to the prevalence of on-street parking in Montreal. Both bus and truck presence seem to have negative impact on perceived risk in particular, with buses posing greater actual risk. Like previous research, most accidents were recorded at intersections and on streets without cycling infrastructure.

Road surface condition did not have an impact either way on cycling safety, however, few sites visited had poor surface conditions. Different road classifications have seemingly little impact on cyclist risk, but collectors and arterials are perceived as less safe than local roads. Cycle tracks were perceived as the least safe type of cycling infrastructure. Accidents were slightly more common on bidirectional facilities which were also perceived as less safe. The average site road speed was approximately 40 km/h, but it should be noted that this may be because cyclists avoid streets with higher operating speeds. Lastly, the average number of junctions per kilometre was higher than the recommended 16 (Pulugurtha & Thakur, 2015) for areas of actual and perceived risk.

Index Map

The resulting risk index map of Montreal's cycling network can be seen below. Road segments that pose a higher risk for cyclists have index values closer to one and are identified in red. As can be expected, the majority of high-risk segments were located along arterials. This is likely due to the increased likelihood of heavy vehicle presence as well as higher traffic speeds and volumes. Some segments identified already have cycling facilities present, indicating that different interventions, an alternate route, and/or further risk assessment is needed to improve cyclist safety in these areas.

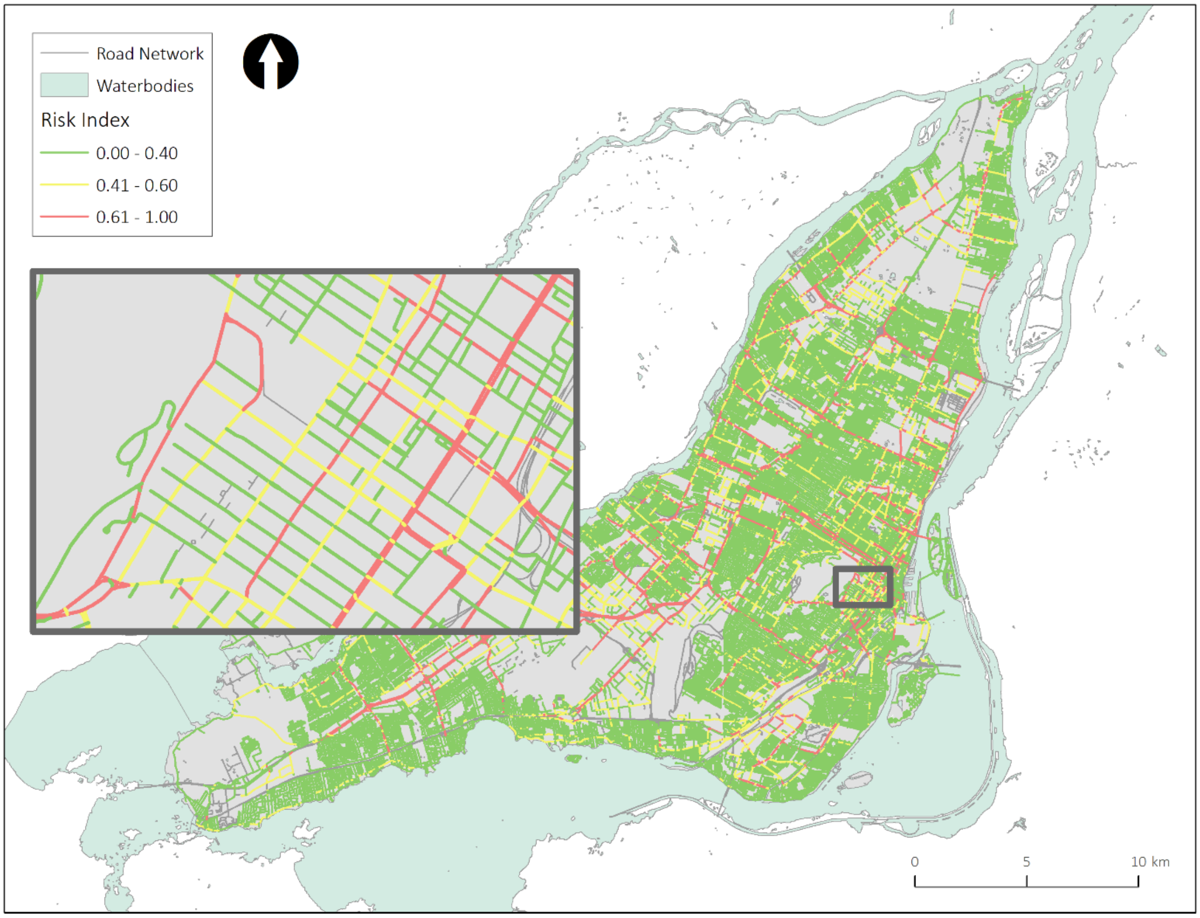

Figure 4. Composite risk index map

Over 65 percent of accidents corresponded to segments with a risk index over 0.4, with over 30 percent corresponding to segments with a risk index over 0.6. Similarly, over 70 percent of intersections perceived as dangerous corresponded to segments with a risk index over 0.4, with nearly 60 percent corresponding to segments with a risk index above 0.6.

6. Limitations

Due to the limited amount of time and resources available for this project, in addition to the COVID-19 pandemic, a relatively small number of site visits were conducted as part of the infrastructure inventory. Ideally, enough observations would be collected in order to perform a regression analysis to more accurately determine risk factors weights from parameter coefficients. However, due to the limited sample size, the methodology presented here had to rely on descriptive statistics and qualitative analysis to derive factor weights. This likely introduces some subjectivity into the analysis, however, results were tested against accident data and areas perceived as high risk for accuracy.

For the MCA, analysis was limited to what geospatial data was publicly available for the whole cycling network for the island of Montreal. Like many municipalities, open data concerning Montreal's infrastructure is currently lacking, therefore, not all relevant risk factors identified in the literature and infrastructure inventory could be included in the assessment.

In terms of data analysis, there is likely error in the interpolated DEM as well as error when assigning risk values for each road segment. For example, due to differences in data sources, network shapefiles did not always align. This made selecting segments for analysis more difficult and some may have been accidently included/excluded.

7. Recommendations

The following section provides recommendations for North American cities when it comes to what data should be collected and how it should be recorded to be able to perform this type of analysis. In addition, a brief overview on safe network planning and design is provided to inform planners, engineers, and decision-makers of what planning interventions are best suited to mitigate certain elements of risk.

Data Collection

In order to perform more accurate analyses of cyclist risk going forward, cities need to collect sufficient cyclist count or GPS data in order to be able to accurately measure demand and, therefore, accident rates. Collecting more detailed information about cycling incidents in terms of the nature of the accident and physical surroundings is also recommended. Up-to-date open data about transportation infrastructure and operations should also be maintained to be used for analysis. Standards for data collection and methodology are recommended between cities to allow for network safety comparisons to be made.

It is recommended that the gathering and recording of this information be coordinated between departments where possible so that accurate records can be maintained over time and that there are no discrepancies in format.

Network Planning and Design

Safety is major consideration when cyclists plan their route (Rybarczyk & Wu, 2010). Multiple studies have shown that improvements to cycling infrastructure lead to an increase in cycling rates (Boss et al., 2018) and safety (Conway et al., 2013). Therefore, cities are likely to improve cycling infrastructure as cycling rates increase and vice versa (Schepers & Heinen, 2013). Further, a safe cycling network will encourage more people to bike, and more people biking improves safety (NACTO, 2017).

Improving cycling infrastructure has the benefit of not requiring any adjustment or active participation on the part of the individual and does not require repeated enforcement unlike other initiatives (Reynolds et al., 2009). Improvements in cycling infrastructure also have an impact on overall safety, unlike helmets and education programs which impact solely the user with the benefits being short-lived (Harris et al., 2011).

Implementing cycling infrastructure also helps reverse some of the urban problems caused by the proliferation of motor vehicles (Conway et al., 2013). It requires less space compared to infrastructure for motor vehicles and public transit, allowing for more land to be used for public space or development (Terh & Cao, 2018).

To encourage cycling, infrastructure needs to be designed to reduce risks and initiatives are needed to improve safety perceptions. However, it should be noted that cycling infrastructure on high traffic roads was found to only marginally reduce perceived risk and there are limits to the additional travel time cyclists are willing to spend in order to use safer facilities (Manton et al., 2016). It is also difficult to prove a causal relationship between an increase in cycling facilities and safety; however, results have been positive in a number of countries (Pucher & Buehler, 2008).

Cycling rates are much higher in European countries like the Netherlands, Denmark, and Germany – largely because it is safer to bike there. Since the 1970s, Dutch cities in particular have heavily invested in cycling infrastructure which has resulted in an 81 percent drop in cyclist fatality rates from 1978 to 2006 and a 36 percent increase in kilometres cycled per person (Pucher & Buehler, 2008). However, it should be noted that safety outcomes cannot be easily generalized between countries due to cultural and environmental differences (Schepers et al., 2014b). Environmental conditions in the Netherlands are conducive to cycling as terrain is flat, the climate is mild, and high-density cities and mixed land uses reduce travel distances (Schepers et al., 2017). It is, therefore, important to assess which treatment is best suited to a particular location (DiGioia et al., 2017).

Planning a safe cycling network requires a comprehensive and coordinated approach with many policies and programs (Pucher & Buehler, 2008; Conway et al., 2013). Implementing cycling infrastructure often still needs to be justified as it often requires the repurposing of street space that is used for driving or parking. While cycling is the more sustainability option, the feasibility of removing vehicle capacity must still be considered, particularly when it poses a safety risk (Conway et al., 2013). It is recommended that high risk locations along a network be identified and investments in cycling infrastructure be made to mitigate risk at these locations (Bíl et al., 2010). Ideally, data would be collected before and after the implementation of new interventions (DiGioia et al., 2017) in order to demonstrate their effectiveness.

Vision Zero

Developed in Sweden, the vision zero approach strives to eliminate death and serious injuries from roads (Cushing et al., 2016). It relies on adapting and learning from accidents and injuries in order to build a safer transportation system. The goal is to prevent future collisions and provide a safe environment, free from risk imposed by motorists (Jacobsen & Rutter, 2012).

Vision Zero places the blames on planners, therefore, infrastructure design is central to these plans in order to reduce the likelihood of collision in the first place. This involves separating traffic of different speeds, reducing speeds on shared roads, and reducing conflict zones (Cushing et al., 2016). Similarly, the sustainable safety vision relies on infrastructure design to inherently and drastically reduce crash risk and, should a crash occur, reduce crash severity. It relies on the principles of functionality, homogeneity, predictability, forgiveness, and state awareness (Wegman et al., 2012). Cyclists fare better in predictable and recognizable environments as humans have limited information processing capacity and can become overloaded by overly complex road designs (Schepers et al., 2014b).

A long-term vision of eliminating cyclist death and injury is needed and can be achieved through incremental measures that can be adjusted and improved along the way (Cushing et al., 2016). Law enforcement, education, and cycling promotion activities are often done simultaneously (Cushing et al., 2016).

Safe Network Design

There are three different ways to improve the safety of a cycling network. Changing the design of the network by adding cycling infrastructure creates dedicated space for cyclists but is often more disruptive and costly. Operational changes, such as speed reductions, signal changes, and curbside management, can often have a quick and significant impact without requiring intensive planning. The final and most powerful option is to change the network by diverting motor vehicle traffic, changing time-of-day regulations, or making other changes to the role of the street (NACTO, 2017).

Detailed design guidelines exist for cycling facilities that describe how each intervention should be applied depending on location characteristics (NACTO, 2014; Jolicœur & Komorowski, 2019), however, a brief summary of different network design elements can be found in this section. Most safety measures involve mitigating the risk posed by motor vehicles by minimizing interactions, increasing cyclist visibility and predictability, and reducing vehicle speeds (DiGioia et al., 2017).

While there has been some research on the safety impact of bike lanes and on-street parking, most interventions have yet to be rigorously studied (DiGioia et al., 2017). One reason for this is that consistent definitions for cycling infrastructure are lacking and are needed in order to allow for comparisons between studies (Harris et al., 2011; Reynolds et al., 2009).

It should be noted that there have been no conclusive studies showing that riding in designated cycling facilities is safer than riding in the street. Some studies show that injury rates are reduced, but that risks increase at intersections. On-street collisions are also more often fatal (Cushing et al., 2016). Therefore, these strategies are best implemented incrementally (NACTO, 2017).

Regarding bikeways themselves, there are three main categories of cycling facility: (1) lanes that are demarcated with paint or other flexible barriers, (2) lanes that are physically separated from motor vehicles by physical barriers (e.g. planters, parked vehicles), and (3) shared routes, suggested routes, or bicycle boulevards which are located on low traffic streets and indicated via signage or sharrows (Conway et al., 2013).

Bike lanes are designated portions of the road that are demarcated using paint and signage (see Figure 5). They have no physical barrier and are typically located to the right and travel in the same direction as motor vehicle traffic (DiGioia et al., 2017; NACTO, 2014). Bike lanes allow cyclists to travel at their preferred speed and allow drivers to predict their movements (NACTO, 2014).

Bike lanes should be used in areas where traffic volumes and speeds are too high for mixed traffic, but lane invasion, heavy vehicle presence, and/or curb activity is low. Vehicle speeds should not exceed 40 km/h and conflict with vehicles passing, turning, parking, opening doors, loading and unloading should be minimized. Ideally, these lanes would be buffered to provide more room and improve cyclist comfort (NACTO, 2017). Bike lane width should ideally be two metres, with a minimum width of one metre. However, they should be made as wide as possible to allow for comfortable passing (NACTO, 2014). A minimum of 2.5 metres is needed to ride side by side and three metres is required for bidirectional facilities (Jolicœur & Komorowski, 2019; City of Vancouver, 2017).

Figure 5. Buffered bike lane (left) and contraflow bike lane (right). Sources: NACTO (left) and Spacing Montreal (right)

Buffered bike lanes provide additional space separating cyclists from vehicles and are preferred where there is adequate space (DiGioia et al., 2017; NACTO, 2014). They allow cyclists to pass without encroaching into vehicle traffic and cyclists perceived a lower risk of dooring in buffered bike lanes. Buffers must be at least 50 centimetres wide (NACTO, 2014).

Contraflow bike lanes allow cyclists to travel in the opposite direction of vehicle traffic and are often present on one-ways, where high volumes of cyclists travel the wrong way, or to improve network connectivity. They are to be avoided according to the NACTO design guide (2014) as they may introduce new conflict points and are less predictable for drivers. Left sided bike lanes can be used along streets with high truck and transit use or high parking turnover to minimize conflicts between road users. They should only ever be placed on one-way streets or where there is a median (NACTO, 2014).

Separated cycling facilities are needed along truck and transit routes, where there is a lot of parking turnover (NACTO, 2014), where speeds exceed 40 km/h, where traffic volumes exceed 6,000 vehicles per day, or there are multiple lanes of traffic (NACTO, 2017; Pucher & Buehler, 2008; Bíl et al., 2010).

Cycle tracks are physically separated from motor vehicles with a barrier and/or raised above street level (see Figure 6). Common barriers are delineators, planters, raised curbs (NACTO, 2014), and cement barriers. Fences and guardrails should be used over bridges (Jolicœur & Komorowski, 2019). They are typically located to the right next to the curb but are distinct from sidewalks as they are designated for cyclists (NACTO, 2014).

Figure 6. Cycle track (left) and bike path (right). Sources: Livable Cities (left) and NCC (right)

Cycle tracks can be unidirectional or bidirectional (NACTO, 2014; Jolicœur & Komorowski, 2019). However, the Dutch Design Manual for Bicycle Traffic (CROW) advises against implementing bidirectional facilities unless it is likely to greatly reduce the need to cross high traffic roads or to avoid high volumes of contraflow cycling. They also have to be made wider than unidirectional facilities in order to safely accommodate passing (Methorst et al., 2017). The minimum width for a cycle track is 1.5 metres and two metres for raised cycle tracks or where there are high cycling levels, steep inclines (NACTO, 2014), or frequent passing (Schepers et al., 2014b). Bidirectional cycle tracks should ideally have a width of 3.5 metres and a minimum of 2.5 metres where space is limited (NACTO, 2014). It is recommended that cycle tracks wrap behind bus stops to avoid conflicts with buses and pedestrians (NACTO, 2014; Jolicœur & Komorowski, 2019). Vehicles exiting from driveways must also be made to yield to cyclists where there are cycling tracks (NACTO, 2014).

Cycle tracks are preferred by cyclists. In the US, only 6-10 percent of people felt comfortable riding in traffic or in painted bike lanes. Meanwhile, up to 80 percent of people would ride in separated facilities (NACTO, 2017). However, cyclists often feel the need to be extra-vigilant on bidirectional cycling facilities and using parked cars as separation led to concerns over dooring (Van Cauwenberg et al., 2018).

Most developed countries with high cycling rates have cycle tracks as a feature of their cycling networks. Unidirectional cycle tracks have been found to reduce accident frequency and severity, with bidirectional cycle tracks requiring intersection treatments to have the same effect (Thomas & DeRobertis, 2013).

Bike paths, shared-use, or multipurpose trails are cycling corridors that are completely separate from the road network (see Figure 6) (NACTO, 2017). They are the most widely used type of cycling facilities and provide the most separation from motor vehicles. They are perceived as the safest and most comfortable type of cycling infrastructure. However, they are primarily used for recreational purposes as they are often not direct (Pucher et al., 2011). They are typically separated from motor vehicles by open space or other barriers and are used by cyclists, pedestrians, and other active transportation users (DiGioia et al., 2017).

Shared streets are often in areas where traffic speeds are below 15 km/h and there is a greater share of pedestrians and cyclists. Efforts should be made to avoid conflicts with pedestrians. Bicycle boulevards are also often on local roads with low vehicle speeds and volumes. Traffic calming elements are common, and routes are often indicated with signs or sharrows (NACTO, 2017). Sharrows and other road markings (see Figure 8) indicate shared road use, proper cyclist positioning, and serve as wayfinders (NACTO, 2014).

Shared street, protected bike lanes, and off-street pathways appeal to those who are interested in cycling but concerned for their safety (City of Vancouver, 2017). Separated cycling facilities also reduce exposure to air pollutants (Bigazzi & Figliozzi, 2014).

Bikeways need to be planned strategically and prioritise safety, directness, and connectivity. Routes should be planned to minimize changes in topography to reduce risk and physical exertion (Harris et al., 2013; Winters et al., 2011). Ideally, grades should be kept below three percent (City of Vancouver, 2017) while grades up to six percent are acceptable for short distances but should never exceed eight percent grade as most cyclists will find it difficult to maintain balance (Jolicœur & Komorowski, 2019).

Figure 7. Local road with sharrow. Source: NACTO

Cycling facilities should not be located along truck routes (Allen-Munley et al., 2004) or designated loading zones separated from cycling facilities can be restricted to off-peak periods. Transit boarding islands can be provided along bus routes to minimize conflicts (NACTO, 2017). Enough space for cars to safely pass must be given on roads with on-street parking (City of Vancouver, 2017) and cycling facilities should be built outside the door zone (0.8 metres) of parked vehicles (Vandenbulcke et al., 2014).

Cycling facilities should be well lit (Winters et al., 2011) and coloured pavement can be used to increase visibility in high conflict areas or throughout a network (NACTO, 2014; DiGioia et al., 2017). Finally, an adequate supply of secure and, ideally, sheltered bicycle parking is needed at destinations along the cycling network in order to prevent theft and protect bicycles from adverse weather (Pucher et al., 2011).

It is argued that initiatives that improve safety at intersections are the most likely to reduce cyclist risk (Dozza & Werneke, 2014). Safety at intersections is dependent on visibility, speed, and exposure (Jolicœur & Komorowski, 2019). Reductions in motor vehicle speeds and between two and five metre clearance between cycling facilities and the road are thought to improve safety by keeping cyclists out of driver blind spots. It is thought that speed reductions alone have prevented 2.5 percent of collisions in the Netherlands (Schepers et al., 2017). Vehicle speeds should not exceed 20 km/h when turning left and 10 km/h when turning right (Jolicœur & Komorowski, 2019). Driveways and other junctions should be limited to less than 80 per kilometre and other junctions to less than 16 per kilometre. Signalized intersections should also be limited to less than five per kilometre (Pulugurtha & Thakur, 2015).

Intersection treatments should minimize conflict between road users by increasing visibility, communicating clear right-of-way, and encouraging eye contact and awareness between users (NACTO, 2014). Intersection visibility depends on configuration, visual obstructions, lighting, and cyclist markings and signage (Jolicœur & Komorowski, 2019).

Intersection markings are dotted lines that indicate clear paths for cyclists and make movements more predictable for drivers. They should be used where the cycling path is unclear and standardized to avoid confusion. Dotted, through bike lanes may be necessary when approaching intersections to indicate proper positioning for cyclists where there are right turn lanes and remind drivers to yield to bike traffic (NACTO, 2014). However, these should be avoided as they are riskier. A safer alternative is to have bike lanes kept to the far right and utilize connecting tracks to cross right turn lanes (Jolicœur & Komorowski, 2019). Cyclist shortcuts can also allow cyclists to turn right before an intersection (Pucher & Buehler, 2008).

Cyclist crossing distances should be minimized where possible with curb extensions and medians (NACTO, 2014; Jolicœur & Komorowski, 2019). Median refuge islands provide a protected space in the middle of the two-way streets to make crossing safer and easier (NACTO, 2014). They are recommended where there are multiple lanes of traffic in both directions (City of Vancouver, 2017) and/or where there are high traffic volumes. The minimum width for a median refuge is two metres but they should ideally be three metres or more be able to accommodate two-way bicycle traffic (NACTO, 2014).

Protected intersections are the ideal configuration as they better separate different road users, minimize crossing distances, improve perceived safety, and increase visibility (see Figure 9). They involve island refuges at each corner protecting cyclists from motor vehicles (Jolicœur & Komorowski, 2019). Coloured pavement and elephant feet street crossing help improve visibility, predictability (City of Vancouver, 2017), and increase driver yielding. The colour green is often recommended (NACTO, 2014).

Figure 8. Protected intersection with coloured pavement and elephant feet crossing. Source: City of Long Beach

Two-stage queue boxes, bike boxes, or phase separation can be used to mitigate risk at intersections (NACTO, 2017) by separating and making cyclists more visible to drivers (Schepers et al., 2017).

Two-stage turn queues (see Figure 10) allow cyclists to make left turns at intersections without having to merge with vehicle traffic by travelling as a pedestrian would (DiGioia et al., 2017). However, they do cause a delay for cyclists as they must cross two directions of traffic. Two-stage turn queues can be used at signalized and unsignalized intersections and they are recommended where there are cycle tracks as it is more difficult to merge with traffic (NACTO, 2014).

Bike boxes or advanced stop lines (see Figure 10) improve cyclist visibility and facilitate turns by placing them at the front of the queue at intersections (DiGioia et al., 2017; NACTO, 2014; Jolicœur & Komorowski, 2019; City of Vancouver, 2017). They are recommended at signalized intersections where there are frequent cyclist left turns. Motor vehicles cannot be allowed to turn right on red in order to avoid encroachment into the bike box (NACTO, 2014; Jolicœur & Komorowski, 2019). They should be three to five metres deep and include coloured pavement and markings (NACTO, 2014). Bike boxes can be combined with an advanced bike signal to allow clearance prior to vehicle movement (NACTO, 2014; Thomas & DeRobertis, 2013; City of Vancouver, 2017).

Figure 9. Two-stage turn queue (left) and bike box (right). Source: NACTO

Bicycle signals improve safety at major intersections by clarifying when cyclists should cross and by reducing conflicting vehicles movements. The type of signal to implement depends on vehicle speeds, traffic volume, and current or planned intersection configurations. There is currently a lack of clearance interval standards (NACTO, 2014; Jolicœur & Komorowski, 2019), however, in most situations it should be based on intersection width (*W*) and average cyclist travel speed (*V*) using the following formula (NACTO, 2014):

$$C_i = 3 + \frac{W}{V}$$

Where signals need to be activated, sensors (e.g. in-pavement loops, video) are preferred over push-buttons (NACTO, 2014). Flashing lights along bike routes and timed signals can also allow cyclists to avoid having to stop at intersections if they match their speed (Pucher & Buehler, 2008).

Active warning beacons can be used mid-block or at unsignalized intersections to remind drivers to yield to cyclists where they have right-of-way (NACTO, 2014). Ideally, passageways would allow cyclists to cross roads without stopping while on bike paths. Otherwise, cyclists should be made to come to a stop at a crosswalk (Jolicœur & Komorowski, 2019).

Finally, sufficient lighting is needed along a network but is particularly important at intersections. However, further research is needed to determine what qualifies as adequate lighting (City of Vancouver, 2017).

Traffic calming initiatives can provide cyclists with safe spaces to ride without designated cycling facilities. Bicycle boulevards are a type of traffic calmed street which include pavement markings and signage prioritizing bicycle right-of-way (Pucher et al., 2011). Other signage can help with wayfinding and indicate to drivers where to expect cyclists (NACTO, 2014).

Traffic calming is typically area-wide (Pucher & Buehler, 2008) and encourages compliance with posted speed limits (City of Vancouver, 2017; DiGioia et al., 2017). It is best suited to residential areas (Pucher & Buehler, 2008). In the Netherlands, an estimated 60 percent of urban bicycle kilometres are traveled in traffic calmed areas (Schepers et al., 2017).

It is also thought that interventions that reduce traffic speed and volume may also increase cycling rates (Jacobsen & Rutter, 2012), with speeds below 30 km/h and traffic calming initiatives being preferred (Van Cauwenberg et al., 2018; Wegman et al., 2012; Pucher & Buehler, 2008 Schepers et al., 2017; Pucher et al., 2011). Woonerfs are the most extreme form of traffic calming by reducing vehicle travel to walking speeds (Pucher & Buehler, 2008).

Vancouver is at the forefront of traffic calming in North America by imposing speed limits of 30-40 km/h in many residential areas and designing streets to enforce these speeds (Pucher et al., 2011). Prohibiting through-traffic, implementing one-way streets, or removing on-street parking are common traffic calming strategies to reduce vehicle speeds and/or volumes (NACTO, 2017).

Other common interventions (see Figure 11) include speed humps, raised crosswalks and intersections (Pucher & Buehler, 2008; NACTO, 2014; Pucher et al., 2011), narrowing roads, extra curves (Pucher & Buehler, 2008), chicanes, traffic circles, medians, curb extensions, special pavement, diverters, and mid-block street closures with pass-throughs for bicycles (Pucher et al., 2011).

Figure 10. Raised crosswalk (top left), chicanes (top right), mid-block closure with pass-through (bottom left), diverters (bottom right). Sources: U.S. DOT Federal Highway Administration (top left, bottom left), LA DOT Bike Blog (top right), NACTO (bottom right)

The idea behind many of these interventions is that the narrowing or curvature of roadways and elevations in pavement force vehicles to travel at slower speeds (NACTO, 2014). Raised intersections and crosswalks also improve cyclist visibility (Jolicœur & Komorowski, 2019).

Limiting driver field of vision by planting trees, reducing building setbacks, and/or having on-street parking may also help reduce vehicle travel speeds (Jolicœur & Komorowski, 2019). However, while on-street parking is often a part of traffic calming initiatives, it can pose a safety hazard to cyclists (DiGioia et al., 2017).

Finally, cyclists prefer well-maintained, smooth surfaces free from potholes, glass, and debris (Winters et al., 2011; NACTO, 2014). Smooth surfaces are particularly important for older populations and new cyclists as uneven surfaces are less comfortable and can throw off them balance. Asphalt is preferred over concrete, followed by pavers and other textured surfaces

(City of Vancouver, 2017). However, cobbled pavement in low-speed areas is recommended in order to ensure that cyclists can hear other traffic (Stelling et al., 2015).

Lane markings and stencils should be maintained to be clear and legible by all road users and all markings should be skid and wear resistant (NACTO, 2014). Signs and road markings should also be reflective (Jolicœur & Komorowski, 2019).

Vegetation must be trimmed regularly to maintain visibility (NACTO, 2014) and investments in winter maintenance are recommended to ensure safe riding surfaces (Schepers et al., 2014b). Facilities should be plowed and salted (Winters et al., 2011; NACTO, 2014) and snow removal can be simplified for cycle tracks by having them at the same level as the sidewalk. Otherwise, special equipment may be needed, or barriers may need to be made temporary. Coloured pavement may also require more upkeep in areas with abundant ice and/or snow (NACTO, 2014).

Other Safety Initiatives

Cycling education programs often play a role in promoting cycling and improving cycling safety. They often result in increased skills and knowledge, however, impacts on safety are less clear (Wegman et al., 2012). Cycling education programs in the Netherlands have only been found to have minor positive effects on safety (Schepers et al., 2017). A study by Hatfield, Boufous, & Eveston (2019) evaluated the effect of a school-based cycling education program in Australian and found that there were improvements in participant safe cycling knowledge, confidence, and perceived safety. However, there was no evidence that it improved safety behaviour and there was no significant decrease in the number of collision and a near significant increase in the number of near misses. Further, the increase in confidence disappeared after three months, suggesting that the impacts of such programs are short-lived.

Training and licensing for drivers is also more strict in countries with higher levels of cycling (Buehler & Pucher, 2017). ‘Share the road’ campaigns are common in many North American cities (Pucher et al., 2011). Increasing driver responsibility for cycling collisions through traffic regulations has been suggested as a way to decrease risk by forcing drivers to change their behaviour to avoid liability. However, there is a lack of empirical research as to whether this improves safety outcomes (Schepers et al., 2017). Driving in general needs to be made inconvenient in urban areas through restrictions, taxation, or parking costs (Pucher & Buehler, 2008) to encourage a shift towards more sustainable modes.

Land use policies like mixed-use zoning keep cycling distances short. Route planners can allow cyclists to select the safest route as opposed to the most direct route are another method of reducing risk (Pucher & Buehler, 2008). Finally, it has been suggested that artificial sounds be added to hybrid and electric cars to improve detectability (Stelling et al., 2015).

8. Concluding remarks

This cycling safety guide provides cities with a review of the most current information about which factors have the greatest impact on cyclist safety. The MCA method proposed can be used by transportation planners and engineers to evaluate the safety of their cycling networks using publicly available data. This tool can be used to signal to decision-makers which areas are in need of new or improved cycling infrastructure, route alternatives, and/or are in need of further risk analysis. Planners and engineers can then refer to this guide when determining which planning interventions are most appropriate to improve cycling safety.

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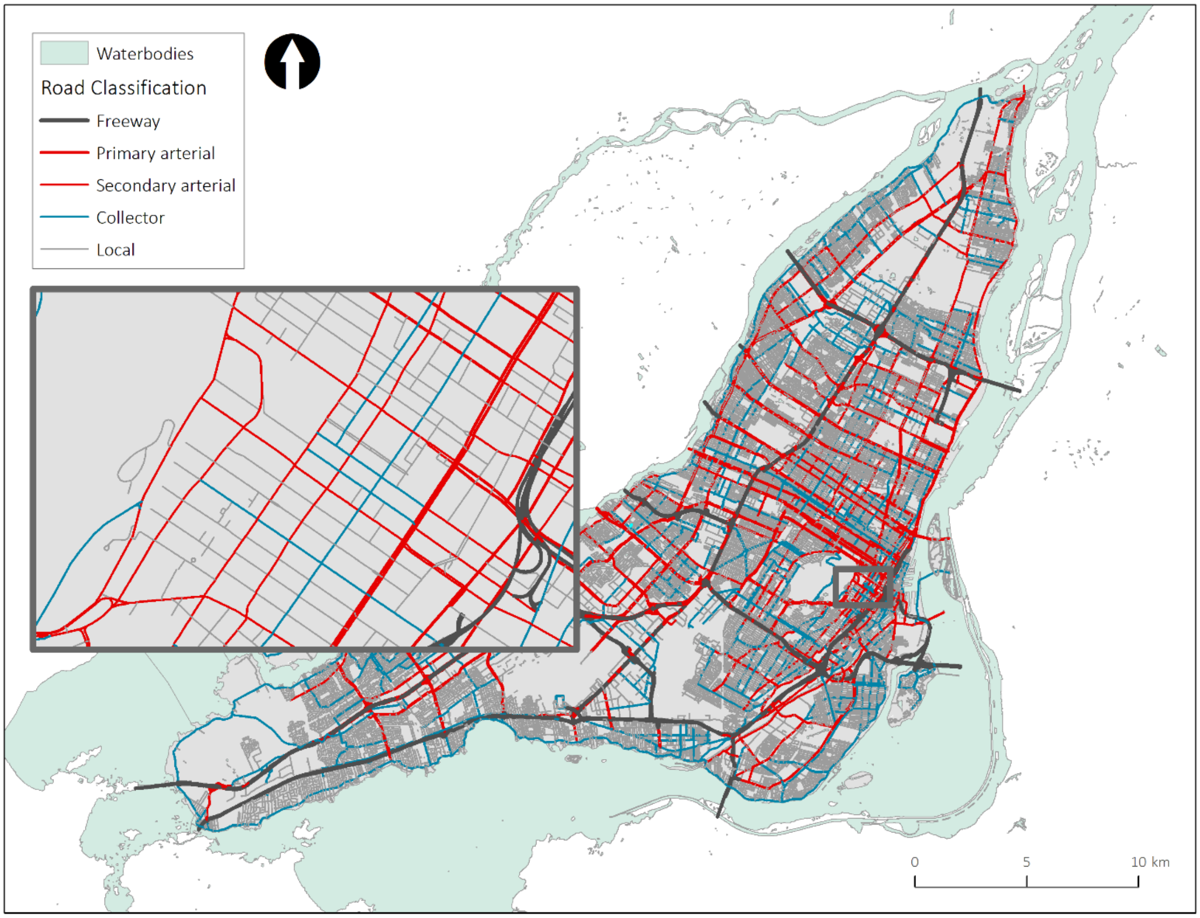
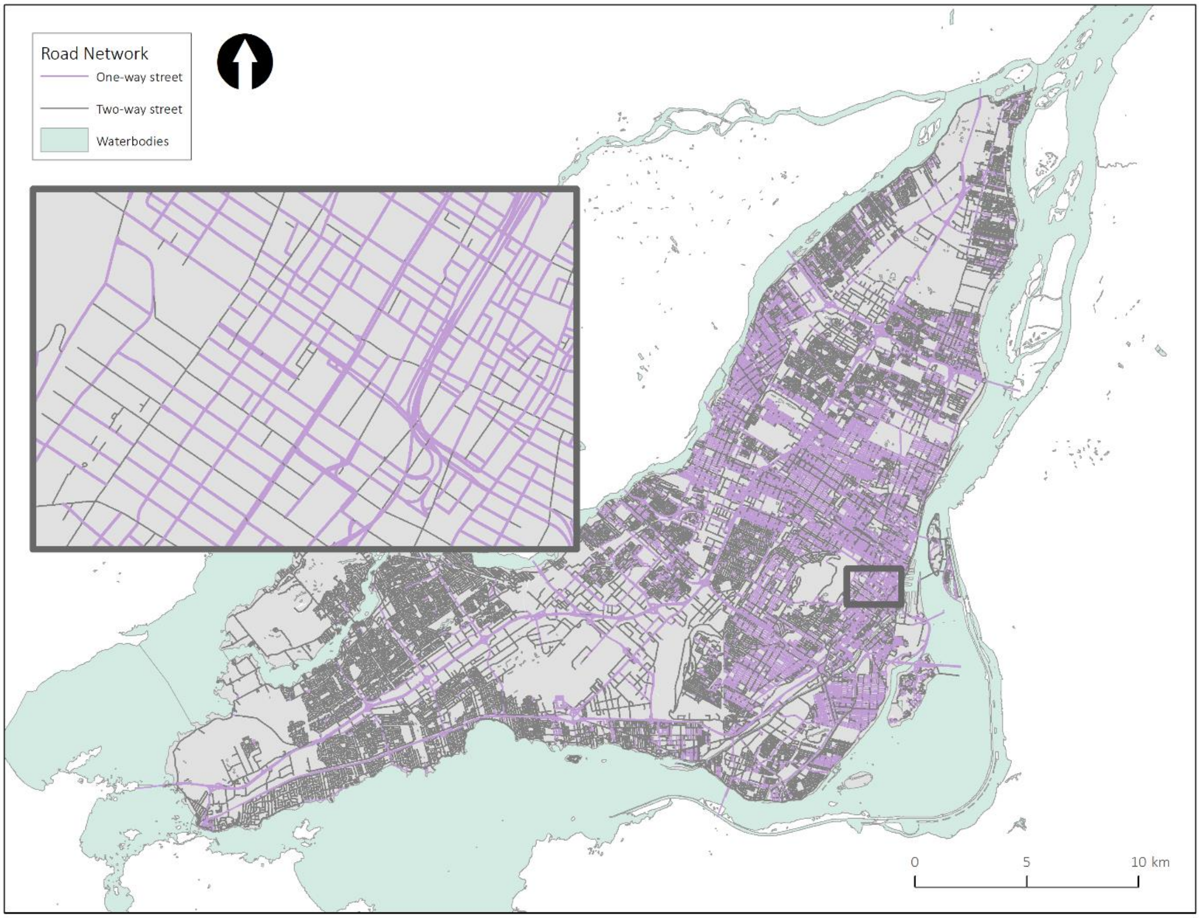
Appendix

Appendix A – Road Network Data

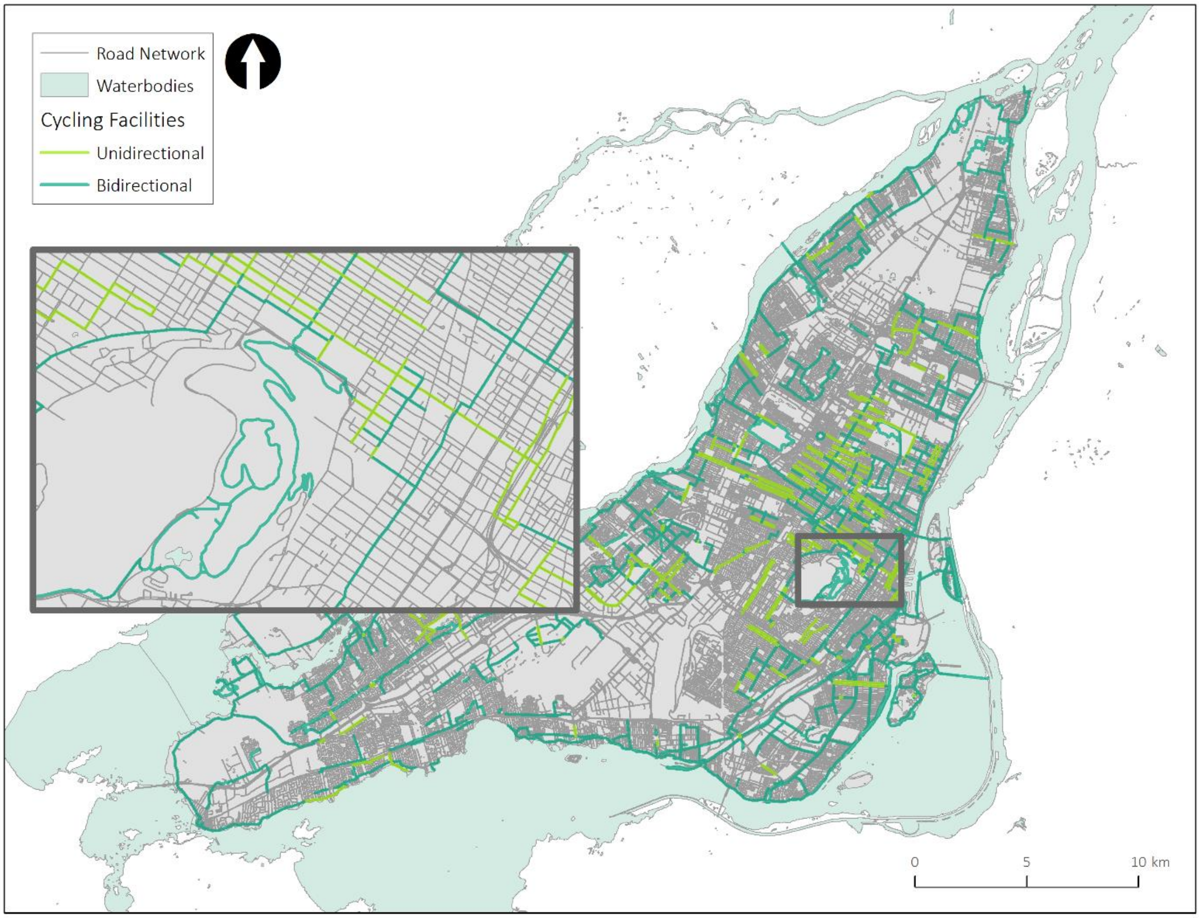


Layer Name	Source	Description	Type
Road Network	[Ville de Montreal Portail Données Ouvertes]() Author: Service des infrastructures du réseau routier Format: SHP Last updated: February 11, 2020 Created: October 6, 2013 Projection: Universal Transverse Mercator Coordinate System: NAD_1983_MTM_8 License: Creative Commons Attribution 4.0 International	Simple polyline data depicting the road network within the limits of the island of Montreal	Vector

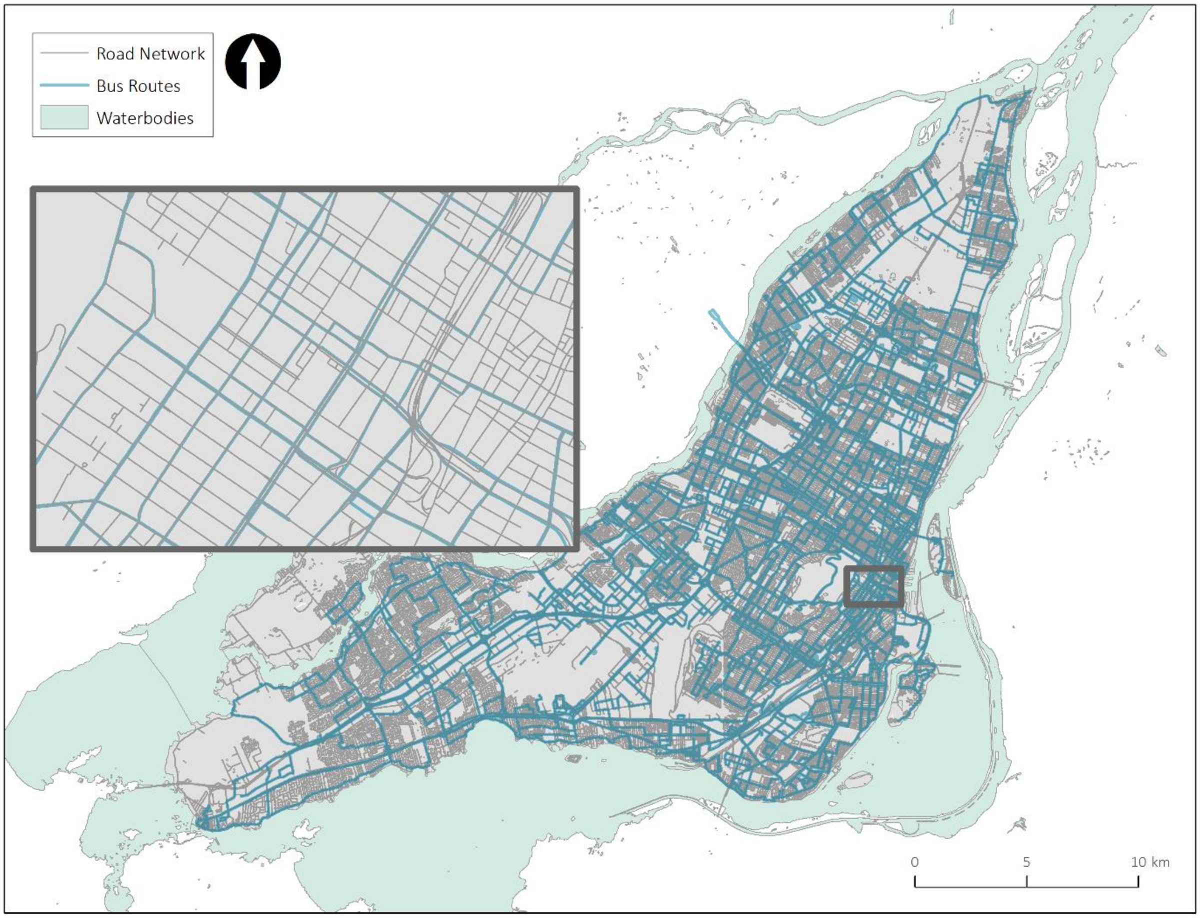

Road Network
One-way street
Two-way street
Waterbodies
0
5
10 km

Appendix B – Cycling Network Data

Layer Name	Source	Description	Type
2018 Cycling Facilities	[Ville de Montreal Portail Données Ouvertes]() Author: Service des infrastructures du réseau routier Format: SHP Last updated: October 17, 2018 Created: October 13, 2013 Projection: Universal Transverse Mercator Coordinate System: NAD83_MTM_zone_8 License: Creative Commons Attribution 4.0 International	Simple polyline data depicting the cycling network within the limits of the island of Montreal	Vector

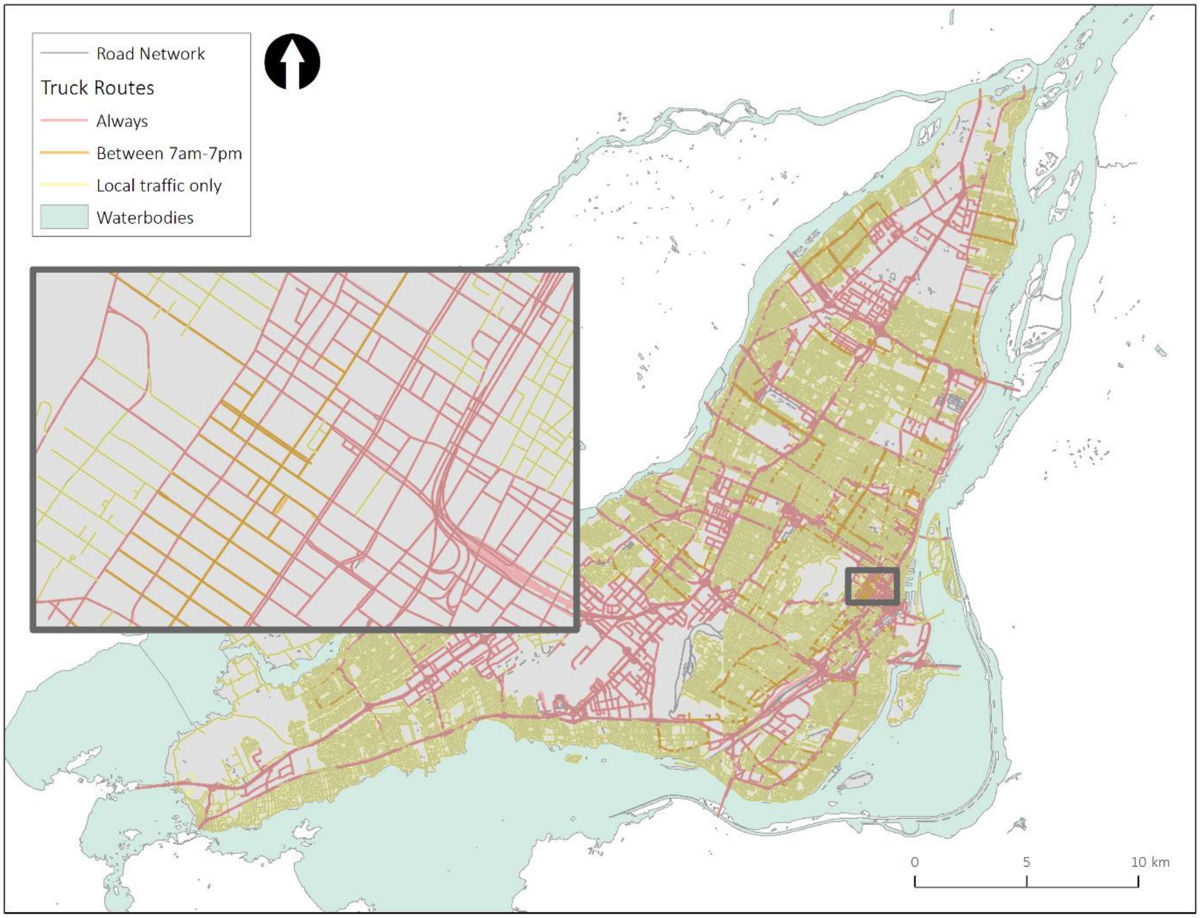

Road Network
Waterbodies
Cycling Facilities
Unidirectional
Bidirectional
0
5
10 km

Appendix C – Bus Route Data



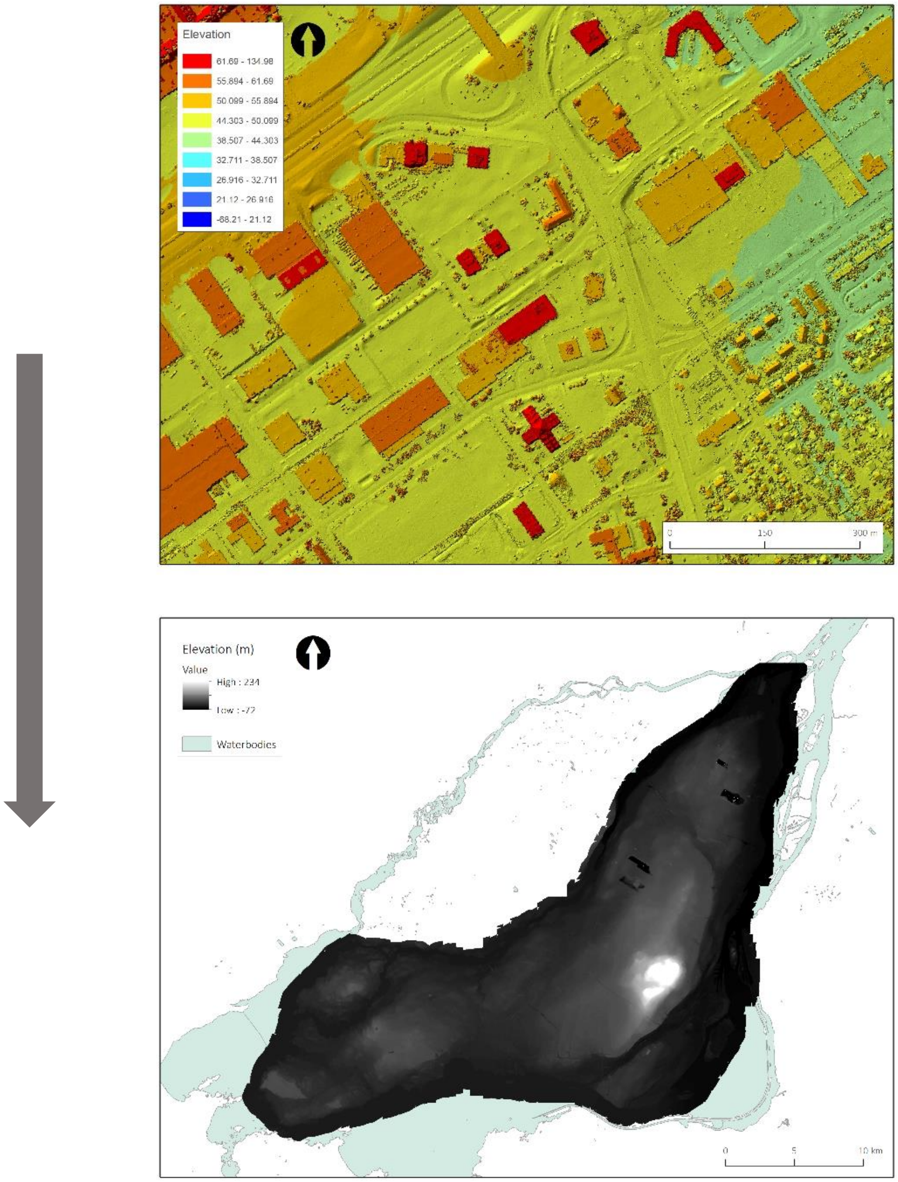
Layer Name	Source	Description	Type
Bus Routes	Ville de Montreal Portail Données Ouvertes Author: STM Format: SHP Last updated: January 17, 2020 Created: April 25, 2016 Projection: Universal Transverse Mercator Coordinate System: NAD_1983_MTM_8 License: Creative Commons Attribution 4.0 International	Simple polyline data depicting STM transit routes within the limits of the island of Montreal	Vector

Appendix D – Truck Route Data



Layer Name	Source	Description	Type
Truck Routes	Ville de Montreal Portail Données Ouvertes Author: Service de l'urbanisme et de la mobilité Format: SHP Last updated: September 24, 2019 Created: May 29, 2014 Projection: Universal Transverse Mercator Coordinate System: GCS_North_American_1983 License: Creative Commons Attribution 4.0 International	Simple polyline data depicting truck routes within the limits of the island of Montreal	Vector

Appendix E – Elevation Data



Layer Name	Source	Description	Type
2015 LiDAR	[Ville de Montreal Portail Données Ouvertes] Author: Division de la géomatique Format: LAS Last updated: January 17, 2020 Created: June 21, 2016 Projection: Universal Transverse Mercator Coordinate System: NAD83_CSRS_MTM_zone_8 License: Creative Commons Attribution 4.0 International	3D topographic representation of the island of Montreal. Converted into a raster DEM.	Point Cloud

Appendix F – Infrastructure Inventory Checklist

Street Name:______________________________

Between:_________________________________

Date: ___________________________________

Actual or Perceived Risk:____________________

ID	Question	Response	Notes
1	Is the segment one-way?		
2	Are opposing directions physically separated?		
3	Does the road profile have a perceptible grade?		
4	Does the road have a perceptible curve?		
5	What is the segment surface condition? (good, fair, poor)		
6	What is the road segment classification?		
7	Is parking permitted?		
8	Is the road a bus route?		
9	Is the road a truck route?		
10	Did the accident occur at an intersection?		
11	Does the segment have adequate lighting?		
12	Type of cycling facilities? (none, sharrow, paved shoulder, bike lane, cycle track, bike path)		
13	Are cycling facilities bidirectional?		
14	Posted speed limit (km/h)		
15	Lane width (m)		
16	Bicycle lane width (m)		
17	Number of lanes		
18	Number of junctions		

Appendix G – Actual Risk Road Segments Studied

Street Name	Between	Accident Count
Cremazie	Berri/Lajeunesse	6
Lajeunesse	Cremazie/Liege	6
Sherbrooke	Sainte-Famille/Saint-Urbain	5
Saint-Urbain	Sherbrooke/Evans	5
Peloquin	Sauriol/Sauve	4
Boyer	Bellechasse/Rosemont	4
Saint-Dominique	Shamrock/Jean Talon	4
Beaubien	De Lorimier/Erables	4
De Lorimier	Beaubien/Saint-Zotique	4
Dandurand	Jeanne-D'Arc/Pie-IX	4
Saint-Joseph	De Lorimier/Erables	4
Saint-Joseph	Hotel-de-Ville/De Bullion	4
Hotel-de-Ville	Saint-Joseph/Laurier	4
Mont-Royal	Parc/Jeanne-Mance	4
Parc	Mont-Royal/Berube	4
Rachel	Laval/Henri-Julien	4
De Maisonneuve	Metcalfe/Mansfield	4
De Maisonneuve	Atwater/Lambert-Closse	4
Metcalfe	Sherbrooke/De Maisonneuve	4
Wellington	Gilbert-Dube/Albert-Denault	4

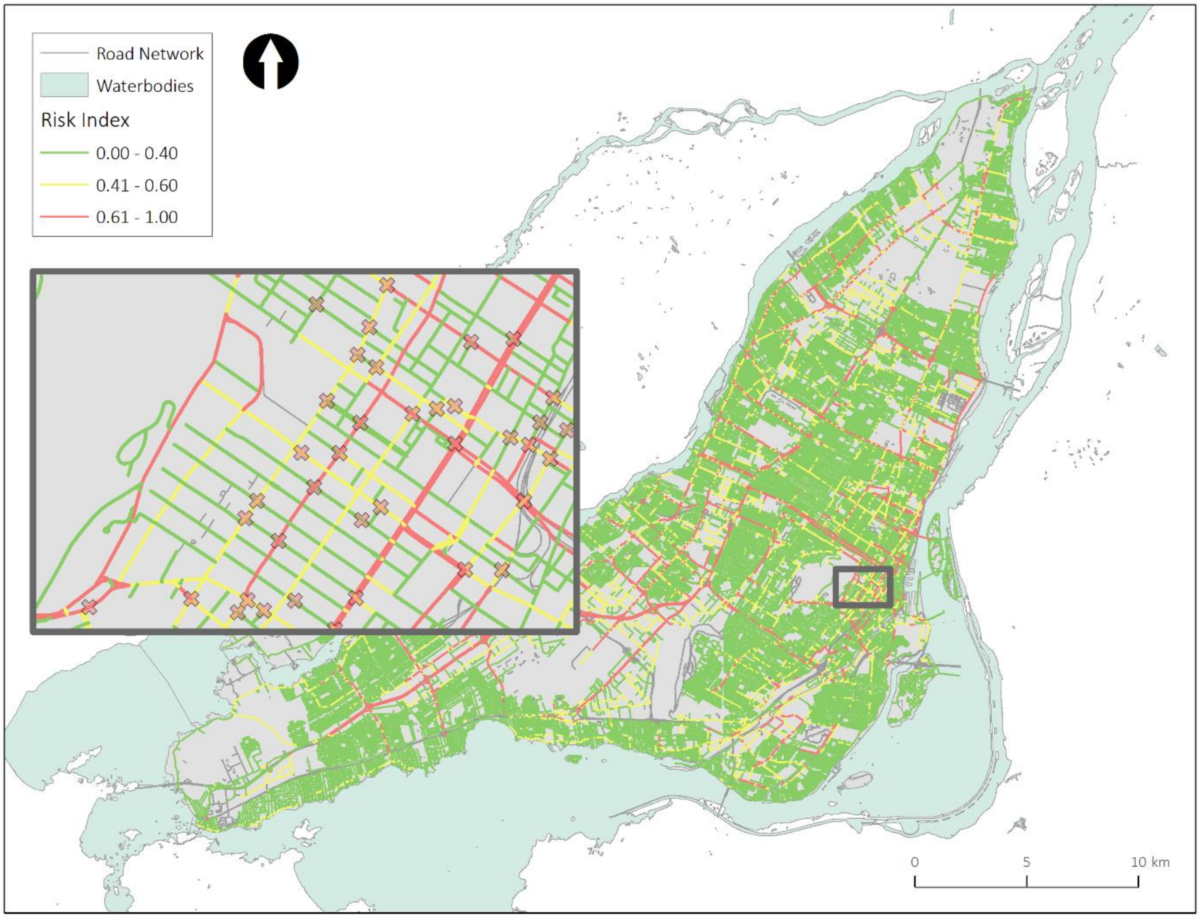
Source: SPVM (2018)

Appendix H - Perceived Risk Road Segments Studied

Street Name	Between	Perception of Danger
Saint-Urbain	Ontario/De Maisonneuve	52
Ontario	Sain-Urbain/Clark	51
D'Iberville	Mont-Royal/Saint-Joseph	36
Saint-Joseph	D'Iberville/Fullum	35
De Maisonneuve	Prud 'homme/Decarie	34
Berri	Sherbrooke/Ontario	34
Mont-Royal	Parc/Jeanne-Mance	24
De Maisonneuve	Robert-Bourassa/McGill College	24
Parc	Mont-Royal/Berube	23
Bellechasse	Saint-Dominique/Saint-Laurent	21
De Maisonneuve	Metcalfe/Peel	18
Robert-Bourassa	De Maisonneuve/Sainte-Catherine	18
Saint-Laurent	Van-Horne/Bellechasse	17
Atwater	Notre-Dame/Duvernay	16
Berri	De Maisonneuve/Sainte-Catherine	14
Parc-La Fontaine	Cherrier/Roy	13
Peel	De Maisonneuve/Sainte-Catherine	13
Pins	Basset/Saint-Urbain	12
Cherrier	Mentana/Parc-La Fontaine	12
Rachel	Molson/Andre-Laurendau	12

Source: Nick Chaloux, TRAM

Appendix I – Actual Risk Comparison



Appendix J - Perceived Risk Comparison