Titre: Title:	Cycling network discontinuities and their effects on cyclist behaviour and safety
Auteur: Author:	Matin Alsadat Nabavi Niaki
Date:	2019
Type:	Mémoire ou thèse / Dissertation or Thesis
Référence: Citation:	Nabavi Niaki, M. A. (2019). Cycling network discontinuities and their effects on cyclist behaviour and safety [Thèse de doctorat, Polytechnique Montréal]. PolyPublie. https://publications.polymtl.ca/3752/

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/3752/
Directeurs de recherche: Advisors:	Nicolas Saunier, & Luis Miranda-Moreno
Programme: Program:	Génies civil, géologique et des mines

UNIVERSITÉ DE MONTRÉAL

CYCLING NETWORK DISCONTINUITIES AND THEIR EFFECTS ON CYCLIST BEHAVIOUR AND SAFETY

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ÉCOLE POLYTECHNIQUE DE MONTRÉAL

THÈSE PRÉSENTÉE EN VUE DE L'OBTENTION

DU DIPLÔME DE PHILOSOPIAE DOCTOR

(GÉNIE CIVIL)

AOÛT 2018

UNIVERSITÉ DE MONTRÉAL

ÉCOLE POLYTECHNIQUE DE MONTRÉAL

Cette thèse intitulée :

CYCLING NETWORK DISCONTINUITIES AND THEIR EFFECTS ON CYCLIST BEHAVIOUR AND SAFETY

présentée par : NABAVI NIAKI Matin Alsadat

en vue de l'obtention du diplôme de : Philosophiae Doctor

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ACKNOWLEDGEMENTS

My work leading to the completion of this dissertation would have been insignificant without the intellectual efforts and moral support of my supervisors and friends. My deepest gratitude goes to my supervisors Dr. Nicolas Saunier, and Dr. Luis Miranda-Moreno for their patience and guidance. My persistent questions and showing up at their office were always rewarded with insightful responses and constructive feedback. I am very lucky to have worked with these remarkable researchers and mentors. Through an international doctoral exchange, I had the fortune of working with Dr. Aliaksei Laureshyn at Lund University, Sweden. The experience was inspiring and memorable.

I would like to thank the Fonds de recherche du Québec - Nature et technologies (FRQNT) grant 2015-NC-180344 and the National Science and Research Council (NSERC), grant 2017-06115 for their financial support, as well as the City of Montréal and boroughs that authorized the data collection. Special thanks to Anae Sobhani, Sohail Zangenehpour, Asad Lesani and Ting Fu for helping me with the early morning data collections.

Finally, I am indebted to my friends and family who supported me throughout this journey.

RESUME

Le cyclisme est généralement considéré comme le mode de transport le plus dangereux, car les collisions avec des véhicules sont plus susceptibles de provoquer des blessures graves et même la mort que les autres usagers de la route à l'exception des piétons. Compte tenu de ses nombreux avantages environnementaux et sociaux, les villes encouragent le cyclisme en tant que mode de transport abordable et développent leur infrastructure cyclable. Alors que les villes visent à augmenter la part modale du vélo, les statistiques de sécurité alarmantes ont forcé les chercheurs et planificateurs des transports ainsi que les responsables municipaux et les décideurs à investir dans la conception, la mise en œuvre et l'amélioration du réseau cyclable afin d'accueillir les cyclistes en toute sécurité. L'amélioration du réseau cyclable pour accroître la part modale du vélo et la sécurité repose sur des informations quantitatives détaillées et des indicateurs de performance. L'une des dimensions de l'analyse du réseau cyclable est sa continuité. La continuité du réseau fournit un ensemble de routes possibles qui sont connectées et accessibles à tous les utilisateurs de la route. Toutefois, les réseaux cyclables sont généralement ajoutés au réseau routier existant, ce qui crée des endroits avec des changements dans les caractéristiques du réseau cyclable et routier. Ces changements sont des interruptions du réseau cyclable qui causent les discontinuités. Malgré les nombreuses mesures sur l'infrastructure, la circulation et l'environnement étudiées dans la littérature du cyclisme, la définition et l'adoption systématiques des discontinuités des réseaux cyclables ont été négligées.

Dans cette dissertation, quatre lacunes ont été identifiées dans la littérature sur le comportement et la sécurité des cyclistes ainsi que sur la performance des réseaux cyclables: la définition et présentation des indicateurs de discontinuité des réseaux cyclables, les effets des discontinuités d'éclairage routier sur la sécurité des cyclistes de nuit, l'analyse du comportement et de la sécurité des cyclistes à des sites avec des discontinuités du réseau cyclable. Pour combler la première lacune, différentes catégories de mesures de discontinuité sont proposées et définies lorsqu'il y a 1) des changements intrinsèques dans le réseau cyclable (fin du réseau cyclable, changement de type d'aménagement cyclable, changement de la largeur des aménagements cyclables, changement de l'emplacement de l'aménagement cyclable sur la route, changement de l'état de la chaussée, changement de l'éclairage routier, changement de la pente de la route, fermeture/détour des réseaux cyclables en raison de travaux), 2) des changements des caractéristiques du réseau routier

(changement de classe, changement du nombre de voies, carrefours) et de la circulation (changement du débit de la circulation, changement de la vitesse de la circulation) et 3) autres changements (entrées de garage, arrêts de bus, stationnement autorisé sur la route). De plus, une méthodologie automatisée est proposée qui peut être appliquée à n'importe quelle zone avec des données de réseau cyclable géoréférencées pour identifier et quantifier les discontinuités infrastructurelles le long du réseau cyclable. La méthodologie est appliquée à une étude de cas de quatre villes nord-américaines, afin de comparer leurs niveaux de discontinuité de manière uniforme et systématique. Les villes étudiées sont classées en fonction de deux indicateurs de discontinuité du réseau cyclable, de la pire à la meilleure, à savoir Portland, Vancouver, Washington D.C. et Montréal.

Pour combler la deuxième lacune de recherche, une méthodologie est proposée pour effectuer un audit nocturne de l'éclairage routier en collectant des mesures de luminosité sur les routes et aux carrefours afin d'identifier les emplacements avec un éclairage discontinu. Les études antérieures utilisant des mesures d'éclairage reposaient sur des méthodes incohérentes et compliquées pour la collecte de données. La méthodologie proposée dans cette thèse fournit une méthodologie uniforme qui peut être appliquée à n'importe quel site pour collecter des données d'éclairage nocturne. La méthodologie est appliquée à Montréal et une analyse statistique des données historiques des accidents montre que les emplacements avec des niveaux d'éclairage plus élevés augmentent le risque d'accident cycliste grave la nuit.

La troisième lacune de recherche abordée dans la thèse est l'analyse du comportement des cyclistes à des endroits où il existe une discontinuité du réseau cyclable. En adoptant la méthodologie proposée, deux paires de sites, un site avec discontinuité et un site de contrôle, sont sélectionnées à Montréal. L’analyse approfondie du comportement des cyclistes nécessite de grandes quantités de données microscopiques, c’est-à-dire des trajectoires des usagers de la route à une échelle temporelle fine. À cette fin, des techniques de vision par ordinateur et des méthodes de regroupement de trajectoires sont appliquées aux données vidéo. Ainsi, un outil d'analyse vidéo automatisé est adopté pour extraire les trajectoires des usagers de la route et grouper les trajectoires cyclistes similaires pour comparer les mouvements des cyclistes traversant les discontinuités du réseau cyclable comparées à leursaux sites de contrôle respectifs. La méthode fournit des informations microscopiques précieuses sur les mouvements des cyclistes qui peuvent être appliquées à n'importe quel site pour évaluer le comportement des cyclistes. Les résultats de cette étude indiquent une plus grande variation du nombre de manœuvres et des vitesses des cyclistes aux endroits du réseau cyclable avec discontinuité par rapport aux sites de contrôle. Enfin, les implications sur la sécurité des cyclistes aux sites avec discontinuité sont étudiées en utilisant des mesures substituts de la sécurité (MSdS) en adoptant une méthode probabiliste (PMSdS) pour prédire les positions futures des usagers de la route. Les deux paires de sites de discontinuité et de contrôle de Montréal sont encore analysées dans une étude de cas. De plus, les temps de collision sont calculés pour les interactions cycliste-véhicule et résumés par manœuvre cycliste pour identifier les manœuvres spécifiques à risque aux sites avec discontinuités. Cette nouvelle approche basée sur les mouvements n'a pas été utilisée dans la littérature pour l'analyse de la sécurité des manœuvres cyclistes. Cette approche fournit un outil utile pour identifier les mouvements exacts importants pour la sécurité des cyclistes. Les résultats montrent que les sites avec discontinuités présentent un plus grand nombre de mouvement dangereux des cyclistes comparé aux sites de contrôle. Au site avec discontinuité où l'emplacement de la piste cyclable change d'un côté de la route à un autre, les cyclistes qui commencent et finissent dans l'aménagement cyclable aux extrémités opposées du carrefour ont les temps à la collision les plus bas.

En résumé, cette thèse comble les lacunes de la littérature en définissant et proposant des indicateurs de discontinuité du réseau cyclable et en évaluant leurs effets sur la performance du réseau cyclable, le comportement et la sécurité des cyclistes. Les résultats de toutes les études de cette thèse confirment l'importance d'inclure des indicateurs de discontinuité dans la planification et l'évaluation des réseaux cyclables. L'absence de ces indicateurs dans les étapes actuelles de planification et d'évaluation fournit une image partielle de la qualité d'un réseau et de l'expérience cycliste et laisse les agences de transport incapables de bien traiter les effets des discontinuités sur les cyclistes. Les informations obtenues grâce aux études sur le comportement et la sécurité des cyclistes aideront les planificateurs et les responsables municipaux à prendre des décisions plus éclairées et à améliorer la conception des points de discontinuité dans les réseaux cyclables afin d'éliminer les mouvements dangereux et d'accommoder tous les cyclistes en sécurité.

ABSTRACT

Cycling is widely considered to be the riskiest mode of transport since collisions with vehicles are more likely to result in serious injuries or even death than other road users except pedestrians. Given its many environmental and social benefits, cities are encouraging cycling as an affordable mode of transport and are expanding their cycling infrastructure. While cities are aiming to increase cycling mode share, their alarming safety statistics have compelled transportation researchers and planners as well as city officials and decision makers to invest resources in designing, implementing and improving the cycling network to safely accommodate cyclists. Improving the cycling network to increase cycling mode share and safety relies on detailed quantitative information on performance indicators. One of the dimensions of cycling network analysis is its continuity. Network continuity provides a set of possible routes that are connected and accessible to all road users. However, cycling networks are usually implemented on the already existing road network, which results in locations where there are changes in road and cycling network characteristics. These changes are interruptions in the cycling network, also referred to as discontinuities. Despite the many infrastructural, traffic and environmental measures studied in cycling literature, the systematic definition of cycling network discontinuities has been overlooked.

In this dissertation, four research gaps have been identified in cyclist behaviour and safety literature as well as cycling network performance studies: the definition and presentation of cycling network discontinuity indicators, the effects of road lighting discontinuities on nighttime cyclist safety, the cyclist behaviour and safety analysis at discontinuity locations in the cycling network. To address the first gap, different categories of discontinuity measures are proposed and defined, where there are 1) intrinsic changes in the cycling network (end of cycling facility, change in cycling facility type, change in cycling facility width, change in cycling facility location on road, change in pavement condition, change in road lighting, change in road grade, closure/rerouting of cycling facility due to construction or maintenance), 2) changes to the road network (change in road class, change in number of road lanes, intersections) and traffic characteristics (change in traffic volume, change in traffic speed), and 3) other changes (driveways, bus stops, parking allowed on road). Moreover, an automated methodology is proposed that can be applied to any area using its georeferenced cycling network data to identify and quantify infrastructural discontinuities along the cycling network. The methodology is applied to a case study of four North American cities, to compare their discontinuity levels in a uniform and systematic way. The areas under study are

ranked based on two cycling network discontinuity indicators from worst to best as: Portland, Vancouver, Washington D.C., and Montréal.

To close the second research gap, a methodology is proposed to perform a nighttime road lighting audit collecting illuminance measurements at an intersection or link level to identify locations with discontinuous lighting. Past studies using illuminance measurements relied on inconsistent and cumbersome methods for collecting data. The proposed methodology in this dissertation provides a uniform methodology that can be applied to any area to collect nighttime illuminance data. The methodology is applied to case study locations in Montréal and a statistical analysis of historical accident data showed that locations with higher illuminance levels are associated with an increase in the chance of a severe cyclist accident at nighttime.

The third research gap addressed in the dissertation is the analysis of cyclist behaviour at locations where there is a cycling network discontinuity. Adopting the proposed methodology, two pairs of discontinuity and control sites are selected in Montréal. The in-depth analysis of cyclist behaviour requires large amounts of microscopic data, i.e. road user trajectories at a fine temporal scale. To this end, computer vision techniques and trajectory clustering methods are applied to video data. Hence, an automated video analysis tool is adopted to extract road user trajectories and cluster similar cyclist trajectories to compare the movements of cyclists traveling through the cycling network discontinuity compared to a control site. The methodology identifies valuable microscopic information on cyclist movements that can be applied to any location to evaluate cyclist behaviour. Results from this study indicated a higher variation in number of cyclist maneuver and speeds at locations of cycling network discontinuity compared to their control site. Finally, the safety implications of discontinuity locations on cyclists is studied using surrogate measures of safety (SMoS) adopting a probabilistic method (PSMoS) of predicting future positions of road users. The two pairs of discontinuity and control sites from Montréal are further analysed in a case study. Time-to-collision (TTC) is computed for cyclist-vehicle interactions and summarised per cyclist maneuver to identify the specific risky maneuver cyclists make at discontinuity locations. This novel movement-based PSMoS approach has not been adopted in literature for the safety analysis of all cyclist maneuvers. The approach is a useful tool to identify the exact movements that influence the safety of cyclists. Results show that the discontinuity locations have a higher number of unsafe cyclist motion patterns compared to their control sites. At the discontinuity site where the physically separated cycling facility location changes from one side of the road to another, cyclists who originate and end in the cycling facility on the opposite ends of the intersection have the lowest TTC.

In Summary, this dissertation closes the gaps in literature by defining and proposing cycling network discontinuity indicators and evaluating their effects on cycling network performance, cyclist behaviour, and safety. Results of all the studies in this dissertation confirm the importance of including discontinuity indicators in the planning and evaluation of cyclist networks. The lack of these indicators in current planning and evaluation stages provides a partial image of the quality of a cycling network and cycling experience and leaves transportation departments unable to fully address the effect of discontinuities on cyclists. The information obtained from the cyclist behavior and safety studies will help planners and city officials make better informed decisions by improving the infrastructural design of the cycling network discontinuity locations to eliminate unsafe movements and safely accommodate all cyclists.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AADT	Average annual daily traffic
BCI	Bicycle compatibility index
BEQI	Bicycle environmental quality index
BLOS	Bicycle level of service
BS	Bike score
BSIR	Bicycle safety index rating
BSL	Bicycle stress level
CI	Copenhagenize index
DST	Deceleration to safety
EB	Empirical Bayes
FHWA	Federal highway administration
FQRNT	Fonds de recherche du Québec - Nature et technologies
GIS	Geographic information system
GNSS	Global navigation satellite system
GPS	Global positioning system
GT	Gap time
IES	Illuminating engineering society
KS	Kolmogorov–Smirnov test
KW	Kruskal–Wallis test
LCSS	Longest common subsequence
LTS	Level of traffic stress
NB	Negative binomial model
OL	Ordered-logit model

PET	Post-encroachment time
PSMoS	Probabilistic surrogate measures of safety
ROC	Risk of collision
SMoS	Surrogate measures of safety
SRID	Spatial reference identifier
TA	Time to accident
TCT	Traffic conflict technique
TTC	Time-to-collision

GLOSSARY

Accident: traffic event involving a collision of a road user with another road user or object resulting in property damage or bodily harm, or non-collision event such as running off the road or roll over.

Collision course: situation of two or more road users with a non-zero probability of colliding in the near future.

Discontinuity: interruptions and changes in the cycling network: end of cycling facility on the road.

Heat-map: a representation of data in the form of colors per cell representing spatial units of a given size over an area based on an attribute of each cell.

Historical accident data: ensemble of accident records gathered by police, ambulance services, or insurance companies, containing information about accidents such as location, time, type, cause(s), environmental factors, road users involved, injury severity levels, etc.

Homography: a mathematical coordinate transformation between two planes used to project positions in image (video) space to world space, and back.

Image space: the coordinate space used to represent data on the projected plane of the camera's field of view.

Interaction: the relationship between two road users within a certain distance and time.

Lux: unit of illuminance measured as the intensity of light as perceived by the human eye.

Maneuver (movement): the movement of a road user on the road at the microscopic level.

Motion pattern: group of similar trajectories, represented by an actual trajectory.

Motion prediction: the process of generating future positions at a given instant, based on their positions up to that instant.

Post-encroachment time: a measure of the difference in arrival time at a crossing zone of two road users with overlapping trajectories.

Safety: refers to the absence of bodily harm, risk of damage or injury for all road users.

Severity: level of closeness to accident measured by injury levels (minor injury, major injury and fatal), or by temporal and spatial proximity to collision point (SMoS thresholds).

Surrogate measure of safety: a non-accident measure used to describe the safety and severity of an interaction.

Time-to-collision: the time remaining for two road users on a collision-course if their movements remain unchanged.

Traffic conflict technique: a non-accident-based method for traffic safety estimation based on traffic conflicts with the basic hypothesis that "accidents and conflicts originate from the same type of processes in traffic and a relation between them can be found" (Laureshyn, 2010).

Traffic conflict: an interaction in which two or more road users approach each other in time and space to such an extent that there is a possibility of collision if their movements remain unchanged (Hyden, 1987).

Trajectory: a series of points in space and time defining the movement of a road user, typically at regular time steps, for example if extracted from video.

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

1.1 Overview

The strive to achieve sustainable transport mobility has lead researchers, city officials, planners and policy makers to invest in research, developments and publicity campaigns to promote non-motorized transport modes. As a result, cycling has gained popularity and attention due to its environmental, social, economic and personal benefits which include reductions in the emissions of pollutants and greenhouse gases, reduced traffic congestion, improved health, reliability and affordability (Boyle, 2005; Sallis, Frank, Saelens, & Kraft, 2004; Sener, Eluru, & Bhat, 2009). An impediment to these efforts and benefits, is the alarming rate of road traffic injuries which is ranked as the number one cause of death among individuals aged 15 to 29 years (World Health Organization, 2015). In 2013, the World Health Organization estimated a total of 50 million traffic-related injuries and 1.25 million road traffic fatalities, 49 % of which were vulnerable road user deaths (World Health Organization, 2015). In 2016, Canadian road accidents accounted for 1,898 fatalities and 160,315 injuries, where 17.6 % and 2.5 % of fatalities were pedestrians and cyclists respectively (Transport Canada, 2017).

This lack of safety has been identified as one of the reasons for low cycling mode share in many regions (Dill & Gliebe, 2008). In North America, despite the extensive implementation and expansion of cycling networks, most short-distance trips are taken with private cars (J. Pucher & Renne, 2003). Cycling as a mode of transport ranges from 1.4 % of all trips in the United States, to over 30 % in the Netherlands and Denmark, while Canada has one of the lowest cycling rates of only 2 % (European Cyclists' Federation, 2014; J. Pucher & Buehler, 2008; Statistics Canada, 2016).

Low cycling mode share and low safety levels for cyclists have motivated researchers to investigate and better understand cyclist's behaviour, safety, and interaction with other road users. Cyclist behaviour and safety can be studied at the macroscopic or microscopic levels as shown in Figure 1-1. Cyclist behaviour varies widely at the macroscopic level, in particular in terms of mode and route choice (see (Casello & Usyukov, 2014; Sener et al., 2009)) or cycling volume (see (J. Pucher & Buehler, 2006)). The macro-level safety studies focus on a city or area, typically based on the total number of accidents. The microscopic level corresponds to the operational and tactical levels, which encompass the road user maneuvers and choice of location on the road (see (Fu, Beitel, et al., 2018; Twaddle, 2017; van Haperen et al., 2018)). Microscopic safety has been studied at an intersection or link level, using accident data, unsafe events and behavioural observations (Gerstenberger, 2015; Wanvik, 2009a).

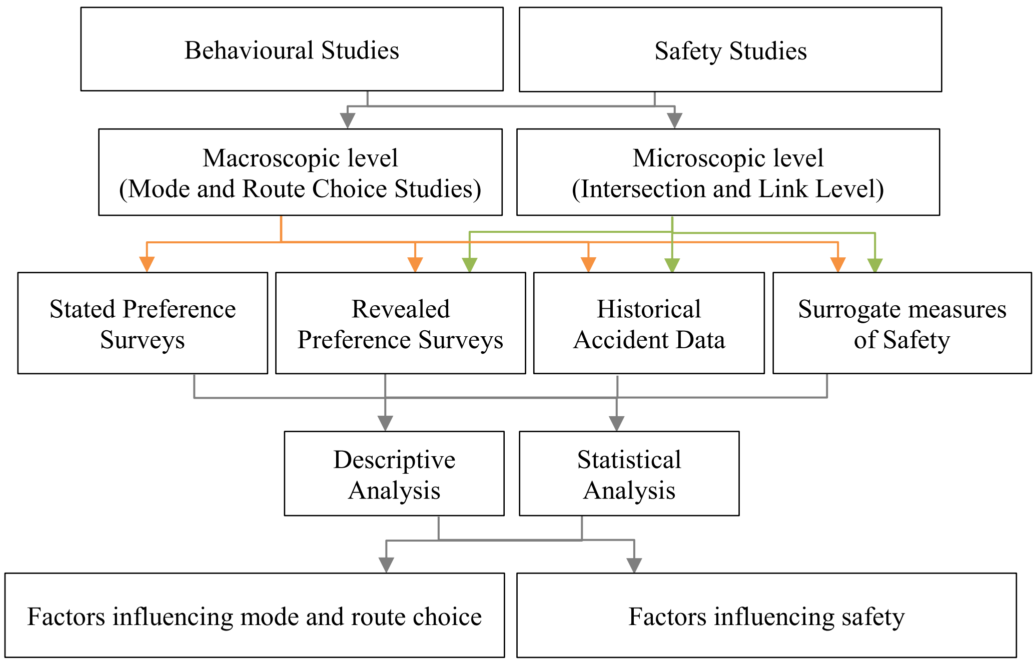

Figure 1-1 Methods of road user behaviour and safety analysis

Cyclists behaviour and safety has also been observed to change in different conditions such as seasons, in summer compared to winter (Nosal & Miranda-Moreno, 2014), weather conditions (Ahmed, Rose, & Jakob, 2013; Helbich, Böcker, & Dijst, 2014), nighttime compared to daytime (Yan, Ma, Huang, Abdel-Aty, & Wu, 2011), and riding through a cycling facility compared to riding on shared roads (J. A. Pucher, 2000). Mode and route choice studies investigate factors that influence these choices, and safety assessments evaluate the causes behind road accidents. This information is then used by city officials, researchers and planners to design, implement and improve cycling infrastructure that aims to attract road users to switch to active modes of transport and safely accommodate cyclists.

1.1.1 Cyclist Behaviour Studies

Behavioural studies have relied on stated and revealed preference survey data such as local and national transport surveys (Santos, McGuckin, Nakamoto, Gray, & Liss, 2011; M. Stinson & Bhat, 2003), on-site or video observational data (Copenhagenize Design Co., 2017), and positional data such as Global Navigation Satellite Systems (GNSS) collected from cyclists (Dhakar & Srinivasan, 2014; Hood, Sall, & Charlton, 2011). Analysis methods include the descriptive presentation of results or the use of statistical models to investigate the unobserved effect of exogenous variables on cyclist behaviour, usually expressed in terms of discrete choices, by using Multinomial Logit, Nested Logit, and Mixed Multinomial logit models (Bovy, Uges, & Hoogendoorn-Lanser, 2003; Casello & Usyukov, 2014; Sener et al., 2009). Macroscopic analysis at the mode and route choice levels using stated and revealed preference surveys have identified poor objective and perceived safety of cyclists as a reason for the low cycling mode share (Dill & Gliebe, 2008; Ehrgott, Wang, Raith, & van Houtte, 2012; Garrard, Rose, & Lo, 2008), as well as the lack of cycling facilities along their route (Dill & Gliebe, 2008; Mitra, Ziemba, & Hess, 2017). Statistical analysis of cyclist route choice has also indicated a preference for routes with a cycling facility (Hood et al., 2011; Sobhani, Alizadeh Aliabadi, & Farooq, 2018) as well as low traffic volumes, lower traffic speed, minimal parking, and fewer stop signs (Sener et al., 2009). These studies help identify factors that affect behaviour and perception, that either encourage cycling or cause concern for some cyclists.

1.1.2 Cyclist Safety Studies

Historical accident data are widely used for safety studies and are obtained from police and hospital reports, or insurance companies. Descriptive and statistical analyses of accident frequency or injury severity are conducted to identify and understand causes of accidents to better propose and implement counter-measures. Statistical frameworks for accident frequency and injury severity adopt negative binomial, ordered logit, Bayesian logistic regression, etc. Studies of bicycle accident injury severity have evaluated the effect of weather conditions, road lighting, time of day, vehicle speed, age and gender (Kim, Kim, Ulfarsson, & Porrello, 2007; Rodgers, 1995). Results show that higher vehicle speeds, middle-aged and older male cyclists, and nighttime accidents had a higher likelihood of resulting in fatal accidents.

Although historical accident data provide a means to study safety, waiting for accidents to happen to diagnose safety is reactive and hardly ethical. To perform a safety assessment, many accidents at the same, and different locations must be collected to investigate the factors and causes of accidents. The problem with this reactive approach is that accidents are few in numbers, and there are usually not enough accidents at the same location to evaluate its safety. Studies commonly compile the number of accidents that occur in the span of five to ten years, which is problematic since infrastructural, traffic and environmental changes could have occurred during the study period. Another shortcoming of using accident data is that there is major underreporting of accidents and a lack of detail on the process of the accident (Alsop & Langley, 2001; Amoros, Martin, & Laumon, 2006). The reporting of cyclist accidents is even more prone to bias and varies across countries depending on the type of accident, type of vehicle involved, and level of severity (Shinar et al., 2018).

The shortcomings related to accident data, as well as its reactive nature, have lead to the introduction of more proactive approaches, where traffic is observed to identify critical interactions (traffic conflicts) between road users in order to predict the risk and severity of accidents. In 1977, Amundsen and Hydén defined some of these unsafe situations as traffic conflicts where “two or more road users approach each other in time and space for such an extent that there is a risk of collision if their movements remain unchanged” (Amundsen & Hyden, 1977). The use of traffic conflicts has gained attention with countries developing traffic conflict techniques (TCT) to quantify safety using surrogate measures of safety (SMoS) without waiting for accidents to happen (e.g. (Hyden, 1987; Kraay & van der Horst, 1985; Sayed & Zein, 1999)). Studies have adopted the use of SMoS indicators such as time-to-collision (TTC), post-encroachment time (PET), gap-time (GT), deceleration-to-safety time (DST), etc. to evaluate vehicle, cyclist and pedestrian safety (Fu, Miranda-Moreno, & Saunier, 2018; Ismail, Sayed, Saunier, & Lim, 2010; Laureshyn, Goede, Saunier, & Fyhri, 2017; Zangenehpour, Strauss, Miranda-Moreno, & Saunier, 2016).

Traditional TCTs rely on the manual observation of traffic conflicts and an estimation of their severity based on approximate road user speed, evasive action and temporal nearness to accident (Hyden, 1987). To eliminate the long hours of on site observation, video recordings of the study site are manually observed for traffic conflict detection. However, the issues with manual observation include the cost of training observers, the reliability and consistency of the observer’s judgement, the interpretation and estimation bias and errors especially when observing long hours of video data (Sayed, Brown, & Navin, 1994). More recent approaches have combined image processing with data mining and computer vision techniques to automatically and more reliably detect road users and obtain road user trajectories, speed and interaction information from video data. These tools provide detailed and more accurate microscopic information on road user’s behaviour and safety, and significantly reduces the issues related to manual detection methods.

1.1.3 Research Gaps

A review of literature on cyclist route choice, accident and SMoS studies revealed a gap in systematically defining and identifying cycling network discontinuities and investigating microscopic cyclist behaviour and safety at these locations. The effects of infrastructure such as the presence of cycling facilities, the types of cycling facilities, the number and width of lanes, the presence of road lighting, the road class, the speed limits, etc. have been studied in the literature. However, locations where there are interruptions and changes in the infrastructure, where the infrastructure is not continuous, such as a change in road type, change in road lighting or change in cycling facility types along a cyclist's route have not been extensively characterized or evaluated. These locations, referred to as discontinuities, have seen little consideration in either macroscopic or microscopic cyclist behaviour and safety studies. The only studies on some form of discontinuity had a limited definition of the variables and only a descriptive scope (Barsotti & Kilgore, 2001; Krizek & Roland, 2005; Sener et al., 2009).

1.1.4 What are Discontinuities

An ideal cycling network entails a riding experience without any added stress, safety concern, effort and mental workload, and allows for easy and timely access to destinations. It has been established that level of cyclist's stress and comfort varies across different facility types, road classes, and other infrastructural factors (Hunt & Abraham, 2007; M. A. Stinson & Bhat, 2005). For example, an investigation of cyclist's perceived safety among different cycling facility types indicated a range of comfort levels associated with different facility types (Jensen, Rosenkilde, & Jensen, 2007). This variation in perceived safety associated with each facility type is an indication that at locations where cycling facility types change, cyclists will undergo a change in comfort and safety perception. Since cyclists prefer to ride on a continuous cycling facility (Sener et al., 2009), interruptions such as frequent changes in cycling facility types, high levels of traffic volume and speed changes, and interruptions in the infrastructure along the cyclist's path all result in increased mental workload, changes in stress and safety levels (Akar & Clifton, 2009; Blanc & Figliozzi, 2016; Vansteenkiste, Zeuwts, Cardon, Philippaerts, & Lenoir, 2014). These changes and interruptions along a cyclist's path are called discontinuities. Discontinuities can occur at road links or intersections where the different infrastructure types "collide", such as where a physically separated cycling facility turns into a designated roadway, or a local road changes to a collector road type with higher traffic speeds and volume, or where roads have uneven lighting levels at nighttime. The transition between different cycling and road infrastructures follows little logic in design and may result in different road user behaviour and safety levels.

From a road lighting discontinuity perspective, nighttime safety studies have used indicators such as the presence or absence of road lighting, or performed a before-after road lighting installation study (Bruneau & Morin, 2005; J. D. Bullough, Donnell, & Rea, 2013; Donnell et al., 2010; Wanvik, 2009a; Yannis, Mitzalis, Kondyli, & Mitzalis, 2012). However, studies have not considered the effects of road lighting variations on safety. The study of discontinuous lighting requires the collection and evaluation of actual illuminance measurement to study its effects on nighttime safety.

Studies that have considered some form of cycling network discontinuities include a study evaluating cyclist preferences which identified discontinuous cycling facilities (presence of a cycling facility on less than 75 % of the cyclist's route) and large changes in traffic flow as inconvenient (Sener et al., 2009). A cycling network evaluation study stated that the comfort of riding on dedicated cycling facilities may not compensate for the uncomfortable and high-stress points of discontinuity along the cyclist's route (Mekuria, Furth, & Nixon, 2012). Although the effects of discontinuities on perceived safety are the focus of the mentioned studies, the microscopic behaviour and objective safety of cyclists at these locations have not been evaluated. To conduct such microscopic studies at discontinuities, detailed trajectory, speed and road user interaction data is required and can be obtained from automated video data analysis methods.

The limited investigation of these fields in the literature and practice as well as the alarming rate of road fatality and injury and the low cycling mode share are the motivational factors behind this dissertation. The impact of two major types of infrastructural discontinuities are studied in this dissertation: road lighting discontinuities and cycling facility discontinuities. Three methodologies are proposed to perform a nighttime road lighting audit, an automated tool to identify discontinuities in cycling networks, and a movement-based approach to surrogate safety analysis. Behavioural and safety studies are conducted by applying the proposed methodologies to case studies in Montréal and other North American cities. The following section highlights the objectives of this dissertation.

1.1.5 Important Definitions

1.1.5.1 Cycling Facility Types

A cycling network is defined as the areas designed specifically for cyclists to ride. These include different cycling facility types that are categorised into four groups:

1. *Physically separate cycling facility:* these are cycling facilities that are physically separated from road traffic by a raised median or bollards, and the only interaction with other road users occurs at intersections, at locations where the separation disappears to allow for vehicles to access driveways, and where pedestrians cross the facility to access bus stops or cross the street. An example is shown in Figure 1-2 a.
2. *Bike lane:* the painted stripe lines on the road, without any physical separation, indicate the location where cyclists may ride. Interactions with other road users is at intersections, locations where vehicles and busses cross their path to access parking spaces or bus stops, and at an adjacent bus stop where passengers getting on or off the bus cross the bike lane. An example is shown in Figure 1-2 b.
3. *Designated roadway:* road paintings indicating where cyclists share the road with vehicles with no separation and in constant interaction with road users. An example is shown in Figure 1-2 c.
4. *Off-road facility:* facilities in areas such as parks that have no interaction with motor vehicles. An example is shown in Figure 1-2 d.

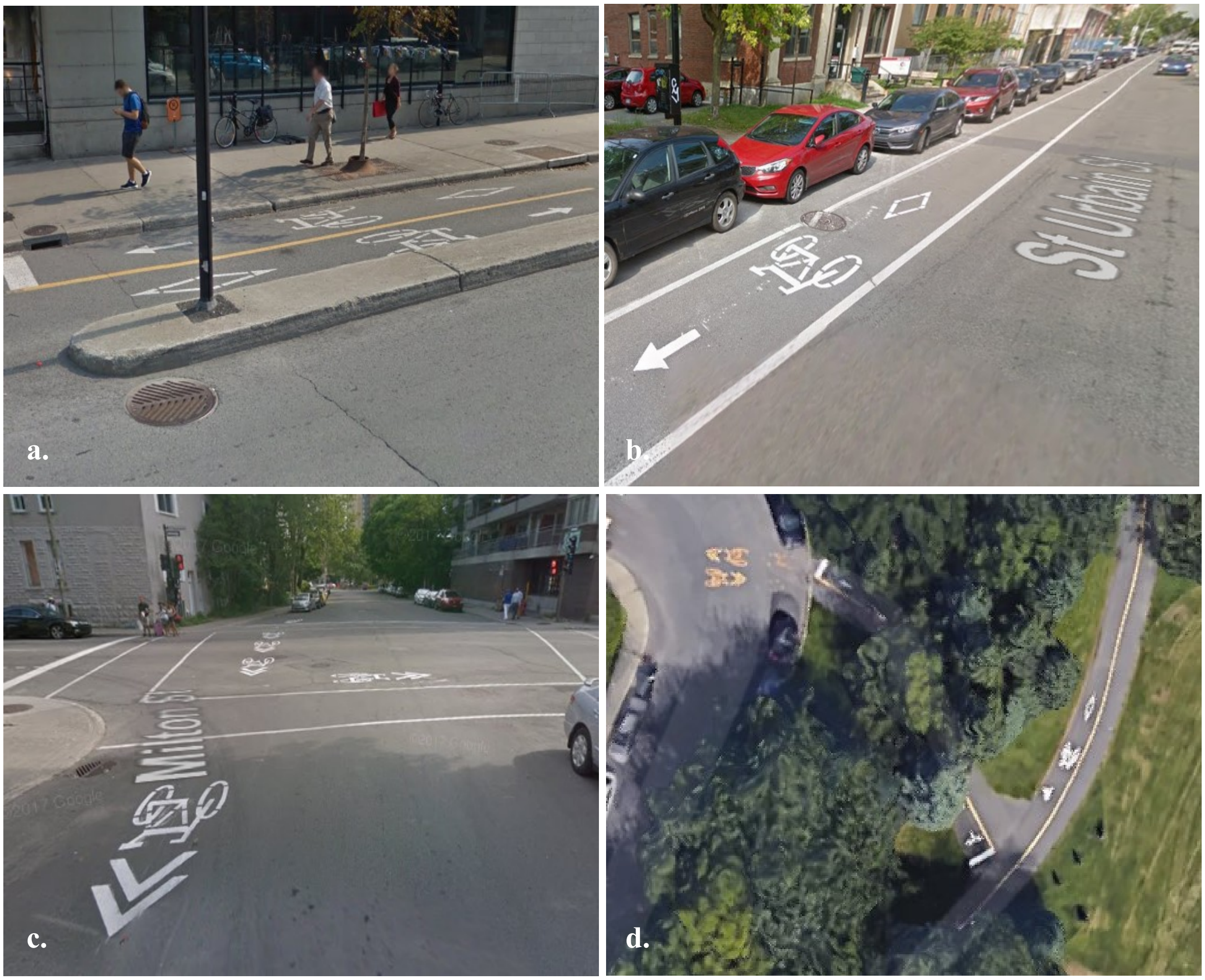

Figure 1-2 Cycling facility types (Google Maps: Montréal)

1.1.5.2 Cycling Network Discontinuities

The interruptions along a cyclist's route can be quantified as discontinuity measures. Discontinuity measures can be used to evaluate an area's cycling network performance, and a cyclist's route choice and behaviour can be considered in relation to the number and type of discontinuities along a cyclist's route. Cyclist safety studies can also be performed at locations with cycling network discontinuities to evaluate the effect of different discontinuities on safety.

Table 1-1 presents the categories of cycling network discontinuity types. Discontinuities are then quantified by normalizing the number of discontinuities depending on the study level. For a study at the level of an area (cycling network continuity of a city or region), the normalization factor can be the length of the cycling network in the area or the area's surface, and at the level of a cyclist route (for example for a route choice study), the normalization factor is the cyclist's route length.

Table 1-1 Discontinuity categories and measures (before normalization)

Category	Types of discontinuities
Intrinsic to Cycling Network	End of cycling facility
	Change in cycling facility type
	Change in cycling facility width
	Change in cycling facility location on road
	Change in road lighting
	Change in pavement condition
	Change in road grade
	Closure/rerouting of cycling facility due to construction or maintenance
Traffic and Road Network	Change in road class
	Change in number of road lanes
	Change in traffic volume
	Change in traffic speed
	Intersections
Other	Driveways
	Bus stops
	Parking allowed on road

1.2 Research Objectives

The general objective of this dissertation is to propose and systematically define cycling network discontinuities and evaluate cyclist behaviour and safety at discontinuities. The four specific objectives are the following:

Objective 1 Propose and define cycling network discontinuities and propose a methodology to identify and quantify them in any area using geospatial data

Objective 2 Perform a nighttime safety analysis to evaluate the effects of road lighting discontinuities on vulnerable road users' safety

Objective 3 Perform microscopic cyclist behaviour analysis at points of infrastructural discontinuity in the cycling network using video data

Objective 4 Propose and apply movement-based safety analysis of cyclist at infrastructural discontinuities in the cycling network using video data and SMoS

1.3 Contributions

The objective of this dissertation is to close the gap in cycling network performance evaluations, cyclist behaviour and cyclist safety literature considering discontinuity locations. The first step is to propose and define cycling network discontinuities and then perform a link-level cycling safety using road lighting discontinuities (measured by illuminance uniformity), and perform a behavioural and safety analysis at infrastructural discontinuities along cycling facilities.

1. The first contribution includes the conceptual definition of discontinuity measures, the definition of indicators to measure discontinuities and the proposed and automated methodology to identify discontinuities in any cycling network using geospatial data. This methodology can be adopted by city planners and researchers to identify locations where cyclists are faced with interruptions in the cycling network. The methodology is applied to four North American cities (Montréal, Vancouver, Washington D.C., and Portland) to evaluate and compare cycling network performance using their discontinuity indicators.
2. The second contribution is a proposed methodology for nighttime illuminance data collection at an intersection and link level that can be adopted by any area to identify discontinuities in road lighting for maintenance and safety analysis purposes. The collected data can then be used to evaluate whether road lighting meets the city standards, and to perform a nighttime safety study using accident data or SMoS.
3. The third contribution is the application of the proposed road lighting audit methodology to evaluate nighttime vulnerable road user safety at Montréal urban intersections and road links. This study is the first to collect nighttime illuminance levels at an intersection and link level to evaluate nighttime safety of cyclists and pedestrians.
4. The fourth contribution is the cyclist behaviour study at discontinuities compared to control sites. Video data collected at two discontinuity and two control sites showed that cyclists undertake a number of maneuvers with varied speeds at discontinuity locations compared to control sites, highlighting the importance of including network discontinuity indicators in road and cycling network performance rankings.
5. The final contribution of this dissertation is a novel movement-based safety evaluation of cyclist at discontinuities, where safety indicators are summarized per cyclist movement

(motion pattern) to be compared across movements and across discontinuity and control locations. Like contribution four, the outcomes of this study emphasise the importance of recognizing discontinuities as hotspots that must be included in network performance evaluation and safety studies. This approach also identifies the specific risky movements that can be used to design better counter-measure.

1.4 Thesis Structure

The following eight Chapters present the research developments to carry out the objectives of this dissertation. Chapter two is a review of the relevant research efforts focusing on discontinuities affecting cyclist behaviour and safety. Chapter three covers the general methodology to complete each objective. Chapter four is the first article which defines discontinuity measures and proposes a methodology to identify discontinuities in any cycling network using its geospatial data. The methodology is automated and made available in an open source repository (Nabavi Niaki, Bourdeau, Saunier, & Miranda-Moreno, 2018). This study has been submitted to the peer reviewed journal of Transportation part A, and recognized in a Montréal research project report for the Canadian Association of Physicians for the Environment (CAPE): Analysis of missing links in Montréal's cycling network (Notebaert & Beitel, 2017).

Chapter five is the second article which proposed the methodology to collect illuminance data at a link level to perform nighttime safety evaluation of vulnerable road users using historical accident data. This article was presented at the 2016 peer reviewed conference: annual meeting of the Transportation Research Board and published in the 2016 Transportation Research Record journal of the Transportation Research Board volume 2555

The third article presented in Chapter six presents the microscopic behaviour study of cyclists at discontinuities using speed and maneuver analysis. This article was published in the 2018 peer reviewed journal of Transactions on Transport Sciences volume 9, issue 1.

Chapter seven, and the fourth article of this dissertation, presents the proposed maneuver-based surrogate safety analysis method. The method is applied to evaluate cyclist safety at discontinuities and control sites. This article is submitted to the peer reviewed conference: 98th annual meeting of the Transportation Research Board, and the peer-reviewed journal of Accident Analysis and Prevention.

Chapter eight is a discussion of the contributions of this dissertation and its research findings. The dissertation is concluded in Chapter nine including the study limitations and recommendations.

Appendix A elaborates on the case study site selection and parameter values used for analysis in chapters four, six and seven. Appendix B presents the methodology to collect nighttime road lighting levels at an intersection level. The safety analysis is performed using vehicle accident data. This article was presented at the 2014 peer reviewed conference: 93rd annual meeting of the Transportation Research Board and published in the 2014 Transportation Research Record journal of the Transportation Research Board volume 2458. Appendix C covers the preliminary methodology extended in Chapter four, and focuses on comparing the cycling network discontinuity of three Montreal boroughs. The paper was presented at the 2016 peer reviewed conference: 95th Annual Meeting of the Transportation Research Board, Washington D.C., 2016

CHAPTER 2 LITERATURE REVIEW

The main goal of this dissertation is to enhance the understanding of cyclist behaviour and safety when there are interruptions and changes along the cycling network and to classify these interruptions as cycling network discontinuities. The review of relevant literature highlights the areas where these topics have been covered and from what perspective, and the research gaps that exist in this field. The scattered and partial use of cycling network discontinuities in cycling route choice, cycling safety and cycling network performance studies has motivated the efforts to systematically define and propose a methodology to identify these locations in any area (presented in Chapter four). In addition to the lack of a conceptual framework for identifying discontinuity indicators, there is a lack of microscopic behavioural and safety studies of cyclists at locations of cycling network discontinuities.

A limited number of studies have used different definitions of cycling network discontinuities in the context of cyclist behaviour (e.g. (Amini, Twaddle, & Leonhardt, 2016; Copenhagenize Design Co., 2017)), route choice (e.g. (Dill & Gliebe, 2008; Menghini, Carrasco, Schüssler, & Axhausen, 2010)), comfort (e.g. (Blanc & Figliozzi, 2016)), perceived safety (e.g. (Foster, Dill, & Clifton, 2015)), and actual safety (e.g. (Prati, Pietrantoni, & Fraboni, 2017; Zangenehpour et al., 2016)). However, the focus of these studies was not on the locations where there are changes in road, traffic, or cycling network characteristics, but rather the effects of the different road and traffic characteristic such as: road class (highway, arterial, collector and local), traffic speed (observed speed or posted speed limit categorised into different levels), traffic volume (range of high to low traffic volume), parking on road (allowed or not allowed), nighttime road lighting (presence of absence of lighting), pavement condition (range from condition quality or pavement type), and presence and type of cycling facility (physically separated, bike lane, designated roadway or off-road facilities) (Buehler & Dill, 2016; Dill & Gliebe, 2008; Hölzel, Höchtl, & Senner, 2012; Hunt & Abraham, 2007; Kang & Fricker, 2013; Kaplan, Vavatsoulas, & Prato, 2014; Menghini et al., 2010).

These studies have established that cyclists route choice, behaviour and safety are affected by the changes of characteristics in each category. Therefore, the conclusion can be drawn that if there is a variability of these measure along a cyclist's route, it will affect his/her behaviour, safety and comfort. For example, studies have shown that riding on a high speed road reduces comfort and safety, therefore locations along the cyclist's route where a transition from low speed road to a high speed road will result in a change from comfortable and safe, to stressful and risky (Akar & Clifton, 2009; Buehler & Dill, 2016; Caulfield, Brick, & McCarthy, 2012; Habib, Mann, Mahmoud, & Weiss, 2014; Meghan Winters, Davidson, Kao, & Teschke, 2011). Another example is the effect of parking on cyclist's perception of safety, where changes from no parking allowed, to parking allowed on the road will result in a change in the cyclist's perceived and actual safety (M. Stinson & Bhat, 2003; Wilkinson, Clarke, Epperson, & Knoblauch, 1994). The results of these studies indicate that at these locations of change, cyclists experience stress and increased mental effort and will behave differently given their comfort and experience levels (Hunt & Abraham, 2007; Krizek & Roland, 2005; Vansteenkiste et al., 2014).

The following subsections focus on different cyclist study aspects (cyclist preference and safety) with specific infrastructural and traffic indicators that have been found to affect cyclists, that can be characterised as discontinuity indicators when there is a change from one variable category to another. Furthermore, relevant literature to cycling network evaluations are covered in the final subsection representing common performance indicators including connectivity and continuity.

2.1 Cyclist Preference Studies

2.1.1 Overview of Findings

In general, the analysis of cyclist behaviour around the world showed similarities between infrastructural preferences. For example, many cyclist's stated and revealed preference studies indicated a preference for:

- roads with cycling facilities (Dill & Gliebe, 2008; Kang & Fricker, 2013; Menghini et al., 2010; Mitra et al., 2017; M. Stinson & Bhat, 2003),
- roads with fewer lanes, lower traffic volume and speed (Abraham, McMillany, Brownlee, & Hunt, 2002; Akar & Clifton, 2009; Antonakos, 1994; Caulfield, 2014; Chataway, Kaplan, Nielsen, & Prato, 2014; Dill & Voros, 2007; Foster et al., 2015; B. Landis, Vattikuti, & Brannick, 1997; J. Pucher & Buehler, 2008; Sener et al., 2009; Sorton & Walsh., 1994; Wilkinson et al., 1994; Meghan Winters et al., 2011), and
- roads without on-street parking (Sener et al., 2009; M. Stinson & Bhat, 2003; Wilkinson et al., 1994).

Among roads with a cycling facility, cyclists have demonstrated a preference for:

- physically separate and off-road cycling facility types over bike lanes and designated roadways (Akar & Clifton, 2009; Antonakos, 1994; Aultman-Hall & Adams, 1998; Broach & Dill, 2016; Broach, Dill, & Gliebe, 2012; Buehler & Dill, 2016; Foster et al., 2015; Gössling, 2013; Høye, Fyhri, & Bjørnskau, 2015; Kang & Fricker, 2013; B. Landis et al., 1997; Wardman, Tight, & Page, 2007; Wendel-Vos, Droomers, Kremers, Brug, & Van Lenthe, 2007; Meghan Winters & Teschke, 2010), and
- wider bike lanes with greater separation from traffic (Z. Li, Wang, Liu, & Ragland, 2012; Monsere, McNeil, & Dill, 2012).

Other attributes affecting cyclists travel route preference include:

- travel time and road gradient (Broach, Gliebe, & Dill, 2011; M. A. Stinson & Bhat, 2005),
- road class type (Bai, Liu, Chan, & Li, 2017; Broach et al., 2011; Dill & Gliebe, 2008; Kang & Fricker, 2013; M. A. Stinson & Bhat, 2005),
- path length, and turning vehicle volume (Broach et al., 2011),
- intersection density (B W Landis et al., 2003),
- traffic signals and stop signs (Ayres & Kensington, 2015; Boudart, Liu, Koonce, & Okimoto, 2015), and
- pavement condition (Bíl, Andrášik, & Kubeček, 2015; Hölzel et al., 2012; M. A. Stinson & Bhat, 2005).

Although the preference for some of these infrastructural and traffic indicators have been established as early as the 1970's (Feilden, 1975; Lott, Tardiff, & Lott, 1978), the locations of changes from one type to another have not explicitly been characterized as cycling network discontinuities, and have not been specifically studied.

2.1.2 Specific Findings on Possible Discontinuity Measures

A stated preference survey conducted in Edmonton, Canada, on a sample of 1,128 cyclist observations indicated that cyclists with less experience and lower comfort levels are more sensitive to traveling on mixed-traffic routes and prefer riding on bike lanes and physically separated cycling facilities, and that sensitivity to trip duration varies substantially per cycling facility type (Hunt & Abraham, 2007). A statistical analysis (binary logit model) of stated preference survey data from 3,145 individuals who are mostly experienced cyclists (91 % of data) indicated a preference for routes with a cycling facility (especially bike lane and physically separated cycling facility), routes with low volume traffic, no on-street parking, smooth pavement and continuous cycling facility (cycling facility along entire route with no interruption, although the types of interruption are not defined) (M. Stinson & Bhat, 2003). Moreover, a descriptive analysis of 162 observations from GPS collected data in Portland by Dill and Gliebe indicated that both frequent (cycling more than 5 days a month) and infrequent cyclists (cycling less than 4 days a month), rank their top three route choice preferences as routes that minimize distance, avoid high traffic roads, and have a bike lane (Dill & Gliebe, 2008). In this study, cyclists are generally observed to ride on roads with cycling facilities compared to no facility, and among those cyclists traveling on the road with no facility, a higher preference was observed for local streets with low traffic volumes (Dill & Gliebe, 2008). Blanc et al. studied the data obtained from a smartphone application collecting route and perception information and concluded that separate cycling facilities increase cyclist comfort, and arterial road type as well as high volume vehicular traffic especially heavy vehicles decreases the comfort and safety perception of cyclists (Blanc & Figliozzi, 2016). A survey conducted by Foster et al., also found that physically separated cycling facilities are generally more comfortable compared to other types of on street cycling facilities (Foster et al., 2015). Although the cyclists' sensitivity to different road, cycling facility and traffic characteristics is recognised, discontinuity indicators have been overlooked in these studies.

2.2 Cyclist Safety Studies

2.2.1 Overview of Findings

Cycling safety studies have identified a set of infrastructural, traffic and other variables that affect cyclist safety using historical accident or SMoS data. Based on literature, the network infrastructural and traffic variables that improve cyclist safety include:

- presence of dedicated cycling facility (physically separated cycling facility, bike lane, and off road facility type) (Kaplan et al., 2014; Lusk et al., 2011; Lusk, Morency, Miranda-Moreno, Willett, & Dennerlein, 2013; Reynolds, Harris, Teschke, Cripton, & Winters, 2009; Teschke et al., 2012; Thomas & De Robertis, 2013; Wan, Kamga, & Liu, 2018; Zangenehpour et al., 2016),

- bicycle boxes at intersections (Dill, Monsere, & McNeil, 2012; Loskorn, Mills, Brady, Duthie, & Machemehl, 2013; Zangenehpour, Miranda-Moreno, & Saunier, 2013),
- low traffic volume and speed (Buch & Jensen, 2017; Glauz & Migletz, 1980; Kaplan et al., 2014; Lovelace, Roberts, & Kellar, 2016; Prati et al., 2017; Sayed, 1998; Shirani, Doustmohammadi, Haleem, & Anderson, 2018; Stipancic, Zangenehpour, Miranda-Moreno, Saunier, & Granié, 2016),
- fewer road lanes (Glauz & Migletz, 1980; Lovelace et al., 2016),
- fewer intersections along a cyclist's route (Osama & Sayed, 2016; Siddiqui, Abdel-Aty, & Choi, 2012; Wei & Lovegrove, 2013),
- presence of road lighting at nighttime (Beyer & Ker, 2010; J. D. Bullough et al., 2013; Donnell et al., 2010; Wanvik, 2009b), and
- increased cycling facility width (A. Richard A van der Horst, De Goede, De Hair-Buijssen, & Methorst, 2014).

2.2.2 Specific Findings on Possible Discontinuity Measures

2.2.2.1 Accident Analysis Methods and Findings

Historical accident data has been used for safety analysis adopting different analysis methods. Basic methods include descriptive analysis of the accident data, summarizing accidents based on type, road user involvement, time of day, injury severity level, weather conditions etc. Furthermore, plotting the geo-referenced accidents on the road network can highlight locations with high accident frequency. An improvement to this approach is the adoption of the Bayesian multiple testing procedure to identify hotspot locations using accident data and traffic volume (Miranda-Moreno, Labbe, & Fu, 2007).

Statistical analysis of accident data has adopted a range of statistical models. For analysis of accident frequency, statistical count models such as Poisson regression, and Negative Binomial models have been adopted (P. Chen, 2015; Dong, Clarke, Yan, Khattak, & Huang, 2014; Lord & Mannering, 2010), while for analysis of accident injury severity, discrete frameworks such as the Ordered Logit, Ordered Probit, and Bayesian logistic regression models have been employed (Clifton, Burnier, & Akar, 2009; Kaplan et al., 2014; Wang, Abdel-Aty, Wang, & Yu, 2018).

A study of accident severity on Danish roads using statistical analysis indicated an increased probability of a severe and fatal cyclist accidents on high speed roads (50–60 km/h), and multi-lane roads, and a lower probability of fatality along cycling facilities (Kaplan et al., 2014). Additionally, a study of accident data showed that in the U.S., cycling risk is higher on the road compared to a physically separated cycling facility (Lusk et al., 2013). A similar study in Canada found separate cycling facilities to have a lower risk of injury compared to other facility types and on the road (Teschke et al., 2012). Analysis of historical accident data in Italy identified road type, traffic speed and presence of heavy vehicles to be the main contributing factors to cyclist accidents and injury severity (Prati et al., 2017). A study in the U.K. on accident data found similar results where cyclist injury severity increased on high speed and high-volume roads (Lovelace et al., 2016). A Seattle based study by Chen, using statistical analysis to evaluate the effects of built environment variables on accident data found bike lanes on arterial roads to be less safe than those on local and collector road classes (P. Chen, 2015).

Studies have found a higher accident risk at nighttime (associated to the lack of clear visibility (Beyer & Ker, 2010; J. D. Bullough et al., 2013; Donnell et al., 2010; Wanvik, 2009b)) and on weekends (Dozza, 2017). Nighttime safety studies have investigated the effects of presence or absence of road lighting on accident frequency and injury severity, where it was concluded that low levels of lighting are as effective as no lighting in reducing nighttime accidents (Beyer & Ker, 2010; J. D. Bullough et al., 2013; J. Bullough, Rea, & Zhou, 2009; Donnell et al., 2010; Wanvik, 2009b; Zhou & Hsu, 2009). The effects of varied lighting levels at nighttime, as measured by uniformity, is proven to cause road user disability glare resulting in unsafe road user encounters (D. DiLaura, Houser, Mistrick, & Steffy, 2000; McLean, 2012). As in other study fields, safety evaluations have not included discontinuity locations in their studies.

The majority of the road safety literature studies the number of accidents (accident frequency), or the injury severity at the level of the intersection or road link over the span of several years (see (Allen-Munley, Daniel, & Dhar, 2004; Kaplan et al., 2014; Zhao & Chen, 2016)). However, in addition to the previously mentioned shortcomings of accident data, the infrastructural, traffic and environmental variables used in the analysis of the accident data usually changes over such a long period: changes in traffic volume over the years, land-use developments, and changes in the geometry of intersections and road links. These changes are usually ignored when analysing accident data and may have an effect on the number of accidents that occur at these locations.

2.2.2.2 SMoS Analysis Methods and Findings

Traffic conflicts refer to interactions between two or more road users approaching each other in time and space to such an extent that there is a possibility of collision if their movements remain unchanged (Hyden, 1987). SMoS are indicators used to describe the safety and severity of interactions. One of the most common SMoS is time-to-collision (TTC). TTC is defined as the time it takes for two road users to collide if their movements remain unchanged. TTC is a continuous function of time for as long as the road users are on a collision course. For road users on a collision course, TTC can be represented by Figure 2-1 where the minimum TTC (TTC_{min}) is often used to indicate the severity of the conflict. TTC_{min} values below 1.5 s have been commonly used to define dangerous conflicts.

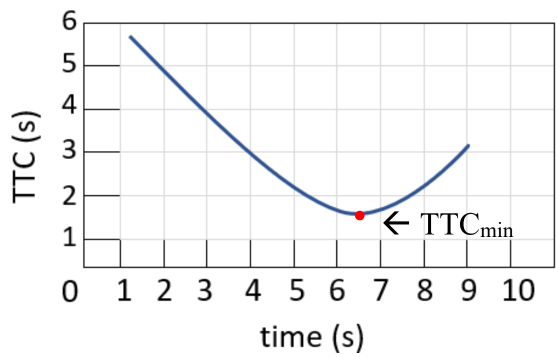

Figure 2-1 TTC curve

Methods to obtain SMoS are proactive methods that do not rely on accident data but rather identify situations where road user interactions could result in an accident, from which SMoS are derived. These interactions occur more frequently than accidents and are commonly represented as the level before accidents in a safety pyramid as shown in Figure 2-2, where the severity or seriousness of a conflict is its “nearness to a serious personal injury” (Fyhri, Sundfør, Bjørnskau, & Laureshyn, 2017). Looking at Figure 2-2, the base of the pyramid is normal undisturbed traffic, moving up, there are safe interactions where road users on a collision course perform slight adjustments to speed or steering. Slight conflicts are safe interactions where there is an observable change in speed or steering to maintain a safe distance between road users. Serious conflicts require major speed and steering referred to as an evasive action to avoid colliding with another road user. In the event that the evasive action is unsuccessful, the interaction results in an accident.

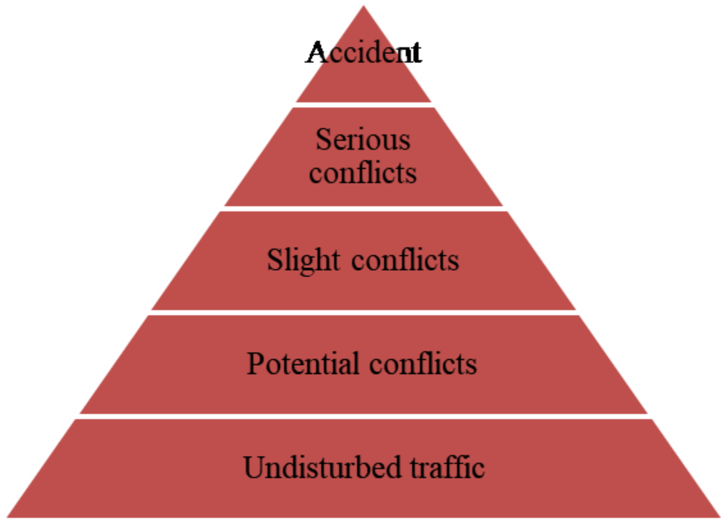

Figure 2-2 Safety pyramid (adapted from (Hyden, 1987))

The main advantage of SMoS is the quick data collection from direct observation of traffic. Traffic conflict techniques (TCT) provide operational definitions of conflicts and indicators to measure their severity i.e. proximity to a collision. There are different TCTs such as the Swedish TCT (Hyden, 1987), the Dutch Objective Conflict Technique for Operation and Research (DOCTOR) (A. R. A. van der Horst & Kraay, 1986), and the Canadian TCT (Brown, 1994). Each of these methods relies on slight differences in the definitions of conflicts. For example, the Swedish TCT relies on three basic concepts: presence of a collision course (course of a road user trajectories that if unchanged, will lead to an accident), presence of an evasive action to avoid the accident, and that interactions have a range of safety levels leading up to an accident. This method computes the severity of an interaction based on the speed of the road user making the evasive action, and an estimation of the TTC at the moment of the evasive action. This instantaneous TTC is called time-to-accident (TA) (Amundsen & Hyden, 1977). The DOCTOR method defines a conflict as an interaction where at least one road user needs to take an evasive action to avoid an accident, and TTC or PET can be computed (Kraay, Horst, & Oppe, 2013; A. R. A. van der Horst & Kraay, 1986). The Canadian TCT classifies conflict severity based on a range of "TTC from evasive action" (TA) values (below 1.5 s, between 1.5 and 3 s, more than 3 s) and an observer's estimate of risk of collision (ROC) (slight, moderate and serious ROC) (Brown, 1994).

Methods for SMoS calculations range from observational conflict identification and severity estimations to precise microscopic trajectory extraction and computation from video data. Extracting SMoS such as TTC requires the specification of a motion prediction method to identify when road users are on a collision course, i.e. if a collision would occur if "their movements remain unchanged". This relies traditionally on the assumption of constant speed and direction to predict the future states of interacting road users. However, the assumption that road users will continue straight does not accurately represent real-world behavior where users perform slight steering or direction changes or major maneuver changes such as turning. Furthermore, this traffic conflict definition is inapplicable in situations where the road user does not have the option to continue along a straight path, for example on a turning road or at a T-intersection. Among the different methods, the probabilistic surrogate measures of safety (PSMoS) relies on future state prediction of road users based on a probabilistic method from observed road user trajectories specific to a site (Gomaa Mohamed & Saunier, 2013; Saunier, Sayed, & Ismail, 2010). The PSMoS method is used for surrogate safety analysis in this dissertation as it is more realistic and more robust. A basic demonstration of this method is presented in Figure 2-3, where the traditional method predicts future motion from which a collision course is identified and TTC is computed, based on the assumption that speed and movement remain unchanged, which is unreasonable in this situation at the T-intersection (Figure 2-3). The PSMoS method (Figure 2-3 b.) predicts the future state of road users based on the observed movements and the probability of the road user belonging to each motion pattern, from which collision points, their probability of occurrence and TTCs are calculated. Based on this method, the TTC of two road users can be calculated at a time t as:

$$TTC\ (U_1, U_2, t) = \frac{\sum_{i=1}^{n}(p_i \times TTC_i)}{\sum_{i=1}^{n} p_i}$$

where U_1 and U_2 are the interacting road users, n is the number of predicted collision points, TTC_i is the predicted time to reach collision point i, i.e. time to collision for collision point i, and p_i is the probability of the road users colliding at collision point i (based on the probabilities to follow the motion patterns that lead to collision point i).

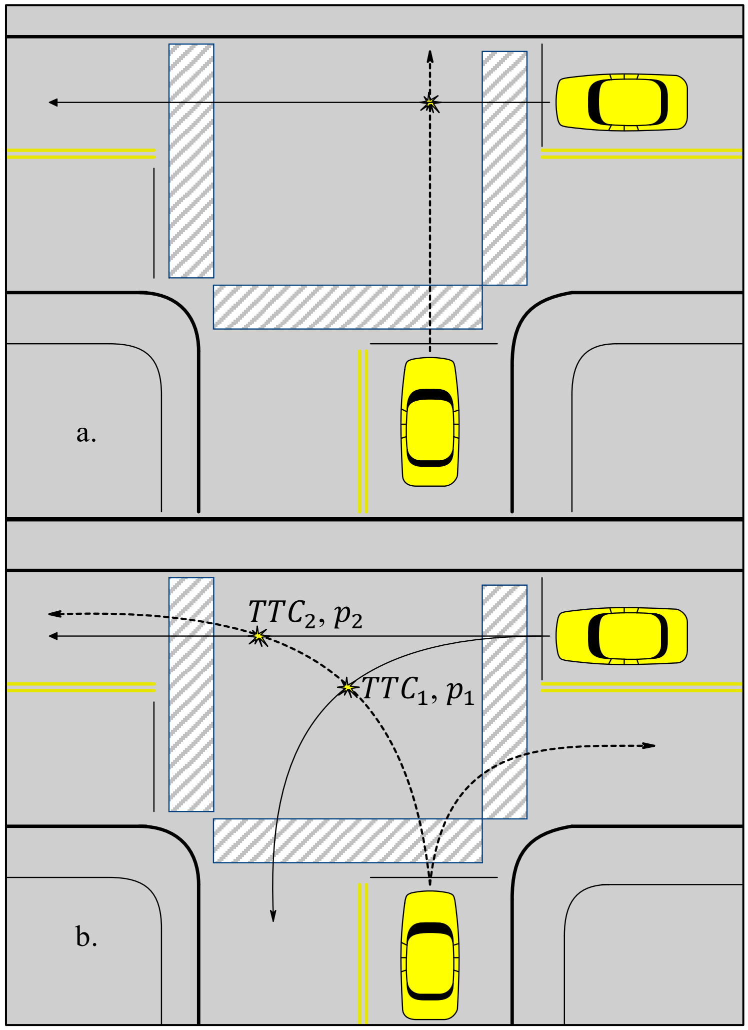

Figure 2-3 a. Traditional motion prediction method assuming constant speed and direction, b. probabilistic motion prediction method using observed motion patterns

The use of conflicts for safety diagnosis is usually done by counting the number of severe conflicts, or SMoS statistics such as mean, median or minimum TTC. To statistically analyse safety using SMoS, in addition to econometric frameworks adopted for accident analysis such as the Negative Binomial model (El-Basyouny & Sayed, 2013) and Analysis of Variance methods (Mikko Räsänen, Koivisto, & Summala, 1999), SMoS analysis methods include the extreme value theory (Songchitruksa & Tarko, 2006; Tarko, 2012), and causal models (G. A. Davis, Hourdos, Xiong, & Chatterjee, 2011). In the former method, risk estimation is based on the number of severe SMoS at a location, and the latter approach calculates the probability of expected number of accidents based on the sum of the conflicts' probabilities of resulting in an accident (G. A. Davis et al., 2011).

In general, there is a very limited number of studies focusing on cyclist safety using SMoS evaluating the effects of traffic and infrastructural variables related to discontinuities. Among past studies, Glauz and Migletz investigated traffic conflicts at 24 intersections in Kansas city, looking at sites with the same characteristics: results showed that intersections with higher traffic volumes and number of road lanes resulted in a higher conflict frequency (Glauz & Migletz, 1980). Video observations evaluating cyclist safety using the number of conflicts at Danish signalized intersections found that cyclists entering the intersection at higher speeds have a higher risk of being involved in a conflict (Buch & Jensen, 2017). Another video analysis study at 23 Canadian intersections categorising PET values into severity levels found that cyclists riding on a physically separated cycling facility on the right of traffic to be safer compared to riding on a physically separated cycling facility on the left of traffic or the road with motor vehicles (Zangenehpour et al., 2016).

The shift from accident data to SMoS eliminates many of the problems associated with accident data. Studies based on SMoS can range from several hours of observation to a couple of months, eliminating the need to accumulate accident data over several years. These studies have also used the total number of surrogate safety events per locations (A. Richard A van der Horst et al., 2014; Zangenehpour et al., 2013). The limitation of this approach is that the specific unsafe maneuvers cannot be identified, and so, the safety countermeasures implemented may not be as appropriate as they could be for the safety problems of the location. Another approach is to evaluate the safety at a more microscopic level of specific movements, such as the safety of through cyclist interactions with right or left turning cars, which would make a stronger link between the specific movements and their safety. The following section summarises movement-based safety studies in the literature.

2.2.3 Movement-Based Safety Studies

Instead of accumulating the total number of accidents or severe conflicts per location, safety and risk levels can be summarized in different ways such as the number of safety events that meet a specific criterion, distribution of indicators, or per movement. The maneuvers can be observed and categorised into a set of general movements. For example, right turning movements can be grouped as sharp right turns (Figure 2-4 a.), wide right turns (Figure 2-4 c.), or in-between sharp and wide turning maneuvers (Figure 2-4 b.). Left turning maneuvers can be grouped as cyclists making a vehicular left turn (Figure 2-4 d.), cyclists crossing the road on both sides with different strategies

(Figure 2-4 d. and e.). Past studies focusing on specific maneuvers have only considered one set of movement such as through cyclists and right turning vehicles without distinguishing between different through or turning maneuvers.

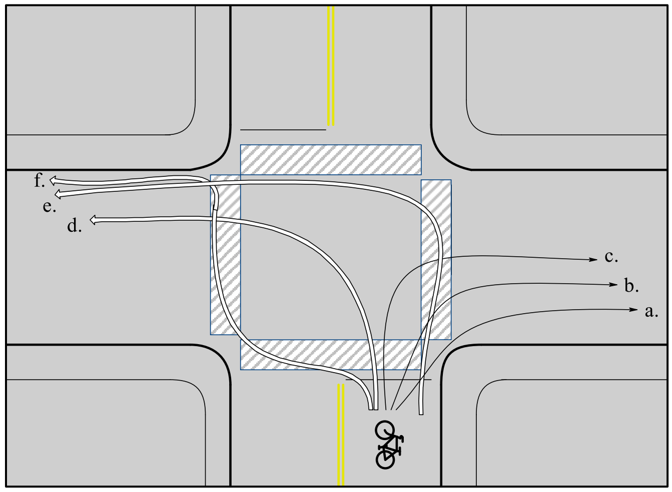

Figure 2-4 Right and left turning movements

2.2.3.1 Movement-Based Behaviour Analysis

Copenhagenize Design performed several on-site and video data observations to record cyclist maneuvers in different areas as their “desire line” and established a set of varied movements for each location. They concluded that the cyclists’ desire lines should be observed and the cycling facility should be adjusted to accommodate the preferred maneuvers (Copenhagenize Design Co., 2017). Another behavioural study observing video data collected at intersections categorised the left turning cyclist maneuvers into vehicular left turn, pedestrian left turn using near crosswalk and pedestrian left turn using far crosswalk (Amini et al., 2016). Twaddle also recorded movement variations among cyclists at intersections using the same open source software used in this work to extract road user trajectories automatically from video data, to develop cyclist models to be incorporated into traffic micro-simulation (Twaddle, 2017).

2.2.3.2 Movement-Based Accident Analysis

A statistical analysis of accident data looking at certain maneuvers identified conflicts involving left turning cyclists and straight moving road users to have the highest risk of severe injury compared to cyclists traveling straight and colliding with a stationary road user (Kaplan et al., 2014). Other studies have identified the through movement cyclists travelling on the right-hand-side of a vehicle to have a higher risk of accident with right turning cars compared to those travelling on the left side and interacting with left-turning vehicles (Herslund & Jørgensen, 2003; M. Räsänen & Summala, 1998; Summala, Pasanen, Räsänen, & Sievänen, 1996). Buch and Jensen performed a before-after safety study of staggered stop lines at signalised intersections using accident data of right-turning vehicles with cyclists and found an increase of 32 % in accident frequency (Buch & Jensen, 2017).

2.2.3.3 Movement-Based Analysis based on SMoS

A study investigated perpendicular conflict scenarios (through moving vehicle with through moving cyclist from right or left direction) using video recorded from inside the vehicle, and found the riskiest encounters to be with cyclists who were not visible when entering the road or intersection (emerging from behind a building or another vehicle) (Matsui, Oikawa, Takahashi, & Hitosugi, 2015). Another study focused on through cyclists with right and left turning vehicles using SMoS from video data observation, and found that through cyclists riding on yellow light at a signalized intersection, and cyclists with higher speeds had a higher chance of being involved in a conflict with turning vehicles (Buch & Jensen, 2017). A study of through cyclists and right turning vehicles in the same direction indicated that separate cycling facilities located on the right-hand side of traffic (in the direction of traffic) are safer than those located on the left-hand side (Zangenehpour et al., 2016). A study of right turning cars through a channelized lane evaluated safety interactions with through cyclists and identified a higher conflict frequency where vehicles had the right of way and cyclists travelled from their right to left to continue straight (van Haperen et al., 2018). Madsen and Lahrmann investigated right and left turning vehicular movements with through cyclists and found right turning maneuvers to have a higher risk compared to left turning, specifically at locations where the cycling facility disappeared before the intersection and cyclists shared the road with right turning traffic (Madsen & Lahrmann, 2017). These studies have summarized safety indicators for generalized maneuvers (e.g. all right turning movements with all through movements); however, this does not provide a comparison among different maneuvers and the in-depth understanding of riskier maneuvers for each movement.

2.3 Cycling Network Performance

Many cycling network performance indicators and frameworks have been proposed in the literature (Barsotti & Kilgore, 2001; Boisjoly & El-geneidy, 2016; W. J. Davis, 1987; Harkey, 1998; B. Landis et al., 1997; Lowry, Furth, & Hadden-Loh, 2016; Mekuria et al., 2012; J. Pucher & Buehler, 2006; Sorton & Walsh., 1994; Transportation Research Board, 2016; Meghan Winters, Brauer, Setton, & Teschke, 2013). These indicators have been studied at different levels with different measuring techniques, yet none of the frameworks adopting these measures incorporate a complete and comprehensive set of indicators representing the infrastructure, environment, traffic, and cycling network, which may result in biased outcomes for each method (Parks et al., 2013; Vale, Saraiva, & Pereira, 2016). Among these indicators, the connectivity of a cycling facility has been most commonly defined as intersection density and dead-end (cul de sac) density (Dill, 2004; Houde, Apparicio, & Séguin, 2018; Huang & Hawley, 2009; Osama & Sayed, 2016), while not systematically defining or including discontinuities.

Studies that have a adopted discontinuity indicators to asses the network performance, include the state of New Hampshire, proposing a guide to assess walkability and bikeability utilizing several indicators such as poor lighting, high vehicle speeds as well as the discontinuity indicator of "cycling facility ends: abrupt end of road facility or disappearance of road shoulder", although their method was not applied to a case study to evaluate the cycling network based on these variables (Coates, 2014). Similarly, Furth proposed factors such as: street width, cycling facility width, speed limit, bike lane blockage (double parked car on facility, bus stops on facility, vehicle maneuvering into parking space, people getting into or out of cars), and parking along street to rank the levels of stress of cyclists (Furth, Mekuria, & Nixon, 2016); however, the methodology was not applied to evaluate the effects of these variables on cyclists. The Lincoln county performed a gap-analysis on the cycling facility to evaluate the maintenance of the cycling infrastructure and found areas with missing signage, and missing cycling routes (Lincoln County, 2015), but did not investigate the effects of these missing links on cyclist behaviour or safety. In an attempt to categorise discontinuities, Krizek and Ronald focused on facility ends and change in facility location on road but did not further investigate cyclist behaviour or safety at these locations (Krizek & Roland, 2005). Although the mentioned studies adopted one or two discontinuity indicators, they were not systematically defined or studied.

2.3.1 Main Cycling Network Performance Indicators

The most commonly used methods to evaluate cycling network performance are the Bicycle Compatibility Index (BCI) (Harkey, 1998), Bicycle Stress Level (BSL) (Sorton & Walsh., 1994), Level of Traffic Stress (LTS) (Mekuria et al., 2012), Bicycle Level of Service (BLOS) (Transportation Research Board, 2016), Bike Score (BS) (Meghan Winters et al., 2013), Bicycle Environmental Quality Index (BEQI) (San Francisco Department of Public Health, 2014), and Bicycle Safety Index Rating (BSIR) (W. J. Davis, 1987). The most used variables among these methods are:

- Traffic speed: average or 85th percentile of the motorized traffic spot speed (Harkey, 1998; Mekuria et al., 2012; San Francisco Department of Public Health, 2014; Sorton & Walsh., 1994; Transportation Research Board, 2016);
- Speed limit: posted speed limit (W. J. Davis, 1987; Mekuria et al., 2012; San Francisco Department of Public Health, 2014);
- Traffic volume: measured as the average annual daily traffic (AADT) (W. J. Davis, 1987; Harkey, 1998; Sorton & Walsh., 1994; Transportation Research Board, 2016);
- Number of road lanes (W. J. Davis, 1987; Mekuria et al., 2012; San Francisco Department of Public Health, 2014; Transportation Research Board, 2016);
- Road lane width: width of the lane adjacent to cycling facility or shoulder (W. J. Davis, 1987; Harkey, 1998; Mekuria et al., 2012; Sorton & Walsh., 1994);
- Parking along the road (W. J. Davis, 1987; Harkey, 1998; San Francisco Department of Public Health, 2014; Transportation Research Board, 2016);
- Parking turnover and occupancy rate (W. J. Davis, 1987; Harkey, 1998; Mekuria et al., 2012);
- Pavement condition (W. J. Davis, 1987; San Francisco Department of Public Health, 2014; Transportation Research Board, 2016);
- Presence of cycling facility (Harkey, 1998);
- Cycling facility type (Mekuria et al., 2012; Meghan Winters et al., 2013); and
- Cycling facility width (Harkey, 1998; Mekuria et al., 2012; San Francisco Department of Public Health, 2014; Transportation Research Board, 2016).

Some of the mentioned frameworks were compiled and compared in a Guidebook for Measuring Network Connectivity (Dill et al., 2018), and ranked based on the level of effort for obtaining and computing the indicators. The guidebook concluded that although each of the frameworks have their strengths and weaknesses, in order to avoid a distorted picture of a cycling network's performance, more sophisticated connectivity measures must be proposed (Dill et al., 2018). Similarly, Parks et al. applied three of the performance frameworks on a before-after study of bicycle facility installations, and concluded that each method has its shortcomings and the development of a nationally accepted bicycle evaluation tool requires more research and evaluation in order to address the different bicycle facility and cyclist characteristics (Parks et al., 2013). Our definition and demonstration of cycling network discontinuity indicators and their effects on cyclist behaviour and safety is an effort to address the shortcomings and limitations in the mentioned frameworks and to complement them to provide a comprehensive evaluation of a cycling network.

2.3.2 Common Connectivity and Continuity Indicators

The most common indicators defined in literature as connectivity and continuity measures are listed below which are related to the cycling network (here, nodes refer to the intersections and dead-ends, and links refer to the road segments connecting the nodes):

- Link-to-node ratio: number of links to number of nodes (Chin, Van Niel, Giles-Corti, & Knuiman, 2008; Dill, 2004; Schoner & Levinson, 2014; Semler et al., 2016; Tal & Handy, 2012; Tresidder, 2005);
- Degree of connectivity: ratio of the existing number of links in relation to the theoretical maximum number of links (S. Chen, Claramunt, & Ray, 2014; Derrible & Kennedy, 2010; Tresidder, 2005);
- Connected nodes ratio: number of intersections divided by number of nodes (Dill, 2004; Semler et al., 2016; Tresidder, 2005);
- Intersection density: number of intersections per area of study (km^2) (Dill, 2004; Osama & Sayed, 2016; Schoner & Levinson, 2014);
- Network density: ratio of the cycling network length (km) to the study area (km^2) (Osama & Sayed, 2016);
- Degree of coverage: ratio of number of links with a cycling facility to number of road links (Osama & Sayed, 2016; Yigitcanlar & Dur, 2010);

- Complexity: number of bike links per node (Osama & Sayed, 2016);

The following variables which are related to the cyclist's trip:

- Detour from shortest path: relative difference between the travelled route length and shortest path length (Boisjoly & El-geneidy, 2016);
- Presence of cycling facility along route (Boisjoly & El-geneidy, 2016);
- Continuous facility: presence of cycling facility for up to 75 % of the route (M. A. Stinson & Bhat, 2005); and

Most of these indicators can be categorised as coverage, density, and directness of trip measures such as the length of the road network over the study area, the number of links with a cycling facility to the number of road links, or the detour from shortest path. As a complementary indicator to coverage, density and directness, connectivity needs to include discontinuity indicators since the longest or densest cycling network may have low connectivity. For example, a long or dense cycling network may have missing links or frequent changes in facility type and other change of cycling facility characteristics, while a short cycling facility of the same type may have low coverage or density but high connectivity.

None of the mentioned cycling network performance methods have used discontinuity indicators in their evaluation or have used indicators such as network length or coverage to measure connectivity that do not consider discontinuities.

In conclusion, three research gaps have been highlighted in this section: the lack of cycling network discontinuity definition and representation, the limited number of cycling network discontinuity indicators in cyclist behaviour and safety studies as well as cycling network performance evaluations. Despite the number of studies on different infrastructural and traffic characteristics, the specific discontinuity locations have not been studied. How does cyclist behaviour or safety change when the cycling facility ends and he/she must merge with traffic? Do cyclists avoid these discontinuity locations? How does a cyclist's speed change at these locations? What are the safety implications of these high-stress locations? The following chapters close the research gaps by proposing and defining discontinuity indicators and performing detailed behavioural and safety studies of cyclists at cycling network discontinuities

CHAPTER 3 METHODOLOGY OVERVIEW

The general methodology of this dissertation follows the steps presented in Figure 3-1. The steps highlight the process to complete each objective. The required datasets are obtained for each objective such as the average annual daily traffic (AADT), the geo-referenced road and cycling network data, and historical accident data. The next step is proposing methodologies to complete each objective that can be disseminated and applied everywhere. The three methodologies include nighttime road lighting audit, cycling network discontinuity characterization, and maneuver-based behaviour and surrogate safety analysis. The proposed methodologies are then applied to case studies by identifying data collection sites for analysis. After data collection, the data analysis includes calculating road lighting discontinuities using illuminance uniformity, extracting road user trajectories from video data and post-processing the results. The final behaviour and safety step rely on the statistical analysis of accident data and factors affecting nighttime safety at locations with a range of illuminance levels, and, at locations with discontinuities along the cycling facility, the analysis of the cyclist motion patterns with their associated speeds and accelerations as well as SMoS.

3.1 Obtain required datasets

The first step is obtaining the required datasets including obtaining accident data, AADT volumes for all road users, and the geo-referenced road and cycling network data.

The accident data was obtained from Montréal police reports from 2001 until the end of 2010 which includes the date and time of the accident, latitude and longitude coordinates of the accident location, type of accident: vehicle-vehicle (including bus and heavy vehicles), vehicle-pedestrian, and vehicle-cyclist accidents, and injury severity at four levels: property-damage only, minor injury, major injury, and fatal accident. The vehicle, pedestrian and cyclist AADT flows are obtained from the McGill University manual intersection data inventory of data collection between 2008 and 2009.

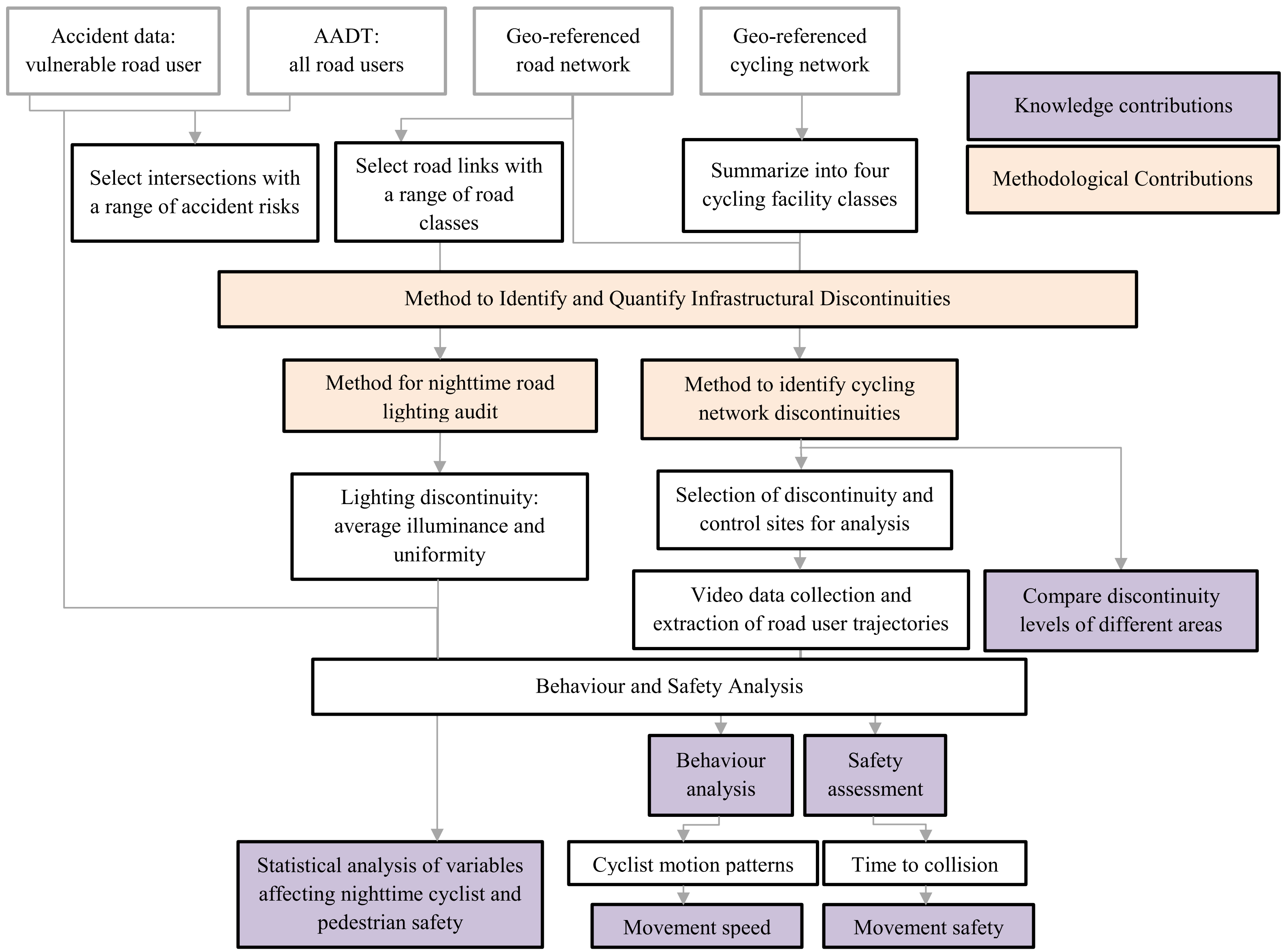

Figure 3-1 Methodology overview

The geo-referenced road and cycling network geospatial data are obtained from open data portals. The georeferenced cycling network data for four cities are obtained: Montréal (City of Montréal, 2015), Vancouver (City of Vancouver, 2015), Washington D.C. (District of Columbia Government, 2015), and Portland (City of Portland, 2015). These datasets have information on road class and cycling facility types.

3.2 Initial Dataset Processing

After obtaining the required datasets, the second step is to prepare the datasets. The cycling networks of the four cities are processed by summarizing facilities into the four main categories considered in this work: physically separated cycling facility, bike lane, designated roadway and off-road. Since each city has a different definition and category of facility types, a google street-view search of all the facility types was performed to label the facilities consistently.

Accident data is filtered for nighttime accidents. To summarize the number of accidents per intersection and road link, all nighttime accidents involving vulnerable road users were plotted along with Montréal's road network and a buffer around each road centerline and intersection counted the number of accidents per road link or intersection.

3.3 Discontinuities Characterization Method

Discontinuity indicators are defined and categorised as intrinsic to the cycling network, related to the adjacent road and traffic, and other. Defined as interruptions in the cycling network that affect cyclist's behaviour, comfort and safety, the following discontinuity measures are proposed that are intrinsic to the cycling facility:

- End of cycling facility (includes both ends of the facility)
- Change in cycling facility type
- Change in cycling facility width
- Change in cycling facility location on road
- Change in road lighting
- Closure/rerouting of cycling facility due to construction or maintenance

Proposed discontinuity measures related to traffic and road network:

- Change in road class
- Change in number of road lanes
- Change in traffic volume
- Change in traffic speed
- Pavement condition
- Road grade
- Intersections

Proposed discontinuity measures categorised as other:

- Driveways
- Bus stops
- Parking allowed on road

Depending on the level of study, the sum of each discontinuity measure is divided by a normalizing factor. If the evaluation is at the macroscopic level the normalizing factor can be the cycling network length. If the analysis is at the microscopic level, for example of individual cycling trips in a route choice study, the normalizing factor can be the cyclist's trip length. An area's discontinuity level may be represented by the sum of its indicators:

$$Area's\ discontinuity\ level = \sum discontinuity\ indicators$$

This value may be used to compare different areas, where lower discontinuity values indicates a more connected cycling network.

3.3.1 Methodology to Identify Infrastructural Discontinuities

The methodology to identify infrastructural and traffic discontinuities along a cycling facility relies on a spatial analyst tool (e.g. ArcGIS) as well as the area's georeferenced road and cycling network data, traffic information, road lighting levels and other infrastructural information. The steps include merging facility types as one line into a single facility line and using a spatial joint to merge road information (number of road lanes, road speed limit, lane width, etc.) to the cycling facility layer. Drawing a buffer around the end of each facility, if there are no other end points or cycling facilities within the buffer, this location is considered the end of a cycling facility, if there is another facility, it is considered a change in cycling facility type. If the information on the bicycle facility location in association with the road network and facility lane width is available, each facility segment is assigned an intersection or road ID and a query is defined to count the segments on a unique road or at an intersection that changes locations or widths. A similar process is done if the information related to road class, traffic volume and speed are available.

3.3.2 Automated Method to Identify Infrastructural Discontinuities

The methodology defined above is automated to identify a subset of the discontinuity measures in any area. The automation is done through *spatialite*, an open source spatially enabled extension of SQLite. The set of scripts to perform the analysis includes merging each cycling facility type as one line, dissolving the merged geometries, identifying the end of the cycling facilities (as points and buffers), and performing a spatial intersection between the end of cycling facilities of different types. The two discontinuity measures extracted using the automated method are the end of cycling facility and the change in cycling facility type.

3.4 Data Collection and Processing

3.4.1 Road Lighting Audit and Data Processing

There are a limited number of studies measuring illuminance levels which use different and cumbersome data collection methods that are not sufficiently accurate (Assum, Bjørnskau, Fosser, & Sagberg, 1999; Gonzalez-Velez, 2011; Jackett & Frith, 2013). Although the effects of the presence or absence of road lighting have been investigated, the actual amount of ambient light and the amount of road lighting differs in different areas, road class types, land use types (commercial, residential, etc.), and depends on the type of light from light poles (sodium vapor light, fluorescent light, LED light, etc.). For these reasons, illuminance levels measured in lux as the intensity of light as perceived by the human eye must be collected to evaluate the effects of actual road lighting and its variation on safety (M. S. Nabavi-Niaki, Saunier, Miranda-Moreno, Amador, & Bruneau, 2014). As part of the first objective, a methodology to perform a road lighting audit, collecting illuminance measures at the intersection and link level is proposed. Nighttime accident hotspot locations are plotted for illuminance data collection on road links (Chapter four), and an empirical Bayes estimator is used to identify intersection hotspots given the number of accidents and traffic flow at the intersection level (Appendix B). Manual data collection steps include holding the illuminance sensor while walking across the four legs of the intersection (Appendix B) or installing the illuminance sensor on a bike and riding through the selected road links (Chapter four). For two-way streets, cyclists go through each direction of the road to collect illuminance levels on both sides. Illuminance measures are recorded every one second and the location of each measurement is logged by a GPS sensor.

For each link and intersection, the average illuminance is calculated, as well as the lighting uniformity as the discontinuity indicator. Uniformity is calculated by dividing the link or intersection average illuminance by its minimum value. Other statistics that can be used to compare lighting levels across links or intersections include the minimum and maximum illuminance measures and standard deviation.

The average illuminance and uniformity values of links and intersections are then used to check whether road lighting is according to standards or not. An area's road lighting standards can be obtained depending on which standards are used in the design of that area. Montréal's road design and maintenance is done at different levels depending on the road class (Bruneau & Morin, 2005). Road lighting of highways and major arterials is provided by Québec Transport Ministry, which uses the Lighting Handbook by the Illuminating Engineering Society (D. L. DiLaura, Steffy, Mistrick, & Houser, 2000), and collector and local road lighting is provided by local municipalities which use the TAC road lighting standards (McLean, 2012). Lighting levels are checked based on road user activity levels and road class type for intersections and road links.

3.4.2 Video Data Collection at Discontinuities

Once the infrastructural and road lighting discontinuities are identified, sites are selected for video data collection and further analysis. In Montréal, two discontinuity and two control sites are selected (details of site selection method are presented in Appendix A). At the intersection of Maisonneuve boulevard west and Ste-Catherine street, a cycling facility is located on the south side of Maisonneuve boulevard, east of the intersection, which changes to the north of Maisonneuve on the west of the intersection indicating a discontinuity of change in cycling facility location on road (Figure 3-3). In addition to the change in side, this location has a change in number of lanes and direction where the one-lane one-way road Maisonneuve changes to a two-lane bi-directional road west of the intersection. The control site located one block east of the discontinuity location is selected: the intersection of Maisonneuve boulevard west and Prince Albert street has a cycling facility running on the south side of Maisonneuve (Figure 3-4).

The second discontinuity is a change in cycling facility type as well as change in number of lanes at Coffee street and Elmhurst avenue (Figure 3-5), where the physically separate cycling facility changes to a designated roadway at the T-intersection, and the one-way one-lane Coffee street changes to a two-lane bi-directional lane on Elmhurst avenue. The control site, located one block east of the discontinuity intersection, is Coffee street and West-Broadway street (Figure 3-6), another T intersection with a physically separate cycling facility on Coffee and the south leg of West-Broadway, and both roads are one-lane and one-way streets.

At each intersection, a GoPro camera is attached to a height-adjustable pole secured to a light pole (Figure 3-2). The camera angle is positioned to capture a good view of the intersection. Video data was collected at these locations on weekdays in October 2015 from 7:00am for around seven hours in mainly sunny and overcast conditions.

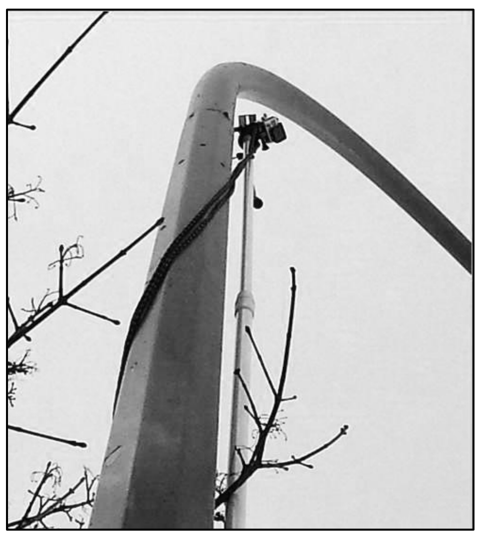

Figure 3-2 Camera setup for video recording

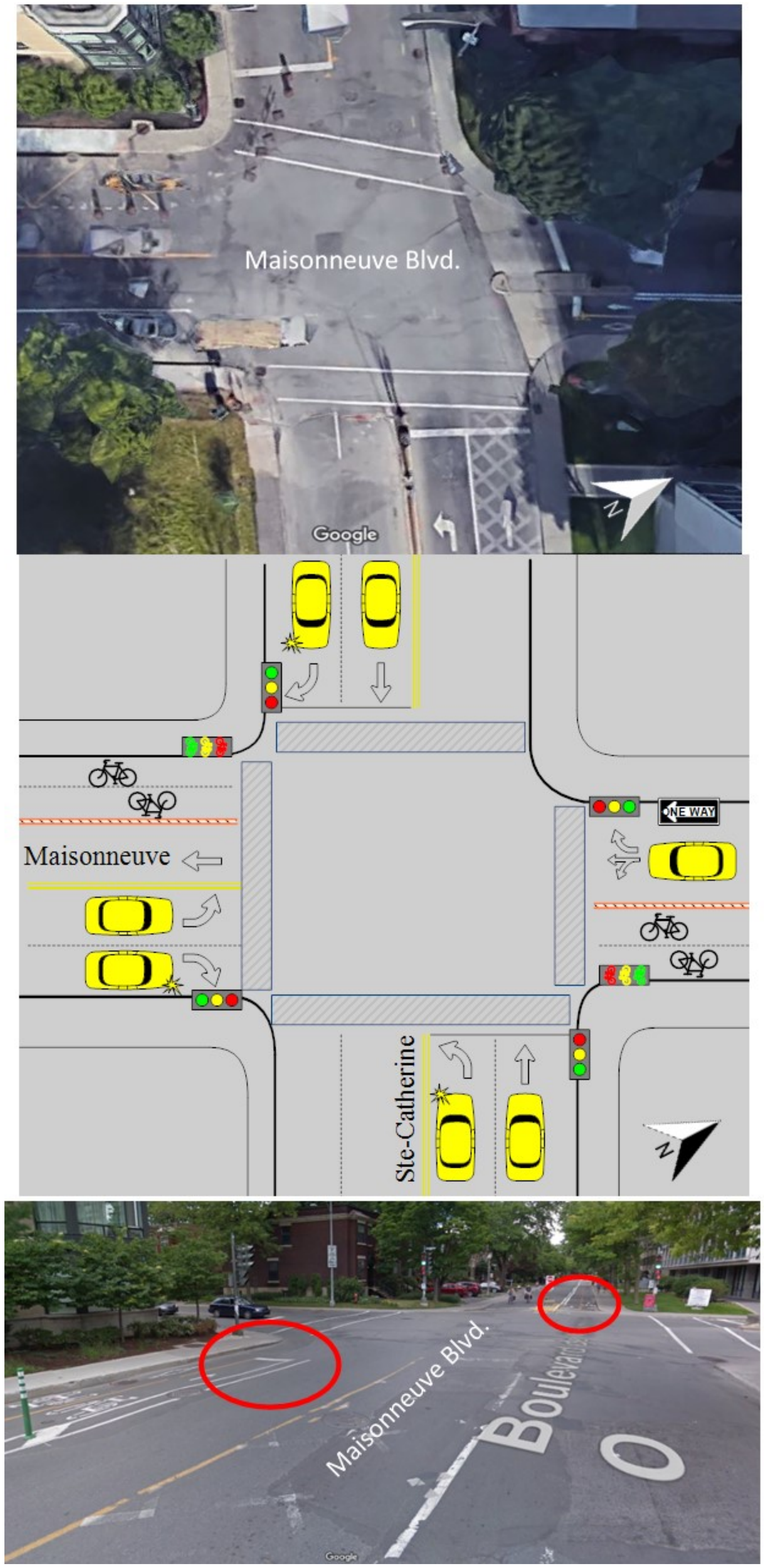

Figure 3-3 Change in cycling facility side discontinuity: Maisonneuve boulevard and Ste-Catherine street (Google Maps)

Note: the aerial view of the intersection does not show the newly built physically separated cycling facility on the southwest corner of Maisonneuve

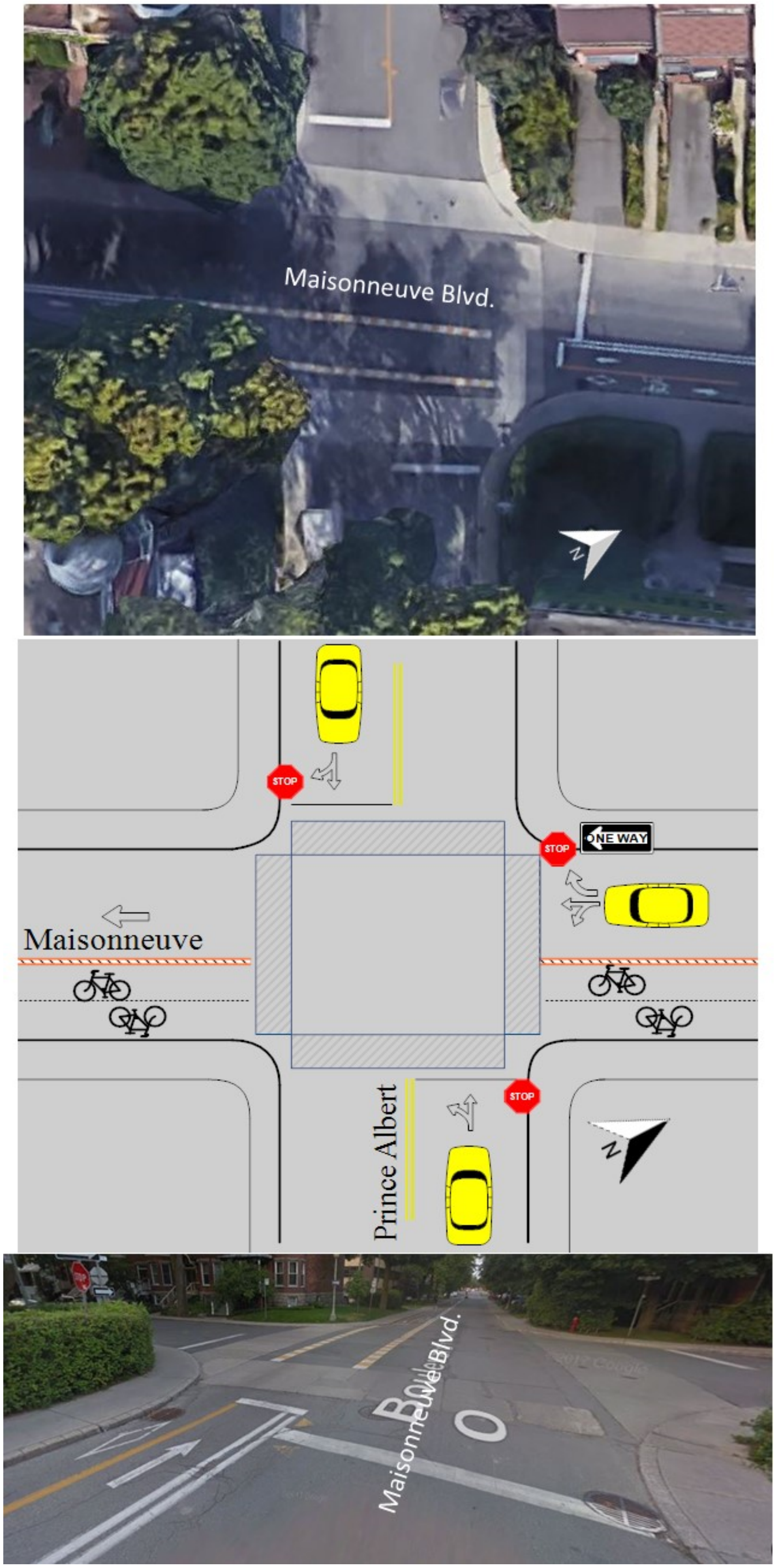

Figure 3-4 Continuous facility: Maisonneuve boulevard and Prince Albert street (Google Maps)

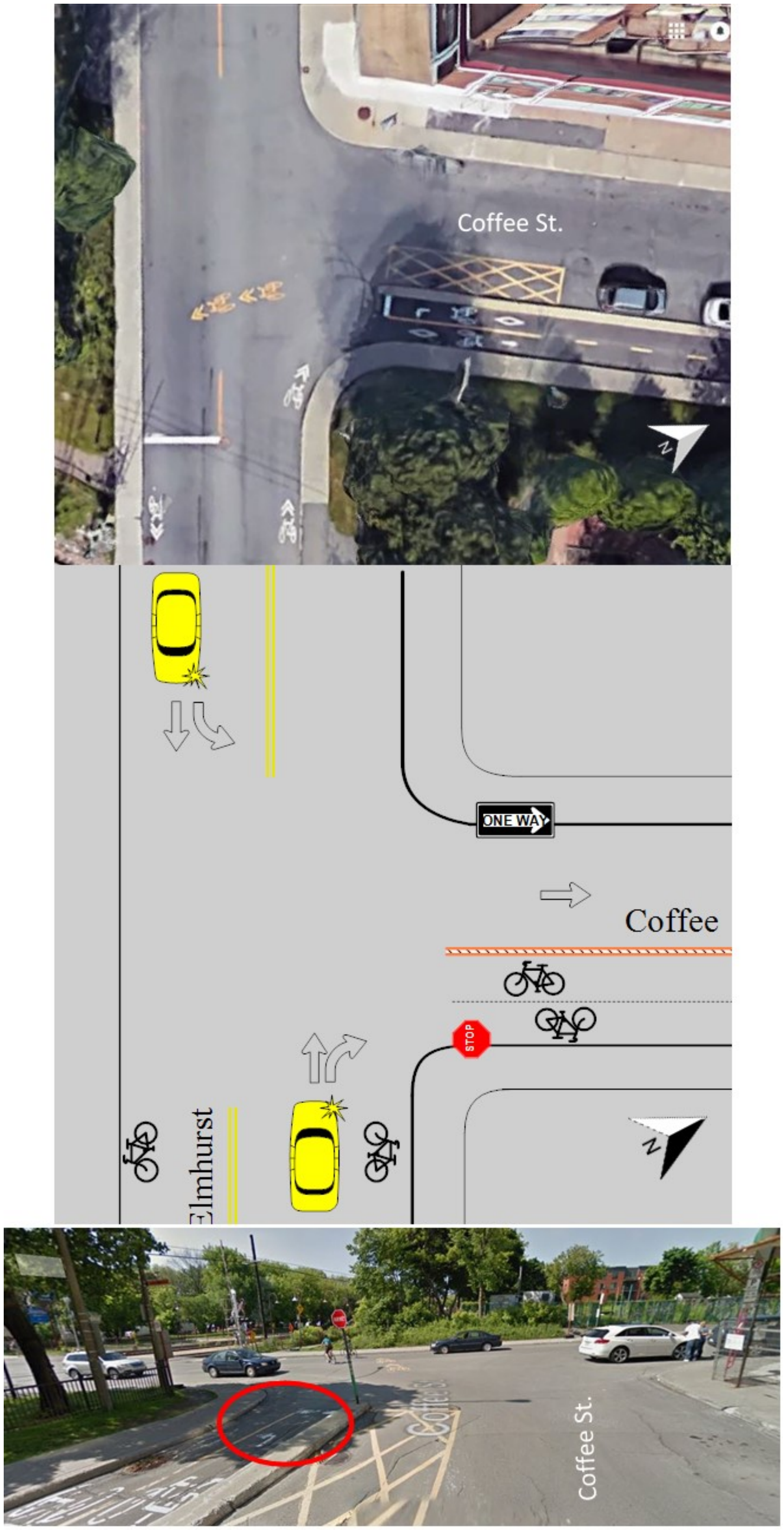

Figure 3-5 Change in cycling facility discontinuity: Coffee street and Elmhurst avenue (Google Maps)

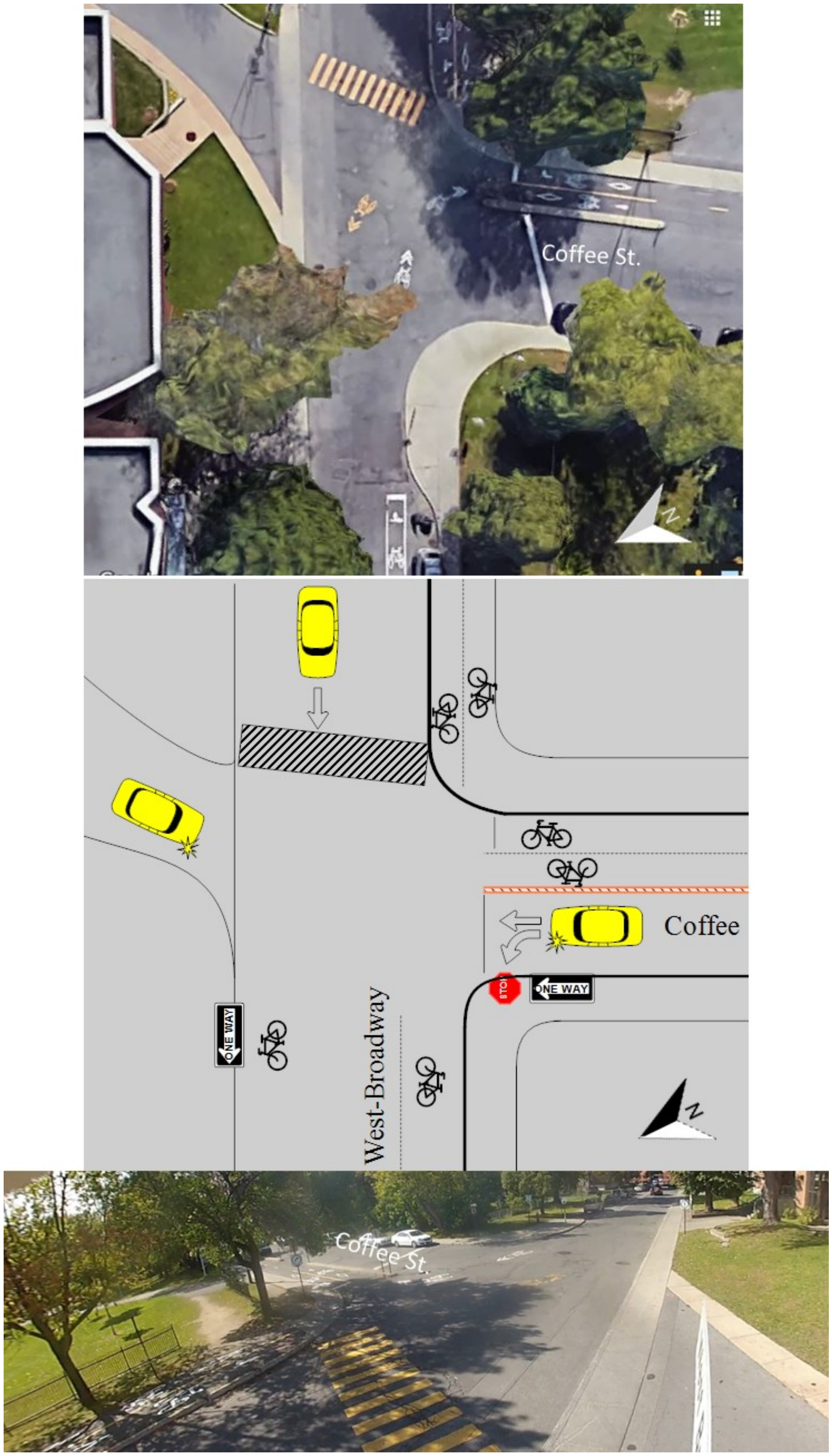

Figure 3-6 Continuous cycling facility on all legs: Coffee street and West Broadway street (Google Maps)

Note: the aerial view of the intersection b. Coffee and West Broadway has the physically separated cycling facility blocked by trees

3.4.3 Video Data Processing

Advancements in image processing have allowed for the detection and tracking of road users in video recordings. The feature-based tracker from the open source project "traffic intelligence" (Jackson, Miranda-Moreno, St-Aubin, & Saunier, 2013) is used to extract trajectories and other tools from "traffic intelligence" for data processing and safety analysis.

3.4.3.1 Camera Calibration

The first step before processing video data is to reduce the video distortion (fish-eye effect). As shown in Figure 3-7 a., distortion increases further away from the center of the image where the geometry, shape and scale of objects are unrealistic. The radial lens distortion coefficient is computed using standard pattern images and adjusted by trial and error (Figure 3-7 b.). Since not all areas in the frame need to be tracked and the distortion in the corners affect tracking, a mask is applied to the corrected image (Figure 3-8), to mark the areas that do not need to be processed for road user detection and tracking.

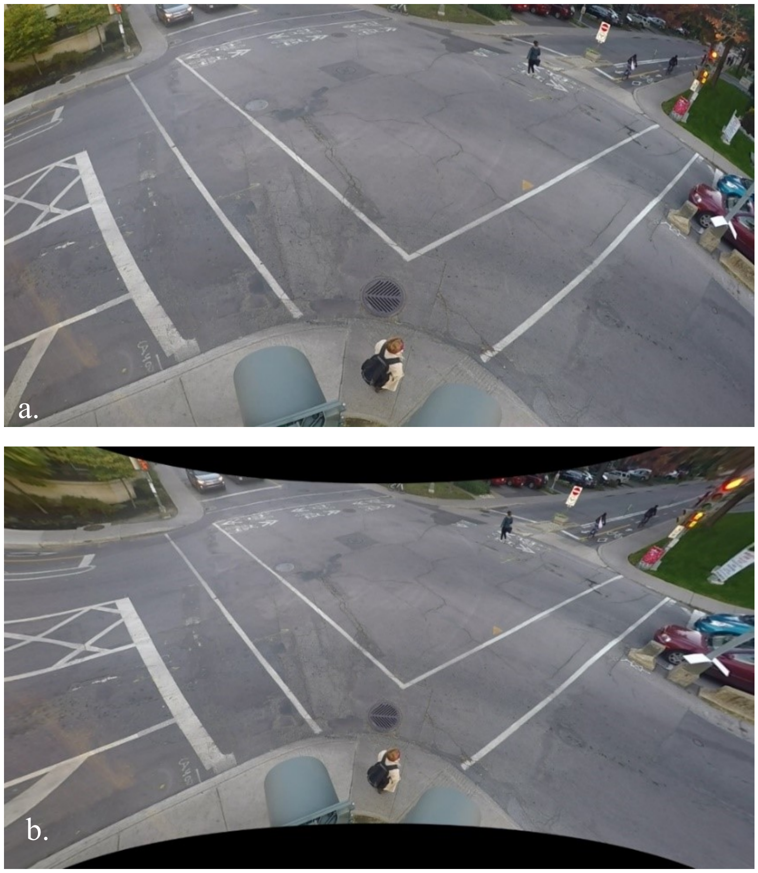

Figure 3-7 a. Distorted frame, b. frame corrected for distortion

Figure 3-8 Mask to delineate the areas for detection and tracking (the area in black is not processed)

The three-dimensional objects captured in a two-dimensional image space in a video frame need to be transferred to real-world coordinates. The mapping process to convert pixels in the image plane to world coordinates relies on a homography matrix. This is done through a selection of common points from the video frame and the aerial image of the site as shown in Figure 3-9, taking into account the scale of pixels per meter in the aerial view image.

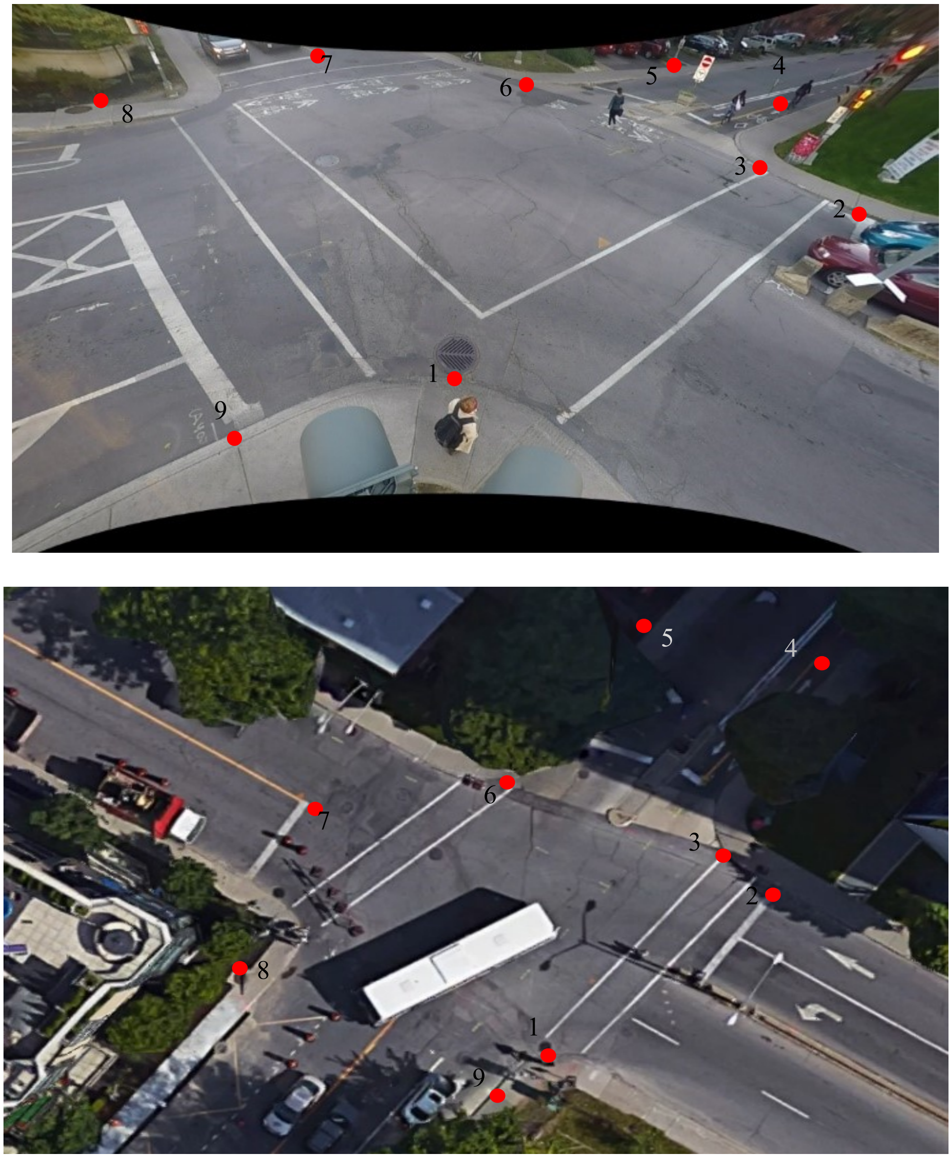

Figure 3-9 Points selected to convert image to world space

This is done so that the objects can be tracked in real world coordinates. The transformation is shown in Figure 3-10.

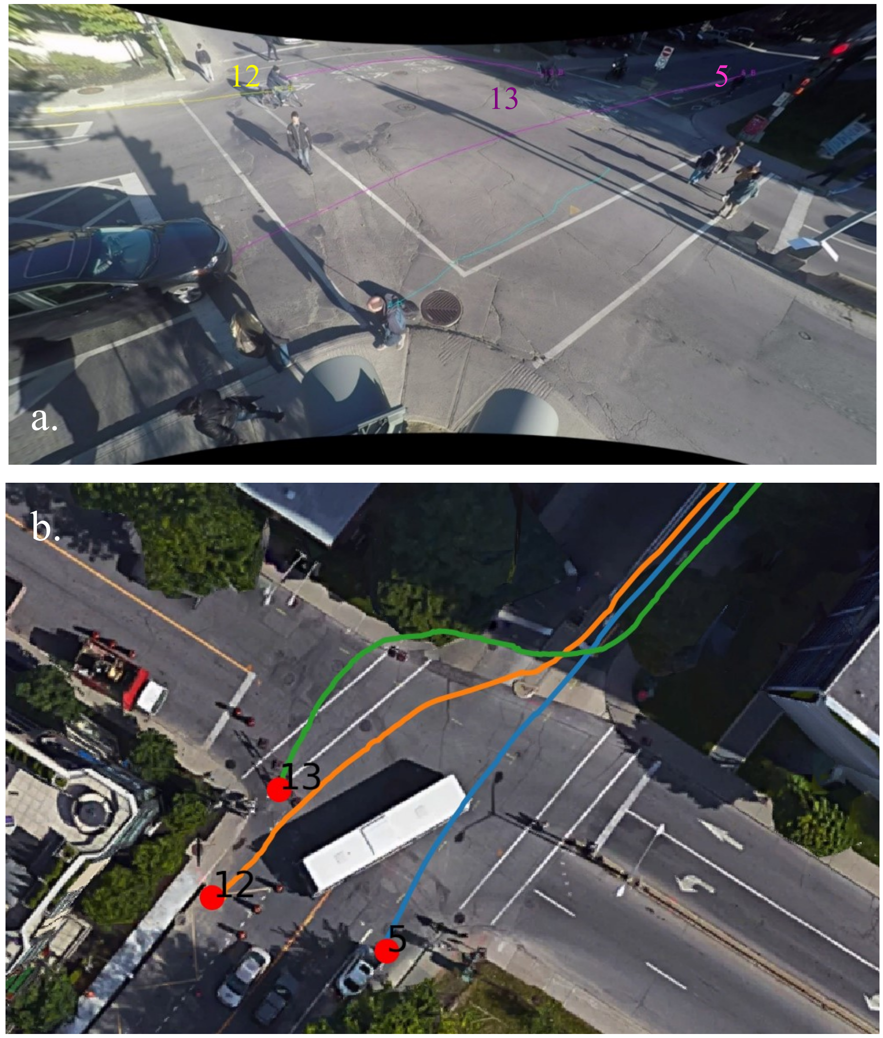

Figure 3-10 a. Three cyclist trajectories tracked overlaid over the video frame, and b. converted to world coordinates overlaid over the aerial view image

3.4.3.2 Road User Detection, Tracking and Classification

The Traffic Intelligence project includes a feature-based detection and tracking algorithm. Features are small patches of pixels with a strong gradient such as corners (e.g. pedestrian and cyclist heads or hands, vehicle license plates or side mirrors, bike pedals or wheels) (Figure 3-11 b.). Features associated with each object are then grouped together using proximity and common motion over as many frames as possible (Figure 3-11 b.)

Figure 3-11 a. Tracked features over a cyclist, and b. grouped cyclist features

Tracking and grouping features are done through the adjustment of several parameters such as the minimum feature quality, displacements to test minimum feature motion, minimum displacement to keep features, maximum feature acceleration, segmentation and connection distance. For each location, depending on the height and angle of the video camera, lighting conditions and other road user dynamics, the tracking parameters should be adjusted to improve tracking. Problems associated with tracking and grouping include over-segmentation (where one road user is tracked as two or more road users), over-grouping (where two or more road users are grouped together as one), windy and sunny conditions (where the camera shakes or road user shadows are tracked as objects).

After trajectory extraction, objects are classified into three classes: cars, pedestrian, and cyclists (Zangenehpour, Miranda-Moreno, & Saunier, 2015). Classification is based on training the classifier using a set of images for cars, pedestrian and cyclists. In addition to image training, speed distribution parameters are also used to classify the three categories of road users based on their average speeds at the study location. Misclassified road users can finally be corrected manually.

3.5 Behavioural and Safety analysis at discontinuities

Once all trajectories are extracted and classified, similar trajectories are clustered. This method identifies the common motion patterns of all road users. The custom clustering algorithm relies on a distance measure, the longest common subsequence (LCSS), where points are matched using the Manhattan distance and a threshold: the number of similar points between the two trajectories are computed and normalized by the minimum length of the two trajectories (Saunier, 2006). If a trajectory is not assigned to a motion pattern, a new motion pattern is created (details of the parameter selection for the Manhattan distance and similarity are presented in Appendix A). Figure 3-12 a. shows road user trajectories and the resulting clusters or motion patterns, each represented by an actual trajectory or prototype in Figure 3-12 b.

Figure 3-12 a. Cyclist trajectories, and b. cyclist motion patterns (origins marked in red circle)

Aside from distinguishing between distinct maneuvers at a location, motion patterns can be used to improve surrogate safety indicator calculations. Once motion patterns are learnt from the observed user trajectories, they can be used to predict the future positions of road users and compute more realistic and robust SMoS, especially compared to the most common method of motion prediction at constant speed and direction. This analysis method is incorporated in the Traffic Intelligence project and is used to extract TTC measures from interactions between cyclists and vehicles at the selected case study locations.

The motion patterns are used to summarize the movement of a group of similar trajectories as well as their speeds. The mean speed of each trajectory and their 15^{th} and 85^{th} percentile speeds as well as their standard deviations are summarized per motion pattern to represent the set of speeds associated to road users belonging to that motion pattern maneuver. The same can be done with safety information. The average and most severe SMoS are summarized per motion pattern. The safety and speed information summarized per motion pattern help in identifying risky maneuvers that road users undertake, improving the understanding of the factors associated with cyclist behavior and safety at the microscopic level.

CHAPTER 4 ARTICLE 1: EVALUATING AND COMPARING THE CYCLING NETWORK CONNECTIVITY OF FOUR CITIES USING DISCONTINUITY INDICATORS

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Submitted to the peer-reviewed journal of Transportation Research Part A: Policy and Pracrtice, Submission Date: 10 August 2018.

The preliminary application of this methodology (Appendix C) identifies and compares discontinuity levels of three Montréal boroughs, and was presented at the peer-reviewed conference: 95th Annual Meeting of the Transportation Research Board, Washington D.C., 2016.

Abstract

The evaluation of the performance of a cycling network relies on a set of indicators, with the goal of better planning future networks or improving existing ones. There are several evaluation methods, each with its set of indicators, none of which provides a complete picture of the cycling network performance. For example, most studies have relied only on the coverage as an indicator for network performance, while others focused on accessibility. The lack of a uniform evaluation system which includes all relevant performance indicators may result in biased rankings. Reviewing existing evaluation methods, it further appears that connectivity or discontinuity indicators have not been systematically identified and are missing from many evaluation methods. Discontinuities can be either intrinsic to the cycling facilities and the cycling network, such as changes in the type of facility or end of facilities, or related to changes in the cycling network environment, in particular the usually adjacent road network and motorized traffic.

This paper formalizes the concept of discontinuities in the cycling network and the various causes of discontinuities, proposes a set of indicators to measure cycling network connectivity and the methodology to calculate them, including automated methods for geospatial data with the code available under an open source licence. The automated method is applied to the comparison of the cycling network connectivity of four North American cities: Montreal and Vancouver in Canada, Portland, and Washington D.C. in the United States.

Keywords: cycling network, performance evaluation, discontinuity, connectivity, geospatial data

4.1 Introduction

Transportation researchers, planners, engineers and policy makers have proposed network performance indicators to help better plan and design cycling networks or improve existing ones. The performance of cycling networks may refer to various characteristics and therefore be evaluated through different methods and criteria. The most common measures are related to the coverage and density of the cycling network, for example in terms of the length of each type of cycling facility, and proportion of the road network with cycling facilities. However, a very long or dense cycling network may also not be well connected, for example if the cycling network is frequently interrupted or the characteristics change frequently. Few methods have evaluated how well-connected cycling networks are, and precisely characterized the various kinds of discontinuities that may affect cyclist comfort, safety and efficiency.

There are different types of discontinuities, which can be either intrinsic to the cycling facilities and the cycling network, or related to changes in the cycling network environment, in particular the usually adjacent road network and motorized traffic. The types of discontinuities, listed in Table 4-2, can be put in three categories related to the different causes, intrinsic, road network or other, and can be measured through different indicators.

Stated and revealed preference studies have indicated that cyclists are sensitive to the presence and types of cycling facility, traffic volume, and number of intersections (Dill & Gliebe, 2008; Menghini et al., 2010; Meghan Winters et al., 2011). Since these factors are shown to influence the cycling experience, then it is expected that cyclists will be sensitive to changes in these factors, such as an increase in traffic volume and changes from one cycling facility type to another. Discontinuities along the road network have been shown to have an effect on driver behaviour when transferring from one type of road class to another (Xie & Levinson, 2007). A small number of studies on cycling network discontinuities have demonstrated they have an effect on cyclist behaviour (Barsotti & Kilgore, 2001; Krizek & Roland, 2005; Nabavi-Niaki, Saunier, & Miranda-Moreno, 2018; Sener et al., 2009). Discontinuity indicators are independent from usual cycling network coverage and density measures and therefore complementary to evaluate a cycling network's performance. Overlooking discontinuity indicators is likely to result in a cycling network that will have lower ridership than it could have if continuous.

This paper formalizes the concept of discontinuities in the cycling network and the various causes of discontinuities, proposes a set of indicators to measure cycling network connectivity and the methodology to calculate them, including automated methods for geospatial data. The automated method is applied to the comparison of the cycling network connectivity of four cities. The contributions of this study include the systematic review of existing methods and indicators to characterize cycling facilities, the description and automation of the methodology to compute discontinuity indicators (making the code available under an open source licence (Nabavi Niaki et al., 2018)), and its application to the cycling networks of four different cities across North America using in particular density maps of the discontinuity indicators. The selected cities are Montréal and Vancouver in Canada, Portland, and Washington D.C. in the United States.

The next section provides a background and methodology with a description of the case study cities. The methodology section highlights the steps to identify discontinuity measures in each city. The findings are summarized in the discussion of results section.

4.2 Background

The evaluation of cycling network performance has received attention in recent years, with the development of a range of performance indicators that have an effect on cyclists as found from surveys and route choice studies (for example (Harkey, 1998; Jensen, 2007; Snizek, Sick Nielsen, & Skov-Petersen, 2013)).

A questionnaire-based study with 4700 respondents by Snizek identified factors that have an impact on cycling, where results showed that high traffic volume, the number of intersections along the route, and road class result in a negative cycling experience (Snizek et al., 2013). Other variables commonly used for cycling network performance measures are: traffic volume, traffic speed, traffic turning volume, presence of cycling facility, cycling facility width, cycling safety, road class type, number of road lanes, presence of parking, percentage of heavy vehicles, pavement surface condition, road grade, number of intersections, average block length, directness and comfortable access to certain destinations (Barsotti & Kilgore, 2001; Boisjoly & El-geneidy, 2016; Harkey, 1998; B. Landis et al., 1997; Lowry et al., 2016; Mekuria et al., 2012; J. Pucher & Buehler, 2006; San Francisco Department of Public Health, 2014; Sorton & Walsh., 1994; Transportation Research Board, 2016; Meghan Winters, Teschke, Brauer, & Fuller, 2016).

Frameworks for assessing cycling network suitability have been proposed as early as 1987 and have been evolving over the years. The following frameworks do not share the same indicators and use different rankings of the indicators: the Bicycle Compatibility Index (BCI) (Harkey, 1998), Bicycle Stress Level (BSL) (Sorton & Walsh., 1994), Level of Traffic Stress (LTS) (Mekuria et al., 2012), Bicycle Level of Service (BLOS) (Transportation Research Board, 2016), Bike Score (BS) (Meghan Winters et al., 2013), Bicycle Environmental Quality Index (BEQI) (San Francisco Department of Public Health, 2014), and Bicycle Safety Index Rating (BSIR) (W. J. Davis, 1987). Each framework uses a different combination of traffic and infrastructure attributes (roadway and network) shown in Table 4-1. One can see that the variables most used in the mentioned frameworks are traffic speed, number of road lanes, traffic volume, speed limit, road lane width, parking along road, pavement condition and cycling facility width.

More recently, the FHWA published the guidebook for measuring multimodal network connectivity where a number of the mentioned connectivity measures were used: proportion and length of cycling facility along roadway, proportion of road with cycling facility, proportion of roads with low level-of-stress (based on the LTS), intersection density, connected link ratio, block length, road network density, and accessibility to certain locations (measured by presence of low-stress cycling facility between origin and destination) (Dill et al., 2018). Some of the mentioned frameworks were compared and ranked based on the level of effort for obtaining and computing indicators. Their findings concluded that all of the studied frameworks have strengths and weaknesses, and in order to avoid a distorted picture, more sophisticated connectivity measures must be used, and planners must be on the lookout for emerging connectivity analysis methods and measures (Dill et al., 2018). Kang et al.'s use of the BCI (Harkey, 1998) in a statistical model to evaluate its effects on cyclist's preference revealed that a higher BCI value (better performance ranked by the BCI method), would not increase the likelihood of cycling along on-road cycling facilities (separate cycling facility or bike lane), but would increase the off-road facility use (Kang & Fricker, 2013). Parks et al. applied three performance frameworks on a before-after study of bicycle facility installations: the BEQI, the BLOS, and the Danish Road Directorate BLOS (Parks et al., 2013). They concluded that each method has shortcomings and the development of a nationally accepted bicycle evaluation tool requires more research and

Table 4-1 List of variables used in the main cycling network performance evaluation methods

	Variables	BLOS	BSIR	BEQI	LTS	BCI	BS	BSL
Traffic	Traffic speed	x		x	x	x		x
	Turning speed				x			
	Speed limit		x	x	x			
	Traffic volume	x	x			x		x
	Heavy vehicle volume	x				x		
	Right-turn volume					x		
	Parking (turnover and occupancy)		x		x	x		
Motorized Infra.	Number of road lanes	x	x	x	x			
	Road lane width		x		x	x		x
	Length of right turn lane				x			
	Parking along roadside	x	x	x		x		
	Parking lane width				x			
Cycling Infrastructure	Presence of cycling facility					x		
	Cycling facility type				x		x	
	Cycling facility length						x	
	Cycling facility width	x		x	x	x		
	Bicycle parking			x				
	Bike lane markings			x				
	Bike lane signs			x				
	Connectivity of bicycle lane			x				
	Dashed bike lane on intersection			x				
	Left turn bicycle lane			x				
	Marked area before bicycle traffic			x				
	Bike lane blockage				x			
General Infrastructure	Type of signalization		x					
	Right turn lane		x					
	Left turn lane		x					
	No turn on red signal		x	x				
	Presence of shoulder	x				x		
	Shoulder width		x			x		
	Paved shoulder		x					
	Pavement condition	x	x	x				
	Presence of curb	x						
	Curb radius		x		x			
	Intersection angle				x			
	Driveway		x	x				
	Restricted sight distance		x	x				
	Presence of street lighting			x				
	Traffic calming features			x				
	Raised median		x					
	Grade		x				x	
Other	Land use		x	x		x	x	
	Intersection density						x	
	Trees			x				

evaluation in order to address the different bicycle facility and cyclist characteristics (Parks et al., 2013). A similar conclusion was drawn from a study by Vale et al. where an extensive literature review on active transport accessibility methods demonstrated conceptual and computational limitations, as well as inconsistencies in accessibility, connectivity and network performance concepts and terms (Vale et al., 2016).

Discontinuity measures are often overlooked or measured by inappropriate "connectivity" indicators such as the length of cycling facilities, the density of cycling facilities, and the distance from shortest path. Such indicators measure coverage, density and the directness of trips through the network, not discontinuities, since the longest or densest cycling network may have low connectivity, e.g. if there are missing links or frequent changes in the type and other characteristics of cycling facilities, while a short cycling facility of the same type in a ring will have low coverage or density, and high connectivity. For example, Boisjoly and El-Geneidy made use of cyclist route data collected from online surveys to assess the cycling network "connectivity" using three (coverage) indicators: the detour or bicycle route diversion to the shortest path (calculated as the relative difference between the travelled route length and shortest path length), the presence of a bicycle facility along observed paths, and route directness as the ratio between the network and Euclidean distances (Boisjoly & El-geneidy, 2016). A study by Semler applied the LTS method (Mekuria et al., 2012) to categorize Washington D.C.'s connectivity of cycling routes between blocks of origin-destinations (Semler et al., 2018). A recent guidebook for developing pedestrian and bicycle performance measures defines a connectivity index based on cycling network density, connected node ratio (ratio of the number of intersections to the number of intersections and dead ends), link to node ratio (ratio of number of road links to the number of intersections and dead ends), and intersection density (Semler et al., 2016). These studies demonstrate the lack of consistency in the indicators used to measure the performance of a cycling network and the need to separately measure connectivity (through discontinuity indicators) and coverage/density.

In addition to cycling network performance evaluations, discontinuity indicators can be used in route choice studies to evaluate the effects of the interruptions on the cyclists' route choice. While some measures have been considered, e.g. related to the density of intersections (Schoner & Levinson, 2014) or the end of cycling facilities to score side path suitability (Barsotti & Kilgore, 2001), this literature review shows that no framework for the characterization of a cycling network connectivity through discontinuity indicators has been proposed. Given the lack of quantitative and objective discontinuity indicators, it is reasonable that little research has directly dealt with discontinuities in the cycling network and their impact on cyclists.

4.3 Methodology

4.3.1 Defining Discontinuity Indicators

Cyclists' preference for riding on a continuous path has been demonstrated in previous studies (Sener et al., 2009). The interruptions along a cyclist's route can be summarized into discontinuity measures or indicators. Examples of these discontinuities include changes in the cycling facility type and their ends, road class type, location of cycling facility on the road (e.g. the side), large changes in traffic speed and volume. Table 4-2 presents a comprehensive categorization of the types of discontinuities in a cycling network and examples of indicators in each category. Some kind of normalization is necessary to compare different areas of different size or with networks of different length and type, depending on the level of the study. The indicators in Table 4-2 are presented before normalization and they will generally be divided by a normalization factor:

- at the level of an area (for example a city or region), the normalization factor can be the length of the cycling network in the area or the area's surface;
- at the level of a cyclist route (for example for a route choice study), the normalization factor can be the route length.

For example, these different normalizations will yield for the ends of cycling facilities the following formulations for a given area and a given cyclist route:

$$DiscEnds_{area} = \frac{number\ of\ ends\ of\ cycling\ facilities\ in\ area}{cycling\ network\ length\ in\ area}$$

$$DiscEnds_{route} = \frac{number\ of\ ends\ of\ cycling\ facilities\ along\ route}{route\ length}$$

Furthermore, there can be variations of the indicators in each category, depending on the way to count or weigh the changes. For example, one could choose to count differently the changes from one type of cycling facility to another, since going from a separated cycle path to a cycle lane is not the same as going to a designated roadway where cyclists do not have dedicated space.

Table 4-2 Types of discontinuities and examples of indicators (before normalization)
(* indicates that a threshold must be defined to characterize the considered changes)

Category	Types of discontinuities	Indicators (before normalization)
Intrinsic to Cycling Network	End of cycling facility	Number of cycling facility ends
	Change in cycling facility type	Number of changes of the type of cycling facility
	Change in cycling facility width	Number of locations where cycling facility width changes*
	Change in cycling facility location on road	number of changes of the cycling facility side on road
	Change in pavement condition	Locations where pavement conditions change from good quality to bad
	Change in road lighting	Number of locations where illuminance changes*
	Change in road grade	Number of locations where there is a change in road grade*
	Closure/rerouting of cycling facility due to construction or maintenance	Number of areas where the cycling facility is closed or rerouted
Traffic and Road Network	Change in road class	Number of locations where road class changes
	Change in number of road lanes	Number of locations where there is a change in number of road lanes*
	Change in traffic volume	Number of locations where traffic volume changes*
	Change in traffic speed	Number of locations where traffic speed changes*
	Intersections	Number of intersections along cycling facility or cyclist's path
Other	Driveways	Number of driveways along cycling facility or cyclist's route
	Bus stops	Number of bus stops along cycling facility or cyclist's path
	Parking allowed on road	Length of road where parking is allowed and cars can cross the cycling facility to enter parking space

Many indicators related to the number of changes of continuous characteristics in the cycling facility or adjacent road traffic require a threshold as indicated in Table 4-2, but other formulations based on these variables are possible, such as the sum of the absolute changes. For the changes in traffic volume, an indicator could be:

$$\frac{\sum_{discontinuity\ location\ in\ area} |q_{after\ discontinuity} - q_{before\ discontinuity}|}{cycling\ network\ length\ in\ area}$$

If one wishes to compare all the discontinuities at the level of an area, the indicators could be summed, although care should be taken for the homogeneity of the result. This work will focus on the comparison of different areas such as cities. The methodology to obtain discontinuity indicators from an area's cycling network is described in the following sections.

4.3.2 Data preparation

The first step in quantifying the cycling network discontinuity in an area is obtaining georeferenced road and cycling network datasets, usually available from open data repositories. If the study area's cycling network dataset includes information on the cycling facility type, then the methodology can be applied to identify the ends and changes in cycling facility type discontinuities. If other information is also available such as the side of street the cycling facility is located on and the cycling facility lane width, or the area's road network with road type and speed limit information, traffic volume and bus stop locations, other discontinuity indicators can be extracted as well.

To unify the definition of cycling facility types, four cycling facility types are proposed: physically separated bike facility (interactions with other road users can occur only at intersections and bus stops where boarding and alighting pedestrians cross the separated facility), painted bike lanes (interaction with other road users occur at intersections, when vehicles cross the facility to access driveway or parking space, and when buses cross the facility at their stops), shared road with designated marking (cyclists have no dedicated space on the road and interaction with other road users can occur everywhere), and off-road cycling facility where there is no shared space and interaction with vehicles. In this study shared roads with designated marking are not considered a cycling facility type since cyclists must share the road with other users as in any other road.

4.3.3 Identifying Discontinuities

4.3.3.1 Manual Method to Identify Discontinuities

After preparing the datasets, the spatial analysis steps to identify the discontinuities and compute the indicators along the cycling network using a geographic analysis tool (e.g. ArcGIS) are presented in Figure 4-1. The buffer sizes used may have to be adjusted on a case by case basis. The first step addresses cases where the cycling facility representation is not joined at intersections or cycling facilities are given a different class category at intersections.

Merge facility types as one line
• Draw a 5-m buffer around each road intersection, identify intersections with two dangling cycling facility ends in a buffer, assign the intersection ID to the two ends and join ends with the same ID • Merge continuous cycling facilities into a single facility line and merge road information to the cycling facility layer using a spatial join
Change in cycling facility type
• Draw a 5-m buffer around the endpoints of the unique cycling facilities • If another facility end, or facility type is present in the 5-m buffer, this end point is considered a change in facility type
End of cycling facility
• Draw a 2-m buffer at the end of each cycling facility • If there are no other end points, or cycling facilities in the buffer, this is considered an end
Change in cycling facility location on road*
• Each end is assigned an intersection or road ID • If there is a change in location on road at an intersection or road link, it is considered a discontinuity
Change in cycling facility width*
• Each cycling facility segment is assigned an intersection or road ID • If a segment changes width on the same road or intersection, it is considered a discontinuity
Change in road class, traffic volume, and traffic speed*
• If there is a change in road class, change in traffic volume, and change in traffic speed along the cycling facility, this is considered a discontinuity
Number of intersections along cycling facility*
• Draw a 40-m buffer around the road centerline to perform a spatial join with the cycling network, so that the information of each bike facility segment merges with the road network information • Count the number of intersections that are located along a cycling facility through a spatial join between the buffer and the road intersections

Figure 4-1 Discontinuity identification methodology using a geographic analysis tool

(* indicates steps that can be performed only if the required information is available)

4.3.3.2 Automated Computation of Indicators

The method is automated to accelerate and simplify the computation of discontinuity indicators and made available under an open source license to allow other researchers and users to replicate and reuse this method on other datasets (Nabavi Niaki et al., 2018) (https://github.com/nsaunier/cycling-discontinuities/). This automation is done through *spatialite*, an open source spatially enabled extension of SQLite, a relational database management system. The methodology scripts include the following treatments: 1) merging the cycling facility as one line for each facility type (separate, bike lane, and off-road), 2) dissolving the merged geometries to identify the discontinuities, 3) creating the ends of cycling facilities (points and buffers), and 4) performing a spatial intersection between the ends of cycling facilities of different types. Only the ends of cycling facilities and the changes of facility types are automated in the provided scripts.

First, batch scripts are made to import the georeferenced data. The SQL scripts to be executed in spatialite need to be written with slight modifications for different cities based on the city's system projection value from their spatial reference system identifier (SRID), with examples provided for each city. At the end of the script, the output files are exported that include point locations of facility ends and change in facility types. To quantify the discontinuities, the number of each discontinuity type is divided by the total length of the area's cycling network to compare results between different areas.

4.3.4 Results Analysis and Visualization

The output of the method is the georeferenced data of discontinuity locations which can be plotted for visualization. The raw map of discontinuity locations on the cycling facility and road maps provides an image of target locations for improvement. For comparison purposes, a density map of the discontinuities is more suitable. In this study, a kernel density with a radius of 1500 m was applied, and a mask showing a buffer around the cycling facility is used to highlight the density only where there is a cycling facility.

4.4 Case Study in Four Areas

To evaluate discontinuity levels using our proposed methodology, cities with publicly available spatial datasets including information on bicycle infrastructure such as facility type (separate bike path, bike lanes, shared road etc.) were selected: Montréal, and Vancouver, in Canada, as well as Portland and Washington D.C. in the United States (City of Montréal, 2015; City of Portland, 2015; City of Vancouver, 2015; District of Columbia Government, 2015). In this study, since not all information was available from the city's georeferenced network data, only the following two discontinuities were extracted: ends of cycling facility, and change of cycling facility type.

These cities were previously subject to a bikeability or cycling network performance evaluation. For example, the Copenhagenize Index (CI) evaluated cycling network performance in major worldwide cities and ranked the top 20 most bicycle friendly cities in the world based on a set of thirteen categories, ranking Montréal as the 20th most bicycle friendly city (Copenhagenize Design Co., 2015). A cycling network performance evaluation of Canada's five largest cities reported that Vancouver has the highest number of cycling trips as well as the highest cycling mode share to work (6.1 %) followed by Montréal (3.9 %) (Statistics Canada, 2016). Although no U.S. cities show up on any major rankings of the world's most cycling friendly list, Washington D.C. and Portland are ranked among the top cycling friendly cities in the U.S., where 6.5 % and 4.3 % of commuters cycle to work in Portland and Washington D.C. respectively (The League of American Bicyclists, 2015; U.S. Census Bureau, 2016). These rankings are neither comparable nor complete as they use different evaluation indicators and methods.

4.4.1 Dataset Standardization

The obtained datasets are prepared uniformly for comparability and consistency in data analysis. Each city has different class definitions for their road and cycling facilities. For example, Vancouver has the following cycling facility classes: separated lanes, painted lanes and shared lanes, while Portland classified their cycling facility as: bike boulevard, bike buffer, bike lane, bike shared, bike track, shoulder wide, and paths. Hence, the facility classes for the four cities are grouped into four categories using Google Street View: physically separated bike facility, painted bike lanes, shared road with designated marking for bikes, and off-road cycling facilities. For our study, shared roadways with road marking for bikes are not considered as a cycling facility type.

4.4.2 City Descriptions

The following sections provide a more detailed description of each city as well as their road and cycling network characteristics as summarized in Table 4-3. The cycling network coverage is defined as the ratio of the cycling facility length to the road length.

Table 4-3 Description of the road and cycling network of the selected cities

Road and Bicycle Network Characteristics						
	Measure type		**Montréal**	**Vancouver**	**Portland**	**Washington D.C.**
City Density	**Surface** *(km^2)*		432	115	376	177
	Population density in 2016 *(residents per km^2)*		3946	5491	1701	3848
	Road density *(km per km^2)*		**13.6**	7.1	11.3	10.6
	Cycling network density *(km per km^2)*		1.2	0.9	**1.5**	0.7
Road and Bicycle Network Summary	**Road network length** *(km)*		5861	815	4254	1875
	Bicycle facility network length *(km)*		503	103	567	118
	Cycling network coverage		8.5 %	12.6 %	**13.3 %**	6.3 %
	Proportion of each type of bike facility in the cycling network	Separated bike path	**64.0 %**	54.0 %	0.7 %	8.0 %
		Bike lane	20.0 %	46.0 %	44.2 %	**92.0 %**
		Off-road bike path	16.0 %	0.0 %	**55.1 %**	0.0 %

4.4.3 Montréal

The island of Montréal in Quebec, Canada has a population of 1.7 million (Statistics Canada, 2016) and an area of 432 km^2. It is the most populated and has the largest area compared to the other cities. Montréal also has the highest road network density as shown in Figure 4-2.a. Montréal is considered to be one of the best cycling cities in the world (Vijayakumar & Burda, 2015). In 2014 Montréal had a total length of 503 km of cycling facility (City of Montréal, 2015), 64 % of which is separated bike paths, 20 % painted bike lanes and 16 % off-road class. Montréal has a cycling network coverage of 8.5 % over its road network length. Compared to the other three cities, Montréal has the highest share of separate cycling facility. Yet, gaps in the cycling facilities and points where cycling facility types change are observed throughout the city.

4.4.4 Vancouver

Vancouver, with a population of roughly 632,000 (Statistics Canada, 2016), has the highest population density among the four cities, which is related to its smallest surface of 115 km^2. The city has the lowest road network density with only 7.1 km road length per square kilometer of the city's surface (Figure 4-2.b). However, it has the second highest cycling network coverage among the cities of 12.6 %. Vancouver's 103 km of cycling facilities in 2015 is 54 % separated cycle tracks and 46 % painted bike lanes, and no reported off-road cycling facilities (City of Vancouver, 2015). Despite the lower population compared to Toronto and Montréal, Vancouver has the highest number of daily cycling trips, which may be associated to its high safety levels, with less than one crash involving a cyclist for every 100,000 cycling trips (Vijayakumar & Burda, 2015).

4.4.5 Portland

Portland has a population of about 640,000 (United States Census Bureau, 2016) and has the lowest population density among the four cities. The city has the second highest surface area of 376 km^2, and second highest road density which can be observed in the compact layout of the road network in Figure 4-2.c. The city's cycling network coverage is the highest, being 13.3 % of its road network length in 2015 (City of Portland, 2015). Portland also has the longest cycling network of 567 km, although separated cycle tracks are only 0.7 % of the total cycling network length. This is in part compensated by the share of off-road bike paths making up 55.1 % of the cycling network, which is the highest among the four cities.

4.4.6 Washington D.C.

Washington's population of roughly 681,000 (United States Census Bureau, 2016) ranks in our selection as the third city for its population density, road network density, road network length and cycling network length. It has the lowest cycling network coverage. As apparent in Figure 4-2.d, the cycling network is composed almost exclusively of painted lanes (92 %) in 2015, with only 8 % as separate cycle tracks (District of Columbia Government, 2015).

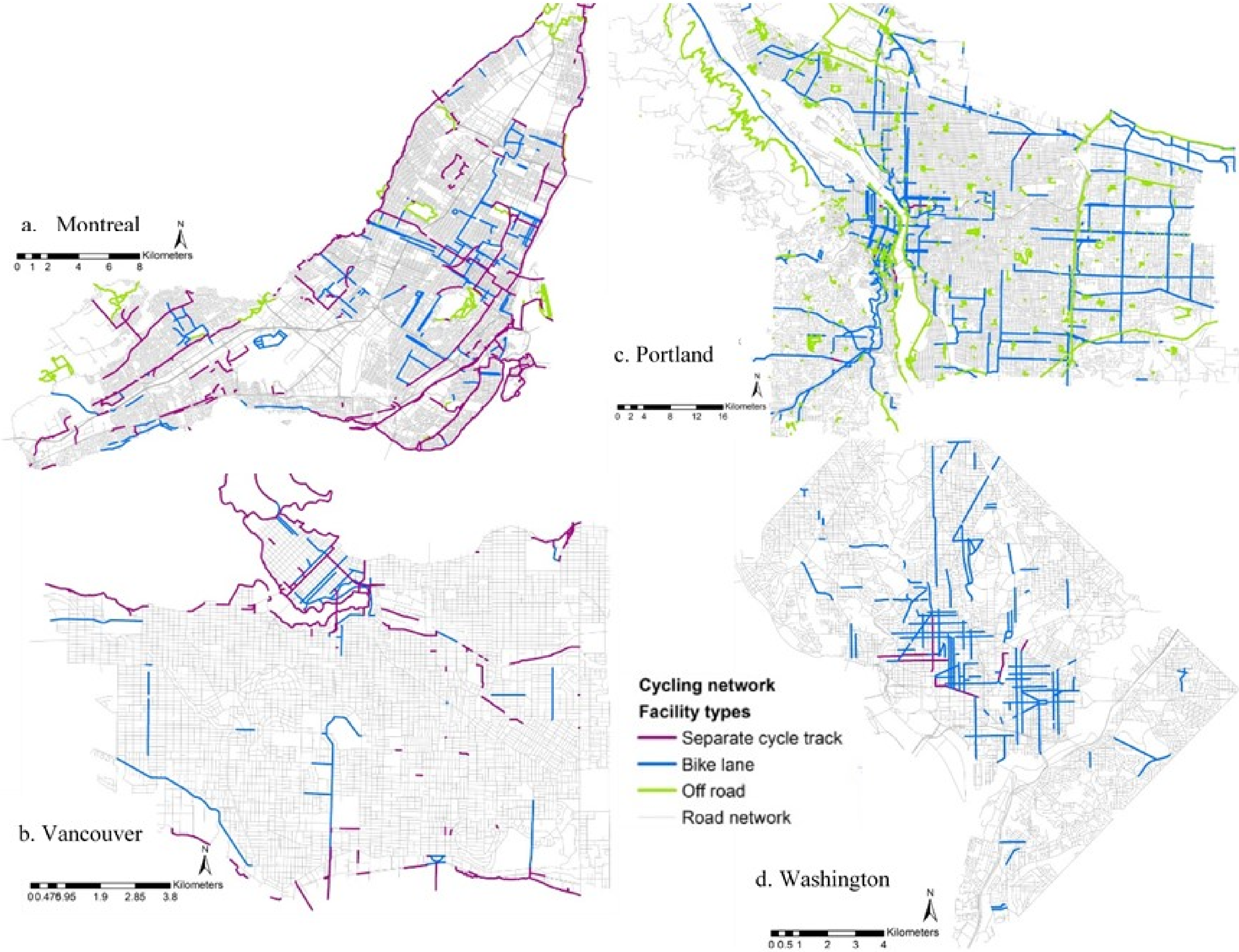


Figure 4-2 Road and cycling networks

4.4.7 Cycling Facility Type Distributions

Figure 4-3 shows the summary of the distribution of each cycling facility type in each city. Two of the cities, Vancouver and Washington, have no available record of off-road cycling facilities. Portland has almost no separate cycling facility, only 4 km of the total 567 km of cycling network. Washington also has a low separate cycling facility class share of only 9 km out of 118 km of cycling facility, 109 km of which is dedicated to painted lanes. Montréal has a fair distribution among the different facility types.

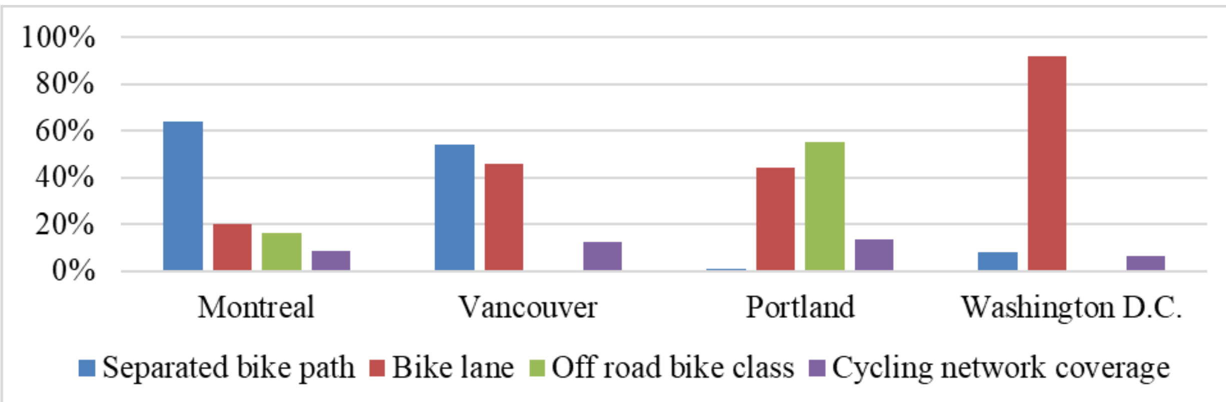


Figure 4-3 Cycling facility class distribution and cycling network coverage for each city

4.5 Results and Discussion

Table 4-4 presents the normalized discontinuity measures for the cycling facility ends for each type and the change in cycling facility for each city as well as the city's total discontinuity. Figure 4-4 shows the density of the cycling facility ends, and Figure 4-5 shows the density of changes in cycling facility type in the four cities.

Table 4-4 Discontinuity indicators of the four cities

Bicycle Network Discontinuity Indicators for Four Cities						
	Measure type	**Bicycle Facility Class**	**Montréal**	**Vancouver**	**Portland**	**Washington D.C.**
Discontinuity Measures	**End of bike facility** *(per km cycle length)*	Separated bike path	0.48	**1.07**	0.01	0.04
		Bike lane	0.28	0.50	0.57	**1.51**
		Off-road bike class	0.09	-	**1.97**	-
		All end points	0.85	1.57	**2.55**	1.55
	Change in bike facility type *(per km cycle length)*		0.35	0.40	**0.47**	0.19
Total discontinuity *(per km cycle length)*			1.20	1.97	**3.02**	1.74

Figure 4-4 End of cycling facility density

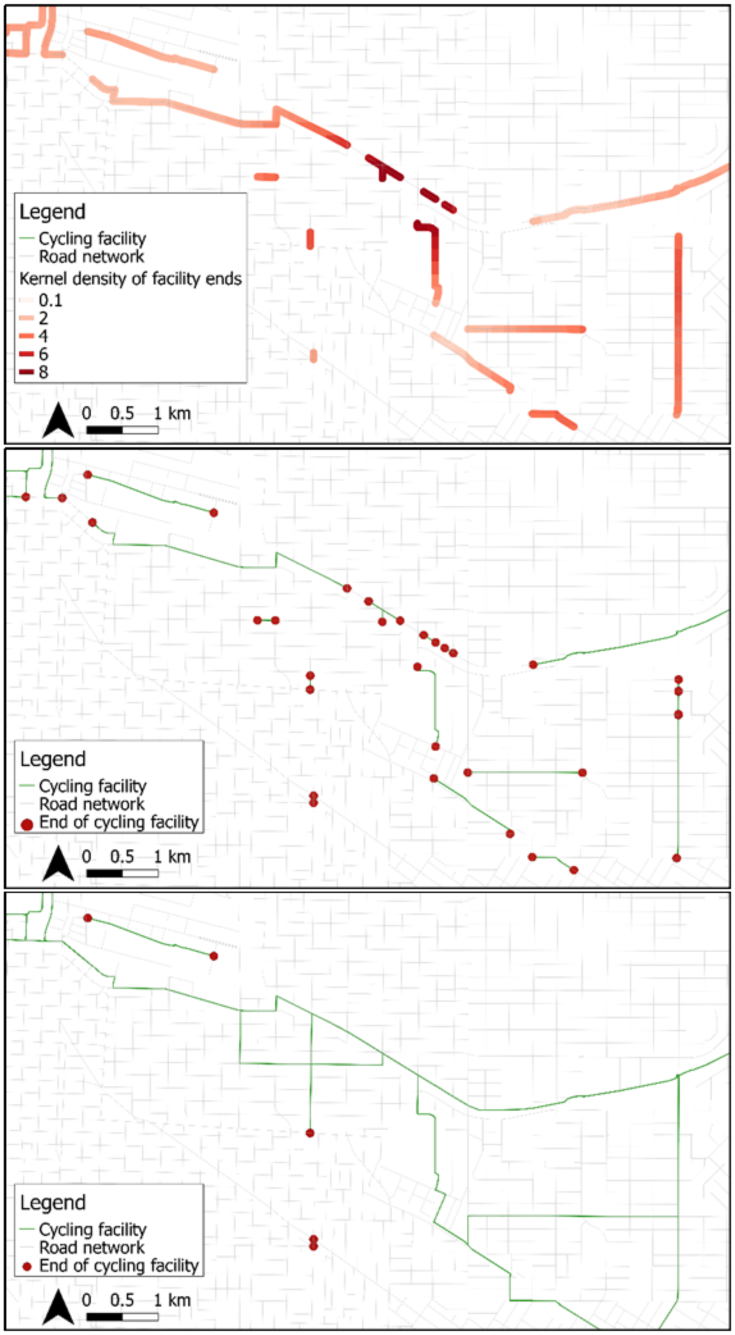
Figure 4-5 Change in cycling facility type density

Based on results of the discontinuity indicators presented in Table 4-4, Portland ranks as the city with the most discontinuities of both types per kilometer of cycling network, which can also be observed in Figure 4-4.c and Figure 4-5.c, while Montréal has the least discontinuities. Focusing on ends of cycling facilities for each cycling facility type, Vancouver has the most separate cycling facility ends, which means there are separate cycling facilities scattered throughout the city that are not connected to each other or other facilities. Washington has the highest value for bike lane ends which is expected since almost the entire cycling network is made up of painted bike lanes (92.0 %). Among the two cities that have off-road cycling facilities, Portland has the highest off-road ends discontinuity level. In general, Montréal has the least discontinuities. The change in cycling facility type discontinuity indicators are close except for Washington which is considerably lower, again because most of its cycling network is of the same type.

Discontinuities in Montréal are distributed throughout the city as shown in Figure 4-4.a and Figure 4-5.a, while Portland's discontinuities are mostly concentrated in the downtown area (Figure 4-4.c and Figure 4-5.c). Vancouver, shown in Figure 4-4.b and Figure 4-5.b, has several hotspots for discontinuity locations throughout the city with the highest concentration in the downtown area. The distribution of discontinuities in Washington is concentrated in an area in and around its downtown covering a large portion of the city (Figure 4-4.d and Figure 4-5.d).

Summarizing the results allows ranking the four cities from the worst (most discontinuities) to the best (least discontinuities): Portland, Vancouver, Washington and Montréal. Discontinuities appear throughout the four studied cities highlighting the importance of further evaluating the effects of these interruptions in the cycling network on cyclist behaviour and safety.

A study found that connecting the gaps in the Boston cycling network, which would result in a facility length increase by a factor of 2.5, the fraction of home-work pairs that will be connected by the network increases by a factor of 13 (Furth & Noursalehi, 2015). Figure 4-4 and Figure 4-5 highlight hotspot locations for improvements in the four cities. For example, the links in the darkest red in Figure 4-4 highlight areas where several cycling facility ends near each other could be connected with the implementation of only a few meters of cycling facility. An example is shown in Figure 4-6 where an area of Vancouver with a high concentration of cycling facility ends is chosen, and the ends are connected in ArcGIS by adding 6.5 km of cycling facilities. This improvement results in better connectivity where the discontinuity indicator for the facility ends decreased from 2.7 to 0.3.



a. Identify locations with a high concentration of facility ends based on the kernel density

b. Identify road links for implementing connections between cycling facility ends

c. Extending the cycling facility to connect ends results in a more connected network

Figure 4-6 Improving the connectivity of the cycling network by connecting the cycling facility ends

4.6 Conclusion

In the literature, the current methods for evaluating cycling network performance are incomplete and sometimes inconsistent. The performance of a cycling network is typically measured by its length and coverage. However, the cycling network's connectedness, or lack thereof, and its points of discontinuity are essential factors in evaluating the network's performance. Given their direct effect on cyclist behaviour, discontinuities must be identified and eliminated to improve cycling facilities and to promote cycling. As most cycling network performance studies and criteria do not include discontinuities, this work proposes a conceptual framework for discontinuities and a methodology to identify discontinuity locations and calculate discontinuity indicators. This is demonstrated in a case study on four cities and can be replicated in any city with some basic data available. For easy extraction of the discontinuity indicators, an automated methodology is made available in an open source repository (Nabavi Niaki et al., 2018). The application of this methodology also helps cities identify locations that can be improved by simple connections of the cycling facility where there are several facility ends concentrated in an area.

A key strength of this method is the minimal data requirements since many areas already have the required road and cycling network geospatial data which includes: the cycling facility type, location on the road, road class, and other network geometric information (number of lanes, lane width, etc.). The results show a high density of discontinuities in the cycling networks of the four compared cities. The cycling network ranking indicates Portland has the most discontinuities, followed by Vancouver, Washington and finally Montréal with the least discontinuities.

Limitations of our study include the limited number of discontinuity indicators that were extracted automatically due to the limited information available from the available cycling network data. Future work includes the evaluation of microscopic road user behaviour and safety at discontinuities, building upon initial work showing that cyclists behave differently at discontinuity locations compared to control sites through automated movement and speed analysis from video data (Nabavi-Niaki et al., 2018). Cyclist GPS data can be used to study the effects of discontinuities on cyclist's observed route choice. Mode choice studies can use discontinuities as a variable that may affect an individual's choice to cycle.

Acknowledgments

The authors acknowledge the funding provided by the Fonds de Recherche du Québec – Nature et Technologies (FRQNT), grant 2015-NC-180344, and the National Science and Research Council (NSERC), grant 2017-06115.

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LINK BETWEEN CHAPTER FOUR AND FIVE

In the previous chapter, cycling network discontinuities are proposed and a methodology to identify the infrastructural discontinuity indicators is proposed. The defined and proposed discontinuity indicators bridge the gap in the literature where cycling network connectivity measures used to evaluate network performance have not systematically considered all sources of discontinuities. The automated methodology is applied to four cities: Montréal and Vancouver in Canada, Portland and Washington D.C. in the U.S. The methodology evaluated cycling network connectivity at a macroscopic level, identifying locations in the cycling network where discontinuities exists. This approach is useful to municipalities and planners to identify locations where improvements can be made in the existing cycling network, as well as in the planning stage of a cycling network, to avoid discontinuities in the network and make better informed decisions on the development.

In the following chapter, a methodology to collect road lighting measures to identify locations with discontinuous and sub-standard lighting is proposed and applied to a case study for analysis of nighttime cyclists and pedestrian safety. The study relies on the collection of road illuminance data on road links during nighttime in downtown Montréal using an illuminance sensor mounted on a bike and calculating the average and uniformity of link-level illuminance.

CHAPTER 5 ARTICLE 2: ROAD LIGHTING EFFECTS ON BICYCLE AND PEDESTRIAN ACCIDENT FREQUENCY: CASE STUDY IN MONTRÉAL

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Published in the peer-reviewed journal of Transportation Research Record: Journal of the Transportation Research Board, 2016, 2555, 86–94. https://doi.org/10.3141/2555-12

Presented at the 95th Annual Meeting of the Transportation Research Board (peer reviewed conference), Washington D.C., 2016.

The initial attempt at this methodology resulted in a journal paper presented in Appendix B, where the road lighting audit is at an intersection level and safety analysis is only based on vehicle-vehicle and vehicle-pedestrian accidents. The folowing article is the improved methodology that collects illuminance data at road link and intersection levels for vulnerable road user accident analysis.

Abstract

Although vehicle, bicycle and pedestrian flows are generally considerably lower during nighttime, this time accounts for a higher number of accidents than expected given lower exposure compared to daytime. A highly influential factor is the lack of clear visibility at nighttime. Several studies have showed the negative effects of the lack of clear visibility on bicycle and pedestrian accident frequency and injury severity at nighttime. Studies that have evaluated this issue have considered only the presence of light. The presence of light is not sufficient to evaluate road users' safety: different amounts of lighting can have different effects on a driver's vision such as discomfort glare, and disability glare, or the available light may not provide adequate contrast for object detection.

Only a limited number of past studies in this field actually measured the amount of nighttime illuminance. Our study relies on the collection of road illuminance data on road links during nighttime in downtown Montréal using an illuminance sensor mounted on an electric scooter.

The pedestrian and bicycle accident frequency were analysed separately using the negative binomial model. Results from this study show unexpectedly that an increase in road lighting is associated with more bicycle and pedestrian accidents, which may be explained by the decision to add or increase the amount of lighting where accidents occur. The presence of a bike facility and arterial roads were associated with a decrease in bicycle accident occurrence. For pedestrians, the number of lanes per link and the pedestrian flow were associated with an increase in nighttime accident frequency, while the vehicle flow is associated with a decreasing number of accidents. The study calls for more investigation of the precise relationship between safety and the amount of light provided by road lighting.

Keywords: Road lighting, illuminance, cyclist and pedestrian safety, accident frequency, nighttime safety

5.1 Introduction

Cycling is widely considered to be the riskiest mode of transportation (Noland, 1995). Pedestrians and cyclists are vulnerable road users since their collision with vehicles are more likely to result in serious injuries or even death. The Canadian Council of Motor Transport Administrators (CCMTA) stated in its Road Safety Vision report that in one year, pedestrian fatalities and serious injuries covered 54.7 % and 47.2 % of all fatal and serious injury accidents respectively (Canadian Council of Motor Transport Administrators, 2010). In the U.S., pedestrian and cyclist fatalities accounted respectively for 13 % and 2.1 % of the total number of fatalities in 2011 (NHTSA & National Household Traffic Survey of America, 2013). Cyclists are considered to be among the most vulnerable road users according to the reports where they account for the largest proportion of near-misses (Daley, Rissel, & Lloyd, 2007), with a much higher probability of an accident resulting in injury compared to drivers of motor vehicles (Watson & Cameron, 2006).

The intensity and importance of vulnerable road user accidents is even more alarming at nighttime where road users experience a lower vision capacity. Cycling at night has been reported to be two to five times more likely to result in an accident compared to cycling during the day (Twisk & Reurings, 2013). A German study showed that even though only 10 % of bicycle trips were during nighttime, about 20 % of bicycle accidents happened at this time (Walter, Cavegn, Allenbach, & Scaramuzza, 2005). Similarly, The Ontario Pedestrian Death Review reported that 60 % of pedestrians were killed at night or during dim light conditions when they were not seen by drivers, which is quite high given the lower pedestrian and vehicle volumes at nighttime (Lauwers, 2010). Therefore, a safe accommodation of vulnerable road users has become a priority, especially at nighttime.

Road lighting is generally assumed to be an effective counter measure for nighttime collisions. Nighttime illuminance levels are directly related to visibility. Several studies have indicated that a driver's ability to react quickly and safely in a risky situation is impeded in a lower lit condition (Elvik, 1995). As reasoned by Kim et al., reduced visibility at nighttime increases the perception time of both bicyclist and driver and affects their evasive action (Kim et al., 2007). This is likely to result in impact at higher speeds and thus more severe outcomes (Yan et al., 2011). Räsänen and Summala claim that only 11 % of car drivers who hit a cyclist on a crossroad had actually seen the cyclist (M. Räsänen & Summala, 1998). This number must be even lower during nighttime since cyclist and pedestrian detection is more difficult due to the lack of clear visibility. Cyclists and pedestrians often assume that drivers can see them clearly at night, based on their own ability to see the oncoming vehicles' headlamps (Federal Highway Administration, 2002). However, drivers often do not see cyclists and pedestrians at night until they are within the stopping sight distance (Federal Highway Administration, 2002).

Lighting aims to increase the visibility of drivers, pedestrians and cyclists at nighttime, thereby providing pedestrians and cyclists with a safer environment, i.e. decreasing the number and the severity of collisions, by making them more visible to vehicles. A study conducted by the Royal Society for the Prevention of Accidents in the UK concluded that the number of pedestrian accidents and their severity were reduced with the presence of road lighting (RoSPA, 2009). However, despite the installation of road lighting on roadways, the numbers of accidents are still much higher during nighttime. A more thorough investigation of this problem is therefore needed.

In order to improve visibility at nighttime, road lighting standards specify an average road illuminance level. The Illuminating Engineering Society (IES) road lighting handbook provides specification standards for road lighting for intersections based on intersecting road classes and nighttime pedestrian activity levels. These standards do not take into account bicycle activity and there is little research on the need for lighting standards to do so.

The increase in the number and severity of accidents involving vulnerable road users at night compared to day time despite lower pedestrian and cyclist activity has prompted researchers to investigate the reasons for this phenomenon. While earlier studies all confirmed the positive effect of the presence of road lighting on road safety, nighttime safety is still an issue compared to daytime, which raises the question of the appropriate amount of lighting required to provide adequate visibility for all road users and specifically for cyclists and pedestrians.

This paper focuses on vulnerable road user accident frequency at nighttime on road links using the actual road lighting levels collected by an illuminance sensor. It aims to evaluate the effects of different lighting levels and lighting uniformity, of the flows of vehicles, bicycles and pedestrians as well as built environment variables such as road class, number of lanes, presence of traffic light, etc., on the frequency of accidents involving pedestrians and bicycles.

The remainder of the papers is arranged as follows: the second section provides background and study motivation, and the third section presents the methodology, data collection, and analysis procedure. Empirical results are offered in the fourth section, and the fifth section concludes the paper.

5.2 Earlier Studies

Earlier studies examined the factors that affect safety of non-motorized road users. For instance, Clifton et al. explored the impact of the road environment on the severity of pedestrian-cyclist accidents (Clifton et al., 2009). A study conducted by Dai et al. also investigated the effects of built environment on pedestrian crashes (Dai, Taquechel, Steward, & Strasser, 2010). Only a few studies have looked into the factors affecting nighttime cyclist and pedestrian safety. Adverse visibility has been identified to be a major cause of these accidents at nighttime (Green, Agent, Barrett, & Pigman, 2003).

Due to the importance of nighttime road safety and the high number of nighttime accidents despite lower traffic volumes compared to day time, several researchers have conducted studies investigating the causes of this situation (Armas & Laugis, 2007; Jackett & Frith, 2013). Road lighting is a counter measure for the lack of clear visibility, and it is believed to help road users obtain enough visual information to move more safely at nighttime (Hallmark, Hawkins, & Smadi, 2008). Many past studies confirmed the negative effects of the lack of clear visibility on bicycle and pedestrian accident frequency and injury severity. Most of these studies focused on nighttime vehicle accidents, while some focused on pedestrian and cyclist nighttime safety. Most past studies which looked at the relationship between road lighting and traffic accidents relied only on the information of presence or absence of road lighting (M. Rea, Bullough, & Zhou, 2010).

There have been several studies on before-after light installation, several studies comparing roads with and without lighting, and only recently some studies have focused on the actual illuminance levels of roads. Most before-after studies in this field have provided evidence that after installing road lighting in an area where previously no road lighting existed, the safety of the area increased substantially. A Norwegian study covering 125 main road sections showed that the number of accidents with injuries and fatal accidents decreased respectively by 34 % and 53 % after installing lighting (Wanvik, 2009d). Investigating the Minnesota and North Carolina accident rate change after installing road lighting showed a 4 % decrease in the number of crashes (Harwood et al., 2007). Other studies also concluded that at nighttime, comparing lit areas with unlit areas, better lighting conditions were shown to reduce the injury severity of crashes (Kim et al., 2007; Rodgers, 1995; Yan et al., 2011). Studies concluded that accidents occurring at areas with no street lighting were more likely to be fatal (Bíl, Bílová, & Müller, 2010; Kim et al., 2007; Klop & Khattak, 1999).

The presence or absence of light is a good indicator but it is not sufficient to ensure road users' safety. This is because different amounts of lighting can have different effects on drivers such as discomfort glare, and disability glare, or it may not provide adequate contrast for object detection (M. S. Nabavi-Niaki et al., 2014). When comparing no lighting with low lighting, it could be argued that poor lighting is as effective as, or even worse than, no lighting at all (J. Bullough, Rea, et al., 2009). Road lighting specifications are used around the world to provide the minimum amount of lighting for clear visibility and safety for nighttime transportation activities. Few studies have measured actual lighting levels and its association to road safety. While it seems clear that adding road lighting reduces the nighttime accident rate, less is known about variations in illuminance levels (Wanvik, 2009b). Recently, studies are starting to demonstrate the importance of actual illuminance levels and lighting uniformity.

Only a few studies conducted field measurements of lighting conditions on the road (Armas & Laugis, 2007; Bryan, 2008; Goodman et al., 2007; M. S. Nabavi-Niaki et al., 2014; M. Rea et al., 2010; Zhou, Pirinccioglu, & Hsu, 2009). Among different measures, the easiest and most common way is to measure actual road illuminance (Goodman et al., 2007; M. Rea et al., 2010). Zhou & Hsu collected illuminance data along a corridor in Florida, and found that nighttime pedestrian crash frequency at highly lit segments is much lower than those with a low lighting level (Zhou & Hsu, 2009). Apart from illuminance, other performance measures of lighting also have a potential impact on road safety. In a project conducted in Oakland, California, Bryan used different measures of lighting performance of LED street luminaires and high pressure sodium luminaires including the illuminance, uniformity (average illuminance/minimum illuminance), and correlated color temperature (Bryan, 2008).

5.3 Methodology

In order to evaluate the effect of road lighting on the number of bicycle and pedestrian accidents, several datasets should be obtained. These datasets and the detailed data preparation steps that are necessary to perform this study are the following:

1. Identification of required data:
   - Geo-referenced accident data for cyclists and pedestrians for several years;
   - Road lighting data;
   - Cyclist, pedestrian and vehicle flows;
   - The road network with attributes such as road class;
   - Other road and environmental features such as presence of trees, traffic light.
2. Data preparation: filter all nighttime accidents and identify areas with high cyclist and pedestrian nighttime accidents using Geographic Information System (GIS) software (e.g. ArcGIS);
3. Sample selection: select a subset of the larger area of interest for illuminance data collection, where there is a high concentration of bicycle and pedestrian accidents;
4. Illuminance data collection for the selected area: collect illuminance data at nighttime using the illuminance sensor on the roadway;
5. Data analysis: evaluate the effects of the average link illuminance and uniformity on the frequency of bicycle and pedestrian accidents using the negative binomial model.

5.3.1 Identification of Required Data and Data Preparation

The first dataset needed is the city's geospatial file that contains the location of all road links and their associated road class, name, the number of lanes, the location of signalized and non-signalized intersections, the location of trees, and the cycling network.

A critical set of required data is the geo-referenced bicycle and pedestrian accident data, which must include the latitude and longitude coordinates of the accident location. Among all accidents, the ones that occurred after the evening twilight and before the morning twilight were filtered as nighttime accidents. Once the accidents are plotted along with the city's road network in GIS software, the accidents that fall on each link will be associated to that link using a 5 meter buffer around the link. These link buffers will have a 5 meter overlap at each intersection, including the intersection, which means an accident that is located at an intersection will be associated to each link covering that intersection. Since the direction of movement of the bicycle or vehicle involved in a collision is unknown, an accident that occurs at an intersection will be associated with all the adjoining links to include all the possibly relevant lighting characteristics of that link that might have caused the accident.

The nighttime bicycle, pedestrian and vehicle flows can be collected using manual counts, pneumatic tubes, specific (e.g. pedestrian) counting sensors, etc. These variables are generally the primary factor for the number of accidents and must be controlled for to study other factors such as road lighting. Flow data is generally available at an intersection level: for a link-based analysis, the flows for each intersection movement will be summed to obtain the link-level flows. Other road and environmental features may be obtained from the city's open data portal.

5.3.2 Select the Data Collection Area

The data collection area is selected based on the area which has the highest pedestrian and cyclist accident concentration. Plotting the city's bicycle and pedestrian accidents, and applying the kernel density function produces a heatmap that makes it visually easy to select an area for data collection and analysis purposes. An area that covers a range of high to low accident concentration and is well connected in a corridor or grid network for an easier data collection process is chosen.

5.3.3 Illuminance Data Collection

An illuminance meter is used to collect illuminance data similarly to some recent studies (Goodman et al., 2007; M. S. Nabavi-Niaki et al., 2014; M. Rea et al., 2010). Considering the fact that cyclists usually ride on the right hand side of the road, and that pedestrians are on the sidewalks, the data collection process for this paper was done using the illuminance sensors mounted on a bicycle to be able to collect the amount of lighting that is perceived by the cyclist, pedestrian and vehicles while riding on the right lane of the road close to the sidewalk. Some sensitivity tests were performed given different weather conditions, height of data collection sensor to check the effects of these factors on the resulting data.

For two way roads, the data collector should ride in both directions to collect data from both sides. For example, as used in this study, the SpectroSense2+ (SKL 925) logging meter can be used for illuminance data collection. The SKL 925 logger records the illuminance level in units of Lux every second along with the date, time, and the location with coordinates using the logger's GPS Figure

5-1 a. shows the SKL 925 data logger and sensor, and Figure 5-1 b. and c. show the sensor and GPS mounted on a scooter.

(a) (b) (c)

Figure 5-1 a. Data logger and sensor held by the data collector; b. and c. illuminance sensor and GPS mounted on electric scooter

5.3.4 Data Analysis

5.3.4.1 Aggregating the Data at the Link Level

Once the point illuminance data is collected, the measurements can be plotted along with the road network of interest. The link's average illuminance can be calculated by associating the point illuminance measurements of each link within a buffer distance from the link. This is done so that all point illuminance measurements that fall a distance away from the link are included in the link buffer. The buffer distance depends on how well the point illuminance GPS locations are aligned with the road network. After the average illuminance is calculated, the link uniformity value is calculated by dividing the average link illuminance by the minimum illuminance measurement in the link, in order to measure how well the link is evenly lit.

Once the number of pedestrian and bicycle accidents are obtained, the road user flows and the road and environment characteristics are attached to each link, the chosen statistical model, here the negative binomial model, can be estimated.

5.3.4.2 Model Structure

The Negative Binomial distribution assumes a Bernoulli trial where there are two possible outcomes (0 or 1). Negative binomial regression is implemented using maximum likelihood estimation. Negative binomial regression is a type of generalized linear model in which the dependent variable Y is a count of the number of times an event occurs. The probability function is:

$$p(y) = P(Y = y) = \frac{\Gamma\left(y + \frac{1}{\alpha}\right)}{\Gamma(y+1)\Gamma\left(\frac{1}{\alpha}\right)} \left(\frac{1}{1 + \alpha\,\mu}\right)^{1/\alpha} \left(\frac{\alpha\,\mu}{1 + \alpha\,\mu}\right)^{y}$$

where $\mu > 0$ is the mean of Y and $\alpha > 0$ is the heterogeneity parameter. The traditional negative binomial regression model utility function is:

$$\ln\mu = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_p x_p$$

where the independent variables $(x_1, x_2, \ldots, x_p)$ are given, and the coefficients (β_1, β_2, … β_p) are to be estimated.

The log-likelihood function is:

$$\ln L(\alpha,\beta) = \sum_{i=1}^{n}\left(y_i \ln\alpha + y_i\,(x_i \cdot \beta) - \left(y_i + \frac{1}{\alpha}\right)\ln\left(1 + \alpha\, e^{x_i\beta}\right) + \ln\Gamma\left(y_i + \frac{1}{\alpha}\right) - \ln\Gamma(y_i + 1) - \ln\Gamma\left(\frac{1}{\alpha}\right)\right)$$

The values of α and β that maximize *ln L(α, β)* will be estimated as the output of the model. The model is estimated using the statistical software STATA.

5.4 Montréal Case study

5.4.1 Data Collection and Preparation

The geospatial data for the Island of Montréal is obtained from the city's open data portal along with the geospatial files for the cycling facility network, the locations of trees and signalized intersections.

The geo-referenced accident data was obtained from Montréal police reports from 2001 to the end of 2010 with the assumption that road lighting did not change significantly throughout this time. This dataset includes the latitude and longitude coordinates of the accident location. Throughout the 10 years of day and night accident data, 15 % of all bicycle accidents, and 27 % of all pedestrian accidents occurred during nighttime.

The bicycle, pedestrian and vehicle average annual daily traffic (AADT) flows were obtained from the McGill intersection data inventory. Due to the unavailability of nighttime traffic flows, AADT flows were used in the analysis. Since the vehicle, pedestrian and bicycle flow data was intersection-based, individual intersection flow movements were used to calculate the flows in each link. The allocation of traffic flow from intersection to link was done using SPSS and ArcGIS.

The nighttime bicycle and pedestrian accidents were plotted over a map of the Island of Montréal. The accident spatial distribution concentration was visualized using the kernel density analysis tool in ArcGIS. The heatmap is shown in Figure 5-2 where the blue area shows lower accident frequency and the red area displays the highest accident frequencies. It clearly highlights the high density of accidents in the downtown Montréal area in red.

Based on Figure 5-2, a set of links were selected for illuminance data collection as shown in black on the map in Figure 5-3. A sample of 1422 road links were selected throughout Montréal's downtown core where a range of high to low pedestrian and bicycle accident frequencies have been observed.

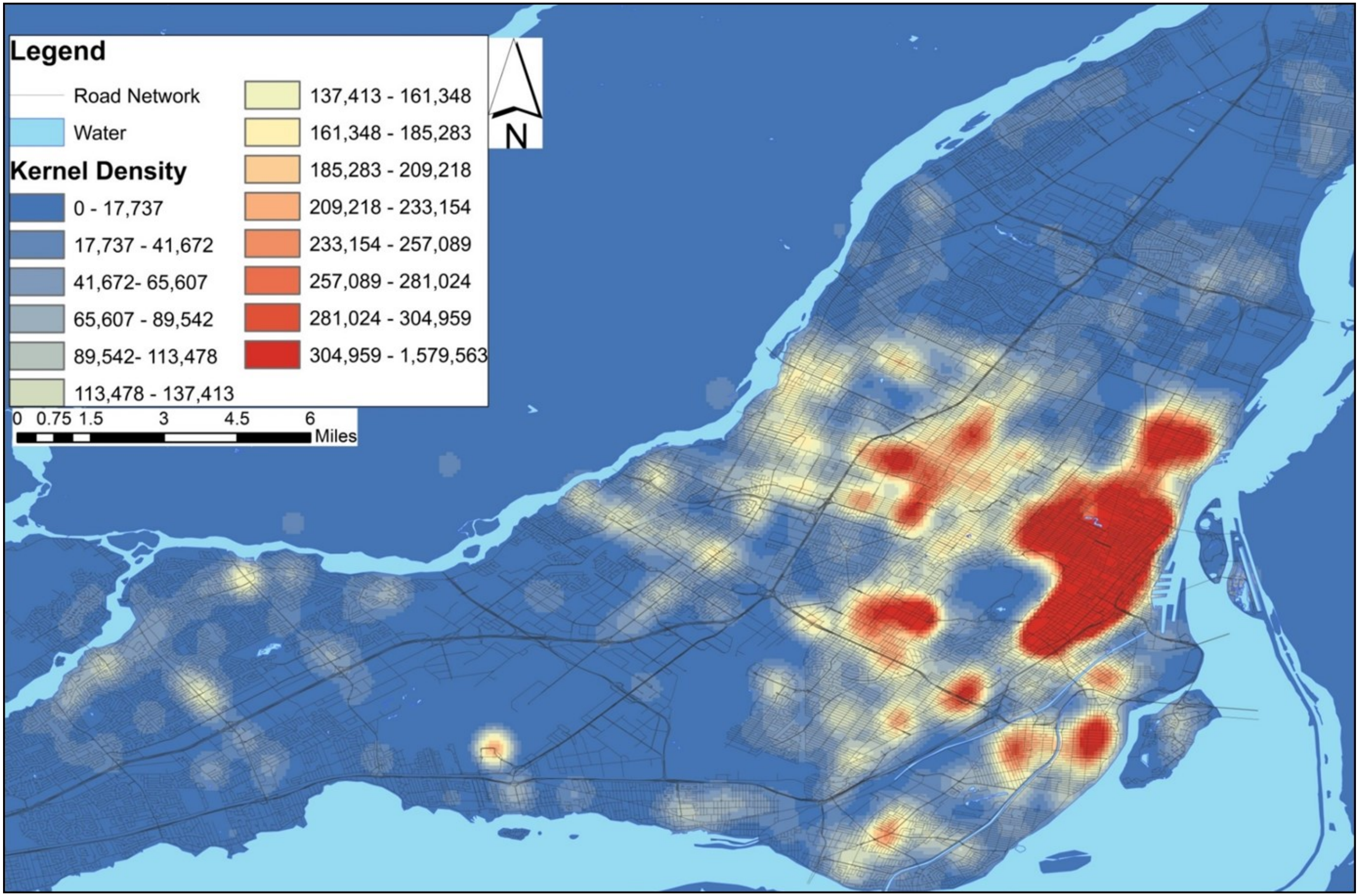

Figure 5-2 Map of the Island of Montréal with a heat map of the nighttime bicycle and pedestrian accident frequency

Figure 5-3 Selected road network for illuminance data collection in downtown Montréal

Illuminance data was collected on weekdays during the months of June and July 2014 from 10 PM until 12 AM. The data is then plotted with the city's road network: a buffer of 15 m is drawn around each link to include all collected point illuminance data as shown in Figure 5-4. The average illuminance and illuminance uniformity of the link are then calculated for each link's buffer. The link illuminance uniformity provides some sense of illuminance variability per link.

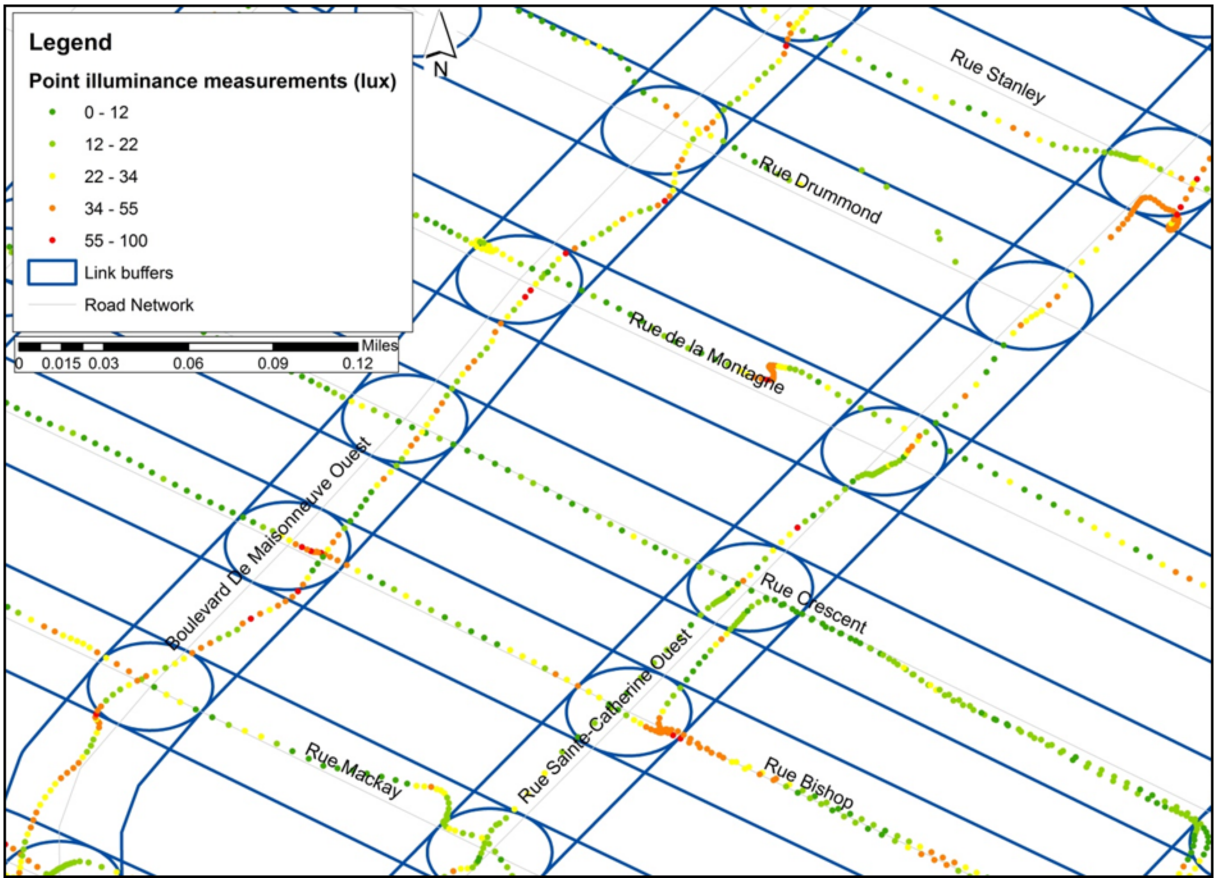

Figure 5-4 Buffer around road links to include all point illuminance measurements related to each link

Finally, the descriptive statistics of all the variables, dependent and independent, considered in this analysis at the link level are presented in Table 5-1.

Table 5-1 Descriptive statistics of all the variables for the 1422 links

	Category	Variable	Mean	Standard Deviation	Min	Max
Numeric Variables	**Illuminance**	Average link illuminance *(lux)*	24.4	11.9	2.17	103.9
		Link uniformity	3.28	3.53	1	34.6
	Accidents	Number of bicycle accidents in link	0.17	0.78	0	8
		Number of pedestrian accidents in link	0.31	1.19	0	11
	Flow *(AADT, volume per hour)*	Pedestrian flow in link	88.9	141.1	0	1842
		Bicycle flow in link	5.55	10.6	0	103
		Vehicle flow in link	296.4	214.4	0	1203
	Built Environment	Number of lanes in link	2.07	1.05	1	4
			Yes		***No***	
Categorical Variables (including binary)	**Road class**	Highway	11 (1 %)		1411 (99 %)	
		Arterial	199 (14 %)		1223 (86 %)	
		Collector	504 (35 %)		918 (65 %)	
		Local	700 (49 %)		722 (51 %)	
	Built Environment	Presence of a bicycle facility (lane or path) on link	289 (20 %)		1133 (80 %)	
		Presence of trees on link	436 (31 %)		986 (69 %)	

5.4.2 Empirical Results

5.4.2.1 Evaluation of City's Illuminance Levels

Considering the City's road lighting standards obtained from the Illuminating Engineering Society (IES) handbook, each intersection must have an average maintained illuminance level based on pedestrian activity (counts). Presented in Figure 5-5, assuming medium pedestrian activity, the links that had an average maintained illuminance below the standard are marked in red and the links with standard and above standard lighting are presented in blue. Based on the results from these links, 48 % of the links where data was collected had sub-standard lighting. One can for example notice that the major arterial, rue Sherbrooke, is overwhelmingly below standards.

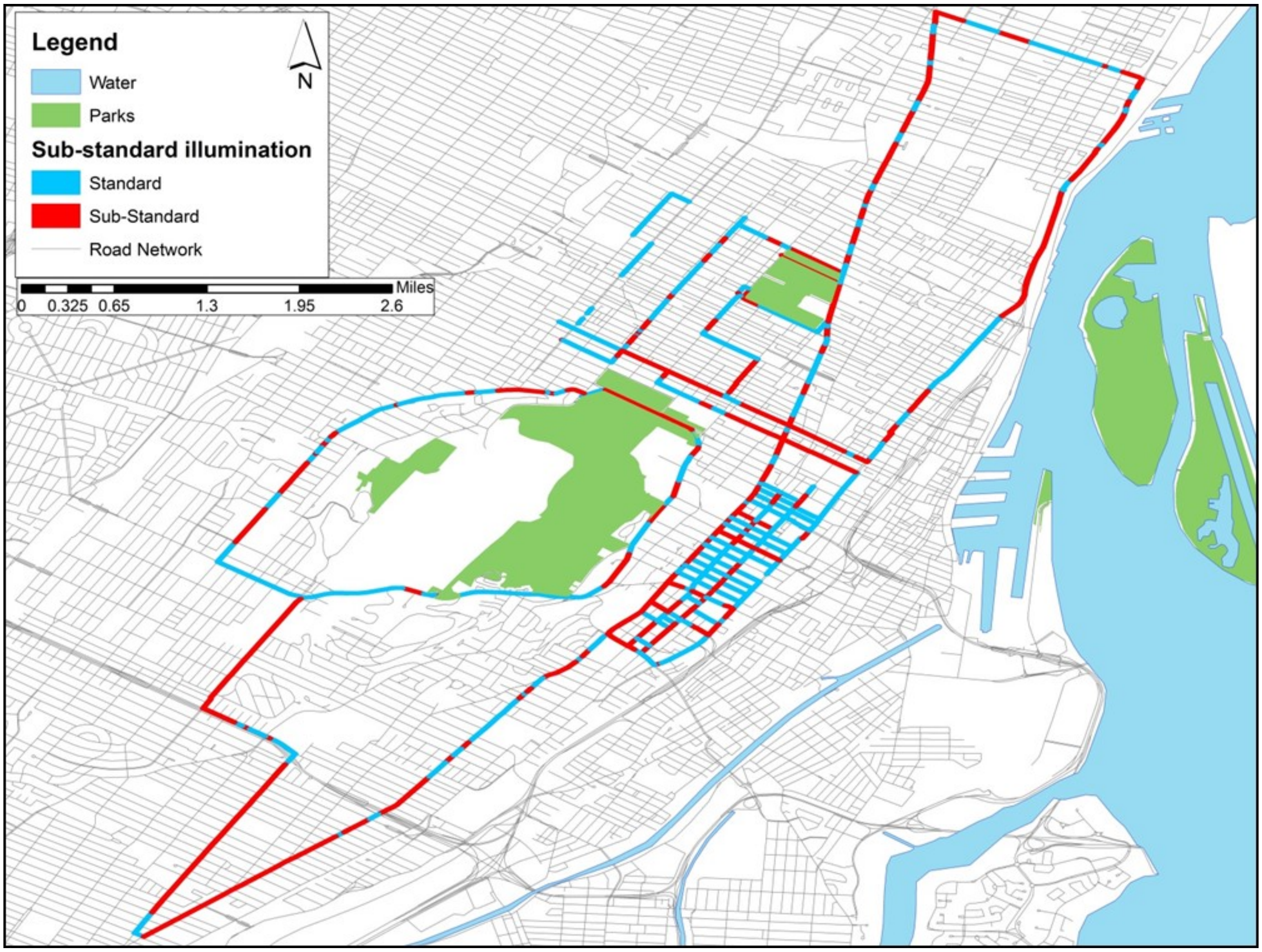

Figure 5-5 Substandard lighting shown in red and standard lighting shown in blue representing the non-uniform lighting of links

5.4.2.2 Regression Model

Table 5-2 and Table 5-3 present the estimated parameters of the negative binomial models respectively for the number of cyclist and pedestrian nighttime accidents. The tables present the variable coefficients, z-value, p-value, and the 95 % confidence interval as estimated by STATA for the variables that are significant at the 95 % confidence level.

For bicycle accident frequency estimation, illuminance, built environment in each link, road class and vehicle and bicycle AADT were considered as exogenous variables in the model estimation. Among these variables, average link illuminance, the presence of bike facility and the arterial road class had a significant positive association with the nighttime bicycle accident frequency (Table 5-2). The causal effect is unclear, as lighting may have been added at locations with more accidents in an attempt to improve safety: more road lighting would not cause more accidents, the causal link would be the other way around (for opposite results see (Kim et al., 2007; Yan et al., 2011)). Another explanation would be that drivers drive more cautiously on links with less lighting and get therefore involved in fewer accidents as a consequence.

Road variables that came out significant include presence of bike facility on the link and arterial road class. As presented in the Table 5-2, the presence of a bike facility is associated with a decrease in the frequency of bicycle accidents during nighttime in Montréal. This is reasonable since separated bike paths provide a space for cyclists where they are more protected from motorized vehicles; also, drivers may pay more attention to cyclists when there is a bike facility on the road. Among road attributes, the arterial road class is associated with significantly lower nighttime bicycle accidents compared to other road classes (collector, local, and highway). This can be explained since cyclists use arterial roads less and as a result there are fewer accidents. The same pattern has been observed in other studies as well (Harwood et al., 2007).

Among all variables considered in the estimation process, it is surprising that bicycle and vehicle flows were not significant, which may be caused by the use of AADT flows instead of nighttime flows. It should be noted that not only is nighttime bicycle accident very low, but also the vehicle and bicycle flow are also much less compared to daytime (there are few nighttime bicycle accidents in the sample: only 6 % of bicycle accidents occurred at night, while 16 % of all accidents occurred at night).

Table 5-2 Estimated coefficients for the nighttime bicycle accident frequency model

Nighttime Bicycle Accident Frequency		Coefficient	z-value	p-value	[95% Conf. Interval]	
Illuminance	Average link illuminance	0.02	2.12	0.03	0.00	0.03
Built Environment	Presence of bike facility	-1.15	-2.92	0.00	-1.92	-0.38
	Arterial	-1.97	-2.75	0.01	-3.37	-0.57
Constants		-2.89	-12.03	0.00	-3.36	-2.42

The same model is estimated on nighttime pedestrian accident frequency by considering illuminance, environment variables (excluding the presence of bike facility), as well as vehicle and pedestrian AADT on the link. The results of the model for nighttime pedestrian accident frequency presented in Table 5-3 show that among the variables that were considered, the average link illuminance, the number of lanes per link, vehicle and pedestrian flows have significant associations with the number of nighttime pedestrian accidents. Table 5-3 illustrates that average link illuminance is again associated with a higher number of nighttime pedestrian accidents. This can be explained by the same hypotheses suggested for bicycle accidents (for similar results see (M. S. Nabavi-Niaki et al., 2014)). It should be noted that illuminance uniformity was not a significant variable in either model.

Among the built environment variables, the number of lanes per link is associated with an increase in nighttime pedestrian accident frequency in the link. A higher number of lanes is related to higher speeds, higher complexity and range of maneuvers (changing lanes, right- and left-turn lanes) and volumes to some extent, which can therefore cause more accidents. Crossing more lanes is also a more difficult task for pedestrians, and length of the crossing is equivalent to the exposure time to vehicles.

The last attribute that has a substantial effect on Montréal's nighttime pedestrian accident rate is vehicle and pedestrian flow through the link. Based on the negative binomial results, the increase of vehicle flow is associated with a decrease in the number of nighttime pedestrian accidents. However, higher pedestrian flows have the opposite effect. This could be explained by the fact that when there is a high vehicle volume on the link, pedestrians are more cautious while crossing the road. However, more pedestrians on a segment increase their exposure to collisions and the number of collisions accordingly.

Table 5-3 Estimated coefficients for the nighttime pedestrian accident frequency model

Nighttime Pedestrian Accident Frequency		**Coefficient**	**z-value**	**p-value**	**[95% Conf. Interval]**	
Illuminance	Average link illuminance	0.02	2.96	0.00	0.01	0.03
Built Environment	Number of lanes per link	0.16	1.78	0.08	-0.02	0.34
Flow (AADT)	Vehicle flow	-0.35	-4.89	0.00	-0.49	-0.21
	Pedestrian flow	0.28	3.96	0.00	0.14	0.42
Constants		-2.42	-5.84	0.00	-3.24	-1.61

5.5 Conclusion

The importance of studying elements contributing to the increase in nighttime vulnerable road user accident frequency is evident in past literature. Worldwide statistics shows that the number of nighttime accidents is higher than should be expected given lower nighttime traffic activity than during daytime (Twisk & Reurings, 2013; Walter et al., 2005). An effective counter-measure for nighttime accidents is road lighting. This research area is seeing a paradigm shift from investigating nighttime road safety using only the presence of light to using actual nighttime ambient light measurement from illuminance sensors.

This paper presented a methodology to collect illuminance data and other potential contributing factors to investigate the influence of road lighting on the number of accidents involving vulnerable road users. This method was applied to a sample of 1422 road links in Montréal's downtown core.

The study yielded some unexpected results, for example that an increase in road lighting is associated with more bicycle and pedestrian accidents. This can be due to the fact that when there is less light and less visibility, drivers drive more slowly and cautiously, resulting in lower accident rates, or that road lighting is added to sites with a higher than average number of accidents as a counter measure. The same pattern has also been observed in Montréal vehicle and pedestrian accident frequency at nighttime in previous research (M. S. Nabavi-Niaki et al., 2014). It puts however into question the effect of road lighting on safety: more research is needed to better understand what type of lighting may truly improve safety. The results highlight the importance of incorporating actual nighttime illuminance measurements along with other safety attributes to study nighttime accident frequency: future work should focus on a more microscopic analysis of illuminance data.

A few other exogenous variables had a significant association with the number of pedestrian or bicycle accidents: presence of bicycle facility, arterial road type, number of lanes per link and vehicle and pedestrian flows. Few recommendations can be made based on these results, except maybe for the already known association of bike facilities with increased safety.

Our study is not without limitations. First, the various data were not collected for the same period, especially the accident data, the flows and the illuminance data. Another issue is the small number of reported nighttime accidents as well as the lack of nighttime vehicle, pedestrian and bicycle flows in Montréal. This low number led to select 10 years of accident data for the analysis, which relies on the assumption that road lighting and illuminance levels did not change throughout this period. The assumption that nighttime flows are uniformly proportional to AADT estimated from daytime counts is probably not true and future research should collect flows specifically at night to better understand safety at this time of day.

Given the relatively low nighttime accident frequency and vulnerable road user activity, alternative methods for safety analysis that rely on direct observations would be very appropriate. Research using sensors that can record road user behavior at night such as thermal cameras is under way to complement the present study. A topic related to this study is the effect of lights (on bicycles and helmets) and of reflective clothes worn by cyclists and pedestrians to make them more visible. In particular, the combined effect on safety of road lighting and increased vulnerable road user visibility through lights and reflective gear has not been jointly studied, whether using accident data or through direct observation.

Acknowledgements

The authors wish to acknowledge the financial support from Fonds de recherche du Québec - Nature et technologies (FQRNT) Team Grant Program for undertaking the research, as well as the City of Montréal and boroughs that authorized the data collection.

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LINK BETWEEN CHAPTER FIVE AND SIX

The previous chapter evaluates the effects of road lighting and its discontinuity on vulnerable road user safety by collecting nighttime illuminance data on road links. The vulnerable road user accident frequency was analyzed using the negative binomial model. Results showed that an increase in road lighting is associated with more bicycle and pedestrian accidents. Illuminance uniformity used to measure lighting discontinuity did not have a significant effect on vulnerable road user accident frequency. Other tested variables indicated that the presence of a bicycle facility and the arterial road class were associated with improved cyclist safety, while cyclist safety decreased with the number of road lanes per link, pedestrian safety improved with higher vehicle flows and decreased with higher pedestrian flows.

The results form Chapter four are used to select two discontinuity locations in Montréal for further detailed analysis. The following chapter adopts a microscopic analysis of cyclist behaviour at the selected locations with cycling network discontinuities and focuses on cyclist movements and speeds compared to control sites. The analysis relies on an automated video analysis tool to extract road user trajectories and cluster similar cyclist movements to observe the general maneuvers and speeds of cyclists at discontinuity and control sites.

CHAPTER 6 ARTICLE 3: ANALYSING CYCLIST BEHAVIOUR AT CYCLING FACILITY DISCONTINUITIES USING VIDEO DATA

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Published in the peer-reviewed journal of Transactions on Transport Sciences (TOTS), 2018, 9(1), 3–17. https://doi.org/10.5507/tots.2018.006

The methodology proposed in this section was presented at the peer-reviewed conference: 96th Annual Meeting of the Transportation Research Board (peer reviewed conference), Washington D.C., 2017.

Abstract

The primary purpose of any transportation network is to provide connectivity between the origin and travel destination. However, given the vehicle oriented structure of the road network in many countries, there are connectivity issues in the cycling network, which has been implemented later. Discontinuities are physical interruptions in the cycling network where cyclists are faced with unexpected situations such as the end of a cycling facility or the change from one facility type to another that are perceived as inconvenient and less safe. The microscopic behaviour of cyclists and the risks they face at these points of discontinuity has not been extensively investigated in the literature. This study aims to evaluate the challenges faced by cyclists at discontinuities by observing cyclist behaviour at these locations and comparing them to control sites using automated video analysis techniques. Our methodology allows the extraction of valuable microscopic data for evaluation of cyclist behaviour at any location. The methodology is applied to a case study of four sites in Montréal, Canada.

Using a set of discontinuity measures proposed in a previous work and applied to Montréal's cycling network, video data was collected from a pole-mounted camera at locations with discontinuity and control sites. After extracting road user trajectories from the video data, a trajectory clustering algorithm was applied to find cyclists' motion patterns and the various maneuver strategies adopted by cyclists. Speeds and acceleration statistics are extracted and compared between different motion patterns and between discontinuity and control sites. Results show that cyclists undertake a larger number of maneuvers at points of discontinuity compared to their control sites, and that both cyclist accelerations and speeds exhibit larger variations at discontinuities compared to larger and more stable speeds at control sites.

Keywords: Cyclist behaviour, discontinuity, motion pattern learning, video analysis, speed analysis, trajectory clustering

6.1 Introduction

Given its many environmental and social benefits, cities are encouraging cycling as an affordable mode of transportation and are investing in expanding bicycle infrastructure. However, especially in North America, there is only a fraction of individuals who cycle either to commute or for recreational purposes (NHTSA & National Household Traffic Survey of America, 2013; U.S. Department of Transportation, 2001). To increase the cycling mode share, cyclists' needs must be recognized and considered for further development of the road and cycling network. The preference of cyclists for dedicated cycling infrastructure like bike lanes, physically separated bike paths or bike boxes has been clearly established in recent research, as well as their positive impact on safety (Lusk et al., 2013; Zangenehpour et al., 2013). Accordingly, cities around the world are building more cycling infrastructure, increasing the length of the cycling network every year. This leads to easily quantifiable targets and announcements by city officials, e.g. 57 km of new cycle lanes or paths in Montréal for 2016-2017.

Despite the growing development of cycling networks, issues remain at specific locations creating discontinuities or interruptions in cycling trips. Road network connectivity is a given for automobiles, however, lack of connectivity is a critical factor in potential and actual bicycle use (Mekuria et al., 2012). Countries where private vehicles are the dominant mode of transportation lack a traffic system that is responsive to the needs of cyclists. Implementing a cycling network on the existing vehicle-oriented road networks leads to discontinuities in the cycling network. These discontinuities include the sudden end of cycling facilities, or unexpected change from one cycling facility type to another, which should be target points for improvement. While discontinuities are considered in practice, for example when building new facilities or improving existing ones (CROW Fietsberaad, n.d.), only recently has a methodology to identify and quantify discontinuity measures been proposed and applied in a case study in Montréal (M. S. Nabavi-Niaki, Saunier, & Miranda-Moreno, 2016).

Given the lack of quantifiable and objective measures of discontinuity, it is not surprising that little research has directly dealt with discontinuities in the cycling network and their impact on cyclists. The in-depth analysis of cyclist behaviour requires large amounts of microscopic data, i.e. road user trajectories at a fine temporal scale. To that end, computer vision techniques and trajectory clustering methods have been applied to video data for a number of road user behaviour and safety studies (Laureshyn et al., 2017; Mohamed & Saunier, 2015; Saunier & Sayed, 2006). This study makes use of video data to compare cyclist behaviour between sites with and without a discontinuity by automatically extracting road user trajectories from video data. The proposed methodology aims to identify and characterize the possible cyclist movements through trajectory clustering. The methodology is applied to a case study of four sites in Montréal, Canada.

The next section provides a background of studies investigating cyclist behaviour and their analysis methods. The proposed methodology is then described, followed by the descriptive analysis and discussion of results. The paper is summarised in the conclusion where limitations of this study and future works are presented.

6.2 Background

6.2.1 Factors Affecting Cyclist Behaviour

Comfortable cycling requires smooth movement with the lowest possible energy input (Hölzel et al., 2012). Unless individuals can cycle to their destinations within a reasonable time and on a safe bike route without any stress or added effort, most of them will use a different mode of travel. Therefore, for a cycling network to attract more users, its fundamental attributes should include low-stress connectivity (Mekuria et al., 2012). To accommodate all cyclists with different comfort and experience levels, planners and policy makers must have an accurate understanding of the needs of all cyclists. Past studies have invested in identifying different cyclist behaviour in different situations. For example, studies have shown that cyclists make an effort to avoid stressful and less safe situations by choosing to add time and distance to their travel by choosing to travel on cycling facilities (Aultman-Hall, Hall, & Baetz, 1997; Megan Winters, Teschke, Grant, Setton, & Brauer, 2010). A study forecasted that the implementation of a physically separate cycling facility would increase the number of cyclists by 55 % (Wardman et al., 2007). However, to attract more cyclists, the comfort of riding on cycling facilities may not compensate for the uncomfortable and high-stress points of discontinuity along the route (Mekuria et al., 2012). For more experienced cyclists, these discontinuities may be much less alarming (Willis, Manaugh, & El-Geneidy, 2013), but for more concerned individuals, discontinuities are at best uncomfortable and may be an actual barrier to cycle (M. S. Nabavi-Niaki et al., 2016; Xie & Levinson, 2007). A recent Dutch study confirmed that increased physical effort, which is likely to occur at discontinuities, affects the mental workload of cyclists (Boele-Vos, Commandeur, & Twisk, 2017). It has been established that vehicle drivers in complex traffic situations reduce their speed in order to compensate for the increase in mental workload (Lansdown, Brook-Carter, & Kersloot, 2004) and it can be assumed that cyclists behave the same way. Although planners understand this problem, there is a lack of quantifiable measures of connectivity to identify and improve discontinuities in the network. An initiative by the Dutch Cyclists' Association and the National Bicycle Platform Foundation (SFL) identified barriers such as motorways, through roads, railway tracks and waterways as interruptions along a cycling facility (Brochure Dutch Cyclists' Association, 2003). Some proposed and implemented solutions to the inconveniences these interruptions pose include the construction of bicycle tunnels under major intersections with high speed and high volume vehicle traffic (CROW Fietsberaad, n.d.). Several researchers have developed methods for qualitatively classifying road segments based on the level of stress they impose on cyclists (see (Bíl et al., 2015; Blanc & Figliozzi, 2016; Harkey, 1998; Bruce W Landis, 1994; Sorton & Walsh., 1994)). However, no study has considered discontinuities as an indicator in the evaluation of cycling network performance nor the microscopic evaluation of cyclist's behaviour at discontinuities.

6.2.2 Analysis Methods

The challenges of studying cyclist behaviour are a result of their dynamic characteristics, including their movements, speed, acceleration and deceleration profiles, and their physical characteristics, including size, flexibility and capability (Twaddle, Schendzielorz, & Fakler, 2014). One of the main challenges of analyzing cyclist behaviour is the lack of reliable data in sufficient quantities. Studying cyclist behaviour requires microscopic level extended and reliable trajectory data. However, despite the growing interest in cycling behaviour, few studies rely on microscopic data (trajectories) at specific sites.

Stated and revealed preference surveys as well as observational data have been widely used to study cyclist behaviour (Dill & Gliebe, 2008; Hunt & Abraham, 2007; Kang & Fricker, 2013; Yang & Mesbah, 2013). More recently GPS and video data are being used to gather more in depth information such as location, speed, trajectory and safety measures (B. Li, Xiong, Li, Liu, & Zhang, 2015; Ma & Luo, 2016; Mereu, 2015; Zaki, Sayed, & Cheung, 2013; Zangenehpour et al., 2016). Most of these studies extracted location and speed measurements manually from GPS or video data. However, manual data analysis is time consuming, not very accurate and prone to error. To overcome these problems, computer vision techniques have been used to extract precise spatial and temporal road user measurements in a more resource efficient manner (Ismail et al., 2010; B. T. Morris & Trivedi, 2008; Zaki et al., 2013; Zangenehpour et al., 2016). Challenges with this approach are caused by lighting variations, shadows, and groups of road users moving close to each other or occluding each other, which is more frequent if the camera angle is low (B. T. Morris & Trivedi, 2008).

Once road user trajectories are obtained, they must be classified into different categories, in particular cyclists. Methods range from simple statistics on the size of the road users in images, to methods combining different sources of information such as speed, appearance and location (Zangenehpour et al., 2015).

The next step is to interpret the cyclist trajectories. A common technique to explore and interpret complex datasets is clustering, i.e. the segmentation of the dataset into more homogeneous subsets. Several methods have been proposed for the particularly challenging problem of trajectory clustering or motion pattern learning as it is also called (B. T. Morris & Trivedi, 2008). Because trajectories are multi-dimensional data structures of varying lengths, common distance or similarity measures like the Euclidean distance cannot be used directly. For that purpose, similarity measures used for sequences like DNA and handwriting have been adapted to spatial trajectories: the most flexible and accurate may be the longest common subsequence (LCSS) (B. Morris & Trivedi, 2009). Another challenge of clustering trajectories is the representation of each cluster (motion pattern): contrary to methods like k-means applied to fixed-length vectors, trajectories cannot be easily averaged. An original model and clustering algorithm based on the LCSS were proposed in (Saunier, Sayed, & Lim, 2007) and refined in (Mohamed & Saunier, 2015) where each cluster is represented by an actual trajectory and trajectories are assigned to the motion pattern cluster based on their highest similarity. Motion pattern learning was initially developed and applied to motion prediction to compute surrogate measures of safety like time to collision (Mohamed & Saunier, 2015; Saunier et al., 2007).

6.3 Methodology

The methodology to study cyclist behaviour at discontinuities consists of five main steps, which are represented in the overview in Figure 6-1.

6.4 Site Selection

To identify sites with discontinuities in Montreal, Canada, the methodology presented in (M. S. Nabavi-Niaki et al., 2016) was applied (Figure 6-1, step 1). Discontinuity sites were selected based on type. To select control sites, locations along the same road near the discontinuity sites were selected with similar vehicle and bike flows. The locations of the four sites (two with a discontinuity and two control sites without a discontinuity) are shown in the second step of Figure 6-1.

6.5 Video Data Collection and Processing

A GoPro camera was used to record video at the four locations on weekdays in October 2015. Recording lasted on average seven hours, starting around 7:00 AM. The cameras were mounted on tall poles supported by an existing light pole to provide stability. The camera was placed in a position and at an angle to capture a good view of the area where cyclists would travel. Data was collected in temperatures between 16 °C and 20 °C and in mainly sunny and overcast conditions.

In the video recordings, three-dimensional objects are captured in a two-dimensional image space, where the image space, distances and angles are distorted. For analysis purposes, to obtain the road user trajectories in real-world coordinates rather than in pixels, the distortion of the video image caused by the camera lens is corrected, and the mapping process to convert coordinates in the image plane to world coordinates relies on a homography matrix.

Data preparation includes four sub-steps (Figure 6-1, step 4): road user feature detection, feature tracking, similar feature grouping based on common motion constraints, and road user classification into three road user types (vehicle, cyclist and pedestrian). These steps are performed using a feature-based tracker and a classification tool from the open-source project “Traffic Intelligence” (Jackson et al., 2013). Tracking parameters are tuned through trial and error in this study to reduce over-segmentation where one road user is tracked as several objects, and over-grouping where many road users are grouped into one object.

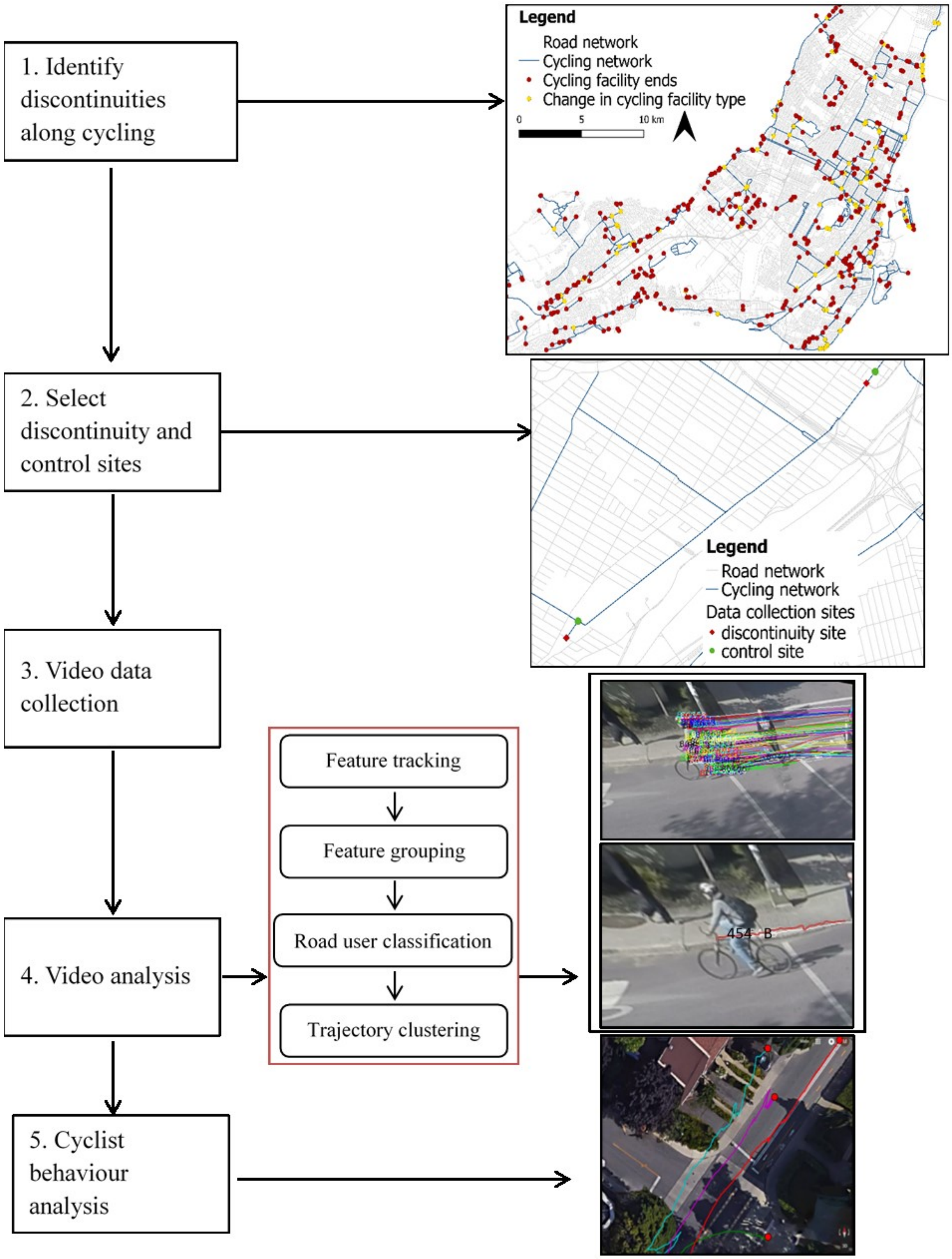


Figure 6-1 Overview of the main methodology steps

The classifier from (Zangenehpour et al., 2015) is used with the updated speed distribution parameters based on site observations. The results of this step are classified road user trajectories.

6.5.1 Cyclist Behaviour Analysis

The final step in the methodology (step 5) relies on the cluster model and clustering algorithm developed in previous work (Mohamed & Saunier, 2015; Saunier & Sayed, 2006). Each cluster is represented by an actual road user trajectory (the longest). The clustering algorithm is a variation on the principle of K-Means that trades the number of clusters for a minimum similarity between a motion pattern cluster and the trajectories assigned to it. The similarity depends on the LCSS, using the Manhattan distance and a threshold to define similar individual positions, and on normalizing the similarity (the number of similar points) by the minimum length of the two trajectories (the reader is referred to (Saunier et al., 2007) for the details). When a trajectory is not similar enough to current clusters, it becomes the prototype of a new cluster. The algorithm therefore has two parameters, the maximum distance for the Manhattan distance and the minimum similarity to assign trajectories to clusters: in this study, they are set to 2 m and 0.6 respectively. To generate higher quality clusters, each road user is represented by its longest feature trajectory instead of the average feature trajectory, which can be very noisy. The result of the algorithm is a set of clusters or motion patterns, where each motion pattern is represented by a real (prototype) trajectory and all the road user trajectories are assigned to a motion pattern (the one with the most similar prototype).

Only the cyclist trajectories potentially affected by the discontinuity are considered in the analysis. These are the trajectories with the same origin and destination as the trajectories that would have used the cycling facility if it was continuous, e.g. in the control site. The analysis relies on the motion patterns that contain the cyclist trajectories with the identified origin-destination.

To characterize the dynamics of cyclist maneuvers, several statistics are extracted from each cyclist speed and acceleration time series (acceleration is computed using the Savitzky–Golay filter with polynomial order 1 and window length 9): the median, 85^{th} centile, 15^{th} centile, and the standard deviation. Each motion pattern is then characterized by the mean of each speed statistic.

6.6 Experimental Results for Cyclist Behaviour

6.6.1 Site Description

The locations of the selected sites are shown in the second step of Figure 6-1. Four sites were selected, two with discontinuities and two control sites. Selected sites were T- or four leg intersections with bi-directional physically separated cycle tracks. Table 6-1 presents the sites with information such as description of discontinuity and traffic control devices for vehicles and bikes. Two different discontinuity types were selected: change of facility side from one side of the street to the other side, and change in facility type from separate cycle track to shared roadway (Table 6-1).

The motion patterns are presented in Figure 6-2 and Figure 6-3. Each figure shows the direction of the road with a grey arrow and the direction of the cycling facility with thin white arrows. As observed in the figures, the actual trajectory locations may be slightly shifted because of perspective when projecting the image coordinates to the ground plane on the aerial images. The point at the beginning of each trajectory represents the starting point of the trajectory, i.e. the first detected position. The colour gradient is representative of the proportion of the number of cyclists in the cluster to the total number of cyclists going through the intersection for the same origin-destination, from yellow for a low proportion to red for high proportions of cyclists (with orange in between). The number of cyclists per motion pattern as well as their proportion for the same origin-destination are presented in tables 6-2 and 6-3.

Table 6-1 Site description

Discontinuity Location	Discontinuity Site Description	Control Location	Control Site Description
Coffee & Elmhurst (Figure 6-2.a)	Discontinuity: facility type change	Coffee & West Broadway (Figure 6-2.b)	Control site
	T-intersection		T-intersection
	Bi-directional separate cycle track on Coffee St changing to a shared roadway at Elmhurst Ave		Bi-directional separate cycle track on Coffee St and southeast leg of West Broadway St
	Origin-destination of movements affected by discontinuity: left turn NE to SE		Comparable origin-destination: left turn NE to SE
	Stop sign for cyclists on Coffee St		Stop sign on Coffee St
	Uncontrolled for vehicles		
	Coffee is a one-way street allowing northwest movements for vehicles		Coffee is a one-way street allowing northwest movements for vehicles
	Elmhurst is a two-way street		West Broadway is a one-way street
Maisonneuve & Ste.-Catherine (Figure 6-3.a)	Discontinuity: facility side change	Maisonneuve & Prince Albert (Figure 6-3.b)	Control site
	Bi-directional separate cycle track located on the south side of Maisonneuve Blvd, east of Ste.-Catherine St changing to the north side of Maisonneuve Blvd, west of Ste.-Catherine St		Bi-directional separate cycle track located on the south side of Maisonneuve Blvd
	Origin-destination of movements affected by discontinuity: straight movements towards NE or SW		Comparable origin-destination: straight movements towards NE or SW
	Maisonneuve is a one-way street allowing southwest movements east of Ste.-Catherine St changing to a bi-directional street west of Ste.-Catherine St		Maisonneuve is a one-way street allowing southwest movements
	Signalized intersection includes all-pedestrian phase		All-way stop controlled intersection

6.6.2 Change in Cycling Facility Type

6.6.2.1 Motion Patterns

The discontinuity at Coffee St and Elmhurst Ave is the change from a separate cycle track on Coffee to a designated roadway on the south leg of Elmhurst Ave and no facility on the north leg of Elmhurst Ave (Figure 6-2.a). At this T-intersection, not only do left turning cyclists at the end of the separate cycle track turn into a shared lane with vehicles, they have no option but to cross a two-lane road to continue their journey (unless they turn left into the sidewalk which is prohibited for cyclists to ride on). As expected, cyclists performed distinctively different movements at the discontinuity site, split into three motion patterns (Figure 6-2.a). The results show that at this discontinuity, 64 % of the left-turning cyclists travel to the far side of the road (motion pattern 2 in Figure 6-2.a) to distance themselves from vehicles on the road. Furthermore, 28 % of cyclists turn immediately into the sidewalk (motion pattern 3 in Figure 6-2.a), which is prohibited in Canada (the trajectory seems to correspond to cyclists on the road, while looking through the videos shows that in fact they were traveling on the sidewalk). The last 8 % of cyclists make a vehicular left turn maneuver and merge with traffic, traveling on the road (motion pattern 1 in Figure 6-2.a). The control site at Coffee and West Broadway St has the same cycle track running on Coffee St, and another cycle track on the southeast leg of West Broadway St as well as a bike lane on the northeast leg of the intersection (Figure 6-2.b) (the cycling facility on West Broadway is not visible due to the aerial view trees blocking the view, however the location of the facility is manually added). Also, West Broadway is a one-way road, eliminating the stress of crossing two lanes with vehicles coming from both directions which is the case at the discontinuity. These factors eliminate the problem from the discontinuity and allow cyclists to turn directly into the cycle track without being disturbed by vehicular traffic from the opposite direction (motion pattern 1 in Figure 6-2.b).

Regarding the other cyclist movement, the right turn from SE to NE (cyclists traveling northwest on Elmhurst and turning right into Coffee and cyclists on West Broadway St traveling southwest and turning right into Coffee), no difference was found with only one motion pattern at both sites (motion pattern 4 in Figure 6-2.a and motion pattern 2 in Figure 6-2.b). In particular, the right turn at the discontinuity site is simpler since the cyclist movement does not conflict with any vehicular movement).

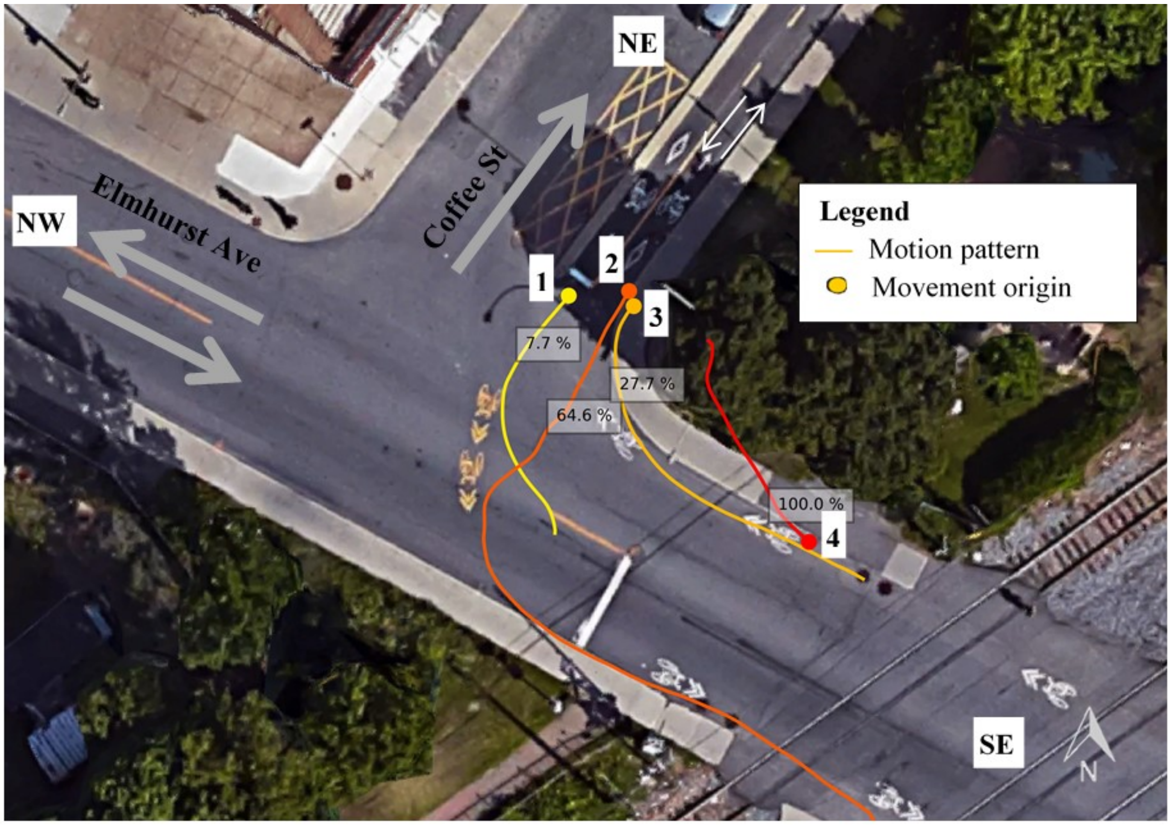
6.6.2.2 Speed and Acceleration

At the discontinuity site, the trajectories belonging to each motion pattern have lower median speeds compared to the control site (Table 6-2). Cyclists crossing the bi-directional road at the end of the separate cycling facility into the shared roadway decelerate and have lower speeds, which is associated with more maneuvers, e.g. braking, and which may be to feel safer. On the other hand, motion pattern 3 has similar mean speed to the control site since cyclists are turning left onto the sidewalk avoiding any interaction with vehicles, while having the largest 85th speed centile and decelerating more strongly since they are entering a space shared with pedestrians (which is not allowed in Canada). Comparing the mean of speed standard deviations shows that there is more variability in the speeds of cyclists within each motion pattern at the discontinuity especially when sharing space with vehicles compared to the control site. Acceleration analysis statistics are also presented in Table 6-2. For the left turn, the speed and acceleration variations are mostly higher at the discontinuity location (Coffee and Elmhurst).

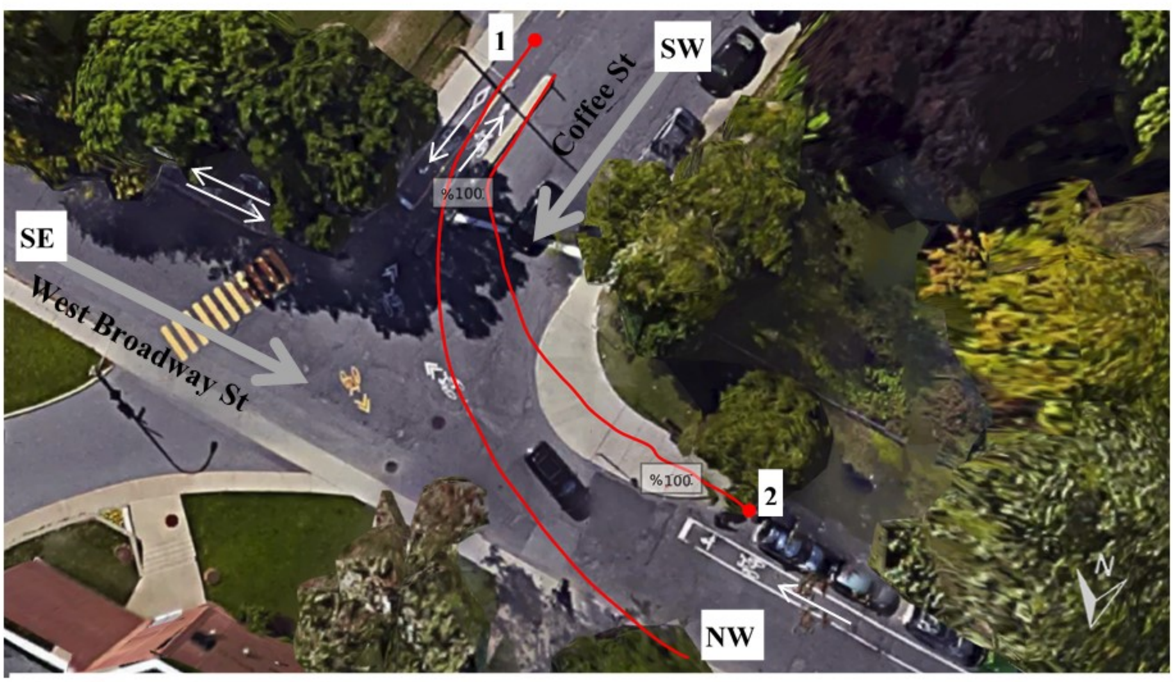
Table 6-2 Speed and acceleration statistics at the discontinuity and control sites

(the most extreme values between the discontinuity and control sites are highlighted in bold).

Description				**Speed statistics**				**Acceleration statistics**			
Direction	Location	**Motion pattern number**	**Number of cyclists in motion pattern**	**Mean of median speeds (m/s)**	**Mean of 85th centile (m/s)**	**Mean of 15th centile (m/s)**	**Mean of St. Dev. (m/s)**	**Mean of median acceleration (m/s²)**	**Mean of 85th centile (m/s²)**	**Mean of 15th centile (m/s²)**	**Mean of St. Dev. (m/s²)**
Left turn	Coffee & West Broadway (control site)	1	62 (100 %)	**15.6**	17.2	14.2	1.7	0.01	0.20	-0.14	0.24
	Coffee & Elmhurst (discontinuity site)	1	5 (7.7 %)	14.4	18.2	10.2	3.6	-0.06	0.09	-0.22	0.17
		2	42 (64.6 %)	13.6	18.5	**9.5**	**4.1**	-0.05	**0.41**	**-0.51**	**0.46**
		3	18 (27.7 %)	**15.6**	**18.8**	12.9	2.8	**-0.07**	0.36	-0.36	0.40
Right turn	Coffee & West Broadway (control site)	2	3 (100 %)	**16.5**	**18.3**	14.6	2.2	**0.01**	**0.27**	**-0.22**	**0.33**
	Coffee & Elmhurst (discontinuity site)	4	3 (100 %)	9.8	11.4	**8.6**	1.7	0.00	0.24	-0.21	0.32



a. Coffee St and Elmhurst Ave (discontinuity)



b. Coffee St and West Broadway St (control)

Figure 6-2 Cyclist motion patterns (represented by their prototype trajectories) for the change in cycling facility type discontinuity

6.6.3 Change in Facility Side

6.6.3.1 Motion patterns

In this category, the discontinuity site is Maisonneuve Blvd west and Sainte-Catherine St where the separate cycle track located on the southeast side of Maisonneuve Blvd is moved to the north side of the road on the west side of the intersection (Figure 6-3.a). The aerial image of the intersection is not up to date and does not show the recently implemented cycle track on the west leg of Maisonneuve Blvd as manually indicated with white arrows.

As observed from the clustering results, cyclists traveling northeast have made four distinctive movements to cross the intersection: motion patterns 1 to 4 in Figure 6-3.a. Three movements are initiated from inside and one from outside the cycle track: 53 % of cyclists cross the west side crosswalk, then steer right to enter the cycle track, corresponding to motion pattern 1 in Figure 6-3.a, 16 % of cyclists cross the east side crosswalk and turn left into the facility, corresponding to motion pattern 2 in Figure 6-3.a, 6 % of cyclists travel straight on Maisonneuve Blvd towards oncoming traffic on the left side of the road and steer right to enter the cycle track further down the road, corresponding to motion pattern 3 in Figure 6-3.a, and the final 25 % of cyclists travel from the right side of the road and not from the cycling facility to be able to continue straight into the cycling facility, corresponding to motion pattern 4 in Figure 6-3.a. On the other hand, in the control intersection, all cyclists travel northeast through the intersection using the cycle track (motion pattern 1 in Figure 6-3.b).

Movements in the opposite direction follow a similar distribution; cyclists traveling southwest made four different maneuvers to cross the intersection at the discontinuity. 62 % of cyclists travel from outside of the facility on the northeast sidewalk (which is prohibited in Canada) straight into the facility, corresponding to motion pattern 5 in Figure 6-3.a. Among cyclists traveling from outside of the facility, 9 % merge with traffic to cross the intersection and enter the cycle track, corresponding to motion pattern 6 in Figure 6-3.a. Initiating from inside the cycle track, 19 % of cyclists travel diagonally into the cycling facility on the opposite side, corresponding to motion pattern 7 in Figure 6-3.a. The final 10 % of cyclists immediately turn right to cross the northeast crosswalk and then turn left to cross the northwest crosswalk and enter the cycle track, corresponding to motion pattern 8 in Figure 6-3.a. At the control site, all cyclists travel northeast on Maisonneuve Blvd through the intersection using the facility, corresponding to motion pattern 2 in Figure 6-3.b.

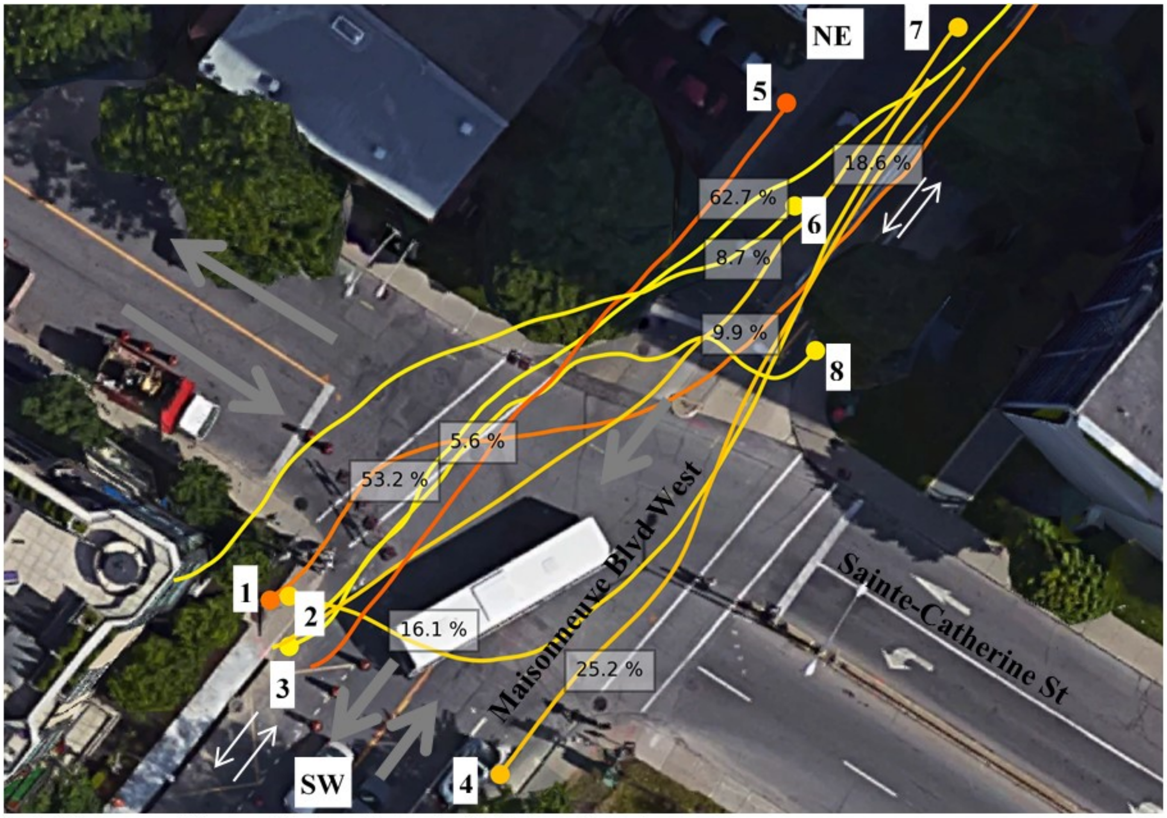
6.6.3.2 Speed and Acceleration

As presented in Table 6-3, cyclists travelling in the control site generally have higher median speeds compared to the discontinuity site Maisonneuve Blvd and Ste.-Catherine St. While there is variation between motion patterns, cyclists in the discontinuity site also show a higher variation in speed and acceleration (measured by higher mean of 85th centiles of speed and acceleration and lower 15th centiles of speed and acceleration) compared to the control site. Acceleration statistics in Table 6-3 show that cyclists perform harsher accelerations or decelerations at the discontinuity as they face more complex tasks and have to undertake more complex maneuvers.

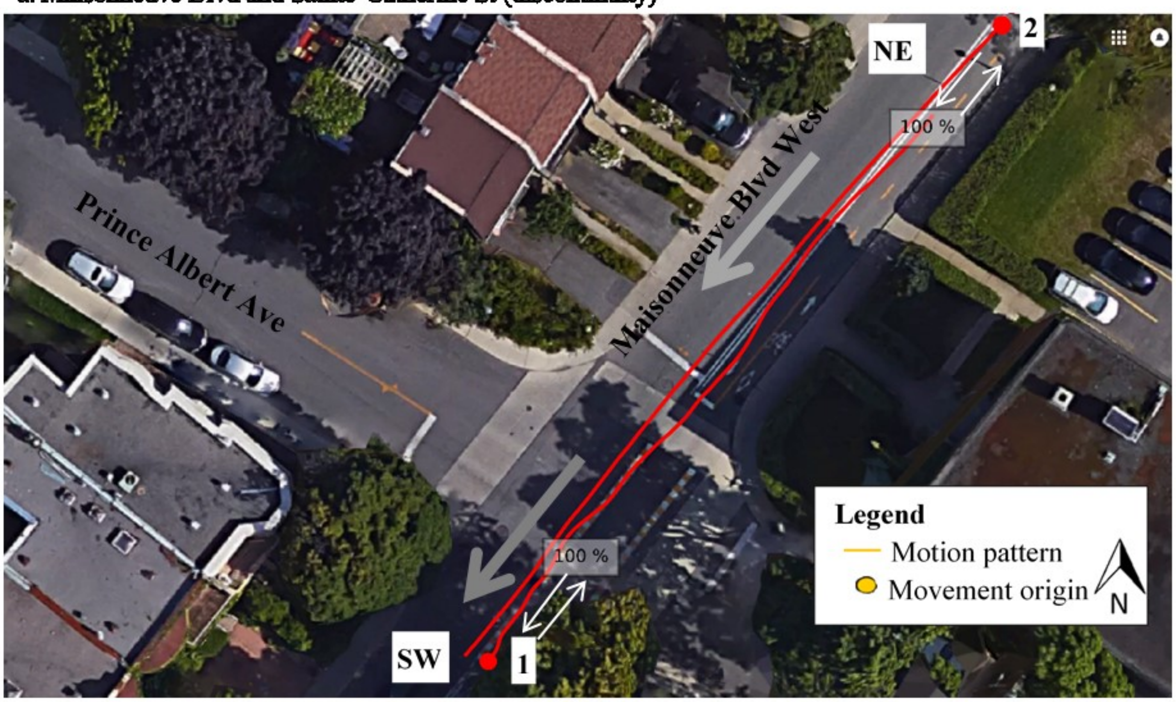
Table 6-3 Speed and acceleration statistics at the discontinuity and control sites

(the most extreme values are highlighted in bold)

Description				**Speed statistics**				**Acceleration statistics**			
Direction	Location	**Motion pattern number**	**Number of cyclists in motion pattern**	**Mean of median speeds (m/s)**	**Mean of 85th centile (m/s)**	**Mean of 15th centile (m/s)**	**Mean of St. Dev. (m/s)**	**Mean of median acceleration (m/s^2)**	**Mean of 85th centile (m/s^2)**	**Mean of 15th centile (m/s^2)**	**Mean of St. Dev. (m/s^2)**
Towards NE	Maisonneuve & Prince Albert (control site)	1	493 (100 %)	**22.0**	24.8	19.8	2.6	-0.01	0.22	-0.23	0.29
	Maisonneuve & Ste.-Catherine (discontinuity)	1	268 (53.2%)	18.9	22.5	**14.7**	**5.0**	0.03	0.23	-0.20	0.41
		2	81 (16.1 %)	20.4	25.3	17.5	3.9	0.02	**0.47**	-0.19	0.39
		3	28 (5.6 %)	21.7	**25.8**	19.1	4.9	0.00	0.26	**-0.23**	**0.44**
		4	127 (25.2%)	20.2	24.3	16.9	4.0	**0.04**	0.26	-0.15	0.31
Towards SW	Maisonneuve & Prince Albert (control site)	2	149 (100 %)	**21.6**	24.5	19.0	2.8	0.01	0.21	**-0.20**	0.26
	Maisonneuve & Ste.-Catherine (discontinuity)	5	101 (62.7%)	21.4	**25.9**	16.6	4.3	0.06	0.26	-0.12	0.26
		6	14 (8.7 %)	21.0	23.3	17.3	3.0	0.01	0.20	-0.13	0.26
		7	30 (18.6 %)	19.4	24.4	14.7	**4.6**	**0.07**	**0.39**	-0.15	**0.29**
		8	16 (9.9 %)	14.9	18.5	**10.4**	3.9	0.04	0.20	-0.09	0.21



a. Maisonneuve Blvd and Sainte-Catherine St (discontinuity)



b. Maisonneuve Blvd west and Prince Albert Ave (control)

Figure 6-3 Cyclist motion patterns (represented by their prototype trajectories) for the change in cycling facility side discontinuity

6.7 Discussion

For the change in cycling facility type (Coffee St – Elmhurst Ave, and Coffee St – West Broadway St), comparing the left turns at the discontinuity and control locations shows that for the three movements through the discontinuity, one movement was observed in the control site (Figure 6-2.a motion patterns 1, 2 and 3 versus Figure 6-2.b motion pattern 1). This shows that cyclists react differently and with more varied strategies at the discontinuity. The same observation is made at the discontinuity site with change in cycling facility side (Maisonneuve Blvd – west and Sainte-Catherine St, and Maisonneuve Blvd – Prince Albert Ave). While there is one movement for cyclists traveling either northeast or southwest at the control site, four different movements were observed at the discontinuity: Figure 6-3.b, motion patterns 1 and 2 versus Figure 6-3.a, motion patterns 1 through 8. The discontinuity also forces cyclists out of the cycle track before they approach the intersection (motion patterns 4 and 5 in Figure 6-3.a) so they can travel straight to the other side of the intersection to enter the cycling facility. At discontinuities, cyclists may not know how to proceed and may contemplate different movements from which they choose depending on their comfort levels, skills and experience. This result supports past findings where cyclists with different comfort and experience levels behave differently (Mereu, 2015).

Another behaviour is observed where cyclists choose to travel outside of the cycle track and actually ride on the sidewalk (motion pattern 3 in Figure 6-2.a, and motion pattern 5 in Figure 6-3.a.), which is prohibited in Canada. Since the cycling facility is designed to provide the most comfort, the fact that cyclists choose to ignore the law and ride on sidewalks at points of discontinuity could be an indication of the cyclists' difficult choices at discontinuities.

However, one needs to investigate other factors than the discontinuities that may influence and explain the observed differences in cyclist movements. Although the comparison of behaviour with a control site is common practice, factors other than the presence of the discontinuity may result in the distinct maneuvers at these locations. The investigation of these factors requires data from more locations and other means of analysis.

Speed and acceleration statistics were extracted from all trajectories and summarized for each motion pattern. Like movement variations, cyclists also had larger variations in speed, acceleration and deceleration at discontinuities compared to the control sites which had more stable speeds, which may be related to the behaviour of cyclists with different experience levels (Mereu, 2015).

Aside from the variation, the highest acceleration and decelerations at each of the four locations were observed at discontinuities. These variations support the fact that discontinuities are locations where cyclists are unsure of the path they should take to safely continue their journey.

It also suggests that other road users are also affected by discontinuities. Vehicles and pedestrians face unexpected maneuvers and speeds from cyclists at these sites where cyclists with different speeds are coming from different sides with different movements, compared to sites without discontinuities where cyclist speeds and maneuvers are more stable and predictable.

6.8 Conclusion

Although many studies have considered cyclist behaviour in different situations and conditions, there have been no in depth microscopic evaluation of the effects of discontinuities on cyclist behaviour. This paper makes use of video data and computer vision techniques to obtain cyclist trajectories at points of discontinuity and trajectory clustering to study cyclist behaviour.

The use of cyclist trajectory clustering provided valuable information on the microscopic movements of cyclists. This approach allowed us to distinguish several motion patterns. Studying two types of discontinuities in the cycling network in Montréal: Coffee St and Elmhurst St (Figure 6-2.a), and Maisonneuve Blvd and Sainte-Catherine St (Figure 6-3.a), showed that cyclists chose between a larger set of movements compared to one single movement at their control sites. Higher variations in speed, acceleration and deceleration are observed at discontinuity locations which indicates that cyclists with different comfort levels adjust their speeds and movements to go through a discontinuity. Overall, the trajectory clustering method allowed us to observe sets of movements and summarize each cluster's components for comparison. This method can be applied to any area for similar analysis or for other purposes.

The results from this study confirm the importance of including discontinuity indicators in the planning and evaluation of cyclist network performances given the effect it has on cyclist behaviour. The lack of these indicators in current evaluation criteria provides a partial image of the quality of a cycling network and cycling experience and leaves transportation departments unable to address the effect of discontinuities on cyclists.

The challenges related to video data analysis include video recordings in windy conditions resulting in shaking in the video, and shadows of road users that are tracked as actual road users. Other challenges such as over-grouping and over-segmentation can be alleviated by optimizing tracking parameters. Classification errors are also observed and can be decreased by retraining and optimizing the classifier for the conditions encountered at the sites under study.

In addition, future work will focus on analyzing more sites to draw stronger conclusions. Cyclist behaviour will be analysed more comprehensively using more indicators and the safety of cyclists will be assessed using surrogate measures of safety. To confirm our findings on observed behaviour and gain better insight into the cyclists' underlying motivations, more locations should be studied with different methods such as surveying cyclists to obtain information on their perceived comfort at locations with discontinuities.

Acknowledgements

This research project is funded by the Fonds de Recherche du Québec – Nature et Technologies (FRQNT), grant 2015-NC-180344, as well as the City of Montréal and boroughs that authorized the data collection. The authors acknowledge the assistance of Anae Sobhani, Asad Lesani and Ting Fu for data collection. Finally, the authors thank the anonymous reviewers for their constructive comments.

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LINK BETWEEN CHAPTER SIX AND SEVEN

The previous chapter presented the cyclist behaviour at two cycling network discontinuity locations and control sites in Montréal as a case study. The automated video analysis tool extracted road user trajectories and clustered similar trajectories to obtain cyclist motion patterns at the four sites. Results showed that at both locations with a discontinuity: change in cycling facility type and change in cycling facility location on road, cyclists made a larger number of movements with varied speeds than at the control site. While the previous chapter confirms that cycling network discontinuities are related with different cyclist behaviours, the safety implication of cycling network discontinuities is the focus of the next chapter. In the following chapter, the probabilistic surrogate measure of safety (PSMoS) approach is employed to extract TTCs of cyclist-vehicle interactions for the same case studies presented in the previous chapter. The TTCs are then aggregated per motion pattern to identify the risky cyclist maneuvers at discontinuity and control sites. The microscopic maneuver-based PSMoS is a novel approach that has not been adopted in literature for cyclists. The approach is a useful tool to identify the exact movements that influence the safety of cyclists. This information will help planners and city officials make better informed decisions by improving the infrastructural design of discontinuity locations to improve the safety of cyclist movements.

CHAPTER 7 ARTICLE 4: IS THAT MOVE SAFE? CASE STUDY OF CYCLIST MOVEMENTS AT INTERSECTIONS WITH CYCLING DISCONTINUITIES

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Accepted for presentation at the 98th Annual Meeting of the Transportation Research Board (peer reviewed conference), Washington D.C., 2019; and **submitted** to the the peer-reviewed journal of Accident Analysis and Prevention, 2019.

Submission date: July 31, 2018

Abstract

The cycling safety research literature has proposed methods to analyse safety and case studies to better understand the factors that lead to cyclist crashes. Surrogate measures of safety (SMoS) are being used as a proactive approach to identify severe interactions that do not result in an accident and interpreting them for a safety diagnosis. While most cyclist studies adopting SMoS have evaluated interactions by counting the total number of severe events per location, only a few have focused on the interactions between general directions of movement e.g. through cyclists and right turning vehicles. However, road users perform maneuvers that are more varied at a high spatiotemporal resolution such as a range of sharp to wide turning movements. These maneuvers (motion patterns) have not been considered in past studies as a basis for analysis to identify, among a range of possible motion patterns in each direction of travel, which ones are safer, and which are more likely to result in a crash.

In this study, cyclist motion patterns are obtained from two locations of cycling network discontinuity and two control sites in Montréal. A probabilistic SMoS method is adopted to obtain cyclist-vehicle interactions and compute their time-to-collision (TTC). The Kruskal-Wallis and Kolmogorov–Smirnov tests are used to compare the TTC distribution between motion patterns in each site and between sites with and without a discontinuity. Results show that interactions are more severe and less safe at both locations with a cycling network discontinuity and that cyclists following different movements have statistically different levels of safety.

Keywords: cycling network discontinuity, cyclist motion patterns, probabilistic surrogate measures of safety, movement-based safety

7.1 Introduction

While there was a 6.7 % increase in cycling mode share in the past five years in Canada, only 1.4 % of Canadians cycle (Statistics Canada, 2016). Despite their low mode share, cyclist accidents result in 2.2 % and 4.6 % of all road fatality and injuries respectively (Transport Canada, 2017). The increasing number of cyclists and their alarming safety statistics have compelled transportation researchers and planners as well as city officials and decision makers to invest resources in designing, implementing and improving the cycling network to accommodate cyclists while improving their safety, relying on information obtained from cycling studies. These studies focus on infrastructural, traffic and environmental factors that contribute to the safety of cyclists by examining historical accident data (e.g. (Gill, Sakrani, Cheng, & Zhou, 2017; Hubner, Schunemann, Schilling, & Radusch, 2017)) and surrogate measures of safety (SMoS) (e.g. (Guo, Sayed, Zaki, & Liu, 2016; Madsen & Lahrmann, 2017; Zangenehpour et al., 2016)) through descriptive and statistical analyses. Cycling safety studies dating back to the 1970s used accident data and observational traffic conflicts (Amundsen & Hyden, 1977; Noordzij, 1976). In recent years, improvements in sensor technologies, computer vision and data mining techniques have opened new doors to the faster and more accurate automated analysis of traffic and safety data.

SMoS are used as proactive and more ethical safety indicators that are based on events without a collision occurring more frequently than accidents. Traditional SMoS are based on the observation of traffic conflicts, defined as situations in which two or more road users approach each other to an extent that a collision is imminent if their movements remain unchanged (Amundsen & Hyden, 1977). This definition has usually been interpreted by evaluating whether road users are on a collision course if they continue with constant speed and direction (Gomaa Mohamed & Saunier, 2013). However, this simple motion prediction method does not accurately represent real-world situations where drivers perform slight steering or major maneuver changes such as turning. Furthermore, this is inapplicable in situations where road users do not have the option to continue on a straight path, for example at a T-intersection. To capture more naturalistic driving behaviours and better estimate safety, probabilistic surrogate measures of safety (PSMoS) rely on clustering road user trajectories into motion patterns to predict the road user’s future positions and compute more realistic and robust measures (Saunier & Sayed, 2008).

The safety of a site is usually analyzed globally, for example counting the number of severe traffic conflicts. Some studies may consider the locations of the events and the movements of the road users involved, with a coarse categorization based on the origins and destinations, e.g. northbound right turn, left turn and through movement. However, the road user movements are more varied at a high spatio-temporal resolution, e.g. thirty times per second. For example, right turning cyclist movements can vary between sharp and wide right turns, while left turning cyclist movements include vehicular left turns, and crossing the road on the far or near side walks (Figure 7-1.). This more detailed level of analysis will help better understand the different safety levels of specific movements and lead to more appropriate counter-measures.

In this paper, a movement-based PSMoS approach is proposed to evaluate the safety of road users' trajectories, to help researchers and decision makers better understand the relationship of behaviour and infrastructure with safety. To the best of our knowledge, road user safety has not been analyzed based on clusters of trajectories representing various movements and strategies per origin destination at a site-level. The findings can identify whether wide turns result in riskier interactions compared to sharp turns. This is done by clustering road user trajectories into motion patterns and applying the PSMoS technique to evaluate the severity of interactions related to the range of motion patterns traveling in each direction.

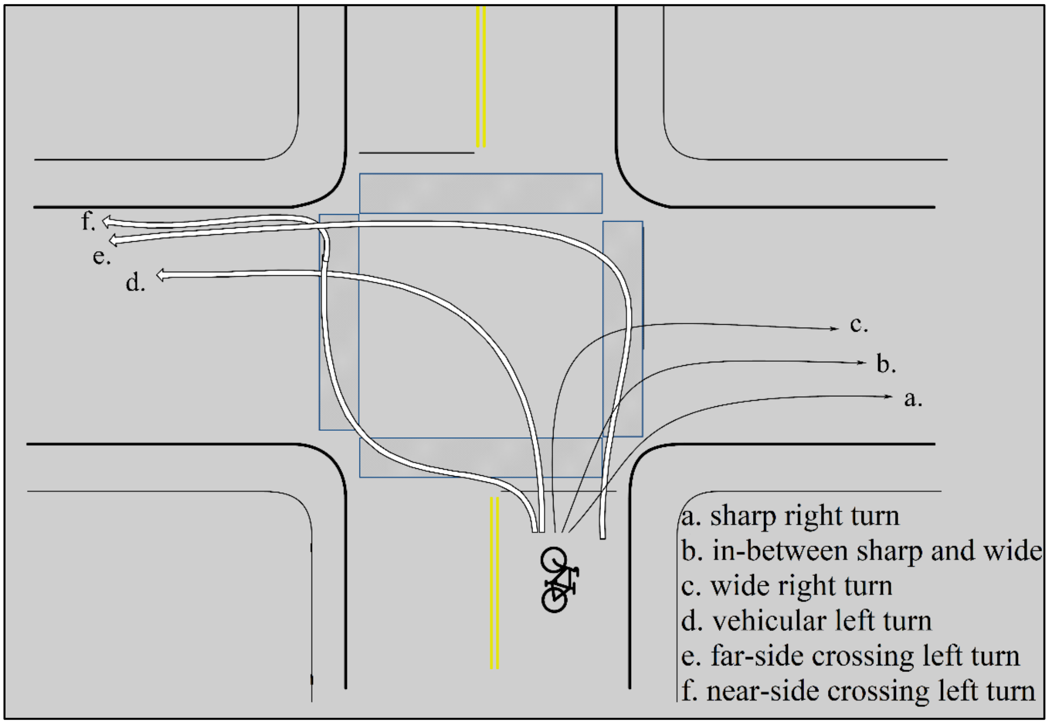


Figure 7-1 Some possible right and left turning movements

The safety of each movement (cluster) can then be compared. This approach is applied to two cycling network discontinuity locations and two control sites in Montréal where cyclists have been observed to follow several distinct motion patterns (Nabavi-Niaki et al., 2018). For the safety analysis, the considered SMoS are based on the time to collision (TTC), aggregated for each interaction by the 15th centile (TTC_{15}). The Kruskal-Wallis and Kolmogorov–Smirnov tests are employed to compare the distribution of TTC_{15} per motion pattern and among sites.

A summary of related past literature is presented in the following section. The whole data workflow and the movement-based PSMoS method are then described in the Methodology section. Descriptive analysis and test results are presented and discussed, and the paper is concluded in the final section.

7.2 Review of SMoS Assessment Methods

Reviewing the literature shows that cyclist SMoS studies have used four general data collection methods: self-reported conflicts, manual observation of traffic conflicts, semi-automated interaction detection, and automated analysis from video data. Additionally, two approaches are employed to analyse the results: interaction analysis, and aggregated movement interaction analysis.

The first class of conflict identification methods is conflicts self-reportings. Aldred and Goodman studied over a thousand self-reported conflicts and found that cyclists with less than two years of experience have much higher conflict frequencies compared to cyclists with more experience (Aldred & Goodman, 2018). Similar results were found by Poulos et al. where a study of over 3400 self-reported conflicts indicated a higher frequency in conflicts for less experienced cyclists and cyclists who rode as a mode of transport compared to leisure and sport (Poulos et al., 2017).

The second category of data collection method relies on trained observers to record the number of traffic conflicts and assign a severity to the event based on estimated speed and proximity from field observations or video recordings (manual video analysis). Glauz and Migletz adapted the field observation method to record the traffic conflict and volume at intersections and found that left turning conflicts with through vehicles are more frequent at two-lane roads, and at roads with higher speed limits (Glauz & Migletz, 1980). A study of manual video analysis at signalised intersections counted the number of observed conflicts if one road user reacted with an avoidance manoeuvre, and applying statistical analysis concluded that cyclists travelling through the yellow phase, and high speed cyclists have a higher chance of being in a conflict with turning vehicles (Buch & Jensen, 2017). Another video observation study of Dutch cycling facilities identified conflicts and their severity based on the Dutch Objective Conflict Technique for Operation and Research (DOCTOR) technique (A. Richard A van der Horst et al., 2014). Their results indicated that narrower cycling facilities resulted in more serious conflicts compared to wider facilities.

The third data collection method is the semi-automated analysis of video data. A study evaluating the seasonal safety in numbers effect utilized a semi-automated video analysis technique and extracted the number of conflicts based on the Swedish traffic conflict technique (TCT) (Fyhri et al., 2017). Their results concluded that cyclists experience a short term safety in numbers effect further into the cycling season and fewer occasions of being overlooked by cars resulting in conflicts (Fyhri et al., 2017). In another study, Madsen and Lahrmann investigated the safety of different cycling facility layouts at intersections using semi-automated video analysis tools and two traffic conflict indicators and found that recessed separated cycling facilities at intersections are safer having the highest TTC compared to the other layouts (Madsen & Lahrmann, 2017).

Finally, automated methods of extracting conflicts from video data have been developed and used more recently in the literature. Stipancic et al. extracted SMoS from video data and evaluate cyclist safety at intersections (Stipancic et al., 2016). They found that female cyclists are more likely to be involved in dangerous interactions compared to male cyclists (Stipancic et al., 2016).

Analysing the generated conflict indicators to evaluate safety has been done by analysing either all interactions or based on their general direction of movement. The majority of the mentioned studies above have analysed all interactions, summarising the SMoS indicators per interaction. On the other hand, studies considering the cyclist movements focused on interactions involving a single general direction of movement such as through cyclists interacting with right and left turning vehicles. Madsen and Lahrmann investigated right and left turning vehicular movements with through cyclists and found right turning maneuvers to have a higher risk compared to left turning, specifically at locations where the cycling facility ended before the intersection and locations where cyclists shared the road with right turning traffic (Madsen & Lahrmann, 2017). A SMoS study by Zangenehpour et al., adopted automated video analysis to evaluate safety of through cyclists and turning vehicles focusing on the location of the cycling facility on the road (Zangenehpour et al., 2016). Their results showed that physically separated cycling facilities on the right side of the road are safer than on the left side of the road or the absence of cycling facility (Zangenehpour et al., 2016). Guo et al. examined the safety of location-based left turn lanes with an automated video analysis tool and found that intersections with outside left-turn lanes (on the right side of the road compared to the conventional left-turn lanes located on the left side of the road) had a higher frequency and severity of traffic conflicts compared to the absence of outside left-turn lane (Guo et al., 2016). Buch et al. compared accident data to conflicts obtained from manual video observations and found similar results between right turning vehicles and through cyclists at signalised intersections where cyclists riding through yellow, and cyclists with higher speeds increased the chance of a conflict between turning vehicles and through cyclists (Buch & Jensen, 2017).

While the safety of interactions has been studied for specific movements at a coarse level, the review of relevant literature did not yield any studies evaluating and comparing the safety of cyclist movements.

7.3 Methodology

Figure 7-2 summarises the general methodology steps which are discussed in detail in the subsections. It should be noted that the cycling facilities throughout the paper are categorised and defined as: physically separated cycling facility (raised median between cyclists and vehicles on the road), bike lane (painted stripe between the cyclist lane and vehicles on the road), designated roadway (painted shared space on the road with vehicles), and no facility (no infrastructure or other control devices for cyclists).

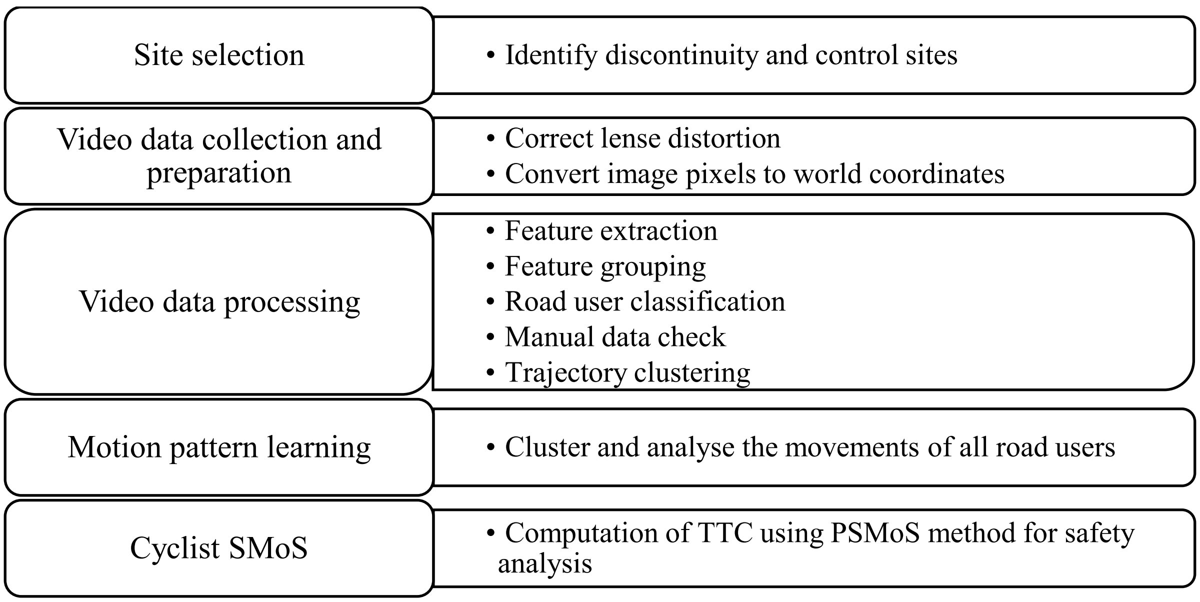
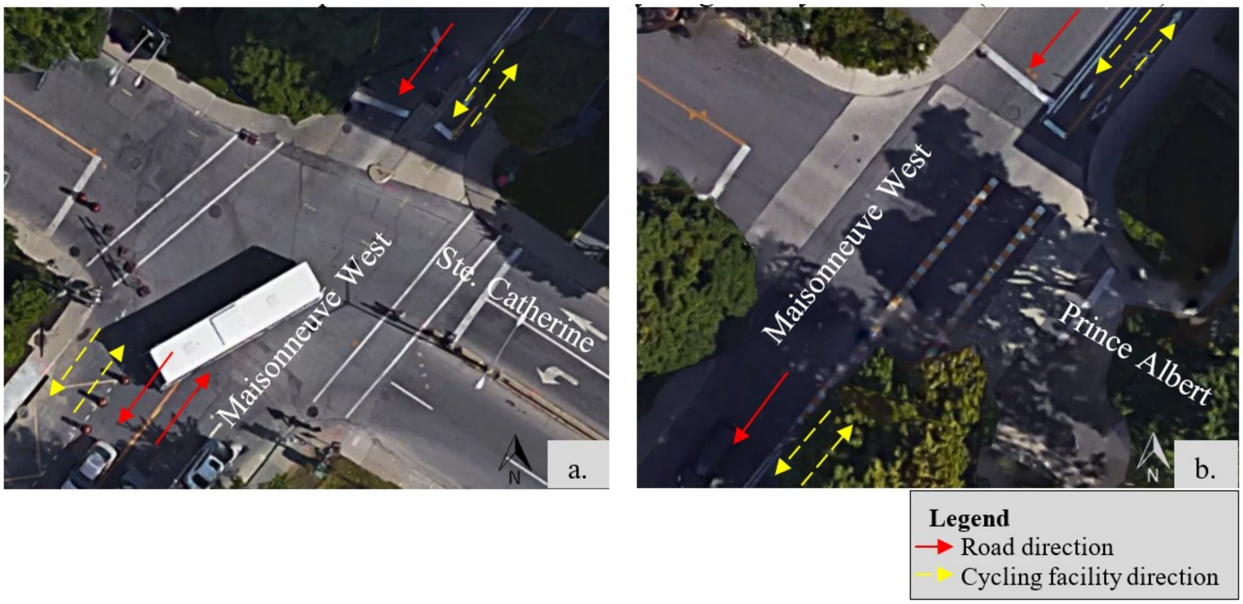


Figure 7-2 Methodology overview

7.3.1 Site Selection and Video Data Collection

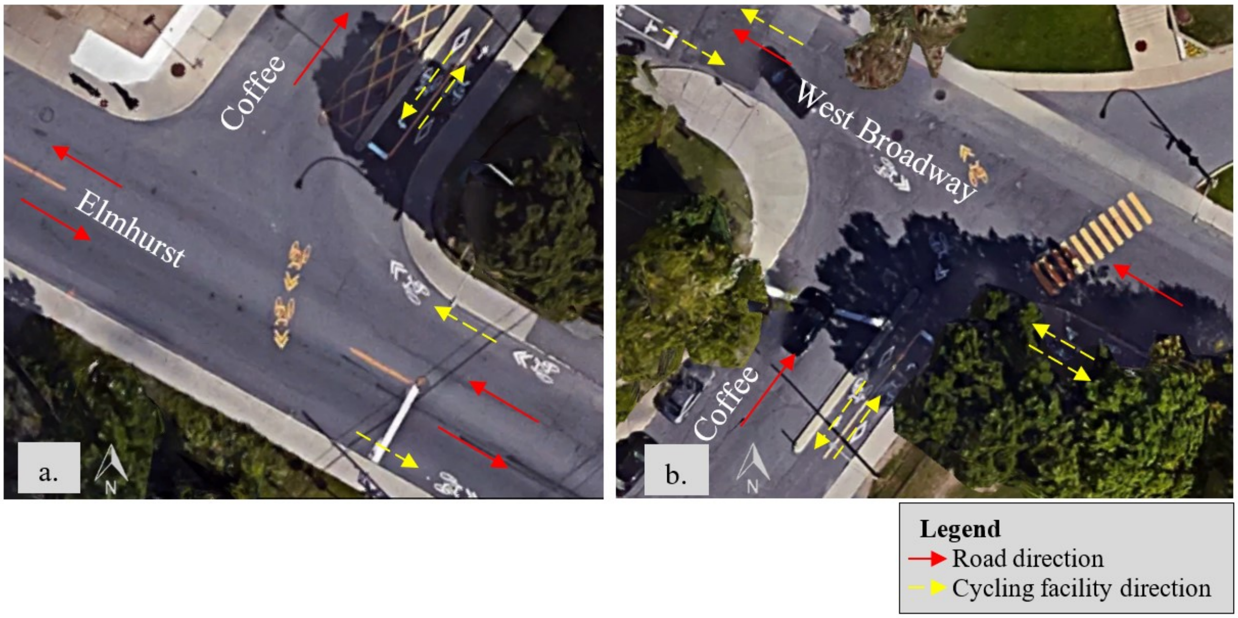
The first and second step to perform the microscopic movement-based PSMoS methodology is the case study site selection and video data collection. Cycling network discontinuity locations are identified in Montréal using the methodology presented in (M. Nabavi-Niaki, Bourdeau, Miranda-Moreno, & Saunier, 2018). Two pairs of discontinuity and control sites that are near each other and have the same cycling facility running through them are chosen. The first discontinuity is a change in cycling facility location on road. At the intersection of Maisonneuve boulevard west and Ste. Catherine street, the physically separated cycling facility running on the south side of Maisonneuve, changes to the north side, west of the intersection, as shown in Figure 7-3a. Besides, at the discontinuity intersection (Figure 7-3a.), Maisonneuve changes from a one lane road east of the intersection to a bi-directional road west of Ste. Catherine. The control site for this discontinuity, is located one block east of the discontinuity intersection, where there is no interruption in the location of cycling facility on the road (Figure 7-3b.).



Note: the aerial view of the intersection does not show the newly built physically separated cycling facility on the southwest corner of Maisonneuve, but the location is indicated with the yellow arrows.

Figure 7-3 Aerial view of the a. Maisonneuve and Ste. Catherine discontinuity, and b. Maisonneuve and Prince Albert control site

The second discontinuity is a change in cycling facility type and change in number of road lanes at the intersection of Coffee street and Elmhurst avenue (Figure 7-4a.). At this location, cyclists traveling from the physically separated cycling facility must turn into a shared roadway on the south leg of Elmhurst while crossing two lanes of bi-directional traffic. Cyclists traveling on Elmhurst have the shared space lane markings for a designated roadway cycling facility, which disappears north of the intersection. The control site is the intersection of Coffee street and West Broadway street (Figure 7-4b.), which is one block east of the discontinuity intersection. At this location, there is a physically separated cycling facility on the southeast side of the intersection a bike lane on the northwest leg of West Broadway for cyclists traveling southeast and designated roadway for cyclists traveling northwest, and both streets are one-lane unidirectional roads.



Note: the aerial view of the intersection b. Coffee and West Broadway has the physically separated cycling facility blocked by trees, the yellow arrows indicate the location where the facility exists

Figure 7-4 Aerial view of the a. Coffee and Elmhurst discontinuity, and b. Coffee and West Broadway control site

Video data was collected on weekdays in October 2015 from 7:00 AM for roughly seven hours, using a GoPro camera installed on a height-adjustable pole placed next to and secured to a light pole. Video data preparation includes the correction of the camera lens distortion, and a homography matrix is used to convert pixels in the image plane to world coordinates to track road user trajectories from the two-dimensional video frame in real-world coordinates.

7.3.2 Video Data Preparation and Analysis

The next step, shown in Figure 7-2, is video data processing. A feature-based tracker and a road user classification tool from the open-source project "Traffic Intelligence" (Jackson et al., 2013) are used to obtain road user trajectories and their type: car, pedestrian, bike. For this study, two hours of video data is selected for each site for detailed analysis. For the Maisonneuve and Ste. Catherine as well as Maisonneuve and Prince Albert locations, the selected time is from 8 AM until 10 AM. At the other two sites however (Coffee and Elmhurst, and Coffee and West Broadway), the early hours of the morning coincided with glare, large shadows cast by road users and some shaking in the camera due to wind. For this reason, the two-hour analysis period for these sites had to be chosen based on a time where these limitations were reduced, for Coffee and Elmhurst the hours between 10 AM and 12 PM are selected, and for the control site Coffee and West Broadway the analysis period is between 12 PM and 2 PM. Although this difference in analysis time frame is not desirable, the quality of the tracking results was of more importance to the scope of this study.

For the analysis duration, tracking parameters are adjusted for each site by trial and error to optimize trajectory extraction. Furthermore, the road user trajectories for each video are observed and over-segmented objects that are tracked as two or more objects are identified and only one trajectory is kept for each road user. Classifiers are updated based on speed parameters of road users for each site, then the video is manually checked for misclassified road users and corrected. The final prepared dataset at each site is a set of trajectories (one for each road user) with their true road user class.

A clustering algorithm developed in previous work (Mohamed & Saunier, 2015; Saunier & Sayed, 2006) is adopted to combine similar trajectories based on the longest common subsequence similarity (LCSS), using the Manhattan distance and a threshold to define similar individual positions between two trajectories, normalized by the minimum length of the two trajectories. In this custom algorithm, if a trajectory is not similar enough to a current cluster, it becomes a new cluster. The parameters used for clustering in this study are a maximum distance of 2 m for the Manhattan distance and 0.6 for the minimum similarity. Each cluster, referred to as motion pattern, is represented by an actual road user trajectory.

For analysis purposes, only the motion patterns with cyclists, potentially affected by the discontinuity along their path, are considered in the analysis. These are the cyclist motion patterns with origins and destinations, that would have used the cycling facility if it was continuous. These motion patterns affected by the discontinuity are referred to as the motion patterns under study throughout the rest of the paper. The comparison of cyclist behaviour at discontinuity and control sites relies on the set of motion patterns associated with each direction of movement under study.

7.3.3 SMoS Computation

The last step (see Figure 7-2) of the methodology computes PSMoS. All interactions with a collision course are identified and their TTC is computed based on the PSMoS method. Using a prediction horizon of 5 s, all TTCs are therefore smaller than 5 s. They are summarized for each interaction using the 15th centile TTC (TTC_{15}) (similar to (St-Aubin, Saunier, & Miranda-Moreno, 2015)). Two statistical tests are employed to confirm the differences in safety levels across motion patterns and sites. Within each site, there are usually three or more motion patterns, and corresponding TTC_{15} distributions, to compare: the non-parametric Kruskal-Wallis (KW) test is adopted, the null hypothesis being that the medians of all groups are equal. TTC_{15} distributions are also compared between each discontinuity site with its corresponding control using the Kolmogorov–Smirnov (KS) two-sample test.

7.4 Case Study

7.4.1 Descriptive Analysis: Change in Cycling Facility Location on Road

7.4.1.1 Movement Analysis

At the discontinuity location, Maisonneuve and Ste. Catherine, a total of 2342 road users are detected in two hours, 369 of which are cyclists. During the same time at the control site Maisonneuve and Prince Albert, out of the 848 detected road users, 343 are cyclists which is roughly the same as the discontinuity location. Looking at the Maisonneuve and Ste. Catherine discontinuity intersection (Figure 7-5a.), there are 38 cyclist motion patterns under study, while at the control site (Figure 7-5b.) there are three motion patterns under study, showing a much higher variation in cyclist motion patterns at the discontinuity location.

Looking more specifically at the motion patterns under study, it is observed that cyclists travelling in both directions can be divided into four groups: those originating from inside the physically separated cycling facility and ending in the cycling facility, those originating from inside the cycling facility but ending on the road or sidewalk, those originating from outside the cycling facility and ending inside the cycling facility, and those originating and ending outside the cycling facility.

Figure 7-5 Cyclist motion patterns under study at the a. site with discontinuity, and b. the control site (origins marked with a red circle)

Cyclists traveling northeast originating from outside the cycling facility and ending in the cycling facility displayed four distinct maneuvers (Figure 7-5a.), and those originating from inside the cycling facility and ending in the cycling facility displayed 12 distinct maneuvers. In the same direction of travel, cyclists at the control site all followed the same movement traveling from inside the cycling facility and ending inside the facility (Figure 7-5b.). In the opposite direction, cyclists traveling southwest at the discontinuity chose among 19 distinct maneuvers. An almost equal number of motion patterns originated from inside the facility and ended inside the facility (10 motion patterns) and from outside the facility ending inside the facility (9 motion patterns). At the control site, there are two motion patterns in the southwest direction one travelling inside the cycling facility and one outside (Figure 7-5b.). At the discontinuity site, very few cyclists made a maneuver belonging to motion pattern number 5 (7 % of all cyclist trajectories) and 6 (7 % of all cyclist trajectories) showing that cyclists prefer not to ride on the road with vehicles. Surprisingly, at the control site, despite the existence of a continuous physically separated cycling facility on Maisonneuve, 23 % of the cyclists traveling southwest chose not to use the cycling facility.

7.4.1.2 Safety Analysis

At the discontinuity location, out of the total of 92 interactions with a collision course (and therefore a TTC_{15}), 65 belong to a cyclist motion pattern under study. Compared to a total of 72 interactions with a collision course at the control site with 69 interactions belonging to a cyclist motion pattern under study (see Table 7-1). Among the cyclist motion patterns under study, 8 motion patterns include cyclists in interactions with a collision course at the discontinuity location, belonging to six motion patterns traveling northeast (Figure 7-6a. motion patterns 1 through 6), and two traveling southwest (Figure 7-6a. motion patterns 7 and 8). At the control site, all motion patterns under study are associated with cyclists in interactions with a collision course (Figure 7-6b. motion patterns 1 through 3).

Comparing the two directions of travel, cyclists traveling northeast at both intersections have a higher number of interactions compared to the opposite direction in the motion patterns under study (60 and 51 interactions at the discontinuity and control site respectively). The median TTC_{15} are generally lower at the discontinuity intersection. Looking at the discontinuity motion patterns in this direction, the lowest median TTC_{15} correspond to cyclist motion patterns 3 (1.6 s) and 4 (1.7 s) (Figure 7-6a. and Table 7-1) representing cyclists travelling from inside the cycling facility and ending in the cycling facility, which constitutes 63 % of the cyclists in this direction. Motion pattern number 4 corresponds to cyclists making a diagonal maneuver originating from and ending in the cycling facility, and motion pattern number 3 corresponds to a maneuver closer to the pedestrian crosswalk. This shows that cyclists using the cycling facility in this direction (originating and ending in the cycling facility, Figure 7-6a. motion patterns 3 and 4) are involved in more interactions that are more dangerous compared to those who do not originate in the cycling facility (Figure 7-6a. motion patterns 5 and 6).

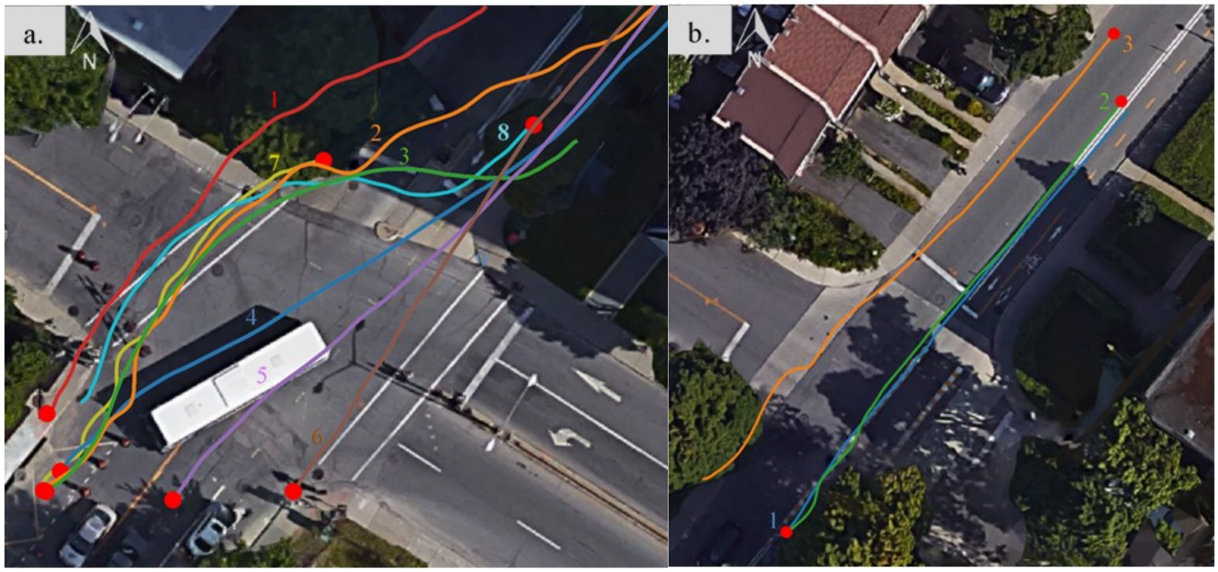


Figure 7-6 Cyclist motion patterns under study with cyclist-vehicle interactions with a collision course at the a. discontinuity location, and b. control site (origins marked with a red circle)

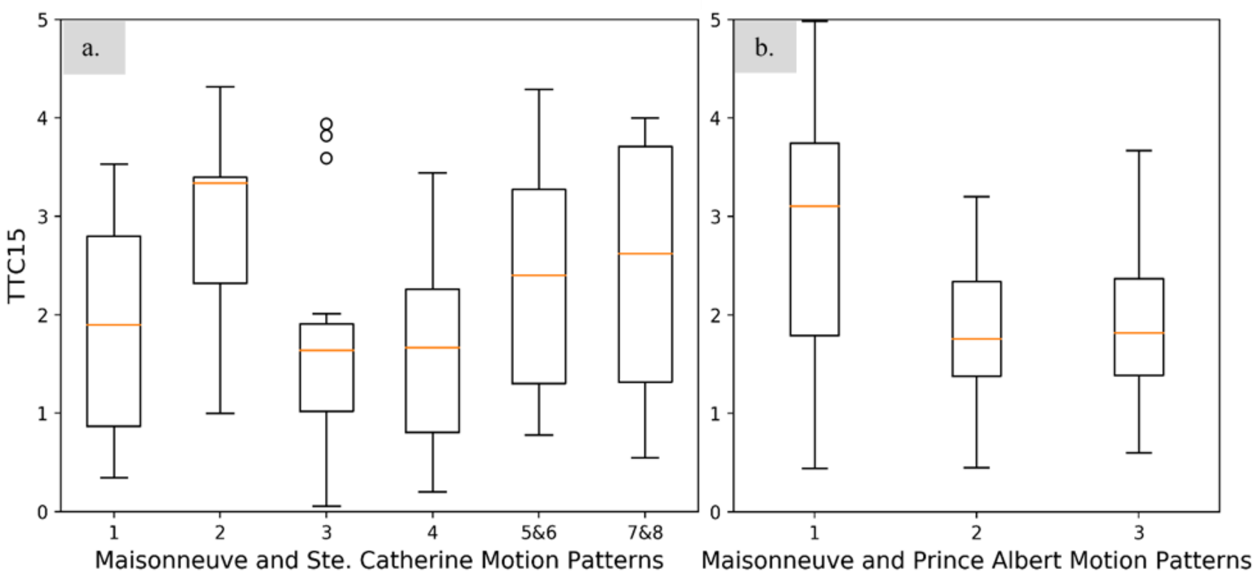
Cyclists traveling southwest and involved in interactions with a TTC_{15} value have two distinct motion patterns at both discontinuity and control sites. At the discontinuity site, 89 % of cyclists in this direction (Figure 7-6a. motion pattern number 7) avoided an irregular maneuver to reach the physically separated cycling facility on the other side of the intersection. Unexpectedly, cyclists traveling in this direction in the control site, corresponding to motion patterns number 2 and 3 in Figure 7-6b., have more interactions (18 interactions compared to 5) that are less safe than at the discontinuity location (Table 7-1).

Figure 7-7 shows the boxplot of all TTC_{15} recorded for each motion pattern. There is a clear variation in the TTC_{15} values among the motion patterns. The results of the KW test for differences in TTC_{15} medians among motion patterns within each site are the following: both tests are significant at the 0.1 level, $H = 12.4$, p-value = 0.09 for Maisonneuve and Ste Catherine (discontinuity), and $H = 8.3$, p-value = 0.01 for Maisonneuve and Prince Albert (control). In each site, there are significant differences in median TTC_{15} for the different movements, demonstrating that cyclists choosing different strategies to cross the intersection and the discontinuity in particular, are exposed to different levels of risk of collision.

Table 7-1 Summary of motion patterns with interactions

Direction of travel	Location	Motion pattern number	Number of cyclists (% cyclists in travel direction)	Number of interactions	Median TTC_{15}
Cyclists Traveling NE	Control	1	234 (100 %)	51	3.1
	Discontinuity	1	15 (9 %)	9	1.9
		2	24 (14 %)	17	3.3
		3	52 (31 %)	17	1.6
		4	53 (32 %)	10	1.7
		5	11 (7 %)	4	2.4
		6	12 (7 %)	3	
Cyclists Traveling SW	Control	2	61 (77 %)	11	1.8
		3	18 (23 %)	7	1.8
	Discontinuity	7	24 (89 %)	3	2.6
		8	3 (11 %)	2	

Note: TTC_{15} samples for motion patterns with less than 5 interactions traveling in the same direction are pooled



Note: TTC_{15} samples for motion patterns with less than 5 interactions traveling in the same direction are pooled

Figure 7-7 Boxplot of TTC15 per motion patterns under study at the a. discontinuity, and b. control site

7.4.2 Descriptive Analysis: Changes in Cycling Facility Type

7.4.2.1 Movement Analysis

The second discontinuity location Coffee and Elmhurst has 1204 road users detected during the two hours, 26 of which are cyclists. At the control site Coffee and West Broadway, out of the 471 detected road users 34 are cyclists. The clustering algorithm applied to these locations resulted in 11 distinct cyclist motion patterns at the discontinuity location shown in Figure 7-8a., and seven at the control site shown in Figure 7-8b. Similar to the previous sites, the number of motion patterns at this discontinuity location is higher than at the control site. Since all cyclist movements at these locations are affected by the discontinuity, all cyclist motion patterns are considered as motion patterns under study as shown and numbered in Figure 7-8.

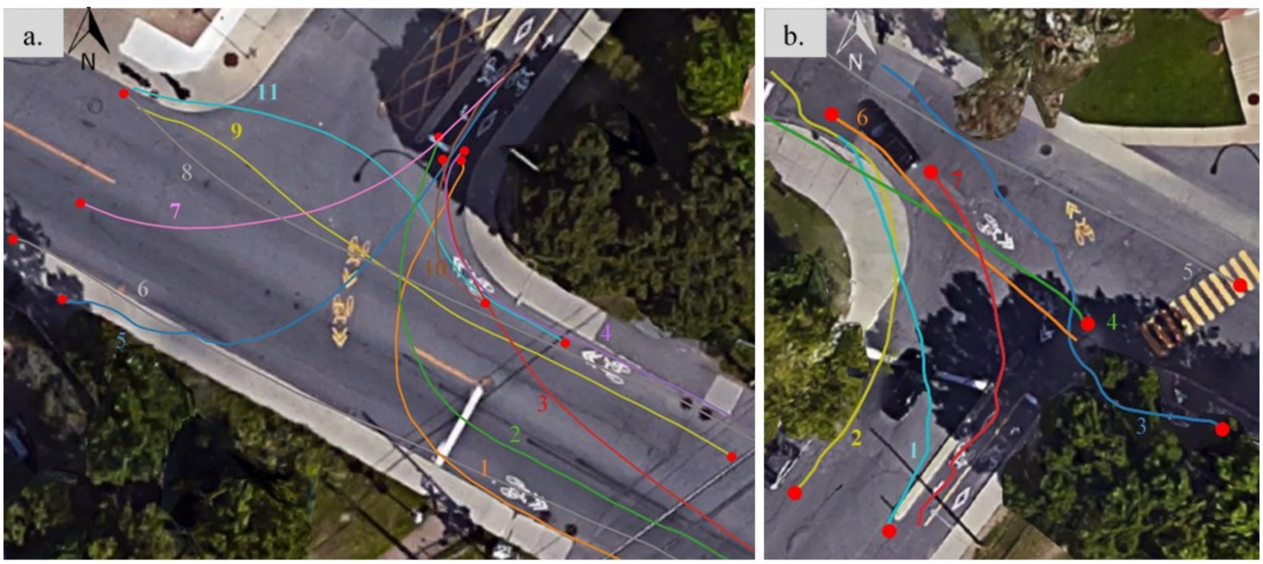


Figure 7-8 Cyclist motion patterns under study at the a. site with discontinuity location, and b. control site (origins marked with a red circle)

Motion patterns at these locations can be categorised into right turning, left turning and straight movements, where right or left turning cyclists are affected by the discontinuity either by a change from a physically separated cycling facility to a shared roadway, or crossing two lanes of bi-directional traffic from a one-way road. In the right-turning movements, both discontinuity and control sites have one cyclist motion patterns (Figure 7-8a., motion pattern number 10; and Figure 7-8b., motion pattern number 7). For the left turning movement, there are four distinct maneuvers at the discontinuity location for cyclists originating from inside the physically separated facility and ending in the designated roadway (Figure 7-8a., motion patterns 1 through 4) where cyclists in motion patterns 1, 2, and 3, crossed the two lanes of traffic, but cyclists in motion pattern number 4 turned into the road with oncoming traffic and avoided crossing the bi-directional traffic. At the control site there is one motion pattern corresponding to the same movement and origin destination (Figure 7-8b. motion pattern number 2), where the cyclists did not have to cross any lanes to enter the designated area. The other left turning movements at the location with discontinuity did not originate from a facility and cyclists travelled into the physically separated cycling facility (Figure 7-8a. motion patterns 5 and 7), with no observed corresponding movement at the control site.

Straight moving cyclists traveling northwest made two distinct maneuvers at the discontinuity location (Figure 7-8a. motion patterns 9 and 11), both traveling from the designated roadway to no facility. Motion pattern number 11 is closer to the sidewalk compared to number 9 traveling closer to vehicles on the road, while they both perform a swerving maneuver at the intersection to distance themselves from vehicles where there is no designated road lane marking. At the control site, three distinct cyclist motion patterns are observed two of which originate from inside the physically separated cycling facility and end in the designated roadway (Figure 7-8b. motion patterns 3 and 4), and one which originates from outside the facility traveling on the road (Figure 7-8b. motion pattern number 5). In the opposite direction at the discontinuity location, cyclists traveling southeast belonged to two motion patterns (Figure 7-8a. motion patterns 6 and 8), both of which are traveling on no facility and enter the designated roadway after the intersection. An unusual motion pattern which corresponds to only one cyclist movement is motion pattern number 8 at the discontinuity where the cyclists is traveling in the wrong direction on the road. For the same direction, cyclists at the control site belong to one motion pattern traveling from inside the bike lane to the physically separated cycling facility.

7.4.2.2 Safety Analysis

There is a total of 39 cyclist-vehicle interactions with a collision course (and therefore a TTC_{15} value) at the site with a discontinuity, assigned to the motion patterns under study (see Table 7-2). At the control site, 15 cyclist-vehicle interactions with a collision course are associated with the motion patterns under study. The lower number of interactions at the control site could be due to the fact that vehicle flow volume was lower compared to the discontinuity site. Keeping this in mind, the median TTC_{15} of motion patterns given the small sample size.

Considering the movement directions, cyclists turning left from inside the physically separated cycling facility at the discontinuity site have much lower median TTC_{15} (0.5 s) compared to its control site (3.1 s) (Table 7-2), This can be due to the cyclists crossing the bi-directional road and merging with traffic on the designated roadway (motion pattern number 1 and 2), and the cyclist travelling the wrong way (motion pattern number 4). The control site has higher, and therefore less dangerous, median TTC_{15} (3.1 s) for the three interactions in motion patterns 1 and 2. The right turning movement at both sites had only one motion pattern: motion pattern number 10 at the discontinuity site with five cyclists and four interactions (median TTC_{15} of 3 s), and motion pattern number 7 at the discontinuity site with only one cyclist and one interaction. Through cyclists traveling northwest at the discontinuity location made two maneuvers compared to three maneuvers at the control site. The motion patterns in this direction have a lower median TTC_{15} (1.2 s and 1.5 s) at the discontinuity site (motion patterns number 9 and 11 in Figure 7-8a.). In the last direction, cyclists traveling southeast with two distinct motion patterns and five interactions at the discontinuity location recorded the lowest median TTC_{15} (0.8 s for motion patterns 6 and 8, Table 7-2), compared to a median TTC_{15} of 2.7 s at the control site.

Table 7-2 Summary of motion patterns with interactions

Direction of travel	Location	Motion pattern number	Number of cyclists (% cyclists in travel direction)	Number of interactions	Median TTC_{15}
Left turn from facility	Control	1	3 (25 %)	2	3.1
		2	9 (75 %)	1	
	Discontinuity	1	1 (20 %)	1	0.5
		2	2 (40 %)	2	
		3	1 (20 %)	-	
		4	1 (20 %)	1	
Right turn into facility	Control	7	1 (100 %)	1	-
	Discontinuity	10	5 (100 %)	4	3.0
Traveling northwest	Control	3	7 (58 %)	3	3.0
		4	3 (25 %)	-	
		5	2 (17 %)	1	
	Discontinuity	9	3 (50 %)	8	1.2
		11	3 (50 %)	10	1.5
Traveling southeast	Control	6	9 (100 %)	7	2.7
	Discontinuity	6	4 (80 %)	4	0.8
		8	1 (20 %)	1	
Left turn into facility	Discontinuity	5	1 (20 %)	1	1.0
		7	4 (80 %)	7	

Note: median of TTC_{15} of motion patterns with less than 5 interactions traveling in the same direction are combined

As shown in Figure 7-9, almost all of the motion patterns at the discontinuity location have one or all quartiles below 1.5 s, except for number 10 corresponding to cyclists turning right from the road to the cycling facility, compared to two motion patterns at the control site (motion patterns number 5 and 7) indicating more severe interactions at the discontinuity site. The KW test for the TTC_{15} distributions among motion patterns at the discontinuity site Coffee and Elmhurst shows that at least one motion pattern TTC_{15} median is significantly different from the others (H = 10.5, p-value = 0.06), confirming that some maneuvers at this site are significantly more dangerous than others. The test results for the control site Coffee and West Broadway is not significant (H = 0.8, p-value = 0.7), owing probably to the small sample sizes.

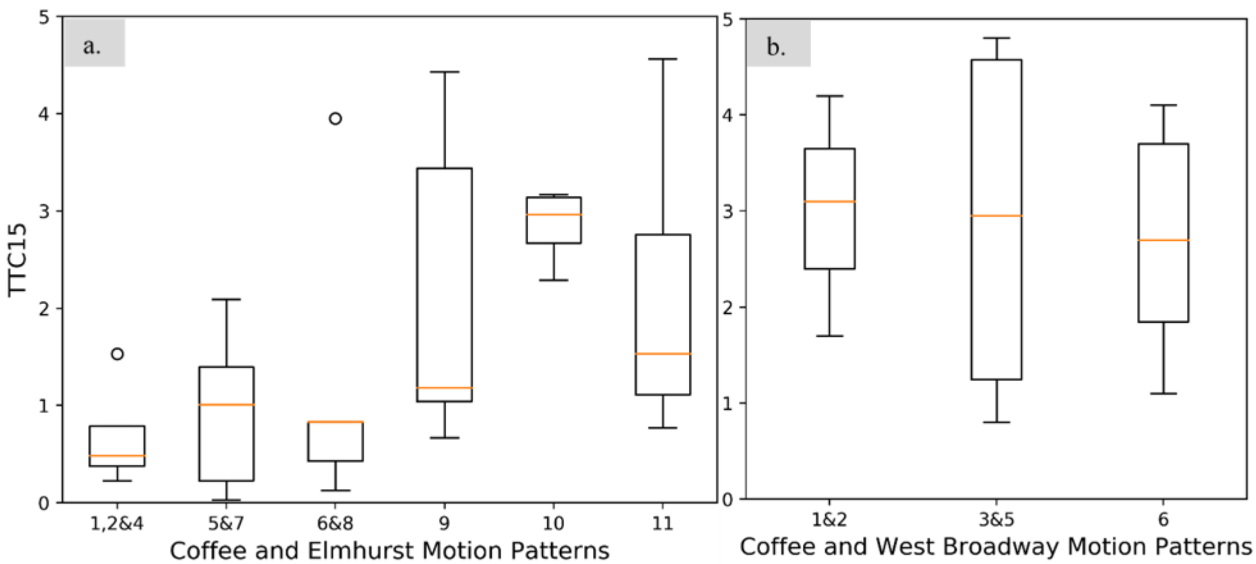


Figure 7-9 Boxplot of TTC15 per motion patterns under study at the a. discontinuity, and b. control site

7.4.3 Comparison of All Sites

Comparing the distribution of TTC_{15} among all sites (Figure 7-10) shows that both intersections with a discontinuity (Maisonneuve and Ste. Catherine, and Coffee and Elmhurst) have a lower TTC_{15} compared to their respective control sites (Maisonneuve and Prince Albert, and Coffee and West Broadway). The discontinuity locations have their TTC_{15} quartiles shifted towards lower TTC_{15} values compared to the control sites. In fact, the cumulative distribution functions shown in Figure 7-11 and Figure 7-12 show that the whole TTC_{15} distributions are shifted towards lower values at the sites with a discontinuity, indicating lower cyclist safety at these sites. The KS test confirms the difference to be statistically significant at the Coffee intersections (coefficient = 0.4, p-value = 0.05), but not at the Maisonneuve intersections (coefficient = 0.2, p-value = 0.2).

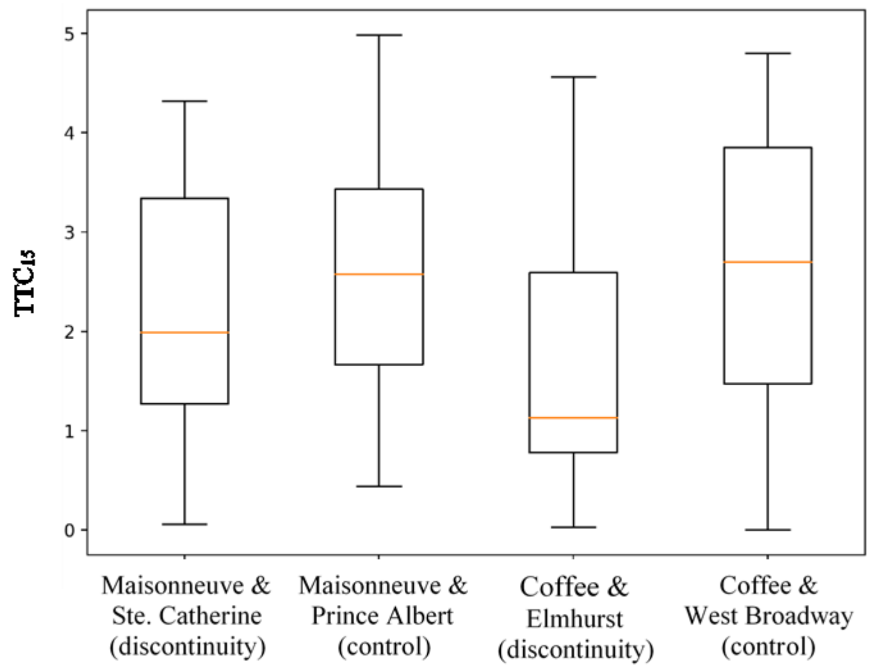


Figure 7-10 Boxplot of TTC15 of interactions affected by the discontinuity per location

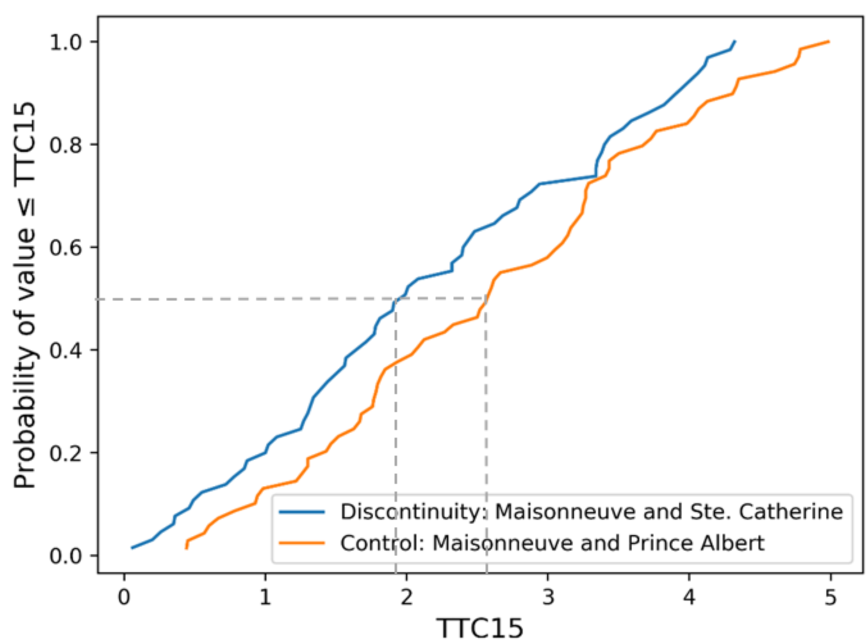


Figure 7-11 Cumulative distribution function of TTC15 of cyclists-vehicle interactions under study

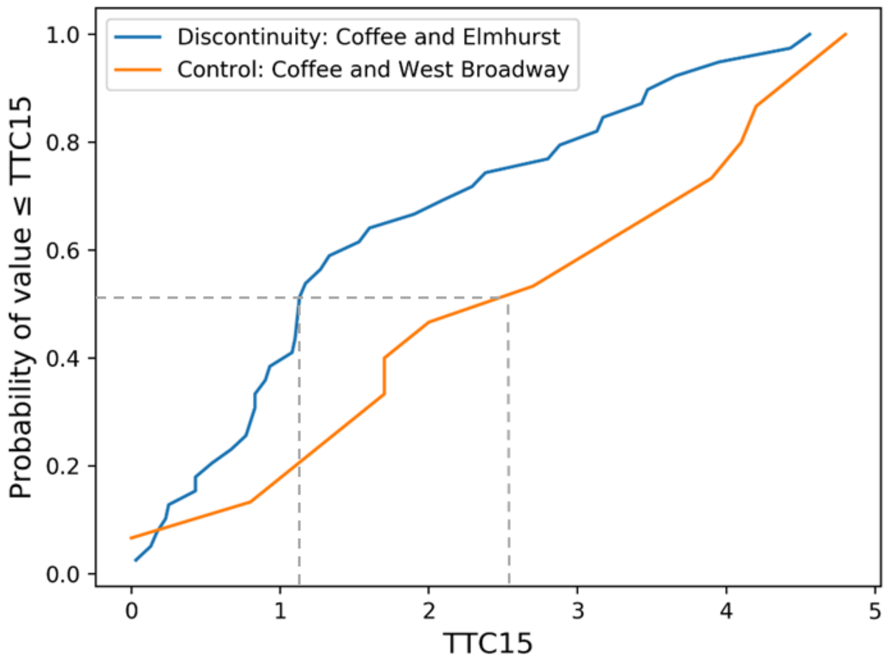


Figure 7-12 Cumulative distribution function of TTC15 of cyclists-vehicle interactions under study

7.5 Conclusion

This study proposes a maneuver-based surrogate safety analysis method and investigates the safety of cyclist maneuvers at locations with cycling facility discontinuities, compared to control sites. Four intersections are selected in Montréal, where the discontinuities include a change in cycling facility location on the road and a change in cycling facility type, with the control sites located one block east of their respective discontinuity sites. Video data is collected and two hours are selected based on video quality (reduced shaking, glare, and large shadows) for each location. An automated video analysis tool is applied to extract road user trajectories and combine similar trajectories as motion patterns. SMoS are adopted to obtain the unsafe interactions using the TTC_{15}, furthermore, the number of interactions and the mean TTC_{15} are summarized per corresponding motion pattern. The comparison of cyclist behaviour and safety among the locations even from the limited two-hour sample size indicates that discontinuity sites have more varied motion patterns and more unsafe interactions. At the discontinuity location where the cycling facility location changes from one side of the road to the other, the cyclists traveling northeast inside the facility have the lowest recorded TTC_{15} values, lower than the same direction at the control site. At the second discontinuity location with a change in cycling facility type, it is observed that left turning cyclists as well as cyclists traveling southeast have the lowest median TTC_{15} values. Among these, there are cyclists traveling in the wrong direction and cyclists crossing two lanes of traffic to ride in the center of the road with motorized vehicles. At the control site, all motion patterns have a higher median TTC_{15} compared to the discontinuity site, although this is from a smaller sample size.

The KW test indicated that for both discontinuity sites and one of the control sites (Maisonneuve and Prince Albert), there are significant differences among the median TTC_{15} values of the motion patterns within each site. This indicates that the movement-based surrogate safety method can pinpoint specific maneuvers that are less safe compared to other maneuvers. Furthermore, the TTC_{15} distributions are clearly shifted toward lower values at the discontinuity sites, compared to their respective control sites. The KS test confirms that the difference is statistically significant at the pair with a change in facility type. This work demonstrates that the different cyclist maneuvers have different levels of safety, and that cyclists at the observed discontinuity locations have more severe interactions with motorized traffic. Limitations of this study include the short duration of study (two hours per location). Although behavioural variability is easily observed, and statistical conclusions could be drawn, a longer duration of study would support stronger conclusions and may include other unsafe motion patterns associated with the discontinuity or control locations. In addition to the discontinuity, other differences within each pair of sites such as road geometry and traffic volumes may explain some of the observed differences in behaviour and safety. Other control and discontinuity locations should be investigated where there are similar and other discontinuities than the ones studied here. Improvements to video data collection, including glare, shadows and shaking of the video camera.

The movement-based safety analysis method can be applied to any area to identify geometric and infrastructural influences on cyclist behaviour and safety. Other SMoS, such as post-encroachment time (PET), may be used. With these results, more informed decisions on improving the design of a location can be drawn. Identifying and designing counter-measures to target the most unsafe maneuvers will significantly improve the safety of a location.

Acknowledgments

This research project is funded by the Fonds de Recherche du Québec – Nature et Technologies (FRQNT), grant 2015-NC-180344, and the National Science and Research Council (NSERC), grant 2017-06115. The authors acknowledge the assistance of Anae Sobhani, Asad Lesani and Ting Fu for data collection.

Author Contribution Statement

The authors confirm contribution to the paper as follows: study conception and design: M. Nabavi Niaki, N. Saunier and L. F. Miranda-Moreno; data collection: M. Nabavi Niaki; analysis and interpretation of results: M. Nabavi Niaki, N. Saunier; draft manuscript preparation: M. Nabavi Niaki, N. Saunier. All authors reviewed the results and approved the final version of the manuscript.

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CHAPTER 8 DISCUSSION

8.1 Overview

The present chapter discusses the methodology applications and focuses on the outcomes of each objective and how they can be used by researchers, city planners and policy makers to improve the comfort, ease and safety of cycling.

The objectives of this dissertation aim to close gaps in the literature by defining cycling network discontinuity indicators and studying their effects on cyclist's behaviour and safety. Discontinuity indicators proposed and defined in the dissertation are selected based on a review of factors known to influence cyclist's behaviour and safety but that are not included in these studies. For example, using a cycling facility is identified to be safer compared to cycling on the road: as a result, the locations where there is a change from presence of cycling facility to no facility on the road are considered discontinuities. A total of 16 types of cycling network discontinuity indicators are proposed and defined, categorised into: 1) infrastructural discontinuities intrinsic to the cycling network (end of cycling facility, change in cycling facility type, change in cycling facility width, change in cycling facility location on road, change in pavement condition, change in road lighting, change in road grade, closure/rerouting of cycling facility due to construction or maintenance), 2) road and traffic discontinuities (change in road class, change in number of road lanes, intersections, change in traffic volume, change in traffic speed), and 3) other characteristics (driveways, bus stops, parking allowed on road). These indicators have not been used in the growing field of cycling network performance and safety evaluations.

The identification of discontinuity locations can help planners and city officials to better prioritize locations for improvements that will increase safety and cycling mode share. For this reason, two methodologies are proposed to identify discontinuity indicators and evaluate the continuity of 1), road and cycling infrastructure and 2) nighttime road lighting levels. The methodologies can be applied to identify cycling network discontinuities at different levels: for an area like an entire city or districts within the city or for individual trips. For the safety analysis at discontinuity locations, two types of data were employed: historical accident data and surrogate safety measures extracted from video data.

8.2 Cycling Network Discontinuities

The methodology to identify cycling network discontinuities is proposed in Chapter four of this dissertation. The proposed methodology is automated to provide a novel tool for studies to extract and include discontinuity measures in their analysis, which can be adopted by urban planners and city officials to identify discontinuity hotspot locations for further improvement as well as in the planning stage of a cycling network to eliminate discontinuity locations. The proposed approach is applied at two levels, 1) within the city: three Montréal boroughs (Appendix C); and 2) among regions: four North American areas (Chapter four), to compare and rank the discontinuity of the cycling networks. The borough level analysis in Montréal extracted seven discontinuity indicators based on the available data: end of cycling facility, change in cycling facility type, number of intersections along cycling network, change in number of road lanes, change in road class, change in traffic volume and bus stop locations. The city-level analysis among four North American cities extracted two discontinuity indicators based on the available data from open data portals: end of cycling facility and change in cycling facility type. Although 16 discontinuity indicators are proposed in Table 4-2, due to the lack of available information, only the two mentioned discontinuity indicators can be automatically extracted. This highlights one of the gaps in this field, where despite the significant attention and high importance placed on cycling by planners, city officials and researchers, the availability of data related to this field is limited. One of the basic forms of data is the geo-referenced cycling network that includes information on the number and direction of facility lanes, width of cycling facility, definitions and consistent assignments of cycling facility types, the location of cycling facility on the road: yet some areas lack even basic information such as cycling facility type and their direction of travel. For example, the city of Amsterdam, known as one of the most cycling friendly cities, provides open access to the city's cycling network; however, the cycling facility types are defined based on functional class (commuter facility type and leisure facility type) or categorised as origin-destination class, all of which can include shared road segments, shared space with pedestrian, physically separate sections and bike lanes. Other information that is not easily accessible is road characteristics such as the number of lanes, the lane width, the road class, the location of bus stops, the parking locations, and the type of signalization. Traffic volume which includes cyclist and pedestrian flows are even more difficult to access. Road related information is usually easier to find given the years of experience in auto-based data registry (from insurance and automotive companies), and cities with a more significant interest in promoting walking and cycling may have more robust and detailed data that can be accessed. However, the varying level of quality and detail of open access data limits the opportunity to perform studies and evaluations for analysis and comparison purposes. This limitation emphasizes the importance of recording and sharing high quality data by different governmental levels and transportation agencies. The automated method proposed in this dissertation is made available under an open source license so that cycling network discontinuity indicators can easily be extracted with available data (Nabavi Niaki et al., 2018).

One of the discontinuity indicators proposed in Chapter four is change in road lighting. The lack of nighttime road lighting audit methodologies motivated the development of easily applicable road illuminance data collection procedures in this dissertation for maintenance and safety analysis purposes. The initial intersection-based data collection method (presented in Appendix B) relies on walking across four legs of an intersection starting around 15 meters before the intersection and ending roughly 15 meters after the intersection. Since the GPS sensor is not accurate at the small intersection scale, especially in dense areas with high-rise buildings, the start time at each crossing is recorded to identify the exact set of illuminance measurements for each intersection leg. This methodology was applied to 158 intersections in Montréal for safety analysis. The methodology was then improved to eliminate the time it took to walk across intersections and record starting times at the beginning of each leg crossing. This improved methodology collects illuminance data at road link and intersections by attaching the illuminance sensor to a bike or scooter to travel along roads. This method allows for safety analysis at both intersection and road link levels, with faster data collection and processing times. The collected illuminance data can be summarized per road link or intersection by aggregating the illuminance measures within a buffer around the intersection or road link. The road lighting discontinuity indicator is calculated as the illuminance uniformity (ratio of average illuminance to minimum illuminance). The average illuminance and uniformity per location can be checked against road lighting standards to identify locations where road lighting is below standards. In Montréal, out of the 1442 downtown road links where illuminance data was collected, 48 % of links and 59 % of the 158 intersections had sub-standard lighting based on a medium pedestrian activity level (selected based on the assumed nighttime urban area pedestrian volume).

8.3 Cyclist Behaviour and Safety at Discontinuities

In chapter four, once the discontinuity indicators are proposed, macroscopic evaluation of cycling network performance is performed using discontinuity indicators. To evaluate the effects of road lighting discontinuity on vulnerable road user safety, the average link illuminance and uniformity are used along with Montréal's accident data. The statistical analysis employed the Negative Binomial model to correlate the frequencies of cyclist and pedestrian accidents separately with the following variables: illuminance variables (average illuminance, uniformity), accident data (number of cyclist accidents, number of pedestrian accidents), traffic flow (vehicle, pedestrian, and bicycle volumes), built environment (number of road lanes, presence of cycling facility, presence of tree) and road class (arterial, collector, local). The results indicated a higher risk of nighttime bike and pedestrian accidents at locations with higher illuminance levels, which is in contrast with past findings (Bryan, 2008; Rodgers, 1995; Zhou & Hsu, 2009). Also, the presence of a cycling facility and the arterial road type have a negative association with accident frequency. It should be noted that the road lighting standards used in Montréal do not specify an average maintained illuminance for cycling activity at intersections (McLean, 2012). Our results indicate that when proposing lighting standards, cyclist volumes should also be taken into consideration in addition to pedestrian and motor vehicle traffic volumes since effects of lighting can be different for the different road user types.

Furthermore, the proposed discontinuity methodology (Chapter four) is applied to the Island of Montréal to identify the city's infrastructural cycling network discontinuity locations to evaluate the microscopic effects of infrastructural discontinuity indicators on cyclist behaviour and safety. Among these locations, two discontinuity sites are selected for further analysis: 1) an intersection with a change in cycling facility type as well as change in number of road lanes and direction, and 2) an intersection with change in cycling facility location on the road and a change in the number of road lanes and direction. For comparison purposes, two control sites without any discontinuities are selected in close proximity to the discontinuity locations, and have the same cycling facility running through them. Video data is collected for the four sites on weekdays. The automated video and trajectory analysis tool (Traffic Intelligence (Jackson et al., 2013)) is used to extract road user trajectories and a clustering algorithm is adopted to cluster similar movements as motion patterns to identify the various cyclist maneuvers at the discontinuity and control sites. Also, cyclist speeds and accelerations are calculated and aggregated per motion pattern. The results are a set of cyclist motion patterns with the number of cyclists and median speed and acceleration of the cyclists associated to each motion pattern. This allows to identify the cyclist maneuvers, which can be used to change or adjust the cycling network to safely accommodate the favoured movements. An interesting behaviour is observed at the discontinuity locations where cyclists choose to travel outside of the physically separated cycling facility and instead ride on the sidewalk which is prohibited in Canada. Since a cycling facility is implemented to provide the most comfort, the fact that cyclists choose to ignore the law and ride on sidewalks at points of discontinuity could be an indication of the cyclists' high level of stress and difficult choices at discontinuities. In addition, the cyclist behaviour study indicates that locations with discontinuities contain a considerably higher range of cyclist maneuvers and speeds compared to locations where there is no discontinuity. At the location with a change in cycling facility type, cyclists performed three distinct left turning maneuvers compared to one movement observed at the control site. At the site with a change in cycling facility location, cyclists performed four motion patterns traveling in each direction compared to one motion pattern at the control site. Previous studies have identified the variations in cyclist speeds and cyclists approaching from different directions to be difficult to handle for drivers and may be less safe (Gerstenberger, 2015; Herslund & Jørgensen, 2003). These results denote the importance of including discontinuity indicators in designing or improving a cycling network, in performance evaluations as well as behavioural and safety studies.

The cyclist motion patterns are used to predict the future positions of road users to compute more robust SMoS. A unique microscopic movement-based surrogate safety analysis method is proposed in Chapter seven of the dissertation, to evaluate the safety associated with each motion pattern. The safety of different movements can then be compared, at the same and at different locations. Historical accident data is only able at best to capture the safety of general maneuvers such as right- or left-turn or through-movement as recorded by the police or ambulance paramedic. Video analysis methods have also focused on interactions between these general movements. However, movements are different, more microscopic: for example, turning movements can be categorised into sharp turns or wide turns each with different speed variations. Using the PSMoS method and the motion patterns, the TTC time series are computed for each interaction. The output of the method is a set of cyclist motion patterns with the number of cyclists and the 15^{th} centile TTC value (TTC_{15}) of each interaction. Descriptive analysis of the results shows that at both locations with a cycling network discontinuity there is a higher variability in cyclist motion pattern TTC_{15} values compared to their control site. At the discontinuity location with a change in cycling facility type, it is observed that left turning cyclists as well as through cyclists traveling southeast have the lowest median TTC_{15} values. Among these, there are cyclists traveling in the wrong direction, as well as cyclists crossing two lanes of traffic to ride in the center of the road with motorized vehicles. At the control site of the mentioned discontinuity, all motion patterns have a higher median TTC_{15} compared to the discontinuity site indicating safer interactions. At the discontinuity location where the cycling facility location changes from one side of the road to the other, the cyclists originating and ending in the physically separated cycling facility by performing a diagonal movement across the intersections, and those cyclists belonging to the motion pattern crossing the pedestrian crosswalks have the lowest recorded TTC_{15} values, considerably lower than the same direction at the control site. A Kruskal-Wallis test is adopted to evaluate whether there are motion patterns that have significant differences in their TTC_{15} distributions at each site. The results indicated that at both discontinuity locations, there are motion patterns that have significant differences in TTC_{15} values compared to other motion patterns. The Kolmogorov–Smirnov test results also indicate that cycling network discontinuities are associated with shifts to lower TTC_{15} values, which is related to less cyclist safety, and there are maneuvers at these locations that increase the risk of a severe conflict.

The next chapter summarizes and concludes the dissertation and covers the limitations and recommendations

CHAPTER 9 CONCLUSION AND RECOMMENDATIONS

9.1 Overview

Despite efforts by transportation agencies, cities and other levels of government, planning a cycling network within the existing road infrastructure has resulted in discontinuities along the cycling facility. Increasing coverage to bring accessibility means there will be locations where cyclists have to travel next to high speed traffic, on roads with less preferential cycling facilities such as bike lanes where there is parking allowed, and locations where road lighting is not implemented or well maintained. Although the presence of cycling facilities is preferred compared to riding on the road with motorized vehicles, the transition between cycling facility types especially when cyclists are forced to cross a road to continue riding on the facility results in a less safe and comfortable situation. Similarly, when riding on a cycling facility, changes in road lighting levels may have an effect on safety and security. That said, the effects of discontinuities as interruptions cyclists face along a cycling facility is a topic that has been overlooked in literature.

The focus of this dissertation is to propose and define cycling network discontinuity measures and demonstrate the safety and behavioural characteristics of cyclists when faced with changes along their route. To this end, cycling network discontinuity categories and indicators are proposed, and a methodology is provided to identify discontinuity locations along any cycling network (Chapter four). The methodology is applied to four North American cities to rank their cycling network performance based on discontinuity indicators (Chapter four). Furthermore, a set of discontinuity locations were selected in Montréal for further investigation. Nighttime road illuminance levels were collected to identify changes in road lighting levels, find locations where road lighting maintenance may have been overlooked by identifying sub-standard illuminance levels, and examine the safety of vulnerable road users using road accident data (Chapter five). Moreover, infrastructural discontinuities were identified in Montréal where two discontinuity and two control locations were selected for video data collection. Cyclist motion pattern and speed analysis was performed and compared between discontinuity and control sites (Chapter six). A movement-based surrogate safety analysis method is proposed and applied to evaluate the safety of movements within discontinuity sites and compared to control sites (Chapter seven). The following sections summarize the objectives and contributions of the dissertation, findings, study limitations and direction for future research.

9.2 Objectives and Contributions

The dissertation objectives aim to close the gap in the literature by defining cycling network discontinuity indicators and evaluating their relationship with cyclist behaviour and safety. Four objectives are defined to structure the dissertation.

The first objective is to define cycling network discontinuity indicators and to propose an automated methodology to identify and quantify cycling network discontinuities in any area. This objective is mirrored in three contributions summarized in the dissertation (Chapter four). The first contribution of this objective is the systematic definition of cycling network discontinuity categories and indicators. The second contribution is the innovative automated methodology to identify discontinuities in any location: within a city (at the municipality level covered in Appendix C), or at the regional level (Chapter four). This methodology can be adopted by city planners and researchers to identify locations where cyclists are faced with interruptions in the cycling network and to implement countermeasures. The third contribution is the application of the proposed methodology to four North American regions to evaluate and compare cycling network performance using some of the proposed discontinuity indicators.

The second objective is to perform a safety analysis of nighttime vulnerable road users considering road lighting discontinuities. This objective leads to two contributions which are demonstrated in Chapter four and Appendix B in the dissertation. The first contribution of this objective includes a new methodology to perform a manual data collection of nighttime illuminance data at an intersection (Appendix B) and link level (Chapter five) that can be adopted by any area to collect nighttime lighting levels and identify discontinuities in road lighting for maintenance and safety analysis purposes. The second contribution is the application of the methodology to Montréal urban signalized intersections (Appendix B) and road links (Chapter four) to collect road illuminance data to identify sub-standard lighting levels and evaluate nighttime vulnerable road user safety.

The third objective relies on performing a microscopic analysis of cyclist behaviour at discontinuity locations in the cycling network using video data (Chapter six). The contribution includes video data collection and analysis at two discontinuity sites showing varied motion pattern strategies and speeds compared to control sites (Chapter six). The different speeds and movements at discontinuities denote the importance of including discontinuity indicators in safety and behavioural studies, as well as in cycling network performance evaluations to highlight locations that require improvement.

The fourth and final objective is a novel movement-based approach to surrogate safety analysis of cyclists at cycling network discontinuities using video data and computer vision techniques (Chapter seven). Motion patterns are used to improve the prediction of SMoS. Furthermore, the safety results are aggregated per motion pattern, which has not been done in past safety studies. This method identifies which motion patterns are safer and which pose a higher risk to road users. More specifically, the first contribution is the innovative movement-based surrogate safety evaluation method, where safety indicators are summarized per motion pattern to compare safety across movements and between discontinuity and control locations. Similar to the previous objective, the outcomes of this study emphasise the importance of recognizing discontinuities as potential hotspot locations that must be included in network performance and safety studies. Another contribution of this method is the identification of the microscopic movements that increase the chance of being involved in a severe conflict, which will help researchers and transportation planners to better design movement-specific safety counter-measures.

9.3 Research Findings

The methodology is applied to compare the cycling network performance of four North American cities: Montréal, Vancouver, Portland and Washington D.C., based on two discontinuity indicators, change in cycling facility type and end of cycling facilities. Results show a high level of discontinuity in the cycling networks of the four cities. The city's discontinuity ranking from highest (worst) discontinuity level to lowest (best) are Portland (3.05), Vancouver (2.0), Washington (1.75) and Montréal (1.3).

Chapter five results are drawn from illuminance data of 1422 road links in Montréal. In this chapter, lighting discontinuity is measured by illuminance uniformity. The average illuminance and uniformity levels are calculated per road link as lighting indicators. These variables indicated that 48 % of the studied links had sub-standard illuminance levels. Furthermore, the statistical analysis of nighttime vulnerable road user accidents indicated that an increase in road lighting is associated with a higher risk of cyclist and pedestrian nighttime accidents, which is contrary to past findings (Bryan, 2008; Rodgers, 1995; Zhou & Hsu, 2009). This may be because darker areas with less visibility propel drivers to drive more cautiously and slowly, resulting in lower accident rates. It also suggests that over the ten years of the studied accident data, road lighting has been installed as a counter measure at locations with a high number of accidents. Discontinuous lighting (calculated as illuminance uniformity: the ratio of average intersection or link illuminance to its minimum point illuminance measurement), did not have a significant association with nighttime vulnerable road user accident. Other variables shown to have a significant association with the number of pedestrian or bicycle accidents are the presence of a bicycle facility (increase safety), the arterial road class (increase safety), the number of lanes per link (decreases safety), the vehicle flow (increases safety) and pedestrian flows (decreases safety).

The use of cyclist trajectory clustering in Chapter six provided valuable information on the microscopic movements of cyclists. This approach allowed us to distinguish several cyclist motion patterns. Cyclist behaviour analysis at discontinuity and control sites indicated that at the change in cycling facility type discontinuity location in Montréal, cyclists performed three distinct left turning maneuvers compared to one left turning maneuver at the control site. Similarly, at the discontinuity site with a cycling facility change in location on road, cyclists performed four distinct northeast-bound and four distinct southwest-bound maneuvers compared to one motion pattern in each direction at the control site. Furthermore, higher variations in road user speed, acceleration and deceleration are observed at discontinuity locations compared to more stable speeds at control sites. The results indicate that cyclists adjust their maneuver strategy and speed at these discontinuity locations depending on their experience or comfort levels when faced with these interruptions.

In Chapter seven, safety is evaluated at the same discontinuity and control sites as in Chapter six. After obtaining the motion patterns, the PSMoS method is used to compute the TTC time series and its 15th percentile (TTC_{15}) for all cyclist-vehicle interactions. The TTC_{15} results are aggregated per motion pattern. Results show that at both locations with a cycling network discontinuity there is a higher TTC_{15} variability among cyclist motion patterns. The unsafe maneuvers are identified, and the KW test is adopted to evaluate whether there are motion patterns that have significant differences in TTC_{15} distributions compared to other motion patterns at a site. The results indicate that at both discontinuity locations, there are motion patterns that have a significant difference among their TTC_{15} values compared to other motion patterns. The KS test confirms that the difference in TTC_{15} distributions is statistically significant between each pair of discontinuity and control locations. This work clearly demonstrates that different cyclist maneuvers have different levels of safety, and that discontinuities in the cycling network may result in more severe cyclist interactions with motorized vehicles. At the discontinuity location where the cycling facility location changes from one side of the road to the other, the cyclists traveling northeast originating from inside the cycling facility, traveling diagonally across the intersection, and those using the pedestrian crosswalks to end in the physically separated cycling facility on the opposite side of the road have the lowest recorded TTC_{15} values, considerably lower than the same origin-destination at the control site. At the second discontinuity location with a change in cycling facility type, it is observed that cyclists traveling in the wrong direction have the lowest recorded TTC_{15} values, as well as the left turning cyclists crossing two lanes of traffic to ride in the center of the road with other vehicles all of which are considerably lower than corresponding motion patterns at the control site. In summary, findings from this chapter indicate that the observed cycling network discontinuities have a negative association with cyclist safety.

9.4 Research Limitations and Recommendations

This dissertation is not without limitations. In this section, the limitations of each chapter are presented, and the recommendations are discussed.

Limitations related to Chapter four is the restricted number of cities studied which is due to the difficulty of finding cities with available cycling network data that included sufficient facility type information, resulting in the few indicators identified and compared between the cities. Among the 16 proposed discontinuity indicators, only the extraction of end of cycling facilities and change in cycling facility type were automated and made available in the open source repository (Nabavi Niaki et al., 2018).

The study carried out in Chapter five made use of various datasets which were not collected during the same time period. Inconsistencies in the time-frames for accident data (between 2001 and 2010), the traffic flows (2008 and 2009) and the illuminance data collection (2013) may not be able to capture the whole relationships of each variable with the other. Moreover, an issue with using AADT as traffic volumes is that nighttime traffic volumes are significantly lower than the AADT which might overestimate the effects of nighttime flows on safety. Given the low frequency of nighttime road accidents, to acquire a sufficient number of data points, ten years of accident data was used for the analysis. This is problematic since over the span of ten years road lighting and illuminance levels may have changed due to new road lighting implementations. To eliminate these problems, it is recommended to collect road user traffic flows specifically at night to better estimate its effects on nighttime safety, and proactive safety approaches can be used to eliminate the use of several years of accident data. This can be done by collecting nighttime video data using thermal cameras and calculating SMoS indicators (Fu, Miranda-Moreno, & Saunier, 2016).

The challenges related to video data analysis in Chapters six and seven include video recordings in windy conditions resulting in shaking in the video, sunny conditions resulting in shadows that might be tracked as actual road users. Other challenges such as over-grouping and over-segmentation can be alleviated by optimizing tracking parameters for each site. Classification errors are also observed and can be decreased by retraining and optimizing the classifier for the conditions encountered at the sites under study. Recommendations include checking the angle of the camera to obtain a top view of the area under study that would capture the road user trajectories from a few meters before to a few meters after the location of interest. The camera should be secured to a pole in such a way that windy conditions do not shake the camera, or preferably video data should not be collected during windy conditions. Other weather conditions that are not preferable are rainy and sunny conditions where road users cast a shadow that might be tracked as road users. To eliminate these problems however, thermal cameras are a better option that do not capture shadows or rain and can record data throughout the night.

9.5 Direction of Future Work

Future work related to the research in this dissertation include extensive video data collection and processing at more discontinuity locations and control sites. This can be done at different scales, within a city and between cities, to evaluate cyclist behaviour and safety across locations with the same discontinuity type. The different discontinuity measures can be further studied to identify the discontinuity type that has the most severe interactions. Adopting the movement-based safety method to discontinuity location can provide a comprehensive dataset, and advanced models can be employed to statistically evaluate the safety of road user motion patterns.

Additionally, the methodology to identify cycling network discontinuities can be applied by obtaining better quality cycling and road network datasets where all 16 discontinuity indicators can be extracted to summarize an area's discontinuity level. A macroscopic level of analysis can also be performed using cyclist route information to investigate the effects of discontinuities on cyclist route choice. GNSS data from cyclists can be used to identify how cyclists behave throughout the cycling network with different discontinuities. Finally, cyclist perceptions can be studied at locations of cycling network discontinuities. Stated preference surveys can be conducted to complement the revealed preference data from cyclist route choice studies to capture the latent class variable and its correlation with the various discontinuity locations.

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APPENDIX A – SITE SELECTION AND PARAMETER VALUES

The following section elaborates on the the practical details of selecting case study locations and parameter values for data processing and analysis. The case study location selection is related to Chapter six and seven while the parameter selection for data processing and analysis is relatd to Chapters four, six and seven. The recommendations for the selection of these locations and parameters are discussed for future studies.

Infrastructural Discontinuity and Control Site Selection

The methodology presented in chapter four is used to select the infrastructural discontinuity locations along Montreal's cycling network studied in Chapters six and seven. In Montreal, the georeferenced cycling data allowed for the identification of two discontinuity types: end of cycling facility and change in cycling facility type. Throughout the city, there were 428 locations of cycling facility ends and 176 locations where the cycling facility type changes. From these, a total of six discontinuity locations were randomly chosen. The municipalities/boroughs where the discontinuity sites were located were contacted for video data collection permition. Four out of the five boroughs granted permission for video data collection at four discontinuity locations for around eight hours. For each of the four discontinuity sites, a control site was selected. To select control sites, intersections immediately one block from the discontinuity site were selected to allow for similar bike and vehicle flow going through the cycling facility. Another factor that was considered was the similarity of the intersection geometry and built environment. From the four discontinuity and four control sites, two sets of locations had very few cyclist flow volume on the data collection day to allow for a conclusive behaviour and safety analysis and were consequently not analyzed in further deteail.

A recommendation for site selection for future studies is to identify as many discontinuity types in the cycling network as possible, and consider more discontinuity locations for data collection. Sites with higher cyclist and vehicle volumes should be prioritized for data collection. The control sites should be selected if the geometry and built environment of the intersections along the same cycling facility are similar to the discontinuity sites and the cycling facility is continuous in the direction of travel affected by the discontinuity.

Parameter Value Selection for Data Processing and Analysis

The selection of parameters to perform some of the data processing and analysis were done for the specific case studies based on manual sensitivity analysis. The buffer sizes used in chapter four were selected based on Montreal's georeferenced cycling and road networks. To apply this methodology to another area, the city's georeferenced road and cycling network should be considered when selecting buffer sizes. For example, a city with a very dense road network would require smaller buffer sizes compared to a rural area with a less densely distributed road network.

For the clustering of cyclist trajectories into motion patterns, the algorithm uses two parameters: the distance threshold for position similarity, and maximum similarity for a trajectory to belong to a cluster. The parameter values used in chapter six and seven were 2 m for the Manhattan distance and 0.6 for the minimum similarity. A sensitivity analysis was performed to select the parameters that result in the number of motion patterns with the most cyclists ranging from 1 to 3 m for the distance threshold and 0.4 to 0.7 for the minimum similarity. For future studies, the parameters can be adjusted depending on the data collection location and the number of different observed maneuvers. To increase the total number of motion patterns, the distance can be reduced, or the the similarity value increased. When selecting the parameters, it is important to collect and process enough data to guarantee a minimum number of cyclists per motion pattern and be able to draw conclusion from the analysis.

APPENDIX B – ARTICLE 5: METHOD FOR ROAD LIGHTING AUDIT AND SAFETY SCREENING AT URBAN INTERSECTIONS

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Published in Transportation Research Record: Journal of the Transportation Research Board, 2014, 2458, 27–36. doi.org/10.3141/2458-04

Presented at the peer-reviewed conference: 93rd Annual Meeting of the Transportation Research Board, Washington D.C., 2014.

Abstract

The review of recent research efforts in road lighting and safety shows an inconsistency in the methods to measure ambient road lighting. The importance of road lighting on improving night time safety is evident; however, the lack of actual illuminance field measurements results in a gap in the knowledge of whether installed road lighting provides adequate illuminance for clear visibility at night time or not. Previous studies considered the presence or absence of road lighting on safety without measuring actual illuminance of the road. This paper aims to propose a uniform methodology to perform a simple road lighting audit and safety screening that can be applied to any area.

To perform the proposed audit, a photometric sensor, data logger and information on the city lighting standards, geo-referenced accident data and traffic flow data are needed. To collect field measurements, the data collectors cross each side of the intersection with the sensors starting and ending 15 m before and after the intersection. Information on land use, road type, location of light poles, location of trees and weather conditions is collected. Based on the collected data, average illuminance of each approach of an intersection as well as the average illuminance of the whole intersection and the uniformity ratio of the intersection was calculated. These results are then used to compare to the city lighting standard to check if the installed road lighting is performing adequately. If illuminance values of an intersection were bellow the standard specifications, the intersections were ranked as sub-standard.

This methodology was then applied to a case study in Montréal, Québec, where 59 % of the selected sample intersections had sub-standard lighting. Statistical analysis showed that the number of night-time accidents was affected by traffic flow (or the ratio of minor to major flows) and the fact that the intersection average intersection illuminance did not meet the standard. For average illuminance, contributing factors were clear sky, hour of the night of the data collection, and presence of light poles and commercial lights.

Introduction

The purpose of road lighting is to provide visibility, security and safety for all road users during the night (Beyer & Ker, 2010; Bruneau & Morin, 2005; J. D. Bullough et al., 2013; J. Bullough, Zhang, Skinner, & Rea, 2009; Ekrias, Eloholma, & Halonen, 2008). Once light poles are installed according to specification standards, they are assumed to provide adequate illumination to road users at night. However, lighting equipment might not be well maintained and there are hardly any follow-ups on the performance of lighting and its effect on safety. With time and resources constraints, there are usually few field measurements done by municipalities to check if lighting meets the specification standards. This is problematic because with the rapid change in traffic flow and land use, the amount of illumination needed for visibility also changes (D. DiLaura et al., 2000). Safety issues at night where lighting standards are not checked can be related to illumination deficiencies (Beyer & Ker, 2010; Bruneau & Morin, 2005; J. D. Bullough et al., 2013; J. Bullough, Zhang, et al., 2009). Therefore, it is important to inspect the adequacy of road lighting performance on a regular schedule (Dussault, 2005).

A study done by the University of London reports that only a quarter of all travel done by cars are between the hours of 7pm and 8am, yet this period accounts for 40 % of fatal and serious injuries (Ward, Shepherd, Robertson, & Thomas, 2005). Another European study confirms that even though only 25 % of the vehicle-miles traveled is during the night, nearly 50 % of fatalities occur in those hours, making night time fatality rate three times higher than the daytime rate (Hasson & Lutkevich, 2002). This indicates that night time travelling is done a greater risk but some important night time issues, not directly linked to lighting, such as drunk driving and speeding, along with infrequent police controls, also contributes to overall risk. This brings up the importance of investigating night time accidents factors, the most important being lack of clear visibility (Beyer & Ker, 2010; Bruneau & Morin, 2005; J. D. Bullough et al., 2013; J. Bullough, Zhang, et al., 2009). Even though some studies looked at the effects of road lighting on accidents and safety (Beyer & Ker, 2010; J. D. Bullough et al., 2013; Donnell et al., 2010; Rohwer, 2011; RoSPA, 2009; Transport Quebec, 2013; Wanvik, 2009c; Yannis et al., 2012), a limited number of studies did actual field measurements. These studies use different ways of measuring illuminance most of which are cumbersome and often not sufficiently accurate (D. DiLaura et al., 2000). The methodology presented in this paper aims to propose a uniform practice to be applied to any area.

Studies considering road lighting and safety mostly measured only the presence and absence of light, or relied on before-after studies for road lighting implementations (Assum et al., 1999; Beyer & Ker, 2010; Donnell et al., 2010; Goodman et al., 2007; Griffith, 1994; Isebrands, Hallmark, & Hans, 2004; Wanvik, 2009c; Yannis et al., 2012). Although the presence or absence of lighting is a key factor, the amount of lighting provided could be inappropriate (too low or too high), resulting in non-adequate visibility and glare. More recent studies evaluate illuminance levels and meeting standards in relation with safety. One of the papers that considered illuminance measurements studied a sample of street lighting installations in urban areas using illuminance meters (Jackett & Frith, 2013). The authors concluded that average road illuminance has a significant effect on road safety, and the effect propensity is higher at locations with more severe levels of injury. Another study aimed to find the relationship between crash injury severity at night time and average road lighting illuminance (Gonzalez-Velez, 2011). Using illuminance measurements, they concluded that providing a certain amount of lighting in urban areas decreases the probability of crashes with injuries during night time.

This raises the question of the link between land use (residential, commercial, etc.), road lighting, and safety. If there is a link, what is the causal relationship between these factors? The assumption is that road lighting level is governed by land use development and therefore safety is related to the built environment and land use. For example, illuminance coming from other source than lighting poles is much higher in commercial areas.

This paper highlights the importance of conducting field audits on road lighting by introducing a simple method to systematically measure road lighting and evaluate its performance, and also by proposing a screening approach for identifying locations for lighting improvements. The methodology of auditing road lighting presented in this paper can be applied to any area to check if road lighting meets the requirements. A significant contribution with respect to past studies is to carry out actual field measurements of road lighting for analysis at urban and sub-urban intersections. The amount of ambient road light is measured using a photometric light sensor. Another goal of this paper is to study the relationship between lighting, safety and other characteristics of the built environment in urban and sub-urban areas. The methodology presented in this paper focuses on lighting at signalised and non-signalised intersections in urban and sub-urban areas as intersections are critical points in a road network where vehicles, pedestrians and cyclists share the same space. In Canada, more than 30 % of fatalities and 40 % of serious injuries occur at intersections (Transport Canada, 2011).

The proposed road lighting audit methodology is applied to Montréal's signalized intersections to check if the cities road lighting specifications are met. A statistical analysis is also done to relate the number of night time accidents to average illuminance and built environment characteristics.

The remainder of the paper is organized as follows; the background section provides a brief review of earlier research in context. Followed by that is the proposed road lighting audit methodology. Further it is followed by the application of the methodology to a case study of urban and sub-urban signalized intersections in Montréal. Finally the paper is concluded and future work is discussed.

Background

Road Lighting

The issue that people face after sunset is darkness and the lack of clear visibility. With the development of cities, the idea of illuminating human walkways during night time emerged. The main reason for illumination during night was to provide visibility, increase the sense of security and safety and to allow activities to take place in the later hours of the evening (Bradbury, Cameron, Castell, & Jones, 2007). Street lighting later on became a major factor in pedestrian safety and crime reduction during the night (Bradbury et al., 2007). With the rapid increase in population, vehicle ownership and size of cities, municipalities proposed lighting standard specifications aiming to create an environment with consistent lighting and adequate visibility for the safety of all road users. Yet there are no guarantees that the installed road lighting is performing sufficiently at all times, and therefore road lighting audits must be done to check if road lighting has an impact on safety or not.

In order to deal with light measurements, it is important to get familiar with units and technical terms. Illuminance is visible light as seen by the human eye and is measured in units of lux. The lux is carefully defined to weigh each wavelength by the luminosity function to reflect how light is perceived by human eyes (Green et al., 2003). Average illuminance is the brightness of the road as seen by a driver. Uniformity ratio is a measure of how evenly lit the road surface is, and is calculated by dividing average illuminance by the minimum illuminance of the road segment.

Road Lighting Specifications

By its nature, a standard defines adequate and acceptable practices. Different countries, cities and municipalities follow different lighting specification standards (Dussault, 2005; Wanvik, 2009c). Different standards require different pole heights, different distance between poles, different lamps and levels of lighting. The major North American lighting specification guide is the Illuminating Engineering Society of North America (IESNA) Lighting Handbook (D. DiLaura et al., 2000). The transportation association of Canada (TAC) also has a guide for the design of roadway lighting which provides lighting standards used by Canadian provincial transportation agencies ("Transportation Association of Canada (TAC)," n.d.).

Most of the road lighting standards only present the average maintained illuminance levels based on intersection types (D. DiLaura et al., 2000). Some standards include a minimum illuminance value for different types of intersection roads ("Transportation Association of Canada (TAC)," n.d.) and some give a maximum uniformity ratio value above which lighting will result in disability glare.

Road Safety

In cities where the national/provincial and municipal road lighting are dealt with separately, road lighting throughout the city will not be consistent, and many roads will be under-lit (Bruneau & Morin, 2005). A major point of interest in a transportation network is therefore at intersections (Canada, 2007). Different municipalities may use different lighting standards, which may also be different from national/provincial lighting standards. This results in intersections where one street is lit according to provincial standards and the other street according to municipal standards. There are some evidence that if one street has a high average illuminance and the other has substantially lower light, a driver turning from the well-lit road to the under-lit street will take a few seconds for his/her eyes to adjust to the darker road and also, if the driver is turning from the under-lit road into the well-lit road, he/she will be blinded by light for the first few seconds (J. Bullough, Rea, et al., 2009; Lighting Research Center & Systems, 2011; MS Rea, Bullough, & Fay, 2009). The glare recovery time ranges from 1 to 7 seconds depending on the age and optical health of the driver (Schieber, 1994). Disability glare occurs when the introduction of a stray light source reduces one's ability to resolve spatial detail (Schieber, 1994). The IES proposes maximum illuminance values and uniformity ratio to avoid the disability glare and the temporary reductions in visibility when the eye is adapting from alternately looking at areas of widely different illuminances (D. DiLaura et al., 2000). A study conducted by Box (Box, 1970) found that the number of night time accidents decreased as light levels increased up to an illuminance threshold, and then increased for higher light levels, which is hypothesized to be related to the impact of glare in locations with substantial lighting variation.

Several studies have looked at road lighting and safety. These studies focused on the absence or presence of road lighting. For example, a study showed that the presence of road lighting at night not only reduces the risk of accidents, but also their severity (RoSPA, 2009). Another study conducted in the Netherlands showed that an improvement in the lighting from very bad to good in an urban area reduced accidents with injuries by approximately 30 % (Schreuder, 1985, 1989). A study done in Minnesota looked at the effects of lighting on accident frequency for different intersection types, where the results showed that the presence of road lighting at intersections contributes to 12 % lower night-to-day accident ratio with respect to an unlit intersections (J. D. Bullough et al., 2013). Another study considering road lighting and safety concluded that the effect of road lighting on injury accidents during darkness is 49 % on Dutch motorways (Wanvik, 2009c). The same results were found in a study investigating the effect of lighting conditions on frequency and severity of road accidents at urban and rural roads in Greece. This research concluded that the presence of night time road lighting has an effect on improving traffic safety and reducing accident severity (Yannis et al., 2012).

Road Lighting Audit Methodology

This section presents the step-by-step methodology to systematically perform a lighting audit at signalised and non-signalised intersections. This practice can be applied to any area if the required data and equipment are available. The main steps of data preparation and analysis are:

1. Data sources: obtaining the city lighting standards, accident data, and traffic flow.
2. Data cleaning process: filtering accident data for accidents occurring at night time, and selecting intersections with night time accidents occurring in their vicinity.
3. Sample selection: identifying intersection hotspots based on traffic flow and the number of night time accidents.

4. Data collection in the intersection sample: collecting illuminance and built environment characteristics in the selected sample intersections.
5. Field data analysis: comparing average illuminance with standards and safety.

The following subsections will describe these steps in more details.

Data Sources

The first step is to find which lighting specification standards the city or municipality follows for installing road lighting. This information can be obtained from the city transportation department.

The primary type of data for this research is geo-referenced accident data, usually obtained from hospital records, police reports or ambulance intervention reports. Accident data should be obtained for a minimum of one year. The other critical information that is needed is traffic flow through intersections; specifically, the annual average daily traffic (AADT) of the major and minor intersecting streets. The accident and traffic flow datasets will be used to select sample intersections for further analysis.

The next step is to clean the obtained accident and flow data according to the needs of this project. If neither of these datasets is available, the intersection sample for data collection will be selected randomly.

Data Cleaning Process

First, the accident data must be filtered to include only accidents that occur at night time. Sunset and sunrise times do not fully represent dark conditions since the sky is not completely dark for some time after sunset and before sunrise. Alternatively, twilight times are used. Based on the Mariam-Webster dictionary, twilight is the "light from the sky between full night and sunrise or between sunset and full night produced by diffusion of sunlight through the atmosphere and its dust". Using this definition, night time is considered as the time when evening twilight ends until the time when morning twilight starts. If twilight times are not available, a thirty-minute interval after sunset and before sunrise can be used.

The second step is to plot all the night time accidents in a geographic mapping and analysis software such as ArcGIS. Accidents occurring in a 15 m radius from an intersection are associated with it using a circular buffer and a spatial joint. The 15 m buffer from the center of the intersection was chosen as the effective area to analyse the night time light measures. It is a result of a sensitivity analysis for four different buffer radiuses, 5, 10, 15 and 20 m. Finally, the intersections with flow data and night time accidents constitute the candidate set from which a sample is selected for field data collection.

Sample Selection

There are two methods to select a sample for data collection, either randomly or by using intersection accident and flow data. If these datasets are not available, or there is a time constraint to perform a light audit where no accident and flow data can be collected, sample intersections for the lighting audit can be selected randomly throughout the city. This random selection must cover different districts within the city and must have variability in the type of roads crossing at the intersection, e.g. arterial-collector, arterial-local, etc.

The other method is to use the cleaned data from the previous step to select intersections for data collection. The sample intersections are selected by identifying hotspots based on the number of accidents and the flow through the intersection.

The accident risk level at intersections is estimated using the Empirical Bayes (EB) approach (Miranda-Moreno et al., 2007). For the statistical analysis, we start by assuming that for each site i, the number of accidents over a period of time (Y_i) follows a Poisson distributions, where θ_i is the mean accident frequency and follows a Gamma distribution, i.e., $Y_i|\theta_i \sim Poisson\ (\theta_i)$ and $\theta_i \sim Gamma\ \left(\varphi, \frac{\varphi}{\mu_i}\right)$. According to this popular Poisson/Gamma model, the conditional probability $p(\theta_i|y_i)$ is also Gamma distributed with shape $a = (y_i + \varphi)$ and scale parameter $b = (1 + \frac{\varphi}{\mu_i})$. From this, the popular EB estimator is given by the posterior mean of θ_i:

$$E(\theta_i|y_i) = \frac{y_i + \varphi}{1 + \varphi/\mu_i} \text{ or } EB_i = E(\theta_i|y_i) = (1 - w_i)y_i + w_i\mu_i \qquad [1]$$

$$w_i = \frac{\varphi}{\varphi + \mu_i} \qquad [2]$$

$$\mu_i = \beta_0\, {F_{1i}}^{\beta_1} {F_{2i}}^{\beta_2} \qquad [3]$$

Where:

F_{1i} – flow in the major approach at intersection i

F_{2i} – flow in the minor approach at intersection i

β – regression coefficients obtained from the data

μ_i – safety performance function depending on site-specific factors

φ – dispersion parameter

Using the number of accidents for each intersection as well as the flow in the major and minor approaches, a negative binomial regression model is run using a statistical analysis program such as Stata. From there, the regression coefficients and the dispersion parameter are used in the formula to obtain the safety performance function and EB. Then, the potential improvement factor, called risk thereafter, is calculated as follows:

$$PI_i = EB_i - \overline{EB}_{rp}$$

where $\overline{EB}_{rp}$ is average number of night time accidents in the reference population. Based on the PI results, arbitrary thresholds are used to indicate high-risk, medium-risk, low-risk and PI values below zero can be considered as safe intersections.

Data Collection Procedure on Sample Intersections

Equipment Used for Data Collection

Skye Instruments Ltd ("Skye Instruments," n.d.) manufactures light measurement sensors and data loggers. For this project, the SpectroSense2+ (SKL 925) logging meter was used. The SKL 925 has the option of recording measurement position via a GPS receiver. The sensors (SKP 218) manufactured by the same company are two one channel sensors. The sensors have a photodiode detector responsive to wavelengths from 280 to 1100 nm which includes the visible light wavelengths. The sensors measure illuminance levels in units of kilo-lux.

For data collection purposes, these sensors should be attached to a stable handle in a way that one sensor is facing up and the other is facing down. The sensor facing up is collecting data from the sources of the light representing the ambient light perceived by the eyes. The sensor facing down indicates how bright the road surface is, measuring the road surface reflectance: this sensor is not used in the present study as no requirement for lighting is based on it. The following is the list of what is needed for the data collection:

- Data logger
- Photometric sensors
- Data collection sheets with pen or pencil
- Construction vest

Sample Data Collection Process

Since the data collection process happens during the night, and some intersections may be located in unsafe areas, there should be at least two people collecting data. The twilight time for each evening should be checked and data collection should start after the evening twilight ends. Safety vests should be worn in order to be clearly visible to drivers.

Before starting, the logger must be checked for battery level and memory space. The light measurement interval is selected to be 1 s. The SKL 925 logger records the date, time, illuminance level from both sensors, and GPS coordinates. One of the problems with analysing the data from the logger is that in urban areas, the GPS does not give accurate readings because of the urban canyon effect, especially when the distance traveled is only from one side of the street to the other. In order to overcome this problem, before starting to cross the street with the logger, the time and location of crossing is recorded. In this way, when retrieving the data, the illuminance measurement from each crossing has a unique start time and intersection name.

At signalised intersections, since the data collector starts at a distance away from the intersection, roughly 15 m as shown in Figure B. 1, and data logging should happen at relatively constant speed, there should be enough time to cross the intersection. To avoid stopping behind red lights when logging data, the data collector starts logging just when the traffic signal in their direction turns green so that there is enough time to reach the intersection and cross with a constant speed while the light is still green. For non-signalised intersections, the same procedure is followed without waiting for the traffic lights.

Using the mentioned sensors and logger, several tests were performed for sensitivity analysis. Initially, data was collected at a single intersection in different weather conditions to check for illuminance variability according to different weather conditions (clear sky, mainly clear, overcast, after rain, snow on the ground). Results showed no correlation between the two factors, meaning that the variation of light measurements were not dependent on the weather. The second test was performed using a pole with the sensors attached to it. Data was collected with different pole heights ranging from 80 cm to 260 cm. The results did not show much variability with regards to height. Therefore, for the data collection, the data collector can collect data holding the sensors at any convenient height. For each night of the data collection, the temperature, sky condition and moon phase are recorded for further analysis.

While the illuminance data is being collected, the accompanying data collector fills in a data collection sheet (Figure B. 1). The data collection sheet aims to gather information on the type of intersection, location of light poles, locations of trees which may block light, location of commercial light (defined as the light coming from stores, restaurants and other roadside buildings), built environment characteristics and any other notes about the intersection.

Field Data Analysis

At the end of each data collection, the illuminance measurements from the sensor should be downloaded from the logger using the SpectroSense2+ software. The average illuminance values for each approach of the intersection are calculated using their corresponding start times. The average illuminance of the four approaches is taken as the average illuminance of the intersection. Then, the uniformity ratio of the approaches is calculated. Table B. 1and Figure B. 3 in the case study section represent the average illuminance calculated for each approach of an intersection and the raw measurements from the sensors respectively.

Draw the location of light poles (L) and the location of trees (T)
Intersection Name:
Date:

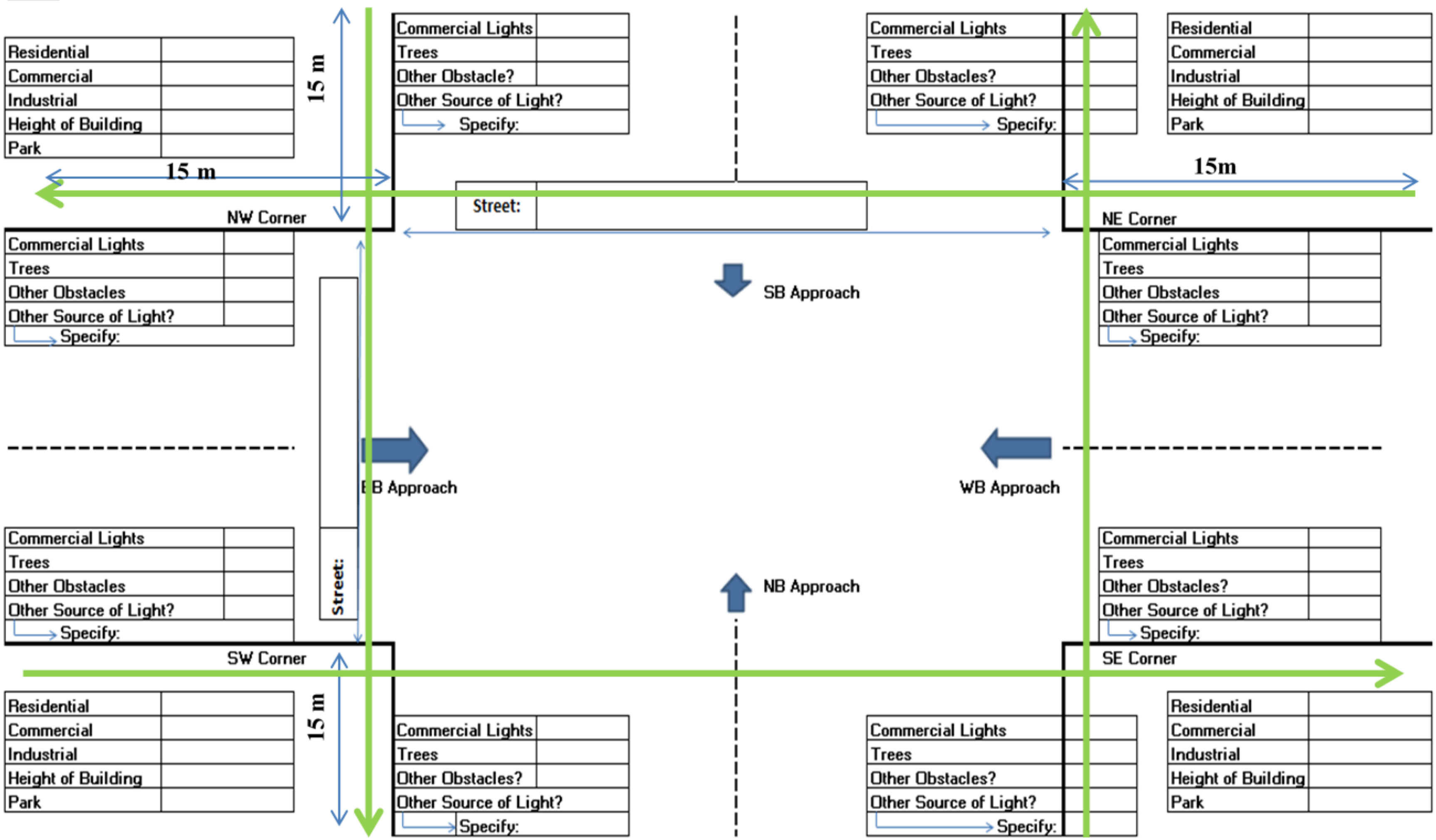

Figure B. 1 Data collection sheet

Montréal Case study

Study Area

The case study for applying the mentioned methodology is in the Island of Montréal, Québec, Canada. The Island of Montréal has two different types of lighting specifications provided by the Ministère des Transports du Québec, and lighting provided by local municipalities (Bruneau & Morin, 2005). The former uses IES standards and the latter uses TAC standards for road lighting. Given the two different standards, the problem of inconsistent lighting arises throughout the city, especially at intersections (Bruneau & Morin, 2005).

Data Source, Sample Selection and Data Collection

Accident data for this project was obtained from Montréal police reports from 2001 to the end of 2010. This data included the vehicle-vehicle and pedestrian-vehicle accidents, their location in latitude and longitude coordinates. Bicycle accident data is not used in this study because night time bicycle accidents are under-reported and the flow of bicycles during night time is very low.

The intersection geometry and traffic flows were acquired from data collected manually by the McGill university transportation engineering group in 2008-2009. These Manual counts were done during 8 hours and used to determine AADT for vehicles. Counts were taken during the two peak periods (3 hours each) and 2 hours during the noon period. Expansion factors considering weekly, monthly and the 24 hours of the day were used to extrapolate counts. Here it is assumed that flow intensity during the day is proportional to the night period; therefore AADT is still used as a measure of traffic activity during night time. This intersection inventory includes the intersection ID, names of intersecting streets, latitude and longitude coordinates of the intersection point, the AADT flow for each approach and the road type (national, arterial, collector, and local).

These two datasets, accident and intersection flow, were used to select a sample of intersections with a wide range of accident frequency and land use variability, which are discussed in the following sections.

Accident Data Cleaning

From the Montréal accident data, twilight times were used for each day of the year to filter through the 10 years of accident data and select only accidents that occurred during night time. Based on this approach, 12,433 accidents occurred at night time, which accounts for approximately 19 % of the total vehicle-vehicle and pedestrian-vehicle accidents recorded in Montréal throughout the 10 years. Accidents that occurred within a 15 m radius of an intersection were then selected using ArcGIS.

Selecting Intersection Sample

Using the EB approach, intersections with night time accidents were ranked based on their accident risk level and a random sample of intersections were selected for data collection. Based on the potential improvement values, risk thresholds were defined as follows:

- PI > 7 as High-risk
- 2 < PI < 7 as Medium-risk
- 0 < PI < 2 as Low-risk
- PI < 0 as No-risk

Factors considered for selecting the intersection sample were the number of night time accidents per intersection and AADT flow for major and minor approaches. A total of 85 intersections were randomly selected within all the accident risk categories, from high to low accident risk, including intersections without any accident, as shown in Figure B. 2. These intersections were selected throughout the city covering the downtown and suburban areas. Different types of roads with different land use were selected in different districts. Of the selected intersections, 26 % intersections were high-risk, 33 % were medium-risk, 28 % were low-risk and 13 % were no risk intersections as shown in Figure B. 2.

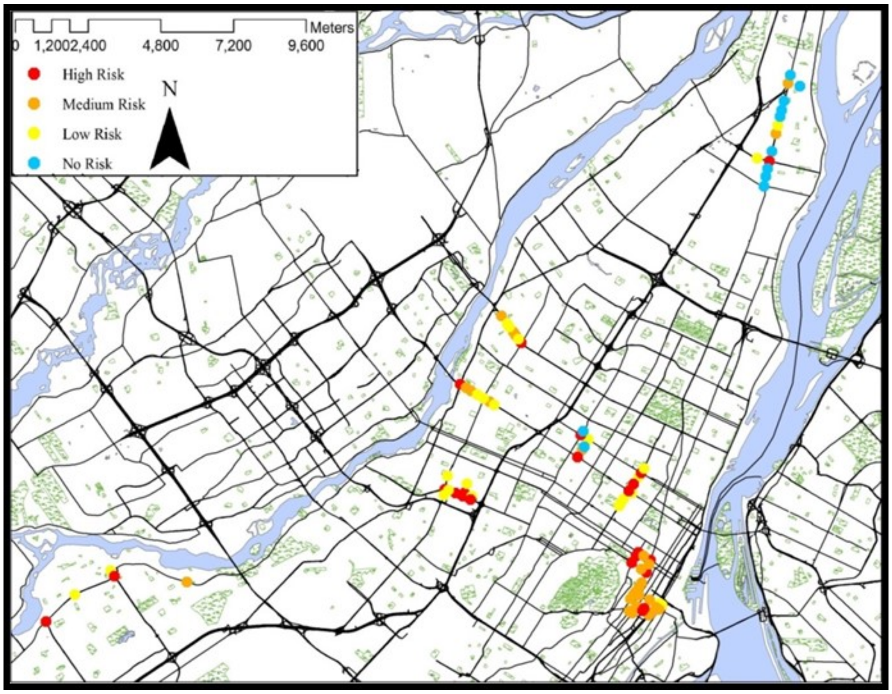

Figure B. 2 Map of selected intersections with risk variation

Data Collection on Sample Intersections

Data was collected for the selected intersections in June and July 2013, from the end of the evening twilight before the morning twilight. For each night of the data collection, the temperature, weather and moon phase was recorded from Environment Canada (Environment Canada, n.d.). The data was collected using the procedure described in the previous section.

Sample Descriptive Analysis and Model

This section covers the analysis of the illuminance of the intersection sample and of the night time accidents, and the effects of exogenous variables on them.

From the lighting point of view, some indicators such as the average illuminance of each approach, the total average illuminance for the whole intersection, the uniformity and sub-standard uniformity measures were compiled. The uniformity ratio for each intersection is calculated using the average intersection illuminance over the minimum average illuminance of the four approaches of the intersection. The average illuminance value and uniformity ratio of each intersection are compared with the lighting standards. Table B. 1 illustrates the average illuminance measured for each approach of one of the intersection samples; while Figure B. 3 presents the point measurements collected by the sensor for the same intersection. In other words, this figure illustrates the amount of illuminance of each point in each direction. Comparing the information in Table B. 1 and Figure B. 3 shows that east side of the intersection is brighter at night than the west side.

Table B. 1 Average Illuminance of Each Approach in a Sample Intersection

ID	**Date**	**Street name**	**Street name**	**Approach**	**Direction**	**Average Illuminance (lux)**
1246	08-Jul-2013	Louvain E *(Local)*	Acadie *(Arterial)*	North	E to W	17.5
1246	08-Jul-2013	Louvain E *(Local)*	Acadie *(Arterial)*	West	N to S	8.5
1246	08-Jul-2013	Louvain E *(Local)*	Acadie *(Arterial)*	South	W to E	14.0
1246	08-Jul-2013	Louvain E *(Local)*	Acadie *(Arterial)*	East	S to N	18.8

For this intersection, the average intersection illuminance is 14.7 lux and the uniformity ratio is 1.7. Comparing these values with the arterial-local intersection lighting standards, where the average illuminance must be above 19 lux and uniformity ratio should be below 3, indicates that this intersection is not lit according to standard, but the uniformity ratio meets the standards.

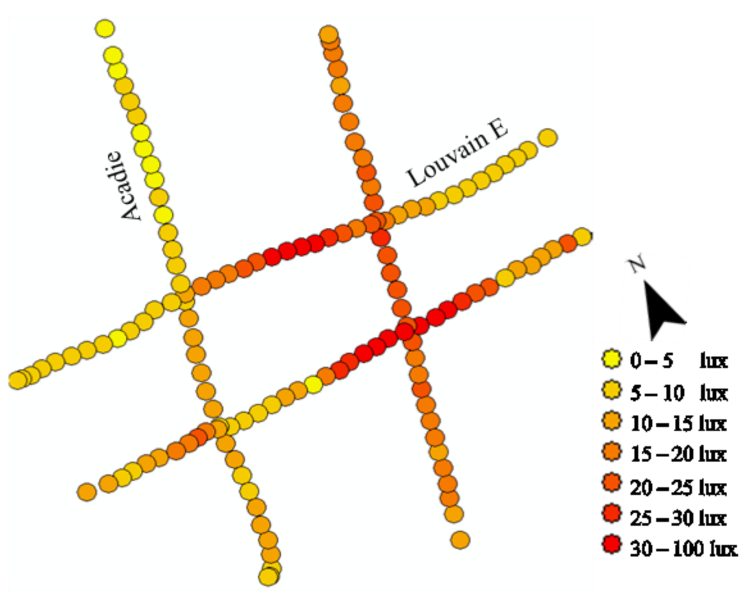

Figure B. 3 Map of the collected illuminance measurements of a sample intersection

Accordingly, the average illuminance and the uniformity ratio of the 85 selected sample intersections are compiled based on the collected point illuminance measurements of each intersection. The analysis of average illuminance indicates that around 60 % of the intersections are below road lighting standards. This can be studied for each intersection along with its level of risk. Figure B. 4**Error! Reference source not found.** shows the distribution of intersections with standard and non-standard lighting over their level of risk. The distributions are very similar and show an absence of a visible link between safety and whether an intersection meets the illuminance standard or not.

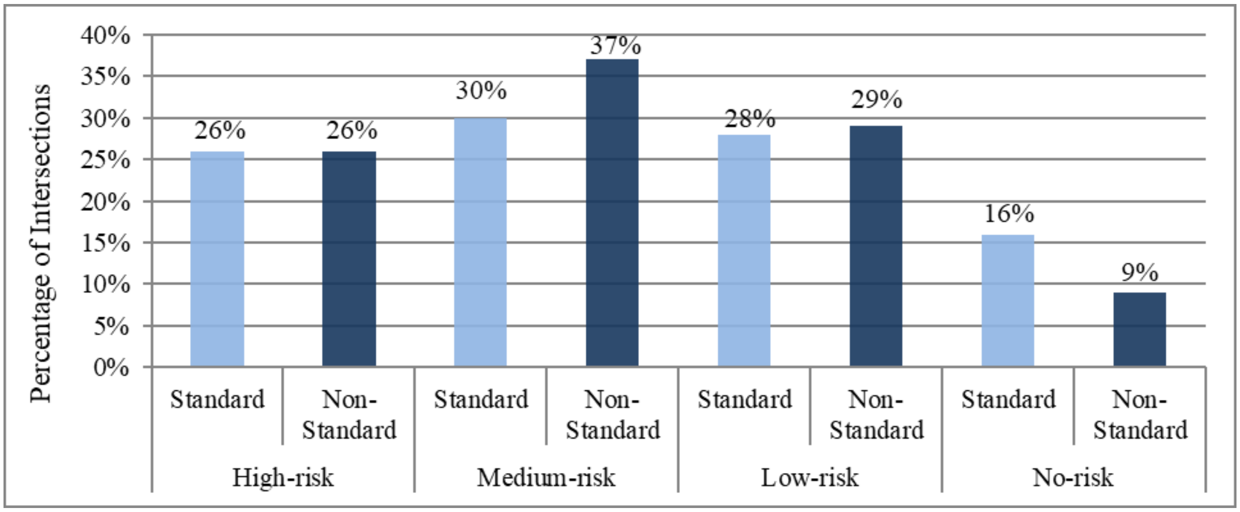

Figure B. 4 Risk distributions among intersections with standard and non-standard lighting

Figure B. 5 shows a sample of four types of road intersections depending on the types of roads. In these diagrams, the points below the red dotted line are those that do not meet the city specification standards for road lighting. The four plots comprise 49 intersections among the 85 samples intersections. It seems again that, even if the sample is stratified by road types at the intersection, there does not seem to be a strong relationship between the average illuminance and safety as measured by PI, or between substandard lighting and risk levels

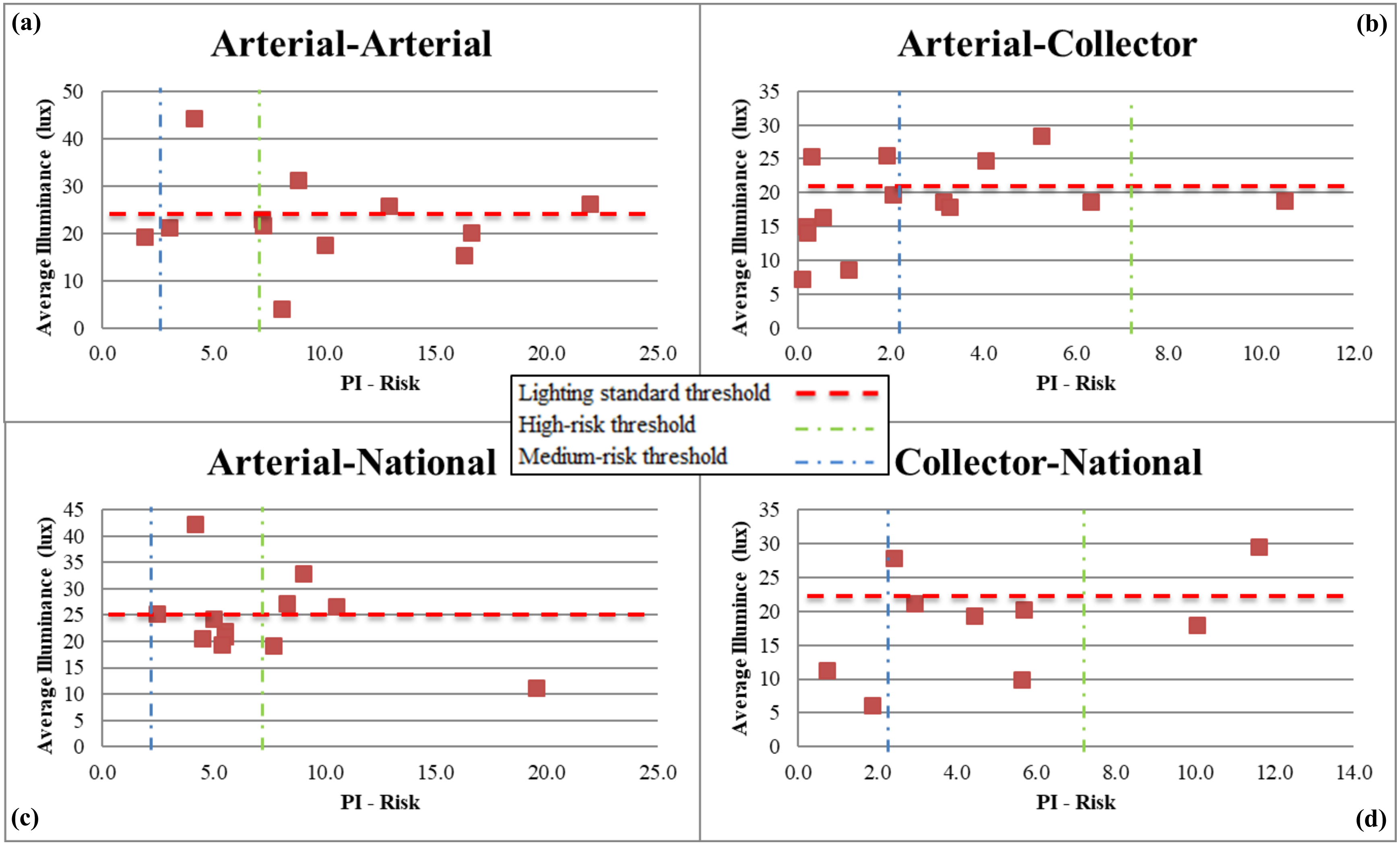

Figure B. 5 Average intersection illuminance as a function of PI: (a) arterial – arterial (14 %), (b) arterial – collector (18 %), (c) arterial – national (14 %), and (d) collector – national (12 %). 42 % of the intersections are not represented in these plots

Model Results

To analyse the effect of night time accident and average illuminance on each other and other built environment indicators, the following set of binary and numerical variables was used:

- Night accidents: raw number of night time accidents, and PI value
- Illuminance: average intersection illuminance, maximum and minimum average illuminance of the four approaches of each intersection, sub-standard illuminance indicator, and uniformity ratio
- Traffic: ratio of minor to major flow
- Temperature
- Weather: clear sky, mainly clear sky, few clouds, cloudy sky
- Moon: more or less than half full
- Hour of night: 9pm-10pm, 10pm-11pm, 11pm-12am, 12am-1am
- Built environment: number of approaches with commercial light present, number of approaches with trees, number of approaches with light pole present
- Land use: number of sides with commercial land use, residential land use, industrial land use, parks parking lots, and gas stations
- Road type: national, arterial, collector, local

The effects of each of these variables were measured on night accident and illuminance. To model night accident, a negative binomial regression is used since accident is a count variable. For the illuminance model, a linear regression model is used since illuminance is a continuous variable. Different combinations of these variables were added to obtain the best fitted model.

The results for significant indicators affecting night time accident are presented in Table B. 2. In general, variables that have an effect on night time accidents based on the variables mentioned above are traffic and illuminance. The coefficients presented in Table B. 2 show that traffic increases the chance of night time accidents. Since the ratio of minor to major flow is used, the number of night time accident will increase when minor flow increases and gets close to the major flow. Intersections with sub-standard illuminance also increase the chance of night time accidents.

Based on the coefficient values, traffic has a more significant effect on night time accident compared to the illuminance indicator.

Table B. 2 Effects of Exogenous Variables on Accident Risk and Average Illuminance

Night accidents		Coefficient	z-value	p-value	[95% Conf. Interval]	
Traffic	ratio minor to major flow	0.91	3.23	0.00	0.36	1.46
Illuminance	substandard illuminance	0.26	-1.60	0.11	-0.58	0.06
Constants		1.60	10.10	0.00	1.29	1.91

Average illuminance		Coefficient	z-value	p-value	[95% Conf. Interval]	
Weather	clear sky	-4.28	-2.60	0.01	-7.56	-1.00
Hour of night	time 12am-1am	7.96	2.75	0.01	2.21	13.72
Built Environment	number of approaches with commercial light	0.91	2.28	0.03	0.12	1.69
	number of approaches with light pole	1.66	3.86	0.00	0.80	2.52
Constants		11.82	5.15	0.00	7.25	16.39

Model results for indicators affecting illuminance are presented in Table B. 2. The significant variables were weather, hour of night, and built environment. The effect of the weather indicator was negative meaning that clear sky reduces average intersection illuminance. This may be due to the fact that the presence of clouds captures and reflects the light from the environment, whereas clear skies do not have that effect. The hour of night indicator has a positive effect on illuminance. Based on the model results, the average intersection illuminance is increased after midnight. The reason for this effect is not known. The built environment variables that came out significant are the number of approaches with commercial light and number of approaches with light poles. This is reasonable since the average intersection illuminance would increase if there are more commercial lights and light poles present at the intersection.

Conclusion

This paper proposed a methodology for the audit of road lighting and safety. The methodology applied to the Island of Montréal showed that from the sample of 85 intersections, 59 % had sub-standard lighting. Statistical results showed that sub-standard average intersection illuminance increases the chance of night time accidents, and minimum to maximum traffic flow ratio also increases night time accidents. It also showed that average illuminance increases with the presence of light poles and commercial light, and after midnight. Average illuminance is decreased when the sky is clear. This study points at a relationship between road lighting and safety and highlights the need for more data collection and analysis.

A limitation of this project is considering 10 years of crash data. This was used due to the low number of crash occurrences at the number of studied intersections. The assumption is that road lighting changes throughout these years was little.

Future work in this field can be done to improve and expand the findings in this paper, such as increasing the sample size and considering more variables. Further work can also make use of the road surface reflectance which is collected from a sensor facing down indicating how bright the road surface is. Further work will also include traffic flow counts during night time instead of using the AADT for night time traffic flow.

Acknowledgements

The authors wish to acknowledge the financial support from Fonds de recherche du Québec - Nature et technologies (FQRNT) Team Grant Program for undertaking the research, as well as the City of Montréal and boroughs that authorized the data collection.

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APPENDIX C – ARTICLE 6: A METHODOLOGY TO QUANTIFY DISCONTINUITIES IN A CYCLING NETWORK – CASE STUDY IN MONTRÉAL BOROUGHS

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Presented at the peer-reviewed conference: 95th Annual Meeting of the Transportation Research Board, Washington D.C., 2016.

Abstract

Many studies have investigated the cause of the low mode share for active modes of transportation, walking and cycling, in North America. Since the primary purpose of any transportation network is to provide connectivity between the origin and travel destination, studies have considered the discontinuities in the cycling facility as a major reason for lower cycling mode shares. Network connectivity decreases travel distances and provides a set of possible routes that are easily accessible for all road users. On the other hand, discontinuities correspond to points in the network were the cycling network is not connected and a cyclist may have to reconsider his/her route and will be more exposed to motorized traffic.

This paper proposes a methodology to identify and quantify discontinuity within a cycling network using geospatial data and a geographic information system. This study identified two types of indicators, A) internal cycling network discontinuity indicators: the number of ends of bike facilities, the changes in bike facility type, and B) discontinuity indicators with respect to the road network: the number of intersections on bike facilities, the variations in the number of lanes, road type, vehicle flow along bike facilities and the number of bus stops on bike facilities. The dataset and step-by-step process of quantifying these discontinuity measures are presented and applied to three boroughs in the island of Montréal for comparison.

Keywords: Discontinuity, connectivity, cycling network, safety

Introduction

Bicycles are used for different activity purposes and contribute to the benefit of the society in many ways. There is an increasing number of people who choose to cycle as a mode of everyday transportation, for recreational and leisure purposes, as a sport and means for a healthy lifestyle. Considering its environmental and social benefits, many North American cities are investing in bicycle infrastructure, bicycle sharing programs and large campaigns to promote cycling as an affordable alternative mode of transportation. Nevertheless, while compact urban areas promote active transportation, they must also provide quality and safety levels that meet the highest standards.

According to the 2011 Canadian National Household Survey, there were 201,800 commuters who cycled to work, accounting for 1.3 % of all commuters (NHTSA & National Household Traffic Survey of America, 2013). According to the American 2001 Nationwide Household Travel Survey (NHTS), only about 1 % of trips in the U.S. are on bicycles even though the majority of trips lend themselves to walking and cycling since short distance trips (less than five miles) account for over 60 % of all personal trips and 40 % of all trips were less than two miles (U.S. Department of Transportation, 2001). Many studies have identified as one of the reasons for this low cycling mode share to be the real and perceived lack of safety due in particular to the quality of the cycling network, or lack thereof (Dill & Gliebe, 2008; Ehrgott et al., 2012; Garrard et al., 2008; Mekuria et al., 2012). Based on studies conducted in three different U.S. cities, 12 to 17 % of active cyclists ranked the lack of dedicated facilities as the top reason for not cycling (Dill & Gliebe, 2008). Another study in Portland, U.S. provided evidence that safe bicycle facilities encourage 20 % more adults to ride to work (Dill & Gliebe, 2008). Given the lack of facilities, network connectedness and perception of lack of safety, it is important to improve the cycling network facilities and infrastructure in order to increase the cycling mode share in cities.

Among those who do cycle, many do not take the shortest path to their destination. In Canada, a study reported that 75 % of cycling trips were within 10 % of the shortest path and 90 % were within 25 % of the shortest path (Megan Winters et al., 2010). This observation has also been reported in another study, where the cyclist’s route choice is dependent on factors such as green cover and bicycle-actuated signals (Aultman-Hall et al., 1997). Commuters in Portland are willing to add 16 % to the shortest travel distance in order to ride on a bike path, and 11 % to ride on a low-stress route (local streets, separated cycle tracks) (Broach et al., 2011). Another study conducted in Portland, reported that 52 % of bicycle miles were traveled on streets with bicycle infrastructure such as striped bike lanes, separated bike paths, or cycle tracks. Another 28 % of bicycle miles were traveled on minor, low traffic volume, residential streets without bike infrastructure, leaving roughly 20 % of the travelled bicycle miles on roads with high traffic volumes and no separate cycling facility (Dill & Gliebe, 2008). It has been proven that cyclists will choose longer routes if there is a path with bicycle facilities, less traffic, and less elevation (Dill, 2004; Dill & Gliebe, 2008).

In order to increase cycling, cities often implement bicycle safety measures such as the addition of signage, road markings for bike lanes and the construction of bike paths. Unfortunately, cycling networks are often developed in an ad hoc and piecemeal way, where engineers and planners look initially for opportunities to add infrastructure, without considering the big picture of the planned network. As studies have shown, cyclists do not equally use all roads and paths. Traveling comfortably on a cycling network does not only depend on the quality and features of the links, but also on how the links are connected (Rietveld, 1997). The primary purpose of any transportation network is to provide connectivity between the destinations that people want to reach (Dill, 2004). A key component for a good transportation network design is to provide a high level of street connectivity. Past studies have shown that grid networks are superior to networks with long blocks and dead ends where the resulting increase in travel distances discourages walking and cycling (Dill, 2004). Network connectivity not only decreases travel distances, but also provides a set of possible routes that are comfortable and easily accessible to all road users. When cyclists travel on a road network that consists of different types of cycling facilities, there are points where they have to transfer from one facility to another, including the absence of dedicated facility as in Figure C. 1. Throughout the network, these changes create discontinuities that are perceived as inconvenient and are less safe (Xie & Levinson, 2007). Despite the contributions of the mentioned studies, no study has investigated the discontinuity of cycling networks systematically and proposed quantitative measures of discontinuity.

Figure C. 1 End of cycle track where cyclists wishing to continue through the intersection must move to the right hand side of the lane with cars moving in the opposite direction (Google images, Montréal: Maisonneuve and St. Catherine)

This research aims to identify, measure and quantify the level of discontinuity in the cycling network. The methodology proposed in this study will allow measuring the cycling network's level of discontinuity in any area, as well as provide a basis for comparison between different cycling networks in different cities or boroughs. One end goal of the paper is to help engineers and planners measure the network continuity quantitatively and locate discontinuities in order to improve the network by removing the discontinuities.

The following section provides the methodology of how to measure discontinuity, how to normalize discontinuity variables and how to quantify a network's discontinuity level. Followed by that is a case study to measure the discontinuity of the cycling network in three different Montréal boroughs. Finally, the conclusion and future work are presented.

Background

A transportation network is described as a set of nodes indicating spatial locations and a set of links representing connections between nodes, that have geometric, topographic and elevation attributes (Xie & Levinson, 2007). In Canada, cyclists can use all roads and paths where cycling is permitted.

Given the low number of people who ride a bike regularly due to the of lack cycling facilities and safe routes to ride, some researchers have proposed another definition to describe the cycling network, which is the "set of streets and paths that do not exceed people's tolerance for traffic stress" (Mekuria et al., 2012). Several factors influence the cyclist's decision to take a certain path. While cyclists try to minimise their travel distance, they are also ready to take longer routes if they can ride on cycling facilities. Along the way, there may be different levels of safety and comfort that could be unsuitable for cyclists.

Discontinuities are points in the network where the cycling network is not connected, most obviously interruptions in the cycling network and especially in the dedicated cycling facilities. Examples are where bike lanes or paths end or are re-routed to another street, but also when characteristics of the cycling facilities change more or less drastically, such as the lane/path width, the type of pavement, the slope, a bridge to cross a physical barrier (a river or a highway), or lighting at night time. Navigating these discontinuities is at best uncomfortable for regular trips and can be disconcerting when encountered for the first time and cyclists must reconsider their route.

The importance of good cycling facilities is highlighted by the different cyclist profiles found in the literature, for example in Portland, Oregon, where Geller introduces four different types of cyclists (Geller, 2009): "no way no how", "interested but concerned", "enthused and confident", and "strong and fearless". The most confident will be relatively insensitive to the quality of cycling facilities, while it becomes a crucial factor for the largest group of interested but concerned users.

A well-designed, continuous and safe cycling network will provide comfortable access to encourage cycling for all users. However, the planning, design and implementation of a connected network demands a thorough and in depth understanding of the network and trade-offs individuals make while choosing a route for cycling: road gradient versus route length, traffic volume on route versus traffic speeds, bicycle lanes versus bike paths, type of intersections on different routes, presence of parking (Menghini et al., 2010)**.**

In one study, in order to quantify cyclists' level of stress, participants cycled 30 roadway segments and recorded information such as traffic exposure, posted speed limit, percentage of heavy vehicles, adjoining land use, width of outside through lane, and pavement conditions in order to standardise cyclist's perception of a network's acceptable level of service and safety (Krizek & Roland, 2005; B. Landis et al., 1997). Several studies have confirmed a cyclist's behaviour and route choice is substantially influenced by their safety perceptions (Akar & Clifton, 2009; Dill & Carr, 2003; Ehrgott et al., 2012; Hopkinson & Wardman, 1996). Hopkinson and Wardman even found that safety is more highly valued than time in many cases (Hopkinson & Wardman, 1996). A study conducted by Dill and Gilebe reported that cyclists ranked their route choice preferences based on minimizing distance, avoiding streets with high traffic volumes and choosing streets with bicycle lane (Dill & Gliebe, 2008). Another study ranked the top preferred route as one that has a bicycle path for the entire trip distance separate from traffic (Meghan Winters et al., 2011). These studies confirm that safety and low-stress conditions are important factors for cyclists that can be traded for longer travel times.

Although bike lanes and cycle tracks have been identified as the preferred facility for cycling, they can also generate themselves different levels of comfort and stress when considering the speed of traffic adjacent to the cycling facilities, the presence of on-street parking, and intersections. Bike lanes in particular leave cyclists exposed to motorized traffic and more so on roads with high speeds or turbulent traffic, next to on-street parking with no adequate clearance and at intersections where cyclists are forced to merge with motor traffic (Mekuria et al., 2012).

The identification and quantification of these discontinuities will provide decision makers with more detailed information regarding the cycling network. Sometimes a better bicycle network coverage does not mean cyclists will be travelling smoothly and comfortably if constantly going through discontinuities. The complete quality and performance of a cycling network should therefore consider both coverage and the quality of its coverage, including the amount of discontinuities in the network.

Methodology

Several variables or indicators are proposed in this paper to measure the discontinuity of a cycling network. A geospatial data analysis tool was used to obtain these discontinuity indicators following the steps outlined below. Applying the proposed methodology to different areas allows for comparison of the cycling network discontinuity levels between these areas, e.g. different cities or boroughs within a city.

Identifying Discontinuities

The first step to identify the level of discontinuity of a cycling network is to identify all the discontinuity factors on the network. Information from past studies and a short survey from individuals with a variation of cycling experiences were compiled to generate a list of variables related to network discontinuity that had the possibility of being computed through geospatial analysis.

Discontinuity measures are divided in two main categories: A) internal bike facility discontinuities and B) bike facility discontinuities in association with the road network. In the first group the identified indicators are:

1. the number of end of bicycle facilities,
2. the number of changes of the type of bicycle facilities, and
3. the number of changes of the side of the road of bicycle facilities.

The second group of measurements includes the discontinuity measures in the bicycle network considering the impact of the road network, in cases of changes in the characteristics of the road network that may affect the comfort and safety, perceived or real, of cyclists, especially on bike lanes or designated roadways:

1. the number of road intersections on bike facilities (i.e. roads intersecting bike facilities),
2. the number of changes in the number of lanes in a road along bike facilities,
3. the number of changes in the type (functional class) of road along bike facilities,
4. the variation in motorized traffic volume on roads along bike facilities, and
5. the number of bus stops on a road with bike facilities.

Some of these indicators are expected to be correlated, for example, the variations in the road characteristics (number of lanes, road class and motorized traffic volume). Bus stops are included since pedestrians must cross the bike path to get on or off the bus and otherwise buses will cross non-segregated bike facilities to stop by the curb.

Several other variables were also identified which did not present the possibility for computation and quantification using available city databases. These include for example, temporary discontinuities within the cycling network where there is re-routing due to construction on the road, parking permission on roads which would cut off the cycling facility similar to buses as well as vehicle turning movements and pavement quality.

Quantifying Discontinuity Measures

All of the variables mentioned above can be quantified in a geographic analysis tool given the data required to perform the analysis. The essential data needed is the city's geospatial data for the road network with information such as location of intersections, road class, number of lanes, bus stops and motorized traffic volume (typically average annual daily traffic) on road links. The other dataset required is the city's geospatial data for the cycling network which includes the end points of the cycling facility, cycling facility type, and the side of the road where cycling facilities are located. The availability of such data provides the basis for performing the discontinuity analysis. It should be noted that not all cities will have all the mentioned information in their databases, or that it may be organized in different ways, and therefore computing these measures requires assumptions and further consideration and assessment. For instance, most cities make available some intersection-level road user volume or count data, which must be aggregated to obtain volumes on each link. Table C. 1 provides the main steps to quantify the identified discontinuity indicators, with additional comments and recommendations based on their application to the case study (for example for buffer sizes).

Normalizing the Discontinuity Indicators

In order to normalize the above-mentioned discontinuity indicators with respect to the size of a cycling network, each measure will be divided by the length of the cycling network in the study area. This will enable the comparison of discontinuity measures of bike networks of different lengths or coverage across different areas, for example cities or boroughs in a city.

Table C. 1 Quantifying discontinuity indicators

Indicator	Definition	How to Quantify	Comments
End of Bike Facility	Number of bike facility end points	1) Different bike facility segments that have the same road name and facility type (bike lane, bike path, etc.) are merged ("unsplit") to make a unique bike facility class 2) The merged bike facility is then converted from line into two points: the two ends of the facility 3) A 2 m buffer is drawn around each end point 4) Points that have a bicycle facility going through its buffer, or having an end of another facility type present, are not considered as end points. 5) Counting the rest of the points provide the number and location of the bike facility ends	• Merging different segments to compile a unique bike facility type enables us to create the real end points of the specific bike facility of a given type instead of having multiple start and end points at the beginning and end of each road link. • In order to count the end points, a sensitivity analysis was performed for radiuses of 1 to 10 m around the facility ends, with no significant result change from 2 m radius to 10 m radius, and 2 m was therefore selected • For an illustration of this indicator, see Figure C. 3.a
Change in Bike Facility Type	Number of changes of bike facility type	1) As mentioned in the first step above, the merge function was performed in order to obtain unique end points for each bike facility in the same road 2) A 5 m radius is drawn around each end point of the feature and scanned for any other end points or cycling links 3) In this buffer area, if the type of scanned facility is different from the source facility, it is counted as a change in bike facility class	• Sensitivity analysis was performed for radiuses of 1 to 10 m around the facility end points, with no significant result change from 5 m radius to 10 m radius, and 5 m was therefore selected • For an illustration of this indicator, see Figure C. 3.b
Change in Bike Facility Side	Number of times the bicycle facility changes side of road	1) To locate the bike segment in each road link, a buffer of 40 m of the road segment is created to perform a spatial joint with the bike network, so that the information of each bike facility segment merges with the road network information data 2) Assuming we have the information of the bicycle facility location in association with the road network (e.g. south or north side of the road), we can define a query to count and select the bicycle facility segments in a unique road, with different road side attributes	• The first step can be avoided if the name of the road assigned to each bike facility is already available in the bike facility data • The reason why the buffer is defined as 40 m is to make sure that all bike facilities along the road link are associated to it • For an illustration of this indicator, see Figure C. 3.c
Number of Intersections	Number of intersections on bike facilities	1) To find the number of intersections in the bike map, the 40 m road buffer on the bike network should be generated 3) The number of intersections in the cycling network can be calculated using a spatial joint between the buffer and the road intersections	• For an illustration of this indicator, see Figure C. 3.d

Table C. 1 Quantifying discontinuity indicators continued

Measure	Definition	How to Quantify	Comments
Change in Number of Lanes	Change in number of road lanes along bike facilities	1) For each road, the difference in number of road lanes are calculated for each change 2) By performing a spatial joint between the road network with the added information in step 1, to the bike network links, a query can select and count the bicycle facilities within the same roads that have a variation of number of lanes 3) To include the changes of lane number at intersections where a cycling facility goes from one leg of the intersection to another, a spatial joint between the 40 m road buffer with the intersection georeferenced data is performed which provides us with the rest of the road lane changes on the bicycle facility	• The reason for using spatial joint for the bicycle network and intersection georeferenced data is to cover all the possible road lane changes in different bicycle facilities • Separated cycle tracks and off-road paths may not be considered in this analysis since they are not affected by the variation in number of lanes • For an illustration of this indicator, see Figure C. 3.e
Change in road type	Change in road type along bike facilities	1) Step number 2 for the previous measure is performed and a query is made to count and select the bicycle facility routes with changes in road class segments 2) To include changes in road type at intersections, a spatial joint between the 40 m road buffer with the intersection georeferenced data that has a change in bike facility is performed	• Separated cycle tracks and off road-paths may not be considered in this analysis since they are not affected by the variation in road type • For an illustration of this indicator, see Figure C. 3.f
Change in volume	Change in motorized traffic volume on roads along bike facilities	1) To define the variation of volume in each unique road, the difference between the volume between each successive segment is calculated in one unique road, 2) The next step is to classify the merged road into different volume variations based on the standard deviation of the whole study area: changes in volume are considered large if more than 2 or less than 1.5 standard deviations around the mean 3) A spatial joint between the 40 m road buffers with the added volume variations and the bicycle facility is performed and a query is made to count and select the bicycle facility routes with large changes in volume is defined	• Separated cycle tracks and off-road paths may not be considered in this analysis since they are not affected by the variation in motorized traffic volume
Number of Bus Stops	Number of bus stops on the road along bike facilities	1) To identify whether a bus stop is present or not on the road where a bike facility is located, the 40 m road buffer on the road network is generated 2) The number of bus stops in the cycling network can be calculated using a spatial joint between the road buffer with the location of bus stops	-

Case Study

In this section, we apply the identified discontinuity indicators to a real case using ArcGIS. The island of Montréal is selected for the case study. The city's cycling network includes different bicycle facilities such as separated cycle tracks, bicycle lanes and designated pathways. The cycling facility network data was obtained from the city's open data portal where is was last updated in April 23, 2014 (City of Montréal, 2015). The borough data such as population (updated on October 14, 2013), and surface area were also obtained from the city's open data portal (City of Montréal, 2015). Figure C. 2 present the map of the road and cycling network per type of facility for Montréal. The total length of the Island of Montréal's road network is 5798 km, while the length of the cycling facilities in the city is 649 km.

Montréal has 34 boroughs, from which we selected three different boroughs based on their different cycling network coverage levels. The coverage of each borough is calculated as the ratio of the cycling network length over the road network length. The mean value and standard deviation of the cycling network coverage by borough are respectively 0.11 and 0.08. A borough with cycling network coverage below the mean value (0.11) is considered bad, while good coverage is considered for boroughs with cycling network coverage above the mean plus one standard deviation (0.19), and medium cycling network coverage in considered in between. At the end, among the three cycling coverage classes, we randomly selected one borough from each group for our analysis: St-Leonard (SL) (bad cycling network coverage), Mercier-Hochelaga-Maisonneuve (MHM) (medium cycling network coverage), and Plateau-Mont-Royal (PMR) (good cycling network coverage). Examples of their discontinuity indicators are illustrated in Figure C. 3, and the three boroughs with their cycling facility network are presented in Figure C. 4.

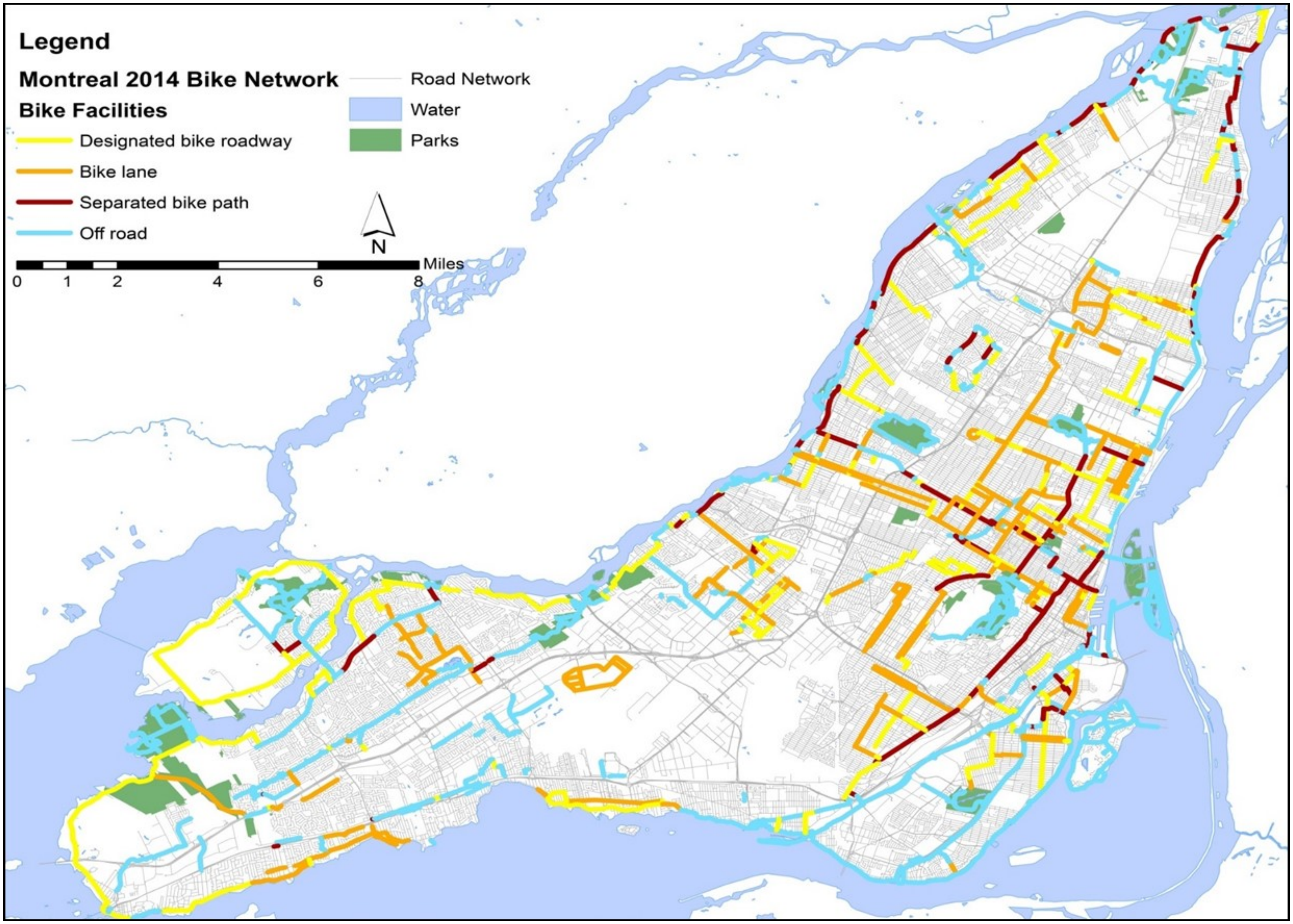

Figure C. 2 Montréal cycling facilities

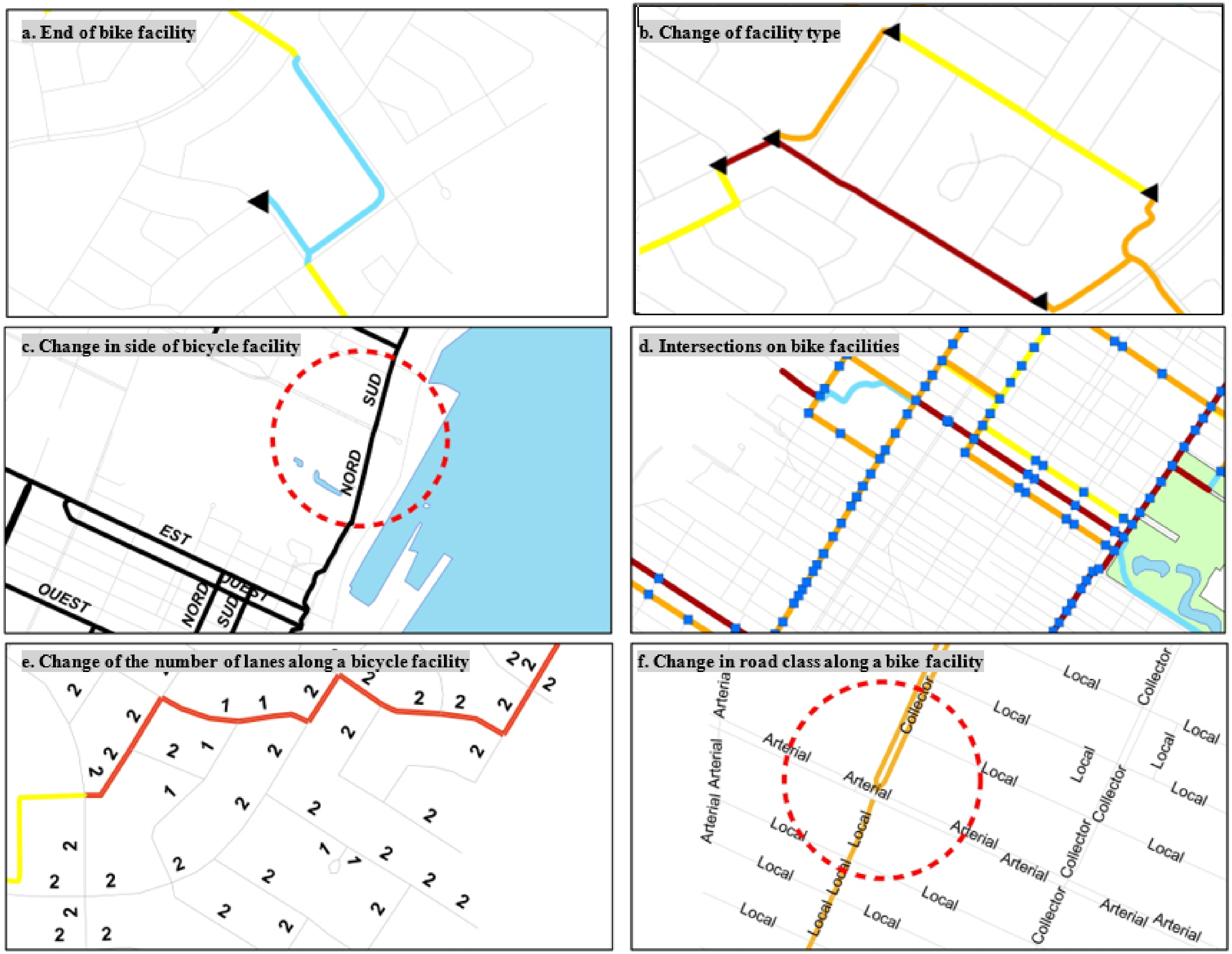

Figure C. 3 Illustration of different bicycle network discontinuity measures

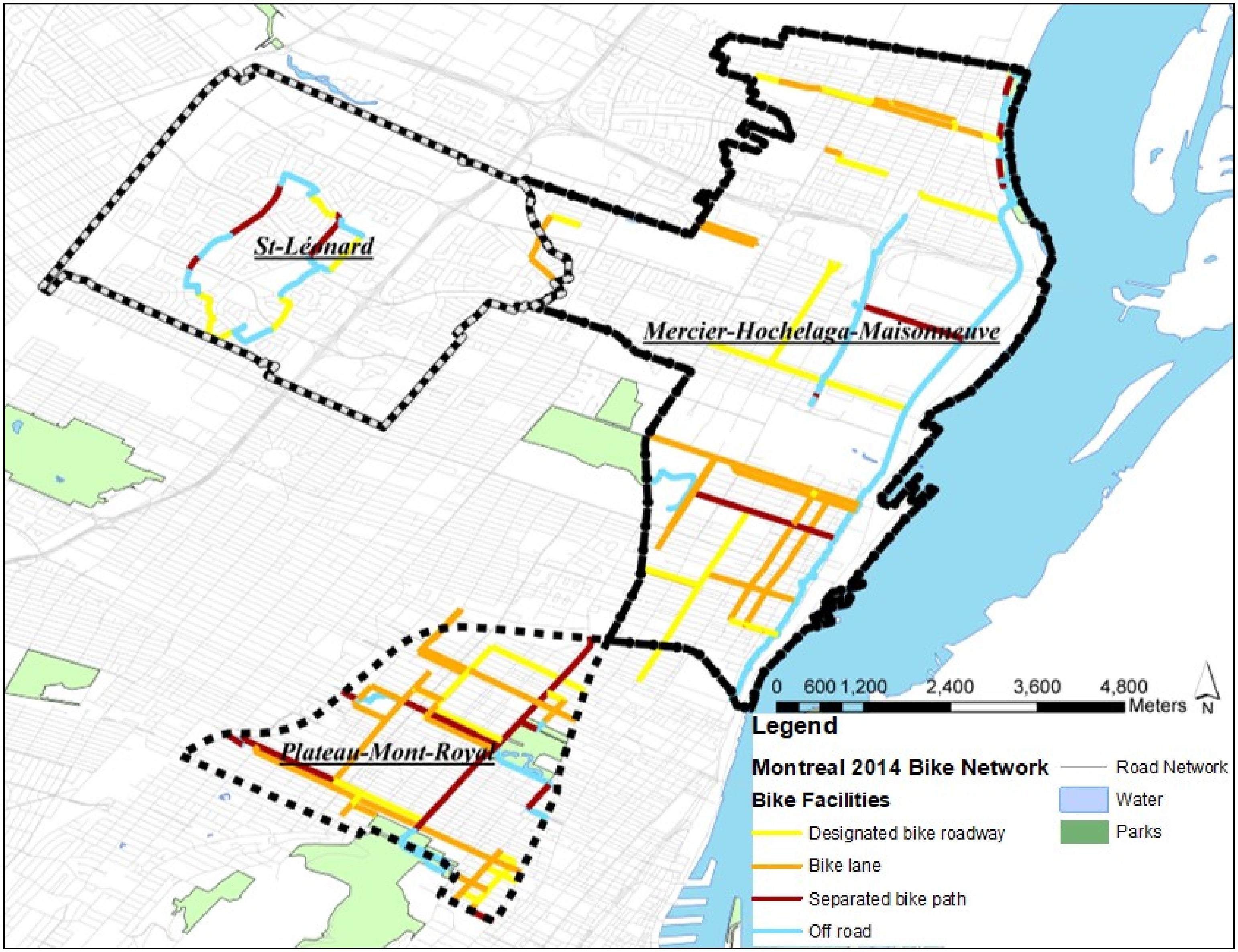

Figure C. 4 Location of Montréal sample boroughs

Sample Descriptive Analysis

As mentioned above, we focused our study on three boroughs in Montréal with the different levels of bicycle facility coverage to analyse and compare discontinuity measures.

The Montréal cycling facility is divided into four different classes:

1. designated cycling roadway, with only shared road markings on the road to guide cyclists through appropriate roads in the network,
2. bike lanes, where one or two painted lanes separate cyclists from traffic,
3. separated cycle tracks, where cyclists are physically separated via a median on the road and
4. off-road bike paths, which includes bike paths on sidewalks and in parks.

From the statistics presented in Table C. 2, it can be seen that PMR has the highest share of separated cycle tracks and the lowest share of designated roadways, while SL has a high share of off-road bike paths. Regarding the cycling network coverage, consistently with the borough selection criterion, the highest coverage belongs to the PMR borough (19.1 %) and the least coverage was for the SL borough (4.5 %). Another parameter that can be considered as a bicycle network coverage measure is the number of signalised intersections with bicycle facility over the total number of signalised intersections in each borough. Comparing this measure among the three sample boroughs shows that 38 % of signalised intersections in the PMR borough have a bicycle facility while this value is 35 % and 10 % for the MHM and SL boroughs respectively. From the coverage point of view, PMR has the best cycling network, followed by MHM and SL. The complementarity of the discontinuity indicators to evaluate the cycling network quality can now be analysed.

Quantifying discontinuity

The top section of Table C. 2 presents all descriptive information regarding the borough, road and cycling networks, and the bottom of the table presents the discontinuity indicators. The first bicycle discontinuity indicator is the number of ends of bike facilities. As shown in Table C. 2, the highest level of discontinuity for this variable is seen in the PMR borough (0.29), while the SL borough has the least discontinuity for that indicator (0.12). This is because, although SL is the borough with the least bicycle network coverage, this borough's cycling network is composed of one main loop with only one end point (Figure C. 4). Looking at this measure in detail by type of bike facility, one can see that the network ends in PMR are mostly for designated cycling roadways that extend the network further, but also correspond to its ends.

Regarding the second indicator, the largest number of changes of facility types occurs in the SL borough (1.64) while the smallest number of changes occurs in the MHM borough (0.82). In addition to the length of each type of facility, this indicator helps characterize how connected each type of facility is. Although the off-road bike paths make up most of the cycling network in SL and MHM, most changes are from designated roads to other types. The same pattern is observed for the MHM borough. For the PMR borough, the most common type of bike facility is the bike lane, which is also the most disconnected since the highest change of facility type is from bike lanes to the other types.

The third indicator depends on the information of the side of road of bike facilities, which was available for only one facility in the available data and is therefore not presented. The highest level of discontinuity caused by the fourth indicator, the number of intersections on bike facilities, is for the PMR borough (0.45) and the lowest level of discontinuity is for the MHM borough (0.22). This is related to the fact that the PMR borough is denser with a higher road density and therefore a higher density of intersections compared to the other boroughs.

The variation in number of road lanes along bike facilities is the highest for the PMR borough (0.84) and the lowest for the SL borough (0.23). This is not surprising as PMR has the highest cycling coverage in the densest road network which increases the probability of having changes in the number of lanes along its roads. Changes in road classes are also the highest for the PMR borough (0.23) compared to the other two boroughs, which is expected for similar reasons. This measure is the smallest for the SL borough (0.12) which is consistent with a mostly residential area without many different types of road as opposed to the mixed land use in the PMR borough with residential, commercial and recreational areas.

The sixth measure is the variation in motorized traffic volume along bicycle facilities. As presented in Table C. 2, the highest variation is for the SL borough (0.94) and the smallest in MHM (0.74). The SL borough, being a residential area, has little traffic through most of its residential areas, causing a high differential with the volume in the links that are feeding residential roads.

The last measure of bicycle network discontinuity in the Montréal sample is the presence of bus stops on the road with bicycle facilities. Since the data for the number of bus stops was not available, the presence of bus stops on links was used for measuring this discontinuity indicator. It shows less variability than other indicators. The PMR has the highest discontinuity level (0.26) compared to SL which has the lowest (0.12). This is again related to fact that PMR is the densest borough, with many bus routes, compared to the residential area of SL where there are fewer bus routes.

Overall, one can see empirically the sensitivity of the indicators in different areas: they paint a more detailed picture than what can be simply derived from measures of coverage. Although PMR has the best cycling network in terms of coverage, it often ranks high in measures of discontinuity because of its dense road network and varied land use, but also because of a relatively large number of change in types of bike facility and too many end points of its network that do not connect to other dedicated facilities.

Table C. 2 Coverage and discontinuity indicators of the cycling networks for three Montréal boroughs (the worst performer for comparable indicators is highlighted in bold)

Montréal Sample Borough's Bicycle Coverage Measures					
	Measure type	Bicycle Facility Class	Measure Value		
			St-Leonard	M-H-M	P-M-R
Borough Density	Borough surface *(km^2)*		14	25	8
	Borough population density *(residents per km^2)*		5408	5259	12549
	Borough road density *(km per km^2)*		0.0136	0.0136	0.0202
	Borough cycling facility density		0.0006	0.0018	0.0038
Road and Bicycle Network Summary	Road network length *(km)*		190.6	339.6	161.6
	Bicycle facility network length *(km)*		8.5	46.2	30.9
	Cycling network coverage		4.5 %	13.6 %	19.1 %
	Proportion of each type of bike facility in the cycling network	Designated cycling roadway	31.1 %	23.2 %	22.7 %
		Bike lane	8.5 %	30 %	45.1 %
		Separated cycle track	20.4 %	7.9 %	21.7 %
		Off road bike class	40 %	32.8 %	10.5 %
	Proportion of each type of road in the road network	Highway	5 %	4 %	-
		Arterial	3 %	9 %	11 %
		Collector	20 %	22 %	25 %
		Local	72 %	65 %	64 %
	Percentage of signalised intersections with bicycle facility		10 %	35 %	38 %
Montréal Sample Borough's Bicycle Network Discontinuity Indicators					
Category A (Bike Facility)	End of bike facility (per km cycle length)	Designated cycling roadway	-	0.11	**0.23**
		Bike lane	-	0.04	-
		Separated cycle track	-	-	0.03
		Off road bike class	0.12	**0.13**	0.03
		All end points	0.12	0.28	**0.29**
	Change in bike facility type *(per km cycle length)*	All changes	**1.64**	0.82	1.13
Category B (w.r.t. Road Network)	**Number of intersections** (per 100 km cycle length)		0.23	0.22	**0.45**
	Variation in number of lanes *(per km cycle length)*		0.23	0.74	**0.84**
	Variation in road class *(per km cycle length)*		0.12	0.19	**0.23**
	Variation in volume (per km cycle length)		**0.94**	0.74	0.81
	Presence of bus stop (per km cycle length)		0.12	0.22	**0.26**

Conclusion

As mentioned in the introduction, most cyclists prefer traveling on dedicated bike facilities. The quality of a cycling network is typically measured by the length and coverage of its road network, but also its connectedness, or lack thereof, and its points of discontinuity. It is important to address these discontinuity factors in order to improve the cycling facilities and to increase the number of cyclists in the city. The purpose of this paper is to evaluate the discontinuity level of a cycling network by identifying discontinuity factors such as changes in bike lane side on road, the ends of the cycling network, transitions between bike facilities, and quantify them for comparison purposes. The proposed indicators can help decision makers identify the discontinuities in a study area's cycling network, to target improvements to an existing network.

The proposed methodology can be used to evaluate the discontinuity levels of any cycling network given the required datasets. As a case study, three Montréal boroughs were selected and the method applied to calculate several indicators for each borough. Comparing the bicycle discontinuity measures for the three substantially different boroughs is a good way to validate the proposed method and evaluate its validity, i.e. whether it can represent well the different types of discontinuity observed in the field.

In summary, the proposed discontinuity indicators paint a more contrasted picture than offered by the more usual measures of coverage, network length and quality of the facilities. Although the PMR borough has the best network in term of coverage and proportion of bike paths, it also has the highest discontinuity levels for all but two indicators. It performed especially poorly for the indicators in category B that are related to the road network. This is easily explained by the dense and connected nature of the road network in that borough and by the mixed land use. At the other end, the borough with the smallest coverage, SL, ranks surprisingly well for many indicators, in particular thanks to its design as one main loop, except for the number of change in bike facility type and variations in motorized traffic volume.

Comparing the different discontinuity measures of the three boroughs that have different bicycle facility coverages shows that the boroughs with better bicycle network coverage are not necessarily the boroughs with the fewer discontinuities. This illustrates the fact even areas with good cycling network coverage can be improved by identifying and removing discontinuities. Other complementary indicators such as discontinuity must also be considered to estimate the performance of a cycling network.

However, not all types of discontinuities can be as easily removed or improved. Discontinuities measured by category A indicators are intrinsic to the cycling network and can be more easily addressed than the discontinuities measured by category B indicators. Addressing the former can be done for example by connecting the ends of the network to the closest bike facility or upgrading short stretches of bike facilities of a different type. Addressing the latter requires to modify characteristics of the road networks such as the number of lanes or to reroute traffic to avoid traffic volume variations.

Among the limitations of this study, several come from the unavailability of some data required to estimate several indicators such as the location of all bicycle facilities (side on road), the bicycle and vehicle turning restrictions, the location of on-street parking that require crossing bicycle facilities, the location of bus stops, etc.. The sensitivity of all indicators to some choices has not been completely investigated, for example whether or not to include designated roadways in the calculations and how to take into account off-road bike paths. The indicator for the number of ends of the cycling network can also be improved by taking into account the types of roads at each end, e.g. if all are high traffic volume arterials or local residential streets.

For further studies, we aim to automate the method to calculate all the proposed discontinuity indicators so that the methodology can be easily applied to different areas and cities. Once the automated process is completed, it will be applied to compare several cities with a variety of cycling friendly networks, such as Copenhagen in Denmark, in order to examine the sensitivity of the proposed indicators. Finally, this work is a preliminary step to identify points of discontinuity in the cycling network that will be investigated through direct video-based observation and analysis of cyclist behaviour and safety using in particular surrogate measures of safety.

Acknowledgments

The authors acknowledge the funding provided by the Fonds de Recherche du Québec – Nature et Technologies (FRQNT), grant 2015-NC-180344, for this research.

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