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Is that move safe? Case study of cyclist movements at intersections with cycling discontinuities

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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.

This paper presents a novel movement-based probabilistic SMoS approach to evaluate the safety of road users' trajectories based on clusters of trajectories representing the various movements. This approach is applied to cyclist-vehicle interactions at two locations of cycling network discontinuity and two control sites in Montréal. The Kruskal-Wallis and Kolmogorov–Smirnov tests are used to compare the time-to-collision (TTC) distribution between motion patterns in each site and between sites with and without a discontinuity. Results demonstrate the insight provided by the new approach and indicate that cyclist interactions are more severe and less safe at locations with a cycling network discontinuity and that cyclists following different movements have statistically different levels of safety.

1. Introduction

While there was a 6.7% increase in cycling mode share in the past five years, 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, 2016). 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 et al., 2017; Hubner et al., 2017)) and surrogate measures of safety (SMoS) (e.g. (Guo et al., 2016; Madsen and 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 and Hyden, 1997; 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 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

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to an extent that a collision is imminent if their movements remain unchanged (Amundsen and Hyden, 1997). 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 and 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 and 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 (Fig. 1). This more detailed level of analysis will help better understand the different safety levels of specific movements and lead to more appropriate countermeasures.

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. 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., 2018a). 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 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.

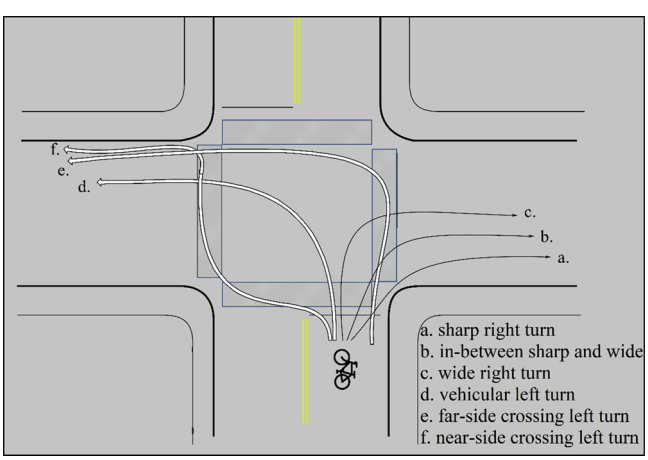

Fig. 1. Possible right and left turning movements.

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 conflict self-reporting. 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 and 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 and Migletz, 1980). A study of manual video analysis at signalized intersections counted the number of observed conflicts if one road user reacted with an avoidance maneuver, 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 and 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 (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 and 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 evaluated 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).

Safety evaluation is done using either all the generated conflict indicators, or aggregated per general direction of movement. The majority of the mentioned studies above have analysed all interactions, summarizing 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

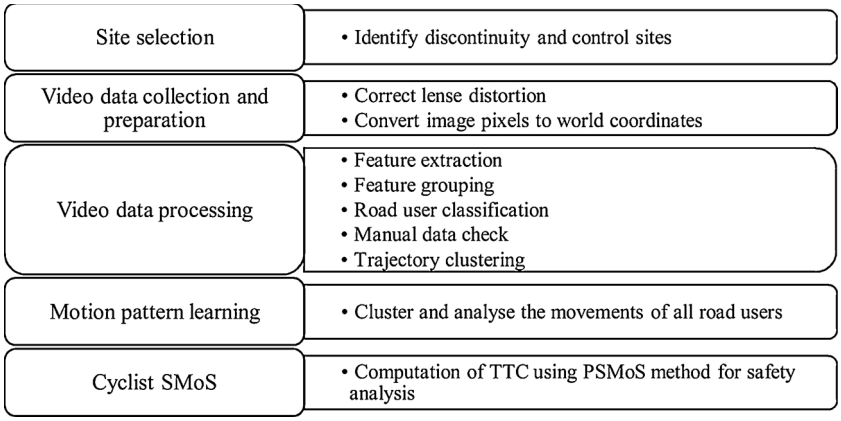

Fig. 2. Methodology overview.
Note: the aerial view of the intersection does not show the newly built physically separated cycling facility on the southwest corner of Maisonneuve, but the location is indicated with the yellow arrows.

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 and 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 signalized intersections where cyclists riding through yellow and cyclists with higher speeds increased the chance of a conflict between turning vehicles and through cyclists (Buch and 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 different cyclist maneuvers in each movement category (e.g. different right turning strategies).

3. Methodology

Fig. 2 summarizes the general methodology steps which are discussed in detail in the subsections. It should be noted that the cycling facilities throughout the paper are categorized 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).

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 previous work (Nabavi-Niaki et al., 2018b). 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 Fig. 3a. Besides, at the discontinuity intersection (Fig. 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 (Fig. 3b).

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 (Fig. 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 (Fig. 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 with 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.

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.

3.2. Video data preparation and analysis

The next step, shown in Fig. 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 A.M. until 10 A.M. 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

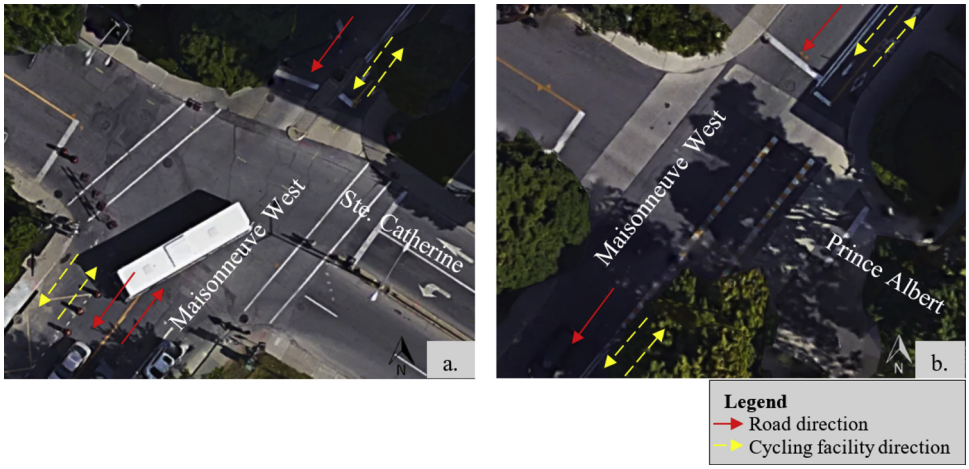

Fig. 3. Aerial view of the a. Maisonneuve and Ste. Catherine discontinuity, and b. Maisonneuve and Prince Albert control site.
Note: the aerial view of the intersection b. Coffee and West Broadway has the physically separated cycling facility blocked by trees, the yellow arrows indicate the location where the facility exists.

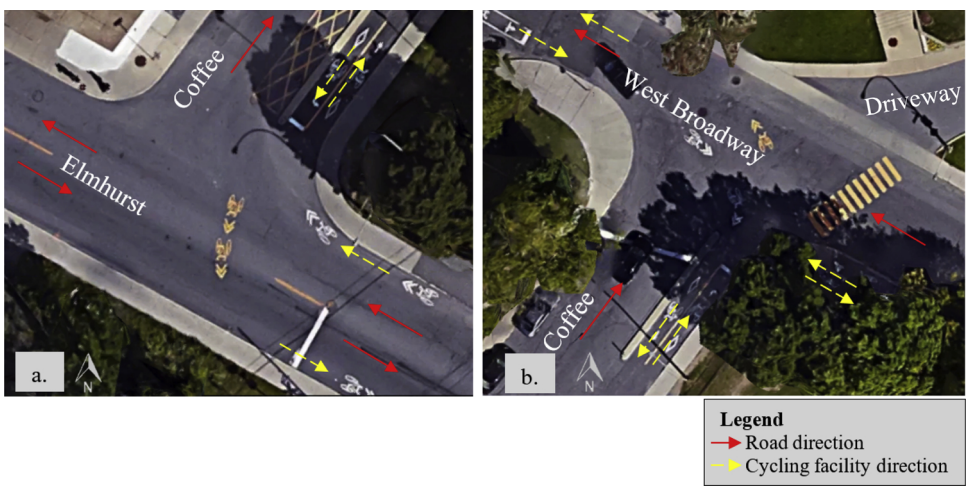

Fig. 4. Aerial view of the a. Coffee and Elmhurst discontinuity, and b. Coffee and West Broadway control site.

these sites had to be chosen based on a time where these limitations were reduced, for Coffee and Elmhurst the hours between 10 A.M. and 12 P.M. are selected, and for the control site Coffee and West Broadway the analysis period is between 12 P.M. and 2 P.M. Although this difference in analysis time frame is not desirable, the quality of the tracking results is 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 and Saunier, 2015; Saunier et al., 2007) is adopted to combine similar trajectories based on the longest common subsequence similarity (LCSS), using the Manhattan distance[1] 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.

3.3. SMoS computation

The last step (see Fig. 2) of the methodology computes the SMoS. 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 et al., 2015)). Two statistical tests are employed to confirm the differences in safety levels across motion patterns and sites. Within each

[1] The Manhattan distance is defined as the sum of the horizontal and vertical paths between two points in a grid network. For two points with coordinates (x_1, y_1) and (x_2, y_2), their Manhattan distance is $|x_1 - x_2| + |y_1 - y_2|$.

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

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.

4. Case study

4.1. Descriptive analysis: change in cycling facility location on road

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 (Fig. 5a), there are 38 cyclist motion patterns under study, while at the control site (Fig. 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.

Cyclists traveling northeast originating from outside the cycling facility and ending in the cycling facility displayed four distinct maneuvers (Fig. 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 one movement traveling from inside the cycling facility and ending inside the facility (Fig. 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 (10 motion patterns) and from outside the facility (9 motion patterns) ending inside the facility. At the control site, there are two motion patterns in the southwest direction one travelling inside the cycling facility and one outside (Fig. 5b). At the discontinuity site, very few cyclists travelling northeast from outside the facility into the facility 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.

4.1.2. Safety analysis

At the discontinuity location, out of the interactions with a collision course (and therefore a TTC_{15}), 65 belong to a cyclist motion pattern under study, compared to 69 interactions belonging to a cyclist motion pattern under study at the control site. The 65 interactions at the

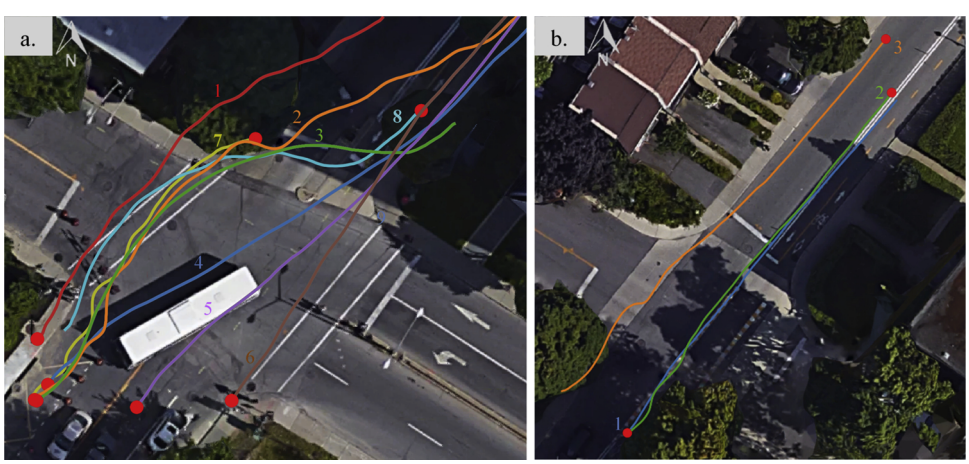

Fig. 6. Cyclist motion patterns under study with cyclist-vehicle interactions with a collision course at the a. discontinuity location, and b. control site (origins marked with a red circle).
Note: TTC_{15} samples for motion patterns with less than 5 interactions traveling in the same direction are pooled.

Table 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.

discontinuity location belong to 8 motion patterns: six motion patterns traveling northeast (Fig. 6a motion patterns 1 through 6), and two traveling southwest (Fig. 6a motion patterns 7 and 8). At the control site, all motion patterns under study are associated with cyclist interactions with a collision course (Fig. 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) (Fig. 6a and Table 1) representing cyclists traveling 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, Fig. 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 (Fig. 6a motion patterns 5 and 6).

Cyclists traveling southwest who are 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 (Fig. 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 Fig. 6b, have more interactions (18 interactions compared to 5) that are less safe than at the discontinuity location (Table 1).

Fig. 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 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 are exposed to different levels of risk of collision.

4.2. Descriptive analysis: changes in cycling facility type

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 Fig. 8a, and seven at the control site shown in Fig. 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 Fig. 8.

Motion patterns at these locations can be categorized 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. The through cyclists are affected by the change from designated roadway to no facility north of the intersection. In the right-turning movements, both discontinuity and control sites have one cyclist motion patterns (Fig. 8a, motion pattern number 10; and Fig. 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 (Fig. 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 (Fig. 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 (Fig. 8a motion patterns 5 and 7), with no observed corresponding movement at

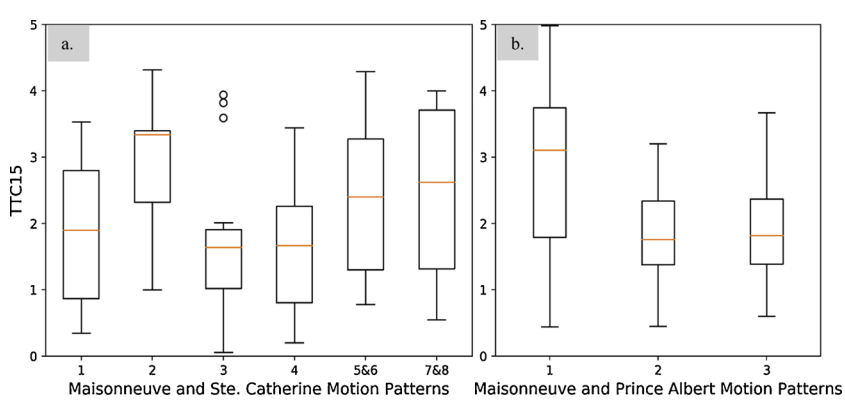

Fig. 7. Boxplot of TTC_{15} per motion patterns under study at the a. discontinuity, and b. control site.

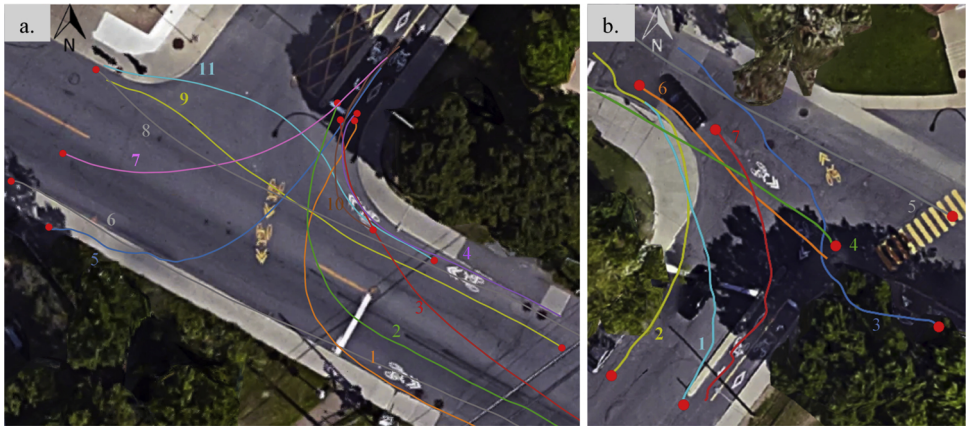

Fig. 8. Cyclist motion patterns under study at the a. discontinuity location, and b. control site (origins marked with a red circle).

the control site.

Straight moving cyclists traveling northwest made two distinct maneuvers at the discontinuity location (Fig. 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 (Fig. 8b motion patterns 3 and 4), and one which originates from outside the facility traveling on the road (Fig. 8b motion pattern number 5). In the opposite direction at the discontinuity location, cyclists traveling southeast belonged to two motion patterns (Fig. 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 (Fig. 8b motion pattern number 6).

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 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 may be related to the lower vehicle flow at the control site compared to the discontinuity site. Keeping this in mind, the median TTC_{15} of motion patterns are presented but strong conclusions cannot be drawn 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 2), This can be due to the cyclists crossing the bi-directional road and merging with traffic on the designated roadway (Fig. 8a motion pattern number 1 and 2), and the cyclist traveling the wrong way (Fig. 8a 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 has only one motion pattern: motion pattern number 10 at the discontinuity site (Fig. 8a) with five cyclists and four interactions (median TTC_{15} of 3 s), and motion pattern number 7 at the control (Fig. 8b) 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 Fig. 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 2), compared to a median TTC_{15} of 2.7 s at the control site.

Table 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.

Despite the small sample size, 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.

4.3. Comparison of all sites

Comparing the distribution of TTC_{15} among all sites (Fig. 9) 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

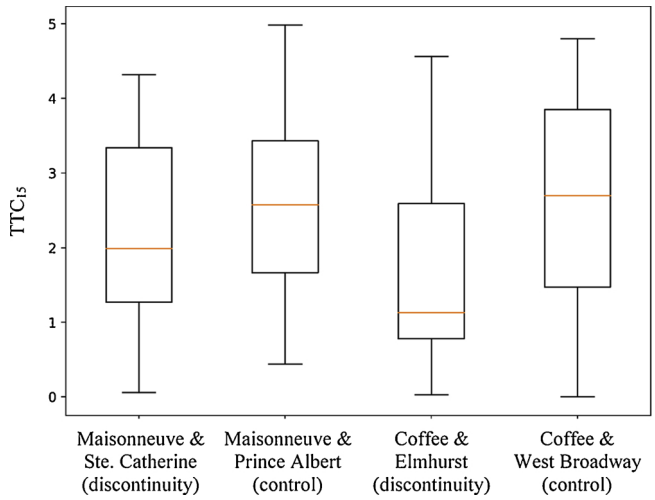

Fig. 9. Boxplot of TTC_{15} of interactions affected by the discontinuity per location.

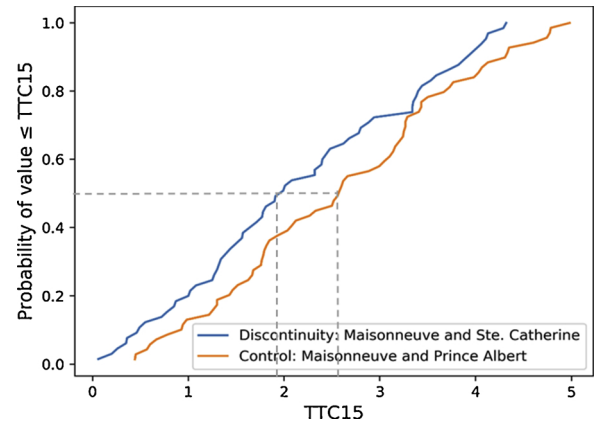

Fig. 10. Cumulative distribution function of TTC_{15} of cyclists-vehicle interactions under study (discontinuity: change in cycling facility location).

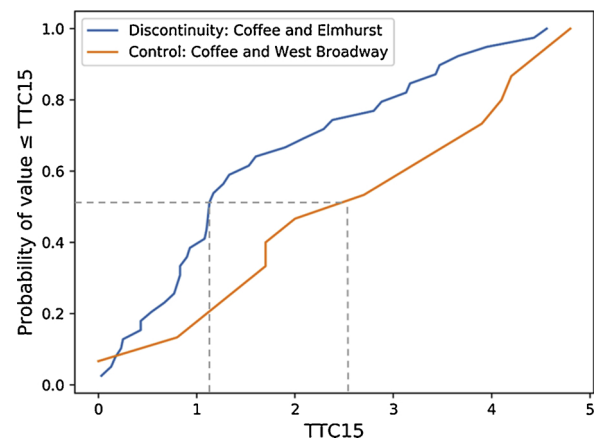

Fig. 11. Cumulative distribution function of TTC_{15} of cyclists-vehicle interactions under study (discontinuity: change in cycling facility type).

TTC_{15} quartiles shifted towards lower TTC_{15} values compared to the control sites. In fact, the cumulative distribution functions shown in Figs. 10 and 11 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 (D = 0.4, p-value = 0.05), but not at the Maisonneuve intersections (D = 0.2, p-value = 0.2).

5. Conclusion

This study proposes a maneuver-based 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. The safety of cyclist-vehicle interactions is characterized using SMoS, namely TTC_{15}. The number of interactions and the median TTC_{15} are then 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 less safe 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 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 with a change in cycling facility side on the road have more severe interactions with motorized traffic. More data is required to make the same conclusion for the discontinuity with a change in cycling facility type. Indeed, limitations of this study include the short duration of study (two hours per location). Although behavioural variability is easily observed, and some 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. More research is needed on the sensitivity of such results with respect to the quantity of data (number of sites, trajectories and interactions). 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 and processing are also to needed to address issues caused by 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.

Author contribution

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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