Are Intersections With Cycle Tracks Safer? A Control-Case Study Based On Automated Surrogate Safety Analysis Using Video Data

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ABSTRACT

In recent years, cities in North America have been building cycle tracks with the intention of providing cyclists with a safer alternative to biking in the street. These facilities have been built and expanded but very little research has been done to investigate the safety impact of cycle tracks, in particular at intersections, where cyclists interact with turning-motor-vehicles. Some of the safety research has looked at observed injuries, finding some positive safety impacts of cycle tracks. The objective of this work is to investigate the safety effects of cycle tracks at intersections using a control-case study. For this purpose, a video-based method is proposed for analysing the post-encroachment time as a surrogate measure of the conflicts between cyclists and turning-vehicles traveling in the same direction. Using the city of Montreal as the case study, a sample of intersections with and without cycle tracks on the right and left sides were carefully selected accounting for intersection geometry and traffic volumes. A total of 90 hours of video were collected and processed in order to obtain cyclist and motor-vehicle trajectories and interactions. After cyclist and motor-vehicle interactions were defined, ordered logit models with random effects were developed to evaluate the safety effects of cycle tracks on conflicts at intersections. Among other results, it was found that intersection approaches with cycle tracks on the right are safer than intersection approaches with no cycle track; however, intersections with cycle tracks on the left compared to no cycle tracks were not found to have be significantly safer. As part of the contributions of this work, one can mention the extraction and use of disaggregate bicycle and vehicle flows in short time intervals such as 10 seconds intervals. The results identify that the likelihood of a cyclist being involved in a dangerous conflict increases with increasing turning-vehicle flow and decreases with cyclist group arrival.

Keywords: Cycle Track, Cyclist Safety, Video Analysis, Surrogate Safety Measure, Random Effects Ordered Logit Model

INTRODUCTION

In recent years, cities throughout North America have begun to follow Europe and Asia's lead and have started to build bicycle infrastructure. Until recently, cities have been building and expanding their cycle tracks but have not carried out many in-depth analyses to quantify their effect on cyclist safety, specifically at intersections where over 60% of cyclist injuries occur *(1)*. Now that cyclist numbers are on the rise, cyclist safety concerns at bicycle facilities have become an important issue. In the US and in Canada, cities have implemented cycle tracks which are physically separated from vehicle traffic by concrete medians or bollards, as well as bicycle lanes delineated from vehicles by painted lines or simple sharrows (shared lane markings) along the roadway for vehicles and cyclists to share the same road. Several facilities of these types can be found in cities like Montreal. Despite their increasing popularity, few studies have investigated whether or not cycle tracks are the appropriate solution and more specifically, how safe intersections with cycle tracks are for cyclists with respect to intersections without cycle tracks.

Despite the growing literature, most previous studies have investigated the safety effect of cycle tracks using historical bicycle injuries also referred to as motor-vehicle-bicycle crash data *(2–5)*. In general, these studies have identified the safety benefits of corridors with cycle tracks. Despite their importance, these studies have not been able to fully answer the question about whether or not intersections with cycle tracks are safer than similar intersections without cycle tracks. Also, given the limitations of the crash data, these studies have not looked at cyclist risk mechanics microscopically focusing on interactions between vehicles and cyclists, such as right-turn and left-turn interactions at intersections with and without cycle tracks. Also, only a few studies have used surrogate safety measures or have relied on manual or semi-automated methods *(6, 7)*. Also, past surrogate studies typically have involved one or very few locations *(6, 7)* and some of them have focused on aggregated conflicts and they have mostly been carried out in Europe *(8–10)*. Overall these studies have not investigated the specific question: what is the effect of cycle tracks on cyclist safety and more specifically what effect does building them on the right or left sides of the road have on safety.

In this work, we tackle the shortcomings in the current literature by developing an automated method based on video data to characterize road user interactions using surrogate safety measures and extract variables from the video to model these conflicts. This surrogate measure is used to study the safety effects of cycle tracks at intersections focusing on conflicts between turning vehicles and cyclists traveling in the same direction. For this purpose, a sample of intersections with cycle tracks (treated) and a sample without cycle tracks (controls) are carefully selected in the city of Montreal, Canada. This study is expected to provide additional insight on the risk of conflict (in terms of probability) of bidirectional cycle tracks at intersections.

At the selected intersections, 90 hours of video are collected and processed in order to obtain the road user trajectories. From the videos, PET (post-encroachment time) is computed for each cyclist as a surrogate safety measure instead of the traditional approach of modeling based on historical injury data for which it is highly likely to have no or a very small number of injuries occurring even over a relatively large study period of several years. Also, variables affecting conflicts, such as bicycle flow and motor-vehicle flow, can be obtained from the video as aggregately or disaggregately as is desired *(11)*. Other geometric design variables are also generated from the video and accounted for in the modeling.

This paper is divided into several sections. First a review of the literature on cyclist safety at cycle tracks, surrogate safety measures as well as automated methods is provided. This is followed by a detailed description of the proposed automated video based methodology. The paper then presents and discusses the modelling results and finally provides the conclusions that are drawn from this study and future work.

LITERATURE REVIEW

Several studies have been published in recent years on cyclist safety in urban environments. In particular, some of these studies have investigated cyclist injury risk on cycle tracks to identify and quantify the safety effectiveness of cycle tracks. Overall studies have concluded that corridors with cycle tracks are either safer or at least not more dangerous than corridors without cycle tracks. We can refer to the literature review of Thomas and deRobertis *(2)* which examined the literature on cycle tracks from different countries mostly in Northern Europe and one study in Canada. Overall, it was found that one-way cycle tracks are safer than bidirectional cycle tracks and that in general, cycle tracks reduce collisions and injuries when effective intersection treatments are also implemented. Another review of the literature by Reynolds et al. *(3)*, revealed that bicycle-specific facilities, not shared roads with vehicles or shared off-road paths with pedestrians, reduce both the risk of accidents and injuries. Also, of the 23 studies reviewed, 8 examined safety at intersections which were for the most part roundabouts.

Safety studies can be divided into cross-sectional studies in which data from a sample of locations or intersections with different geometry and built environment characteristics is used *(1, 12, 13)*, before-after studies, in which data from before and after treatment implementation is available from a sample of treated and non-treated locations *(14–18)* and finally control-case studies in which data from a sample of intersections contains two subsets: a subsample of intersections in which the treatment exists and a subsample of intersections with very similar characteristics (same traffic intensity, geometry) but without treatment *(4, 19)*.

A case-control study carried out in Montreal *(4)*, compared cyclist injury rates on 6 bidirectional cycle tracks and compared them to that on reference streets. Bicycle flows were found to be 2.5 times greater on tracks than on the reference streets and the relative risk of injury on tracks was found to be 0.72 compared to the reference streets, supporting the safety effects of cycle tracks. A study looking at bicycle infrastructure in Toronto and Vancouver found that cycle tracks had the lowest injury risk of other infrastructure types with one ninth of the risk of major streets with parked cars and no bicycle infrastructure *(5)*. Overall quiet streets and bicycle facilities on busy streets provide safest passage for cyclists. An older before-after study in Denmark found that cycle tracks increased bicycle flows by 20 % while decreased vehicle mileage by 10 % *(18)*. However, overall, injuries were found to increase with the implementation of cycle tracks. While injuries were reduced along links, the increase in injuries at intersections was greater than this decrease. The author identified that cycle tracks which end at the stop line of the intersection are dangerous. A decade prior, Garder et al. *(20)* came to a similar conclusion in Sweden, that physically separated tracks should be cut some short distance before the intersection which would not only improve visibility but also cause cyclists to feel less safe influencing them to pay greater attention at intersections.

These previous studies proposed different methodologies to study cyclist safety based on historical crash data and statistical analysis, which can be referred to as the traditional safety approach. Studies using surrogate safety measures are beginning to gain popularity in the literature. For bicycle studies using surrogate measures and analysis, we can refer to *(6, 7)*. Surrogate safety analysis looking at the effects of cycle tracks are rare in the current literature. Also, most of these studies consider only one or a small sample of intersections.

Automated methods of evaluating safety using surrogate measures have begun to emerge in the literature *(7, 21, 22)*. A recent study in Vancouver presented the use of an automated method to obtain TTC (time-to-collision) to identify the severity of cyclist conflicts at one busy intersection *(7)*. Another recent study in Ottawa evaluated cyclist-vehicle conflicts at signalized intersections based on post-encroachment time (PET) *(21)*.

Despite this growing literature, most previous studies have investigated the safety effect of cycle tracks using historical motor-vehicle – bicycle crashes; despite their importance, these studies have not been able to fully answer the question about whether or not intersections with cycle tracks are safer than similar intersections without cycle tracks.

METHODOLOGY

This section describes the methodology consisting of the following steps: i) site selection and video data collection, ii) data processing and iii) statistical analysis. Additional details for each step are provided as follows.

Site Selection and Video Collection

To investigate the safety effect of cycle tracks, several hours of video were recorded from intersections both with and without cycle tracks, all of them in Montreal. A sample of sites with cycle tracks on the right side of the road, on the left side of the road (which can only exist on one way roads) and control sites without cycle tracks (or any other bicycle facilities) were selected. It is worth mentioning that all the studied cycle tracks in this paper are bidirectional. Using other sources of bicycle and vehicle traffic flow data, we were able to identify sites with and without cycle tracks with high levels of bicycle flow providing a large number of cyclists to study. All intersections in this study are signalized where at least one approach is defined as an arterial or a collector. Due to summer road closures and construction, some alternate sites had to be selected. For each cycle track on the right, video was collected the exact same day and time at a control site. The control sites were selected on parallel streets but without having any bicycle infrastructure. Where possible, parallel streets were selected since these streets provide an alternative route for cyclists who do not wish to ride along the street with a cycle track. Also, the control sites were selected to have similar traffic conditions. No control sites were selected for cycle tracks on the left since streets without cycle tracks on the left, would have cyclists riding on the right and therefore this type of conflict does not exist anywhere but where the cycle track is on the left. Figure 1 provides the locations of these intersections.

For the video data collection, GoPro Hero 3+ Black Edition cameras were used in HD resolution at 15 frames per second. These cameras were mounted on tall poles which are then installed next to an existing pole at the intersection to support and provide stability for the pole to prevent the camera view from changing throughout the video. Where possible, these poles were set up on the approach opposite and facing the conflict area. In some cases, alternate poles and locations were necessary since there was no pole at some intersections or the location of the traffic signals prevented the camera from being mounted in the ideal location. Using available bicycle flow data from automatic counters, we were able to identify the peak cycling hours. For this data collection, evening peak was selected as the study period in order to ensure a sufficient number of cyclists to study. Videos were collected on weekdays during the evening peak period from 15:00 to 19:00 and within this time period, the videos were collected for 2 to 4 hours except for "Cote Sainte Catherine" for which videos were recorded for around 8 hours starting from morning peak. The camera angle differed for each site since the angle was changed to have the best view of the conflict area and the cyclists and vehicles entering and leaving the conflict area to accurately obtain their trajectories. Depending on the width of the road, the location of an appropriate pole as well as other obstacles, the camera setup differed by site.

In total, 31 hours of video were collected from intersections with no cycle track (8 different intersections), 37 hours for intersections with cycle track on the right side of the road (8 different intersections) and 22 hours for intersections with cycle track on the left side of the road (7 different intersections).

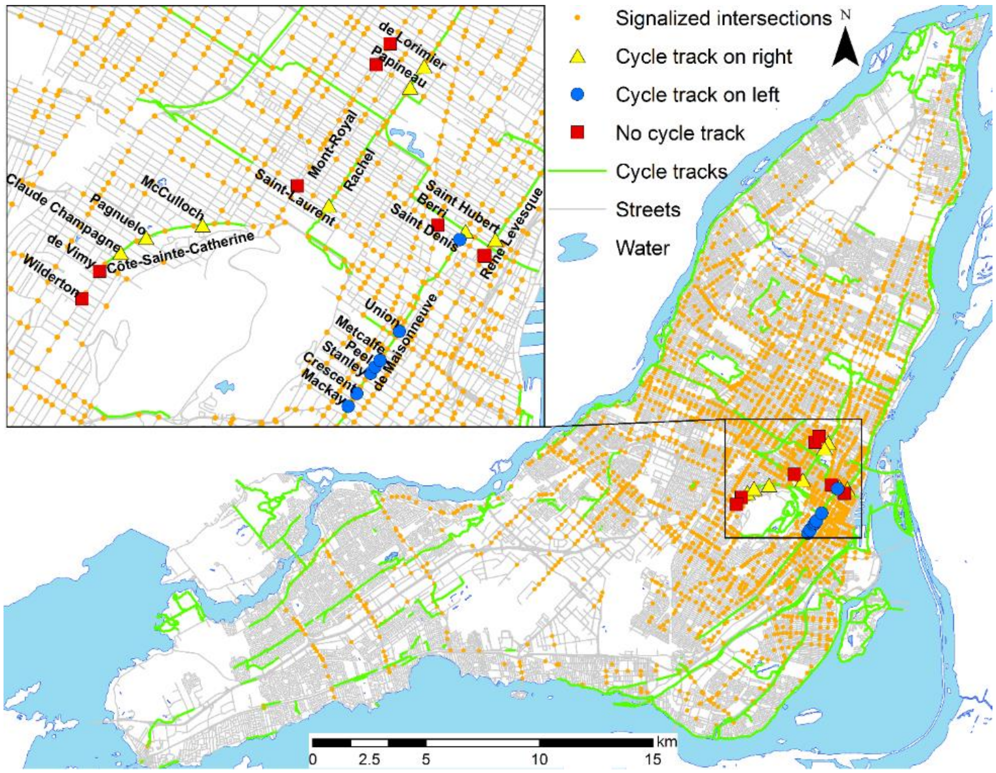


Figure 1. Location of sites selected for recording video in Montreal

Data Processing

Data processing includes four steps: detecting and tracking moving objects in the video, classifying the objects into their road user types (pedestrian, cyclist or vehicle), selecting the road users involved in the conflict under study, and computing the surrogate measures for each cyclist-vehicle interaction *(23)*. Further details are provided as follows:

Tracking Objects in Video

An existing feature-based tracking tool from an open-source project called *Traffic Intelligence (24)* is used for detecting and tracking the objects in the video. The proposed approach uses the output of the moving object tracker *(25)*.

The tracker output is a set of trajectories (sequences of object positions at each frame) of each moving object in the video. The parameters of this algorithm are tuned through trial and error, leading to a trade-off between over-segmentation (one object being tracked as many) and over-grouping (many objects tracked as one). Readers are referred to *(25)* for more details.

Object Classification

At intersections with different road user types, object classification is needed, especially when the subject of study is interaction between two different road user types. In this paper, a modification of previously developed method for object classification in video *(26)* has been used. Classification is done based on the object appearance in each frame combined with its aggregated speed and their speed frequency (or gait parameters). The overall accuracy of this classification method at intersections with high volumes and mixed road user traffic is around 93 % (5 % improvement from the original classification method). The classifier is capable of classifying objects in to three main road user types: pedestrian, cyclist, and motor vehicle. For more details regarding the original classification method, readers are referred to *(26)*.

Selecting Trajectories

Only interactions between turning vehicles and cyclists traveling in the same direction, are of interest in this study. Interacting cyclists and turning-vehicles are selected by defining origin and destination areas in the field of view. A trajectory will be selected as a desired cyclist (or vehicle) if:

1- the object is classified as a cyclist (or vehicle)
2- the object passes through the origin area defined for cyclists, B1 (or vehicles, V1) (Figure 2)
3- after the object passes through the origin area, it passes through the destination area defined for cyclists, B2 (or vehicles, V2) (Figure 2)

One sample of a density map derived from the trajectories (both cyclists and turning-vehicles) extracted and filtered by this algorithm is shown in Figure 2. This density map is useful to see the most used locations of the map by the cyclists and turning-vehicles.

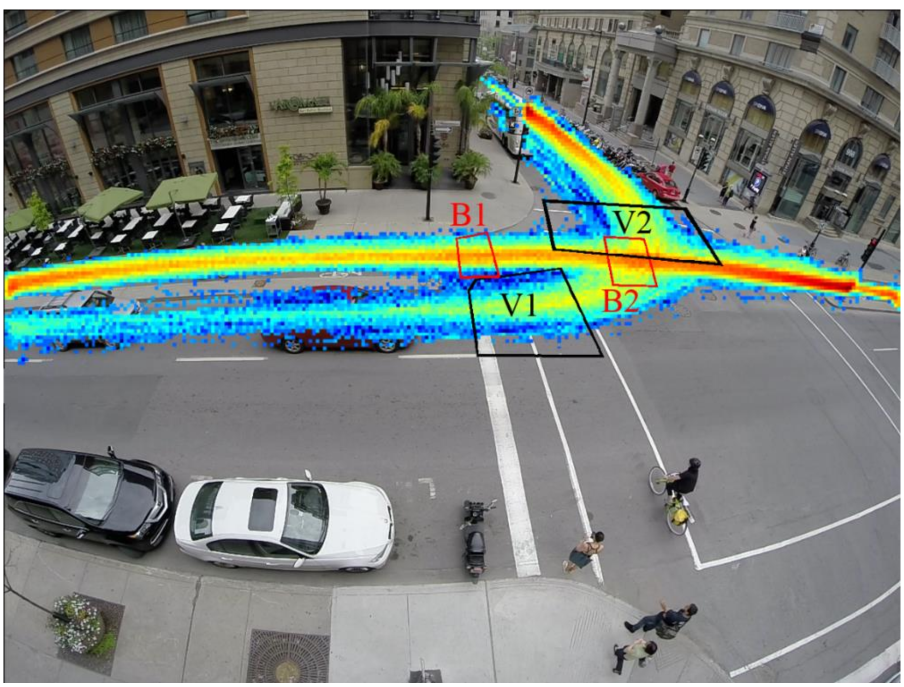


Figure 2. Position density map of the studied cyclists and turning-vehicles in a sample video. The most and least used map locations are respectively red and blue, density map colours range from blue to red, passing through cyan, yellow, and orange. B1 and V1 are the origin areas while B2 and V2 are the destination areas for cyclists and vehicles, respectively.

Surrogate Indicator

The surrogate safety measure used in this study is PET. This measure is the time between the departure of the encroaching cyclist from the potential collision point (at the intersection of the two trajectories) and the arrival of the first vehicle at the potential collision point at the intersection, or vice versa *(27, 28)*. PET is preferred over TTC in this study since all interactions of interest involve the road users' paths crossing each other, so that PET can always be computed. TTC is the most commonly used surrogate measure of safety that depends on the choice of a motion prediction method. The most common motion prediction is constant velocity, which may be inappropriate in many practical cases, in particular if the interactions under study involve turning movements as in this case. Several other methods can be used to alleviate this issue *(29)*, but PET was found to be sufficient for this study. To validate the use of PET, observations with small PET values were automatically extracted from the video and confirmed to be dangerous manually.

Once the desired trajectories are extracted (the ones for cyclists and turning-vehicles), PET can be calculated using the time difference between the instants the two objects (one cyclist and one turning-vehicle) pass through the potential collision point within a threshold distance (selected as one meter). This value is selected for each cyclist as the minimum PET value of that cyclist with the vehicle crossing just before and just after the cyclist.

Statistical Modeling

For the analysis, two approaches are used: raw-risk estimates and statistical models. For the raw-risk estimates, conflict rates and dangerous conflict rates at intersections with cycle track and intersections without cycle track are compared. These rates are defined as follows:

$$Conflict\ (or\ Dangerous\ Conflict)\ Rate = \frac{(NPET_t\ ,\ per\ hour)\ *\ 10^6}{(Cyclists\ per\ hour)\ *\ (Turning - Vehicles\ per\ hour)} \qquad (1)$$

Where in (1):

- $NPET_t$ is number of interactions between cyclists and turning-vehicles per hour with PET less than a predefined threshold value denoted by *t*.
- *t* is a predefined threshold value, 1.5 seconds for dangerous conflicts and 5 seconds for conflicts.

The definition of *t* is based on an average cyclist speed of 18 km/h (5 m/s) and a dangerous deceleration rate of 3.4 m/s^2 as defined by *(30)*. Under these conditions, it takes 1.5 seconds for a cyclist to come to a complete stop so any time shorter than this could result in a dangerous interaction.

In the second analysis, a statistical modeling approach is adopted. For this purpose, the PET value of each individual cyclist arriving to the intersection with the turning-vehicle that turns closest in time to the cyclist (the one that provides the minimum PET for the cyclist) is used as the dependent variable. Only the cyclists riding parallel to the motor-vehicles, in the same direction (prior to turning), are the focus of this study, shown in Figure 3. In order to provide more meaningful results, PET values (for each cyclist) are discretized into four categories, defined as:

1- PET ≤ 1.5 seconds, considered as a very dangerous interaction.
2- 1.5 seconds < PET ≤ 3 seconds, considered as a dangerous interaction.
3- 3 seconds < PET ≤ 5 seconds, considered as a possible interaction.
4- PET > 5 seconds, considered as no interaction.

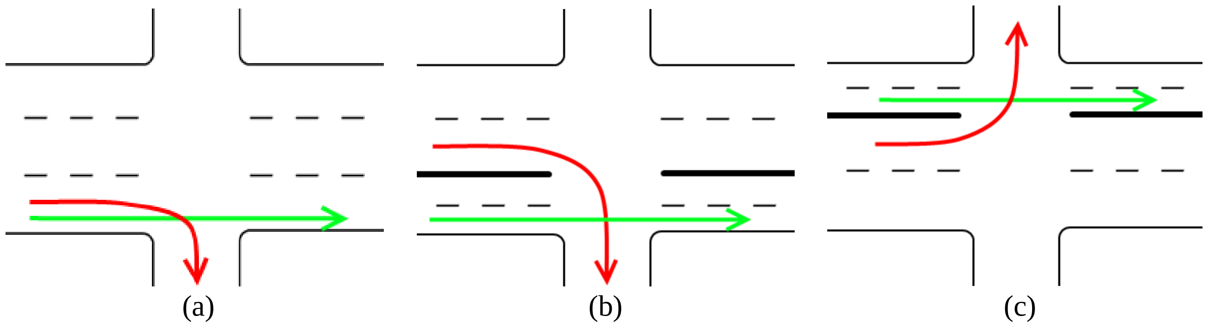


Figure 3. Studied interactions for three different types of intersections: (a) cyclists and right-turning vehicles on intersections without cycle track, (b) cyclists and right-turning vehicles on intersections with cycle track on the right, and (c) cyclists and left-turning vehicles on intersections with cycle track on the left. Red and green arrows show turning-vehicles and cyclists respectively

Once PET is discretized, random effects ordered logit models that are applied to control for the effects of other variables such as traffic conditions and road geometry variables as well as random effect and unobserved variables of each intersection. The random effect ordered logit model is one of the most commonly used statistical models for crash severity analysis. In this model, $y_{ij} = \beta x_{ij} + \varepsilon_{ij} + \delta_j$, where i represents i*'th* observation from site j, x_{ij} is the vector of site-specific and interaction specific attributes such as geometry and traffic flow conditions, β is the vector of unknown parameters, ε_{ij} is the individual error term for each observation and δ_j is the random-effect at the intersection level considering that measurements coming from the same intersections are nested. The dependant variable, y_{ij}, is bound by unknown cut-offs, which define the alternatives. For more details about the random effect ordered logit model, please refer to *(31)*. Several variables were tested as independent variables to find the best possible models. These variables include:

- Cycle track on the right side of the road (dummy variable).
- Cycle track on the left side of the road (dummy variable).
- Number of lanes on the road the vehicles is turning from, parallel to where cyclists are riding.
- Number of lanes on the road that vehicles turn in to.
- Presence of bus stops at the intersection (dummy variable).
- One way street (dummy variable).
- Turning-vehicle and cyclist flows per hour.

Other disaggregate variables are also considered, such as the number of cyclists and turning-vehicles arriving before and after the arrival of each individual cyclist. Considering cyclist i (C_i) arrives at time t_i, these variables are defined individually for cyclist i, as:

- Bicycle flow before C_i: number of cyclists arriving between t_i-t_b and t_i.
- Bicycle flow before and after C_i: number of cyclists arriving between t_i-t_{ba} and t_i+t_{ba}.
- Vehicle flow before C_i: number of turning-vehicles between t_i-t_b and t_i.
- Vehicle flow before and after C_i: number of turning-vehicles arriving between t_i-t_{ba} and t_i+t_{ba}.

Where t_b represents a predefined time interval before the arrival of cyclist i of 10, 30, or 60 seconds and t_{ba} represents a predefined time interval before and after the arrival of cyclist i of 5, 15, or 30 seconds. Different time intervals were selected to determine which has the greatest effect on cyclist safety with respect to turning-vehicles at intersections. The proposed method for counting cyclists in different movements has been shown in *(11)* to provide acceptable counting accuracy.

Using the variables defined previously, different models were proposed to investigate the safety effect of cycle tracks on conflicts between cyclists and turning-vehicles. Three models are developed to compare:

1- Intersections with a cycle track on the right side to intersections without a cycle track.
2- Intersections with a cycle track on the left side to intersections without a cycle track.
3- Intersections with a cycle track on the right side to intersections with a cycle track on the left side.

RESULTS

A summary of the video analysis for the recorded 90 hours of video is shown in Table 1 which shows that:

- Cyclist flow is higher at intersections with cycle track, an average of 18 cyclists per hour for intersections without cycle track, 63 for intersections with cycle track on the right side and 191 for intersections with cycle track on the left side (all the cycle tracks on the left side are on Maisonneuve Boulevard which is one of the busiest cycle tracks in Montreal). This shows that either cyclists prefer to use roads with cycle tracks, or cycle tracks were implemented on roads that have more bicycle flow.
- Looking at the averages at the bottom of the table, the average cyclist speeds are much more similar across site subgroups. Speed is only slightly higher at intersections with cycle tracks which can be due to more space for cyclists to ride and feeling of having more protection at intersections with cycle tracks. Additionally, average cyclist speed is higher at intersections in the downhill direction (like on Cote Sainte Catherine).
- The number of conflicts and dangerous conflicts per hour are on average greater at intersections with cycle tracks. However, accounting for bicycle and turning-vehicle flows, the rate of dangerous conflicts is lower for intersections with cycle tracks as illustrated in Figure 4.
- Figure 5 shows the position density maps for cyclists and turning-vehicles for three different intersection types. These density maps show the acceptable accuracy of detecting, tracking, and classifying road users in the videos. In addition it shows the average distance between cyclists and turning-vehicles at intersections, which can also be related to safety.

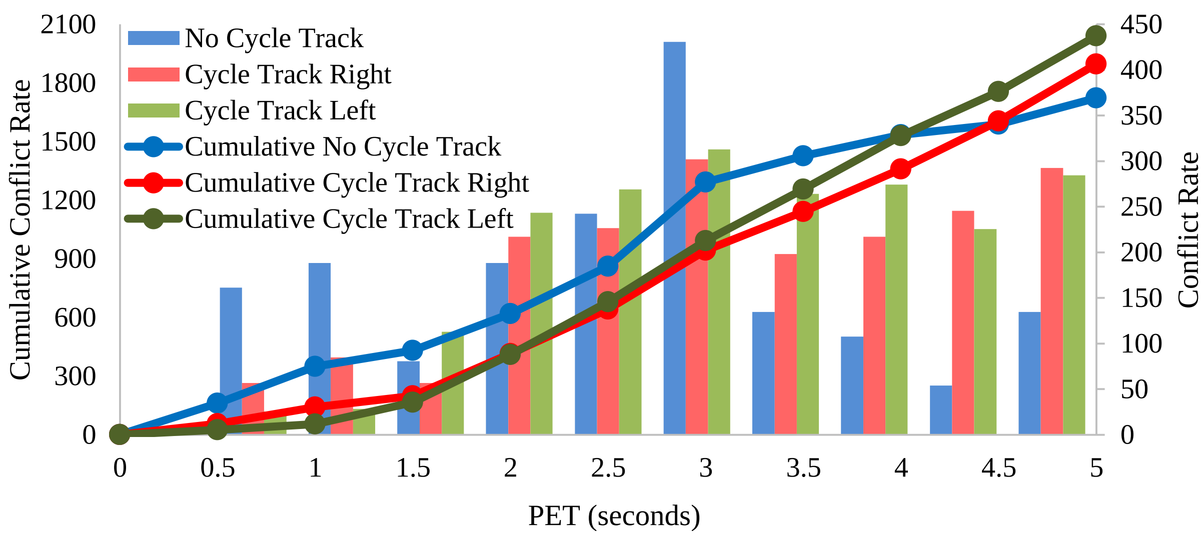
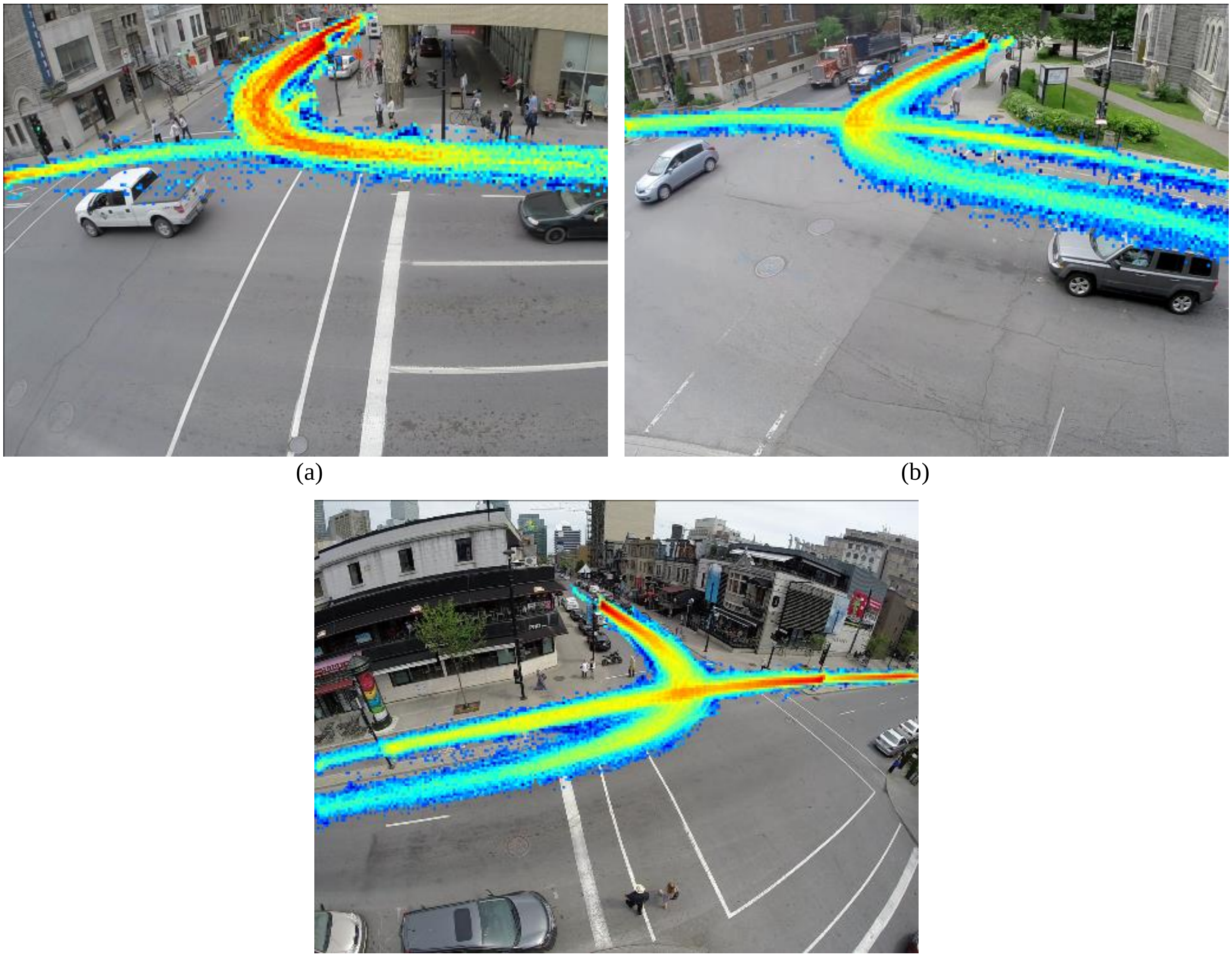


Figure 4. Cumulative distribution and histogram of conflict rate

Table 1. Summary of the processed videos, counts and speeds of cyclists and vehicles

	Intersection	Hours	Number of Bicycles	Number of Vehicles	Bicycle Average Speed (km/h)	Vehicle Average Speed (km/h)	PET < 5	PET < 1.5	Bicycle per Hour	Vehicle per Hour	PET < 5 per Hour	PET < 1.5 per Hour	Conflict Rate*	Dangerous Conflict Rate*
No Cycle Track	Cote Sainte Catherine / Vimy	6.54	56	323	14.3	18.9	6	2	8.6	49.4	0.9	0.3	2169.4	723.1
	Cote Sainte Catherine / Wilderton	8.32	90	843	12.6	9.8	13	2	10.8	101.3	1.6	0.2	1425.6	219.3
	Mont Royal / Lorimier	2.88	106	66	10.9	12.6	4	2	36.8	22.9	1.4	0.7	1646.7	823.3
	Mont Royal / Papineau	1.74	48	50	13.8	10.4	5	2	27.6	28.7	2.9	1.1	3625.0	1450.0
	Mont Royal / Saint Laurent	2.71	53	150	10.4	8.2	6	3	19.6	55.4	2.2	1.1	2045.3	1022.6
	Rene Levesque / Saint Denis	2.8	116	237	10.5	9.3	19	2	41.4	84.6	6.8	0.7	1935.1	203.7
	Saint Denis / Ontario	2.95	43	62	10.1	12.3	2	0	14.6	21.0	0.7	0.0	2213.1	0.0
	Saint Denis / Rene Levesque	2.98	46	328	12.2	14.1	9	3	15.4	110.1	3.0	1.0	1777.6	592.5
Cycle Track on Right	Berri / Maisonneuve	2.89	188	90	8.7	8.4	11	0	65.1	31.1	3.8	0.0	1878.8	0.0
	Cote Sainte Catherine / Claude Champagne	8.28	436	153	18.1	17.8	27	1	52.7	18.5	3.3	0.1	3351.3	124.1
	Cote Sainte Catherine / Mcculloch	7.14	236	125	18.8	18.9	7	0	33.1	17.5	1.0	0.0	1694.2	0.0
	Cote Sainte Catherine / Pagnuelo	8.08	383	340	10.0	13.8	29	1	47.4	42.1	3.6	0.1	1799.4	62.0
	Rachel / Lorimier	2.5	142	63	11.8	11.0	12	0	56.8	25.2	4.8	0.0	3353.5	0.0
	Rachel / Papineau	2.1	226	390	11.7	12.3	16	9	107.6	185.7	7.6	4.3	381.2	214.4
	Rachel / Saint Laurent	2.98	106	350	10.7	9.8	23	6	35.6	117.4	7.7	2.0	1847.4	481.9
	Rene Levesque / Saint Hubert	2.98	605	175	15.7	13.1	76	4	203.0	58.7	25.5	1.3	2139.1	112.6
Cycle Track on Left	Maisonneuve / Crescent	3.5	787	558	14.2	13.7	245	17	224.9	159.4	70.0	4.9	1952.7	135.5
	Maisonneuve / Makay	3.33	476	291	12.5	12.2	82	9	142.9	87.4	24.6	2.7	1971.3	216.4
	Maisonneuve / Metcalfe	3.28	820	358	13.3	12.1	163	15	250.0	109.1	49.7	4.6	1821.2	167.6
	Maisonneuve / Peel	3.48	500	222	13.2	10.4	68	8	143.7	63.8	19.5	2.3	2131.9	250.8
	Maisonneuve / Saint Denis	3.22	398	219	14.2	12.3	73	4	123.6	68.0	22.7	1.2	2696.8	147.8
	Maisonneuve / Stanley	3.32	956	247	12.6	12.4	135	12	288.0	74.4	40.7	3.6	1898.1	168.7
	Maisonneuve / Union	2.09	308	147	14.3	15.5	30	0	147.4	70.3	14.4	0.0	1384.8	0.0
Total	No Cycle Track	30.92	558	2059	11.7	11.9	64	16	18.0	66.6	2.1	0.5	1722.4	430.6
	Cycle Track on Right	36.95	2322	1686	14.0	12.9	201	21	62.8	45.6	5.4	0.6	1897.1	198.2
	Cycle Track on Left	22.22	4245	2042	13.4	12.7	796	65	191.0	91.9	35.8	2.9	2040.4	166.6

* Computed based on equation (1)



(a) (b) (c)

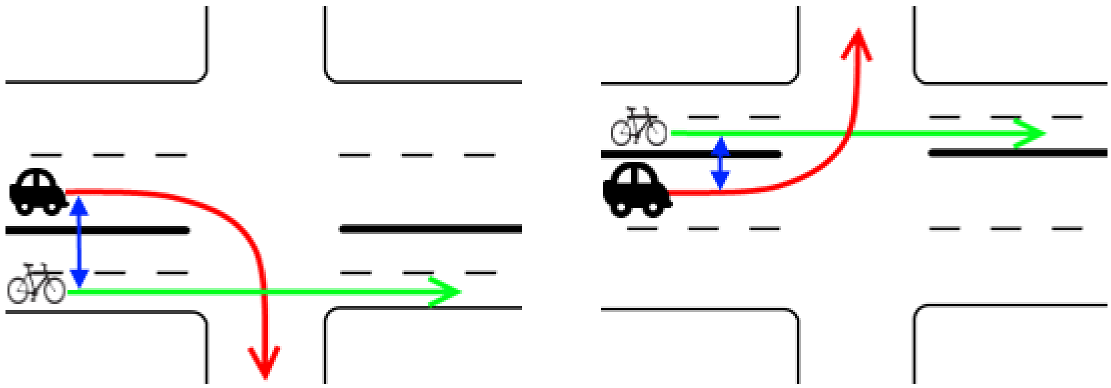
Figure 5. Position density map of cyclists and turning-vehicles for three sample intersections, intersection with no cycle track (a), intersection with a cycle track on the right side of the road (b), and intersection with a cycle track on the left side of the road (c).

The final random effects ordered logit modelling results for PET values are shown in Table 2. Note that different combinations of variables were used to find the best model, and only variables significant to the 95 % confidence level, and which do not have high correlation with any other variable are introduced and presented in the final models.

Table 2. Models for conflicts between cyclists and turning-vehicles

	Model I. Cycle track on the right vs. no cycle track			**Model II. Cycle track on the left vs. no cycle track**			**Model III. Cycle track on the right vs. cycle track on the left**		
	Coef.	Std. Err.	Sig.	Coef.	Std. Err.	Sig.	Coef.	Std. Err.	Sig.
Cycle Track on Right	0.395	0.181	0.03	-	-	-	-	-	-
Cycle Track on Left	-	-	-	Not Significant			-0.513	0.131	0.00
Bicycle Flow for 5s before to 5s after	Not Significant			0.088	0.038	0.02	0.066	0.034	0.05
Turning-Vehicle Flow for 5s before to 5s after	-2.771	0.132	0.00	-3.265	0.090	0.00	-3.131	0.080	0.00
Number of Lane on the Main Road	-0.151	0.078	0.05	Not Significant			Not Significant		
Number of Lane on the Turning Road	Not Significant			0.324	0.146	0.03	0.457	0.178	0.01
Cut-off 1	-6.599	0.353	0.00	-7.372	0.301	0.00	-7.621	0.323	0.00
Cut-off 2	-4.233	0.273	0.00	-3.807	0.223	0.00	-4.125	0.265	0.00
Cut-off 3	-3.150	0.256	0.00	-2.102	0.211	0.00	-2.479	0.258	0.00
Number of Observations	2880			4803			6567		
Log likelihood	-804			-1876			-2330		

The main goal of this complementary regression analysis is to confirm the observed safety effects of cycle tracks, based on conflict rates between cyclists and turning-vehicles. The advantage of regression analysis is that one is able to control for geometry and traffic conditions. Interestingly, the results of the regression analysis are in the same directions, showing that intersections with cycle tracks on the right are safer for cyclists compared to intersections without cycle tracks (Model I). Based on this model, if cycle tracks are built at all the intersections which currently do not have any and keeping all else constant, the expected number of dangerous conflicts (all the conflicts with PET < 3 seconds) does not change but the number of conflicts (all the conflicts with PET < 5 seconds) is expected to reduce by 40 %. However, intersections with cycle tracks on the left (all on Maisonneuve Boulevard) side are not significantly safer than intersections without cycle tracks (Model II). Another finding is that cycle tracks on the right are safer than cycle tracks on the left side (Model III). This may be due to the lateral distance between vehicles and cyclists. At intersections with cycle tracks on the right (Figure 6a), the lateral distance between a vehicle and a cyclist in the same direction is greater than at intersections with cycle tracks on the left (Figure 6b). This means cyclists and drivers have a greater chance of seeing one another and avoiding conflicts. If cycle tracks are moved from the left side to the right side of the intersection and keeping all else constant, based on this model, the expected number of dangerous conflicts (all the conflicts with PET < 3 seconds) does not change but the number of conflicts (all the conflicts with PET < 5 seconds) is expected to reduce by 25 %. These elasticities were computed based on each individual cyclist and with assumption of building cycle tracks on the intersections without cycle track in Model I, and changing the position of cycle tracks on the intersections with cycle track on the left to the right side in Model III.



(a) (b)

Figure 6. Conflict between cyclists and turning-vehicles (the red arrows show a trajectory sample of turning-vehicles, the green arrows show a trajectory sample of cyclists and the blue arrow shows the lateral distance between vehicle and cyclists), for intersections with cycle track on the right side (a), and for intersections with cycle track on the left side (b).

Results show that the number of turning-vehicles is the main factor associated with intersections being dangerous for each individual cyclist. Higher turning-vehicle flow at the time that a cyclist is crossing the intersection provides smaller gaps for the cyclist crossing the intersection and increases the chance of being in a more dangerous conflict with one of the turning-vehicles.

Another variable that makes an intersection dangerous for cyclists is the number of lanes on the main road (the road that vehicles are turning from), meaning that the more lanes on the main road, the more dangerous it is for cyclists on that road (just for Model I). On roads with a higher number of lanes, turning-vehicles need to wait less time for the vehicles in front of them to leave the intersection, so they are less likely to take the time to look for potential cyclists riding next to them prior to turning and this increases the probability of a more dangerous conflict between them and cyclists. In addition, average vehicle speed is higher on roads with a higher number of lanes which can be dangerous for cyclists on that road.

The bicycle flow before and after C_i, defined as the number of cyclists arriving at the intersection between $t_i - 5$ and $t_i + 5$, reduces the risk for each individual cyclist. This means that as the arrival rate of cyclists increases, the chance of being seen by drivers also increases. This variable represents the safety effect of group arrivals, and can also be seen as the "safety in numbers" effect *(32)*. Note that this variable was not significant for comparing intersections with cycle tracks on right to intersections without cycle tracks (Model I).

The higher the number of lanes on the road that vehicles turn in to is another variable that can make intersections safer for cyclists. The more lanes on the road, on to which vehicles turn, means that turning-vehicles have more manoeuvering options for their turning radius to avoid conflicts with cyclists. This variable was not significant for comparing intersections with cycle tracks on the right to intersections with no cycle track (Model I).

It is worth mentioning that a sensitivity analysis was carried out to ensure the results are not dependent on the threshold values chosen to discretize the PET values. Several different thresholds were tested and all the parameter estimates were found to be consistent.

CONCLUSION AND FUTURE WORKS

This work investigates the safety effect of cycle tracks using post-encroachment time as a surrogate measure for the conflicts between cyclists and turning-vehicles traveling in the same direction. As part of the contributions, this research proposed a video-based surrogate methodology with an automated process. This method consists of three main steps, recording video at intersections subject to study, detecting and tracking cyclists and computing their PET with turning-vehicles, and modeling to find the effect of cycle tracks on cyclist safety.

A relatively large sample of sites is involved in this research with many hours of video data. A total of 23 intersections, 8 without cycle track, 8 with cycle track on the right side of the road and 7 with cycle tracks on the left side of the road, representing a total of 90 hours of videos and over 7,000 cyclist-vehicle interactions, were used in this study. Each cyclist represents an observation in the random effects ordered logit modeling framework. Different models were developed to compare the safety effects of intersections based on the presence or absence of cycle tracks and their type (on the right or on the left side of the road). Also, as a contribution of this paper, bicycle and vehicle flow in a short time period before and after the arrival of each cyclist at intersections is used as exposure measure in the models. Usage of these variables instead of just using average hourly flows resulted in better understanding of cyclist behaviours and conflict mechanisms.

With respect to raw conflict and dangerous conflict rates, intersections with cycle tracks on the right and left sides appear to be safer than no cycle track, without accounting for disaggregate traffic flows and geometry characteristics. Based on the regression analysis, which controls for geometry and traffic conditions, intersections with cycle tracks on the right versus no cycle track seem to be safer – in other words, cycle tracks do reduce the likelihood of conflicts at intersections. By adding a cycle track to the right side of the intersections currently without cycle track, conflicts are expected to drop by 40 %. Cycle tracks on the left however, did not show any significant decrease on the chance of conflicts compared to no cycle tracks. Overall, the models showed that cycle tracks on the right are preferred, from a safety perspective, over no cycle tracks or cycle tracks on the left. Moving cycle tracks from the left side of an intersection to the right side has the effect of reducing conflicts by 25 %. Ideally intersection treatments should be implemented as well, to ensure that the safety that cycle tracks provide along road segments are not overruled by conflicts and the potential for collisions they may cause at intersections.

As part of future work, the safety effect of cycle tracks with respect to other cyclist and vehicle movements will be investigated. By adding more data from different cities and countries, the results can be more general and transferable to other cities. To test the accuracy of surrogate safety measures as an indicator of injuries, this analysis will be repeated using historical injury data. Another study will be carried out to compare the safety effects of unidirectional versus bidirectional cycle tracks.

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