Accident Analysis and Prevention 135 (2020) 105360

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Cyclist-motor vehicle collisions before and after implementation of cycle tracks in Toronto, Canada

Rebecca Ling[a,b,*], Linda Rothman[c], Marie-Soleil Cloutier[d], Colin Macarthur[a], Andrew Howard[a]

[a] Child Health Evaluative Sciences, The Hospital for Sick Children Research Institute, 686 Bay Street, Toronto, M5G 0A4, Canada
[b] Dalla Lana School of Public Health, University of Toronto, 155 College Street, Toronto, M5T 3M7, Canada
[c] School of Occupational and Public Health, Ryerson University, 288 Church Street, Toronto, M5B 1Z5, Canada
[d] Institut National de la Recherche Scientifique, 385 Sherbrooke Street E, Montreal, H2X 1E3, Canada

ABSTRACT

Background: Cycling, as a mode of active transportation, has numerous health and societal benefits, but carries risks of injury when performed on-road with vehicles. Cycle tracks are dedicated lanes with a physical separation or barrier between bicycles and motor vehicles. Studies on the effectiveness of cycle tracks in urban areas in North America, as well as the area-wide effects of cycle tracks are limited.

Aims: Study objectives were to examine the effect of cycle track implementation on cyclist-motor vehicle collisions (CMVC) occurring: (1) on streets treated with new cycle tracks; (2) on streets surrounding new cycle tracks in Toronto, Canada.

Methods: Intervention and outcome data were obtained from the City of Toronto. All police-reported CMVC from 2000 to 2016 were mapped. Analyses were restricted to 2 years pre- and 2 years post-track implementation. Rates were calculated for CMVC on streets with cycle tracks (objective 1) and in five defined areas surrounding cycle tracks (objective 2). Zero-Inflated Poisson regression was used to compare changes to CMVC rates before and after cycle track implementation for both objectives. All models controlled for season of collision and cycle track.

Results: The majority of CMVC on cycle tracks occurred at intersections (75%). The crude CMVC rate increased two-fold after cycle track implementation (IRR = 2.06, 95% CI: 1.51–2.81); however, after accounting for the increase in cycling volumes post-implementation, there was a 38% reduction in the CMVC rate per cyclist-month (IRR = 0.62, 95% CI: 0.44–0.89). On streets between 151 m – 550 m from cycle tracks, there was a significant 35% reduction in CMVC rates per km-month following track implementation (IRR = 0.65, 95% CI: 0.54–0.76).

Conclusions: Cycle track implementation was associated with increased safety for cyclists on cycle tracks, after adjusting for cycling volume. In addition, there was a significant reduction in CMVC on streets surrounding cycle tracks between 151 m – 550 m distance from the tracks (a 'safety halo' effect), suggesting an area-wide safety effect of cycle track implementation.

1. Introduction

As a mode of active transportation, cycling offers a wide range of benefits to the individual and to the environment. Cycling helps increase fitness, promote weight loss and reduce stress (Lusk et al., 2011; Chen, 2015). Cycling can also decrease commuting time, reduce road congestion and reduce traffic-related air pollution (Lusk et al., 2011; Chen, 2015; Winters and Teschke, 2010). In Canada, the percentage of trips by bicycle is only 2%; a figure substantially lower than European countries such as the Netherlands, where the percentage is 27% (Pucher and Buehler, 2008). Given the close proximity between cyclists and traffic, cycling on roads is not without risk. In Toronto, between 2003 and 2016, there were 539 events in which a cyclist was killed or seriously injured as a result of a motor vehicle collision (Bhatia et al., 2016). A cyclist in Canada is twice as likely to be killed by a motor vehicle (per kilometer cycled) than a cyclist in the Netherlands (Pucher and Buehler, 2008).

The City of Toronto recently implemented a Vision Zero Road Safety Initiative – a five-year plan from 2017 to 2021 – with the goal of reducing traffic-related deaths and serious injuries to zero (City of Toronto, 2019a). In addition to Vision Zero, the City has also created a Cycling Network Plan, with the goal of building a more connected and comprehensive cycling network in Toronto (City of Toronto, 2018a). The Network plan includes implementing new bike lanes, cycle tracks and trails, adding new cycling routes, and enhancing existing infrastructure (City of Toronto, 2018a). In Toronto, cycling infrastructure includes cycle tracks, cycle lanes, sharrows, multi-use trails, and contra-flow lanes (City of Toronto, 2018b). Cycle tracks provide a physical separation or barrier between the cyclist and the traffic, whereas cycle lanes are separated from traffic by a painted line and do not have a physical separation or barrier (City of Toronto, 2018b). There has been a recent growth in cycle tracks in the City of Toronto since its first

* Corresponding author at: Child Health Evaluative Sciences, The Hospital for Sick Children Research Institute, 686 Bay Street, Toronto, M5G 0A4, Canada.
E-mail address: rebecca.ling@sickkids.ca (R. Ling).

https://doi.org/10.1016/j.aap.2019.105360
Received 28 April 2019; Received in revised form 30 August 2019; Accepted 10 November 2019
Available online 27 November 2019
0001-4575/

introduction in 2013. Cycle tracks accounted for 25% of new cycling infrastructure that has been built (15 of 60 km of total infrastructure) from 2016 to 2018 and is now the fourth most prevalent cycling infrastructure in the city (City of Toronto, 2019b).

A recent literature review on the effectiveness of cycle tracks to prevent cyclist-motor vehicle collisions and injuries showed few studies in North America and limited reporting of "exposure" data, i.e., information on the volume of cyclists before and after implementation of cycle tracks (Thomas and DeRobertis, 2013). With respect to international studies, most cycle track research was conducted 20 years ago, and cyclist volume data were often not reported (Thomas and DeRobertis, 2013). Furthermore, bike networks in Europe are more common on traffic-calmed local neighborhood roads, as opposed to the bike networks on busy downtown streets in North America (Thomas and DeRobertis, 2013; City of Toronto, 2019c). With respect to Canadian studies, Lusk et al. (2011) showed that cycle tracks were associated with a significant reduction in cycling injuries, compared to streets without any cycling infrastructure (RR = 0.72, 95% CI: 0.60–0.85). Similarly, Teschke et al. (2012) conducted a multi-site case-crossover study and showed that cyclists on cycle tracks had the lowest risk of injury, compared to other cycling infrastructure (RR = 0.11, 95% CI: 0.02–0.54). While previous literature has typically focused on effects associated with cycle tracks on treated segments, to our knowledge, there are no studies on area-wide effects, i.e., the effect of cycle tracks on CMVC rates on surrounding streets. We hypothesised that cyclists may change cycling routes after implementation of cycle tracks, which may then lead to a spatial redistribution of CMVC.

The objectives of this study were: (1) to examine the rates of cyclist-motor vehicle collisions (CMVC) on streets with cycle tracks before and after cycle track implementation in Toronto, Canada; and (2) to examine area-wide effects on CMVC rates on streets surrounding cycle tracks before and after cycle track implementation. A pre-post, naturalistic (quasi) experimental design was used for this study.

2. Methods

2.1. Intervention

Cycle tracks were defined as dedicated lanes for cycling, with a physical separation or barrier between the cycling lane and traffic (City of Toronto, 2018b). Implementation dates for cycling tracks (month and year) and geographic location were obtained from the City of Toronto.

2.2. Exposure: cycling volumes

Cycling volumes, on the streets that had cycle tracks implemented, were obtained from the City of Toronto (City of Toronto, 2018c, 2019c). Cycling volume was quantified as the average daily number of cyclists over an eight-hour period (7am to 9am, 10am to 1 pm, and 4 pm to 7 pm). Cyclist counts – before and after cycle track implementation – were conducted on a single occasion, at a single intersection, during the summer, and in dry conditions.

2.3. Outcome: cyclist-motor vehicle collisions

Police-reported collisions involving cyclists and motor vehicles from January 1, 2000 to December 31, 2016 were provided by the City of Toronto, Traffic Services. Police reports included information on age of the cyclist, date and location of CMVC (spatial coordinates), intersection/midblock classification, injury severity, collision type (i.e., driver turning left), lighting, and road surface conditions. Using ArcGIS, ArcMap 10.5.1, CMVC were mapped onto the Toronto road network (Esri: GIS Mapping Software, 2019). Cyclists were categorized as adults (16–59 years) or older adults (60 years and older), based on age groups used by WHO (2019). The police reports record injuries as: none, minimal, minor, major, and fatal. Similar to previous studies, minimal and minor injuries were combined because of frequent misclassification of these injury severity outcomes (Bhatia et al., 2016; Rothman et al., 2015).

2.3.1. Objective 1: CMVC on cycle tracks

For CVMC on streets with cycle tracks, CMVC were included if the collision occurred within a 25 m distance of the street segments with cycle tracks and during the two-year period before, or two-year period after installation of the cycle track. CMVC that occurred in the same month as cycle track implementation were excluded because implementation dates were available only by month and year, and an assumption was made that construction of the cycle tracks would influence cycling patterns during the month of implementation.

2.3.2. Objective 2: CMVC on streets surrounding cycle tracks

To examine area-wide effects, five buffer areas were created using Euclidian distances at 26 m – 150 m, 151 m – 250 m, 251 m – 350 m, 351 m – 450 m, and 451 m – 550 m around the cycle tracks using ArcMap. Areas were defined using 100 m increments to capture surrounding streets and to examine CMVC rates at increasing distances from the cycle tracks. CMVC were included if it occurred in one of the five buffer areas and during the two-year period before or two-year period after cycle-track implementation.

2.4. Statistical analysis

Descriptive trends, by year and season, for all CMVC were examined from 2000 to 2016. Statistical analyses were conducted using SAS 9.4.

2.4.1. Objective 1: CMVC on cycle tracks

Univariate analyses examined differences in CMVC characteristics (i.e. location, injury severity, age, collision types, lighting, and surface conditions) pre- and post-implementation of cycle tracks using Pearson's chi-square test. CMVC rates on treated streets before and after cycle track implementation were compared using Zero-Inflated Poisson regression. The unit of analysis was the number of CMVC per cycle track km-months. Zero-Inflated Poisson models were used to account for over-dispersed data due to excess zero counts, with the month of observation modeled as the inflation variable. The model adjusted for season, given that cycling declines in Toronto during winter months (October to March) and increases in summer months (April to September) (Bhatia et al., 2016). The Vuong test was used to assess model fit. In addition, models were stratified by pre-existing cycling infrastructure as some of the cycle tracks were upgraded from painted bike lanes, to examine differences between streets with bike lanes versus streets without cycling infrastructure prior to cycle track implementation. Incidence rate ratios (IRR) and 95% confidence intervals (CI) were calculated. Using the same modeling approach, a second analysis was conducted to account for changes in exposure, using data on cycling volumes. The unit of analysis for this model was CVMC rates per cyclist-months. IRR and 95% CI were calculated.

2.4.2. Objective 2: CMVC on streets surrounding cycle tracks

Area-wide effects of cycle tracks were evaluated for CMVC rates that occurred within 26 m – 150 m, 151 m – 250 m, 251 m – 350 m, 351 m – 450 m, and 451 m – 550 m surrounding the cycle tracks. CMVC rates in each area were calculated as the number of CMVC per km-months. Using similar modelling techniques described above for objective 1, CMVC rates on surrounding streets were compared before and after cycle track implementation with Zero-Inflated Poisson regression. Models were adjusted for season of collision and cycle track. The analysis was conducted separately for each of the five defined areas. A secondary analysis which combined the data for areas 151 m – 550 m distant from the cycle tracks was also conducted. IRR and 95% CI were calculated.

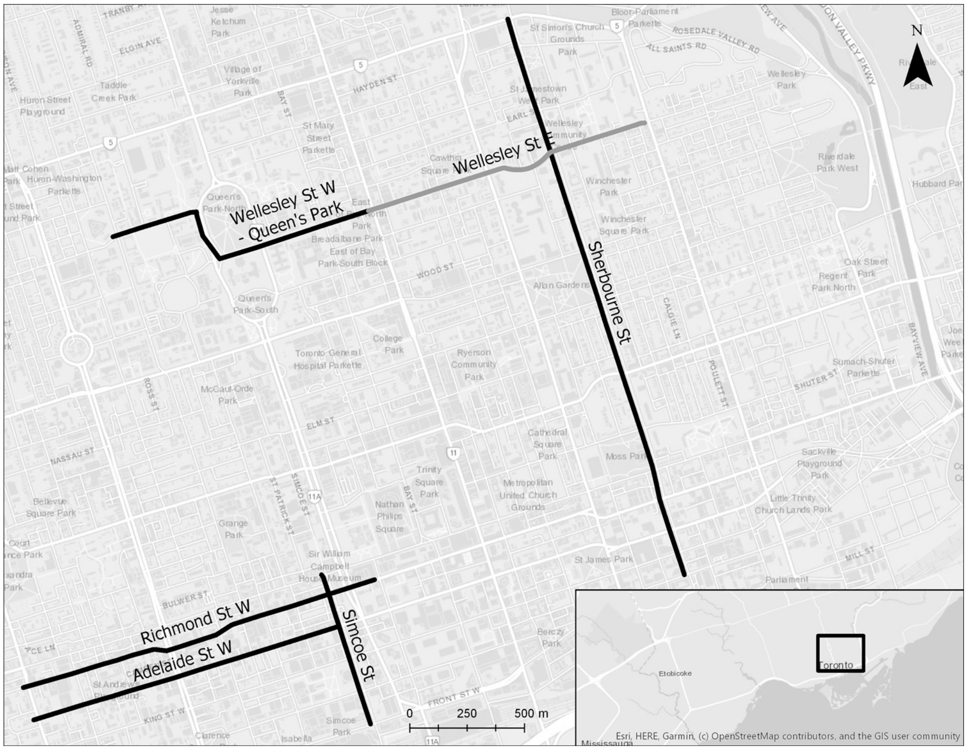

Fig. 1. Locations of the Six Cycle Tracks in Toronto.

3. Results

3.1. Intervention

Six cycle tracks were implemented in the City of Toronto in 2013 and 2014, spanning a total of 8.81 km: Sherbourne St (2.54 km), Adelaide St West (1.61 km), Richmond St West (1.39 km), Simcoe St (0.69 km), Wellesley St East (1.28 km) and Wellesley St West-Queen's Park (1.30 km). Of these six cycle tracks, three were upgraded from painted bike lanes: Wellesley St East, Wellesley St West-Queen's Park, and Sherbourne St. Only two of the six cycle tracks were one-way: Richmond St West and Adelaide St West. The tracks were separated with mixed uses of bollards, planters, raised curbs and raised tracks (City of Toronto, 2019c). A map of the cycle tracks is shown in Fig. 1.

3.2. Overall CMVC trends in Toronto

CVMC on all roads in the City of Toronto increased from 1063 in 2000 to 1196 in 2016 with an average annual increase of 1.04% (see Fig. 2). Major injuries (requiring hospital admission) and fatal injuries rose by an average of 2.27% annually. A seasonal pattern in CMVC was noted; CMVC peaked in the summer and declined in the winter (see Fig. 2). The majority of CMVC occurred in adults between 16–59 years (80%), at intersections (66%), during the day (75%), and on dry road conditions (90%). Additionally, most CMVC resulted in minor/minimal injuries (79%).

3.3. Objective 1: CMVC on cycle tracks

From 2000–2016, a total of 610 CMVC occurred on street segments where cycle tracks were implemented. Of these, 64 CMVC occurred in the two-year period before and 130 CMVC occurred in the two-year period after implementation of cycle tracks. CMVC characteristics are shown in Table 1. Additionally, univariate analyses indicated no significant differences in the frequency of CMVC, before and after implementation of cycle tracks, by location, age, lighting, and road surface condition.

The crude CMVC incidence rate before and after cycle track implementation was 3.02 CMVC per 10 km-months and 6.14 CMVC per 10 km-months, respectively (see Table 2). Collision rates per 10 km-months increased most on Adelaide St West (pre- versus post-implementation: 1.29–7.49, respectively) and on Sherbourne St (pre- versus post-implementation: 3.27 to 5.89, respectively). After adjusting for season, the CMVC rate per 10 km-months significantly increased following the implementation of cycle tracks (Table 3, adjusted IRR = 2.06, 95% CI: 1.51–2.81*)*. Stratified analysis showed a larger increase in CMVC rate on streets that did not have any cycling infrastructure prior to implementation (adjusted IRR = 2.23, 95% CI: 1.47–3.60) compared to streets that were upgraded from painted bike lanes (adjusted IRR = 1.89, 95% CI: 1.24–2.87).

A second analysis adjusted for cycling exposure data before and after cycle track implementation. Cycling volume data were available for 5 of the 6 cycle tracks: Richmond St W, Adelaide St W, Simcoe St, Sherbourne St and Wellesley St E. On average, pre-implementation cycling counts were collected 14 months before cycle track implementation date (range: 9–29 months) and post-implementation cycling counts were collected 34 months after cycle track implementation (range: 9–51 months). The average weekday number of cyclists on all street segments before the cycle tracks were implemented was 2317 cyclists. This increased to an average of 8262 cyclists on the street segments after cycle track implementation. As shown in Table 4, there was an overall crude increase of 257% in cyclist volume following the implementation of cycle tracks on all street segments (range from 5% to 1208% based on the cycle track). In total, 176 CMVC occurred on the 5 cycle tracks. The crude CMVC rate pre-implementation was 23.7 per 1000 cyclist-months which decreased to 14.6 per 1000 cyclist-months post-implementation (see Table 4). Adjusting for season, cycle track implementation was associated with a 38% decline in CMVC (adjusted

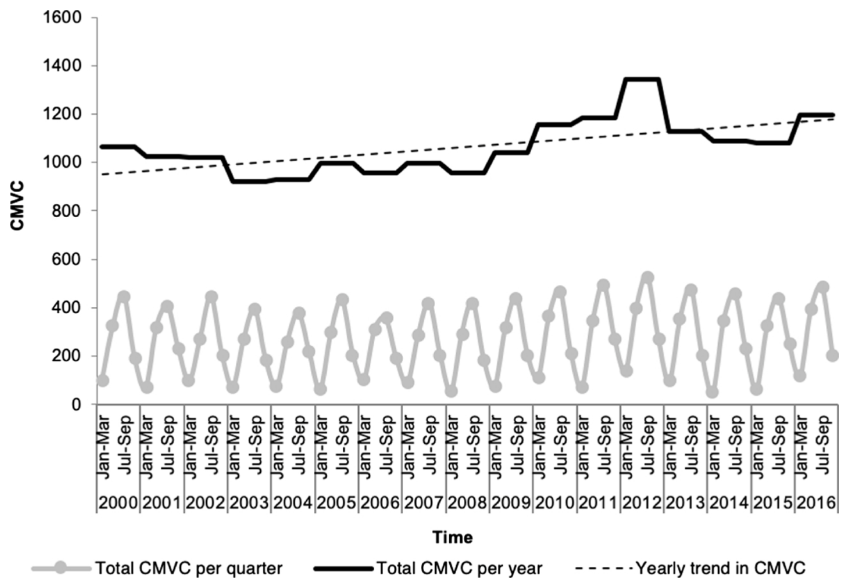

Fig. 2. Quarterly and Yearly Trends in CMVC Counts in Toronto, 2000 to 2016.

Table 1
Collision characteristics on cycle tracks, pre- and post-implementation periods.

Characteristics	2 Years Pre-implementation	2 Years Post-Implementation	Pre vs Post (*p-value*)
CMVC Events	N = 64	N = 130	
Age Categories			0.11
16 – 59 years	63 (98%)	121 (93%)	
≥ 60 years	1 (2%)	9 (7%)	
Injury Severity			0.35
None	10 (16%)	35 (27%)	
Minimal & Minor	50 (78%)	89 (68%)	
Major	3 (5%)	5 (4%)	
Fatal	1 (1%)	0 (0%)	
Unknown	0 (0%)	1 (1%)	
Location			0.73
Intersection	48 (75%)	99 (76%)	
Midblock	14 (22%)	25 (19%)	
Other	2 (3%)	6 (5%)	
Season			0.53
Summer (Apr-Sept)	43 (67%)	93 (72%)	
Winter (Oct-Mar)	21 (33%)	37 (28%)	
Collision Type			0.003
Driver turning at signalized intersection	5 (8%)	29 (22%)	
Driver turning at non-signalized intersection	7 (11%)	11 (8%)	
Dooring	7 (11%)	2 (2%)	
Driver turning left	11 (17%)	12 (9%)	
Other[†]	29 (45%)	35 (27%)	
Unknown	5 (8%)	41 (32%)	
Lighting Conditions			0.73
Day	45 (70%)	99 (76%)	
Dawn, dusk	3 (5%)	5 (4%)	
Dark	15 (23%)	25 (19%)	
Unknown	1 (2%)	1 (1%)	
Road Surface Conditions			0.24
Dry	57 (89%)	122 (94%)	
Other	6 (9%)	8 (6%)	
Unknown	1 (2%)	0 (0%)	

[†] Other includes: rear-ended collisions, sideswiped collisions, cyclist losing control, and motorist reversing/making U-turn.

IRR = 0.62, 95% CI: 0.44–0.89). When stratified by pre-existing infrastructure status, there was a significant 70% reduction in the rate of CMVC per 1000 cyclist-months (adjusted IRR = 0.30, 95% CI: 0.19–0.48) on street segments that did not have prior cycling infrastructure. On street segments that had been upgraded from painted bike lanes to cycle tracks, there was a non-significant increase in the rate of CMVC per 1000 cyclist-months (adjusted IRR= 1.20, 95% CI: 0.74–1.95).

3.4. Objective 2: CMVC on streets surrounding cycle tracks

On the streets 26 m – 550 m from the cycle tracks, a total of 793 CMVC occurred over the 4-year study period. Of the 793 CMVC, 461 (58%) occurred pre-implementation, and 332 (42%) occurred post-cycle track implementation. As shown in Table 5, the majority of CVMC involved adults between 16 and 59 years (94%), occurred at intersections (68%) and resulted in minimal and minor injuries (66%).

On streets 26 m–150 m from the cycle tracks, there was no change in CMVC rate before and after cycle track installation (Table 6, adjusted IRR = 0.95, 95% CI: 0.71–1.28). This area closest to the cycle tracks could be defined as "cycle track access" given that nearby roads may serve as access points to the cycle tracks. On streets more distant from the cycle tracks, there were significant reductions in CMVC rates following cycle track implementation. On streets 151 m – 250 m from the cycle tracks, there was a 45% reduction in CMVC rate after implementation of cycle tracks (adjusted IRR = 0.55, 95% CI: 0.34–0.89). On streets 251 m – 350 m from the tracks, there was a 40% reduction in CMVC rate post-implementation (adjusted IRR = 0.60, 95% CI: 0.42–0.86). On streets 251 m – 350 m from the tracks, the decrease in CMVC rate after track installation was non-significant (adjusted IRR = 0.75, 95% CI: 0.55–1.02). Lastly, on streets 451 m – 550 m from the tracks, there was a 35% reduction in CVMC rate following installation of the cycle tracks (adjusted IRR = 0.65, 95% CI: 0.48–0.88).

A secondary analysis that combined data on streets 151 m – 550 m from the cycle tracks showed that there was a 35% reduction in CVMC rate after cycle track implementation in the areas 151 m – 550 m distant from the cycle tracks (adjusted IRR = 0.65, 95% CI: 0.54–0.76). This result may suggest a "Safety Halo effect" – in the areas 151 m – 550 m distant from the cycle tracks – given the reduction in CVMC rate following the installation of cycle tracks.

4. Discussion

In the two-year period following the installation of 8.81 km of cycle tracks in the City of Toronto, the crude CMVC rate on streets with cycle tracks increased two-fold. Cycle track implementation however, was also associated with a substantial increase in the volume of cyclists. A

Table 2
Crude CMVC rates by cycle track.

Cycle Tracks, Implementation Date	Pre-Implementation Period (dd/mmm/yy)	Post-Implementation Period (dd/mmm/yy)	IR† (Pre) CMVC per 10 km-months (n)	IR† (Post) CMVC per 10 km-months (n)
Adelaide St West, June 2014	01/Jun/12 – 01/May/14	01/Jul/14 – 01/Jun/16	1.29 (5)	7.49 (29)
Richmond St West, June 2014	01/Jun/12 – 01/May/14	01/Jul/14 – 01/Jun/16	5.68 (18)	7.16 (24)
Simcoe St, June 2014	01/Jun/12 – 01/May/14	01/Jul/14 – 01/Jun/16	3.64 (6)	8.49 (14)
Wellesley St East, Sept 2013	01/Sep/11 – 01/Aug/13	01/Oct/13 – 01/Sep/15	1.95 (6)	5.86 (18)
Wellesley St West-Queen's Park, Sept 2014	01/Sep/12 – 01/Aug/14	01/Oct/14 – 01/Sep/16	2.89 (9)	2.89 (9)
Sherbourne St, June 2013	01/Jun/11 – 01/May/13	01/Jul/13 – 01/Jun/15	3.27 (20)	5.89 (36)
Total			**3.02 (64)**	**6.14 (130)**

† IR: Incidence Rate.

multivariate model that considered cycling volumes and season showed that the implementation of cycle tracks was associated with a 38% decline in CMVC rate, from 23.7 to 14.6 per 1000 cyclist-months. Streets with no pre-existing cycling infrastructure prior to installation of cycle tracks showed a 70% decline in CMVC rates; whereas, streets that upgraded cycle lanes to cycle tracks had similar CMVC rates pre- and post-implementation. Recognizing the limited quality and quantity of cycling volume data that were available in Toronto, these findings represent an approximate indication of the effectiveness of cycle tracks in preventing CMVC.

Other studies have also found a protective effect of cycle tracks despite increased cycling volumes. Lusk et al. (2011) conducted a cross sectional study in Montreal and collected counts of cyclists on cycle tracks and selected reference streets that did not have any cycling infrastructure. They observed 2.5 times more cyclists on cycle tracks, compared to reference streets, and the relative risk of injury on cycle tracks compared to the reference streets was 0.72 (95% CI: 0.60–0.85) (Lusk et al. 2011). Second, the evident rise in volume of cyclists following the installation of cycle tracks has also been noted in other studies Lusk et al. (2011); Marqués and Hernández-Herrador (2017). These findings highlight that exposure measurements are a key consideration when examining the safety effects of cycle track interventions (Thomas and DeRobertis, 2013; Mulvaney et al., 2015).

The effectiveness of cycle tracks may be attributed to the physical separation and increased distance between cyclists and motor vehicles, allowing cyclists to feel safe and ride at a comfortable distance from vehicles. The six cycle tracks examined in this study had a variety of physical barriers installed including bollards placed 6 m apart, raised cycle tracks and planters (City of Toronto, 2019c). A survey of cyclists also showed that a majority of cyclists prefer to travel on a separated path rather than ride unprotected on roads without any infrastructure (Winters and Teschke, 2010). Additionally, a "safety in numbers" effect may occur on cycle tracks, i.e., the phenomenon that greater numbers of cyclists on the roads decreases the collision risk per individual (Jacobsen, 2015). An increase in the number of cyclists may make drivers more aware and more cautious when driving alongside cyclists (Teschke et al., 2012).

The majority of CMVC on treated streets with cycle tracks were at intersections (75% before and 76% after cycle track implementation). The frequency of CMVC resulting from drivers turning at signalized intersections increased from 8% before installation to 22% after installation. This finding has been noted in other studies and may be explained by drivers looking left for other cars and not being aware of cyclists on their right (Madsen and Lahrmann, 2017; Strauss et al., 2015; Jensen, 2008). For example, one study reported that only 11% of drivers noticed the cyclist before the collision; whereas 68% of cyclists had been aware of the car (Räsänen and Summala, 1998). In addition, a recent case-crossover study across three U.S. cities by Cicchino et al. (2019) reported a variable risk of injury for cycle tracks with different designs and intersection densities. Cycle tracks at street level had a higher risk of injury compared to cycle tracks that were raised or on bridges, because of the increased number of junctions that intersected the cycle tracks at street level resulting in greater opportunities for potential conflict between cyclists and motor vehicles (Cicchino et al., 2019). Therefore, appropriate intersection treatments on cycle tracks should also be considered when implementing and designing new cycle tracks. Treatments for intersections to enhance safety along cycle tracks in Toronto could include bike boxes and advance stop lines, cyclist signals and raised cycle crossings to improve cyclist visibility and slow vehicle turning speeds (Madsen and Lahrmann, 2017; Strauss et al., 2015).

At distances 151 m – 550 m from cycle tracks, there was a significant 35% reduction in CMVC rates in the two-year period following installation of cycle tracks (362 CMVC before implementation and 240 CMVC after implementation). In other words, there appears to be a "safety halo" effect of cycle tracks, with fewer CMVC on streets surrounding cycle tracks in the period following implementation. It is important to analyze surrounding areas to best understand the public health effects of cycle tracks, particularly since CMVC are more common on surrounding streets than on cycle tracks. When examining CMVC events, 793 collisions were seen within 550 m distances surrounding the cycle tracks while only 194 collisions were seen on the streets treated with cycle tracks over the same period. The reduction in CMVC rates area-wide, therefore, means a larger safety effect of cycle

Table 3
Incidence rate (IR) and incidence rate ratios (IRR) of CMVC by cycle track installation and by pre-existing cycling infrastructure.

Analysis	IR Pre-Implementation† (n)	IR Post-Implementation† (n)	Adjusted IRR (95% CI)
Crude Analysis (no cyclist volume)			
All cycle tracks	3.02 (64)	6.14 (130)	**2.06 (1.51–2.81)**
Cycle track upgraded from cycle lane	2.84 (35)	5.12 (63)	**1.89 (1.24–2.87)**
Cycle track installed (no pre-existing infrastructure)	3.27 (29)	7.55 (67)	**2.23 (1.47–3.60)**
Adjusted Analysis (incorporating cyclist volume)			
All cycle tracks	23.7 (55)	14.6 (121)	**0.62 (0.44–0.89)**
Cycle track upgraded from cycle lane	7.52 (26)	9.12 (54)	1.20 (0.74–1.95)
Cycle track installed (no pre-existing infrastructure)	13.7 (29)	4.81 (67)	**0.30 (0.19–0.48)**

Bolded IRR and 95% CI indicate significance at $p < 0.05$.
† CVMC rates presented in the primary analysis are per 10 km-months and CMVC rates presented in the secondary analysis are per 1000 cyclist-months.

Table 4
Crude CMVC rates with cycling volumes by cycle track.

	Cycling Volume[†] (Rre)	Cycling Volume[†] (Post)	2 Years (Pre) CMVC per 1000 cyclist-months[†]	2 years (Post) CMVC per 1000 cyclist-months[†]
Adelaide St West	180	2,355	27.8	12.3
Richmond St West	220	2,420	81.8	9.9
Simcoe St	480	1,020	12.5	13.7
Wellesley St East	752	790	8.0	22.8
Sherbourne St	685	1,677	29.2	21.5
Total	**2317**	**8262**	**23.7**	**14.6**

[†] represents average number of weekday cyclists over 8 -hr period.

Table 5
Characteristics of CMVC before and after installation of cycle tracks.

CMVC	N	Pre-Implementation N (%)	Post-Implementation N (%)
Age			
Adult (16–59 years)	749	438 (95%)	311 (94%)
Older Adult (≥ 60 years)	44	23 (5%)	21 (6%)
Injury Severity			
None	171	78 (17%)	93 (28%)
Minimal/Minor	520	321 (70%)	199 (60%)
Major	91	57 (12%)	34 (10%)
Fatal	7	5 (1%)	2 (1%)
Unknown	4	0 (0%)	4 (1%)
Location			
Intersection	543	317 (69%)	226 (68%)
Midblock	241	142 (31%)	99 (29%)
Other	2	0 (0%)	2 (1%)
Unknown	7	2 (0%)	5 (2%)
Season			
Summer	535	319 (69%)	216 (65%)
Winter	258	142 (31%)	116 (35%)

tracks on more cyclists. It could be argued that the installation of cycle tracks in Toronto shifted cyclists riding on roads with no cycling infrastructure towards safer cycling infrastructure.

This safety effect may be due to cyclists preferentially choosing to use cycle tracks instead of nearby streets after installation of cycle tracks. Studies of cyclist route preference support this proposed mechanism. Rissel et al. (2015) conducted a quasi-experimental study that examined the effects of introducing new cycle tracks on the cyclists' uptake of these tracks in Sydney, Australia. The authors found that the use of new cycle tracks was strongly associated with users' proximity to the bike path (OR = 1.24, 95% CI: 1.13–1.37) and for those who rode frequently, defined as at least once a week (OR = 7.50, 95% CI: 3.93–14.31) (Rissel et al., 2015). Additionally, in Vancouver, Winters et al. (2010) conducted a survey on cycling route preferences involving 1402 cyclists. They reported that 71% of cyclists would choose to ride on cycle tracks; whereas the least preferred routes were rural roads and major streets (Winters and Teschke, 2010). Similarly, Krenn et al. (2014) examined route preferences among cyclists by comparing "actually used" and the "shortest computed" routes to understand which environmental determinants influenced cycling behaviors. In their study, the actual route taken by cyclists was on average 277 m longer than the shortest possible route (Krenn et al., 2014). This demonstrates that environmental factors can influence cycling route choices, such as the presence of dedicated cycling infrastructure like cycle tracks.

We observed no effect on CMVC rates post-implementation at distances 26 m – 150 m from the cycle tracks. One explanation for this finding may be that the cycle tracks were implemented on common cycling route streets in Toronto. For example, the nearby streets functioned as entryways or exit points to these streets, regardless of the cycle tracks. If this were the case, the number of cyclists in the area would remain relatively unchanged after cycle track installation. This is consistent with a City of Toronto Report that showed that cyclist volumes on streets parallel and adjacent to Adelaide St West and Richmond St West cycle tracks were reduced by only 4%–5% after the tracks were installed (City of Toronto, 2019c).

4.1. Strengths and limitations

Strengths of this study are the use of a pre-post study design and spatial analyses. Such a design is powerful because it controls for built environment and traffic factors by comparing collision events at the same locations before and after an infrastructure change. In addition, cycling volume data were used to estimate exposure and taken into account in the statistical analysis. However, the quality of the cycling volume data was a limitation of the study. The measurement of cycling counts before and after installation of the cycle tracks was made at a single point in time, in the summer, during the day, and in dry conditions. Therefore, the point estimates are neither comprehensive, nor reflective of winter volumes which would be expected to be 75% lower than summer volumes (City of Toronto, 2010). Of note, we performed a sensitivity analysis to account for reduced cycling volumes in the winter months. Based on the Zero-Inflated Poisson model that adjusted for winter cycling volumes, findings were still comparable to the main

Table 6
CMVC frequency, rates, incidence rate ratios (IRR) and 95% confidence intervals (CI) for defined areas surrounding cycle tracks.

Distance from cycle tracks	CMVC Pre-Implementation		CMVC Post-Implementation		IRR[‡] (95% CI)
	N	Rate[†]	N	Rate[†]	
Main Analysis (by 100 m intervals)					
26 m – 150 m	99	1.07	92	0.99	0.95 (0.71–1.28)
151 m – 250 m	47	0.60	26	0.33	**0.55 (0.34–0.89)**
251 m – 350 m	89	1.07	53	0.64	**0.60 (0.42–0.86)**
351 m – 450 m	110	1.20	85	0.93	0.75 (0.55–1.02)
451 m – 550 m	116	0.95	76	0.62	**0.65 (0.48–0.88)**
Secondary Analysis (combined distances)					
151 m – 550 m	362	0.97	240	0.64	**0.65 (0.54–0.76)**

Bolded IRR and 95% CI indicate significance at $p < 0.05$.
[†] CMVC rate per 10 km-months.
[‡] Adjusted for season and cycle track.

results (IRR = 0.64, 95% CI: 0:44–0.90). Furthermore, specific cyclist and vehicle volume data on local and residential streets were not available for the area-wide analysis in objective 2. The observed reduction in CMVC is most likely due to cyclists preferentially using cycle tracks; however, we could not directly measure this redistribution. In general, CMVC are likely underreported, particularly for those resulting in minor injuries (Aultman-Hall and Kaltenecker, 1999). Last, the short time frame of the study was a limitation because only 2 years of post-implementation data were available. The short time frame limited the sample size, particularly for severe and fatal injuries. In addition, the long-term effectiveness of cycle tracks could not be assessed.

5. Conclusions

In summary, this study showed that the installation of cycle tracks in the City of Toronto was associated with two distinct safety benefits. First, cycle tracks were associated with an increase in the volume of cyclists at the locations where cycle tracks were implemented and a reduction in the risk of CMVC, both of which support cycle track implementation as a safe and effective built environment intervention to promote cycling. Second, this study showed a 35% reduction in CMVC on streets at distances of 151 m – 550 m from newly installed cycle tracks, demonstrating a net safety benefit (a 'safety halo' effect) of cycle tracks area-wide. The area-wide effect suggests that the prevention of CMVC after cycle track implementation may extend beyond the streets with cycle track implementation. These findings also suggest a geographic redistribution of both cyclists and CMVC towards cycle tracks after implementation. Further targeted interventions ought to be focused on the cycle tracks, particularly at intersections, to maximize safety of cyclists in Toronto.

Ethics approval

This study used publicly available data and was exempt from Research Ethics Board approval.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

None.

References

Aultman-Hall, L., Kaltenecker, M.G., 1999. Toronto bicycle commuter safety rates. Accid. Anal. Prev. 31 (6), 675–686.
Bhatia, D., Richmond, S.A., Loo, C.K.J., Rothman, L., Macarthur, C., Howard, A., 2016. Examining the impact of cycle lanes on cyclist-motor vehicle collisions in the city of Toronto. J. Transp. Health 3 (4), 523–528.
Chen, P., 2015. Built environment factors in explaining the automobile-involved bicycle crash frequencies: a spatial statistic approach. Saf. Sci. 79, 336–343.
Cicchino, J.B., McCarthy, M.L., Newgard, C.D., Wall Ronald, O.S.P., DiMaggio, C.J., Kulie, P.E., Arnold, B.N., Zuby, D.S., 2019. Not All Protected Bike Lanes Are the Same: Infrastructure and Risk of Cyclist Collisions and Falls Leading to Emergency Department Visits in Three. Retrieved from: https://www.iihs.org/api/datastoredocument/bibliography/2193.
Cycling Study: Tracking Report (1999 and 2009). . Retrieved from: https://nacto.org/wp-content/uploads/2010/08/City-of-Toronto-Cycling-Study-Tracking-Report-1999-and-2009.pdf.
City of Toronto, 2019a. Vision Zero Plan Overview. Retrieved from: https://www.toronto.ca/services-payments/streets-parking-transportation/road-safety/vision-zero/vision-zero-plan-overview/.
City of Toronto, 2018a. Cycling Network 10 Year Plan. Retrieved from: https://www.toronto.ca/services-payments/streets-parking-transportation/cycling-in-toronto/cycle-track-projects/cycling-network-10-year-plan/.
City of Toronto, 2018b. About Toronto's Cycling Infrastructure. Retrieved from: https://www.toronto.ca/services-payments/streets-parking-transportation/cycling-in-toronto/bike-lanes-contraflow-lanes-and-separated-cycle-tracks/.
City of Toronto, 2019b. Cycling Network Plan Update. Retrieved from: https://www.toronto.ca/legdocs/mmis/2019/ie/bgrd/backgroundfile-134913.pdf.
City of Toronto, 2019c. Richmond Street and Adelaide Street Cycle Tracks. Retrieved from: http://app.toronto.ca/tmmis/viewAgendaItemHistory.do?item=2015.PW6.12.
City of Toronto, 2018c. Open Data Catalogue. Retrieved from: https://www.toronto.ca/city-government/data-research-maps/open-data/open-data-catalogue/#3763d352-5f0a-4385-4cec-f255d4860ea5.
Esri: GIS Mapping Software, 2019. Spatial Data Analytics & Location Intelligence. Retrieved from: https://www.esri.com/en-us/home.
Jacobsen, P.L., 2015. Safety in numbers: more walkers and bicyclists, safer walking and bicycling. Inj. Prev. 21 (4), 271–275.
Jensen, S.U., 2008. Safety effects of blue cycle crossings: a before-after study. Accid. Anal. Prev. 40 (2), 742–750.
Krenn, P.J., Oja, P., Titze, S., 2014. Route choices of transport bicyclists: a comparison of actually used and shortest routes. Int. J. Behav. Nutr. Phys. Act. 11 (1), 31.
Lusk, A.C., Furth, P.G., Morency, P., Miranda-Moreno, L.F., Willett, W.C., Dennerlein, J.T., 2011. Risk of injury for bicycling on cycle tracks versus in the street. Inj. Prev. 17 (2), 131–135.
Madsen, T.K.O., Lahrmann, H., 2017. Comparison of five bicycle facility designs in signalized intersections using traffic conflict studies. Transp. Res. Part F Traffic Psychol. Behav. 46, 438–450.
Marqués, R., Hernández-Herrador, V., 2017. On the effect of networks of cycle-tracks on the risk of cycling. The case of Seville. Accid. Anal. Prev. 102, 181–190.
Mulvaney, C.A., Smith, S., Watson, M.C., Parkin, J., Coupland, C., Miller, P., Kendrick, D., Mcclintock, H., 2015. Cycling infrastructure for reducing cycling injuries in cyclists. Cochrane Database Syst. Rev.(12).
Pucher, J., Buehler, R., 2008. Cycling for everyone: Lessons from Europe. Transp. Res. Rec. 2074 (1), 58–65.
Räsänen, M., Summala, H., 1998. Attention and expectation problems in bicycle–car collisions: an in-depth study. Accid. Anal. Prev. 30 (5), 657–666.
Rissel, C., Greaves, S., Wen, L.M., Crane, M., Standen, C., 2015. Use of and short-term impacts of new cycling infrastructure in inner-Sydney, Australia: a quasi-experimental design. Int. J. Behav. Nutr. Phys. Act. 12 (1), 1.
Rothman, L., Macpherson, A., Buliung, R., Macarthur, C., To, T., Larsen, K., Howard, A., 2015. Installation of speed humps and pedestrian-motor vehicle collisions in Toronto, Canada: a quasi-experimental study. BMC Public Health 15 (1), 774.
Strauss, J., Miranda-Moreno, L.F., Morency, P., 2015. Mapping cyclist activity and injury risk in a network combining smartphone GPS data and bicycle counts. Accid. Anal. Prev. 83, 132–142.
Teschke, K., Harris, M.A., Reynolds, C.C.O., Winters, M., Babul, S., Chipman, M., Cusimano, M.D., Brubacher, J.R., Hunte, G., Friedman, S.M., Monro, M., Shen, H., Vernich, L., Cripton, P.A., 2012. Route infrastructure and the risk of injuries to bicyclists: A case-crossover study. Am. J. Public Health 102 (12), 2336–2343.
Thomas, B., DeRobertis, M., 2013. The safety of urban cycle tracks: a review of the literature. Accid. Anal. Prev. 52, 219–227.
WHO, 2019. Global Status Report on Road Safety 2018. . Retrieved from: https://www.who.int/violence_injury_prevention/road_safety_status/2018/en/.
Winters, M., Teschke, K., 2010. Route preferences among adults in the near market for bicycling: findings of the cycling in cities study. Am. J. Health Promot. 25 (1), 40–47.