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Spatial Distribution of Pedestrian-Motor Vehicle Collisions before and after Pedestrian Countdown Signal Installation in Toronto, Canada

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ABSTRACT

Background: Pedestrian countdown signals (PCS) have been installed in many cities over the last 15 years. Few studies have evaluated the effectiveness of PCS on pedestrian motor vehicle collisions (PMVC). This exploratory study compared the spatial patterns of collisions pre and post PCS installation at PCS intersections and intersections or roadways without PCS in Toronto, and examined differences by age.

Methods: PCS were installed at the majority of Toronto intersections from 2007-2009. Spatial patterns were compared between four years of police-reported PMVC prior to PCS installation to four years post installation at 1864 intersections. The spatial distribution of PMVC was estimated using kernel density estimates and simple point patterns examined changes in spatial patterns overall and stratified by age. Areas of higher or lower point density pre to post installation were identified.

Results: There were 14,911 PMVC included in the analysis. There was an overall reduction in PMVC post PCS installation at both PCS locations and non-PCS locations, with a greater reduction at non-PCS locations (22% versus 1%). There was an increase in PMVC involving adults (5%) and older adults (9%) at PCS locations after installation, with increased adult PMVC concentrated downtown, and older adult increases occurring throughout the city following no spatial pattern. There was a reduction in children's PMVC at both PCS and non-PCS locations, with greater reductions at non-PCS locations (35% versus 48%).

Conclusions: Results suggest that the effects of PCS on PMVC may vary by age and location, illustrating the usefulness of exploratory spatial data analysis approaches in road safety. The age and location effects need to be understood in order to consistently improve pedestrian mobility and safety using PCS.

Keywords: Pedestrian motor-vehicle collisions; pedestrian countdown signals; spatiotemporal change.

INTRODUCTION

Pedestrian countdown signals (PCS) have been installed in many cities worldwide over the last 15 years. These devices are intended to provide pedestrians with more information to facilitate safe road crossings at intersections.[1] Most studies examining PCS effectiveness have evaluated changes in pedestrian and driver behaviours after installation with mixed findings.[2-11] For example, a strong correlation was found between countdown signals and an increase in red light violations in pedestrians in China.[3] PCS have also reduced the number of pedestrians who started running when the flashing "don't walk" signal appeared, but have been cited to reduce compliance with the "walk" signal in the U.S.[4] Fu et al. found that PCS were associated with more children's crossing violations and running behaviour leading to more conflicts in China; however, PCS facilitated complete crossing before the red light onset.[7] These studies were limited by small numbers and purposeful sampling of specific locations that may not be representative of all intersections. Similarly, reported effects of PCS on driver behaviours are also inconsistent, and generally emerge from small studies that also restrict their generalizability to other settings. Bundy et al. conducted a study in the US and found that drivers appear to use the information provided from PCS to improve their driving decisions, in that drivers were significantly less likely to increase their speed to reach the intersection before the beginning of the red light phase and some drivers began to slow to a stop before the beginning of the amber phase where there were PCS. [8] Huang et al. found that the installation of PCS and video surveillance at 8 intersections in China, reduced red light violations.[12] Although Chiou et al found that red signal countdown displays did not significantly improve intersection safety with respect to early start ratios of leading vehicles over the longer term, they did increase intersection efficiency with respect to start-up delay and saturated headway at 4.5 months after installation.[13] Chen et al in a study at two intersections in Taiwan, found an increased prevalence of red light violations and early-start manoeuvres at PCS intersections for both motorcyclists and car drivers.[9]

Very few studies have examined the effects of PCS on actual pedestrian motor vehicle collisions (PMVC) on a city-wide level and have also shown contradictory results.[14-17] In Toronto, Canada, PCS were installed at the majority of signalised intersections between the end of 2006 and 2011 pre-PCS collision rates at each intersection and temporal and seasonal effects.[14] Another study in Toronto, published in 2014, found fewer PMVC per month after installation; however, they did not control for the pre-PCS collision rates or season.[17] Huitema et al. in a 2014 city-wide time-series intervention analysis in the U.S. found the introduction of PCS was associated with a 1/3 reduction in pedestrian crashes.[18] Another study investigated the effectiveness of PCS on car-car collisions in 2016 in Toronto, Canada and found that the single or two-vehicle MVC incidence rate increased 7.5% with the introduction of PCS. This negative effect on collisions was postulated to be due to changes in driver behaviour related to increasing vehicle speeds to pass through the intersection, or by coming to a sudden stop before entering the intersection in response to the PCS.[19] Other studies done on a much smaller scale of selected intersections, reported declines in collisions after PCS installation.[15, 16].

As the evidence provided by previous research is contradictory with respect to the effect of PCS on pedestrian and driver behaviour and on collisions rates, it appears that PCS may have effects that differ by urban setting. Therefore, it is essential to consider the context of the locations where PCS have been installed as well the effects by age.[14, 16] An important contextual factor to consider is the spatial distribution of collisions that provides some indication of the effectiveness of PCS in different road environments. In order to better understand the effect of PCS in the City of Toronto, this study examined PMVC before and after the installation of PCS using exploratory spatial data analysis tools.[20] More specifically, the objectives of the study were to: 1) compare the point density spatial patterns of PMVC pre and post installation of PCS at intersections with PCS and roadways without PCS and, 2) determine whether there were significant differences in PMVC spatial point densities related to PCS installation by age group.

METHODS

Study area

The study was conducted in the City of Toronto, Canada. Toronto's older urban core is characterized by pre-World War II traditional neighborhoods with straight grid street patterns. It was amalgamated with 5 inner suburb municipalities, representing newer, car-oriented post-World War II neighborhoods with long winding streets and cul-de sacs.[21] Suburban segregated land use patterns, and street systems with loops and cul-de-sacs increase walking distances between housing and services, which has a negative impact on the use of walking for transport.[22] There are also differences in collision rates by roadway design, with some indication that there is a greater likelihood of non-fatal injury but a lower likelihood of non-injury or fatal injury with loops and lollipop versus grid-iron and other street patterns [23] Maps included a layer delineating the pre-amalgamated City of Toronto versus the inner suburban areas, to examine differences in the PCS effects in these different road traffic environments.

Intervention: Pedestrian countdown signals at intersections in Toronto, Canada

From November 20, 2006 to January 6, 2011, PCS were installed at the majority of signalized intersections throughout Toronto, with 95% of intersections receiving a PCS by November 2009.[24] Prior to PCS installation, these intersections were equipped with traditional "walk" or "don't walk" signals. Signals were changed to indicate an initiation of walk-time when the vehicle green light phase began, and then a 9 to 18 second (depending on roadway width) displayed countdown signal which ended as the vehicle light phase changed from green to yellow (Figure 1). All-red phases which range from 2-4 seconds continue to be provided at all signalized intersections.

FIGURE 1 Example of a Pedestrian Countdown Signal

Outcome: Pedestrian motor vehicle collisions

Data from 2000-2013 were extracted from police PMVC reports filed and verified by the City of Toronto. Each PMVC report represents an individual pedestrian. The reports include individual injury severity as reported by the police and longitudinal and latitudinal geographic coordinates for each collision site. PMVC and PCS were mapped onto City of Toronto street centre lines using ArcGIS 10.3.[25] Intersections where there were less than 6 months between traditional traffic signal installation and PCS installation (n = 145) were excluded as it would not be possible to attribute changes in PMVC at these intersections to the PCS, or to the traffic signal installation.[14] PMVC were excluded if they occurred: 1) on private property, in a parking lot/lane or had missing location codes; 2) during the intervention period (2006-2009); 3) prior to the defined pre intervention period (2002-05); 4) prior to a traditional signal installation, or; 5) on the same day of PCS installation.

Collisions that occurred within a 30-meter radius of a PCS-targeted intersection were considered PCS collisions. This was considered a reasonable buffer to capture all collisions that could be attributed to the PCS intersection and has been used in a previous study of PCS collisions in Toronto.[14] Non-PCS collision locations were located outside the 30-meter radius, at midblock, or at non-major intersections without traffic lights (e.g. stop signs).

Mapping: Point density analysis

The number of pre-installation PMVC that occurred up to 4 years prior to the defined PCS installation time (2002-2005) were compared to PMVC that occurred up to 4 years after the installation period (2010-2013). The analysis was also stratified by age categories used by the World Health Organization: child (0-15 year), adult (16-59 years) and older adult (60+ years).[14, 26] Collisions missing age information were excluded from the age-stratified analyses.

The first step in the spatial pattern exploration was to identify areas of higher PMVC point density through Gaussian kernel density estimate (KDE), for all collisions within the pre and post study-periods (2002-2006 and 2010-2013) at PCS and non-PCS locations. This geostatistical technique is commonly used to identify spatial patterns, including road collision hot spots, and is very useful in cases where road network attributes such as traffic volume are not available at the local scale.[27-29] This non-parametric approach calculates a "continuous crash density surface" based on a kernel function (i.e., a circular search area) over each crash point (Thakali, 2015). The density at each output raster cell is based on the sum of values calculated under this kernel function.[30] Two elements influence the result of the kernel estimate: cell size and chosen bandwidth for the function. The output cell size selected for these analyses was 30 meters in order to avoid having two intersections in the same cell (30 meters is the balance between the high computation time related to very small cells and the minimum distance between two intersections). Several authors have noted that the choice of a specific bandwith distance is mostly subjective.[27 28 31] After several trials with shorter distances (100 m, 250 m, 500 m), the 1 km bandwidth was chosen because of its clear visualization. Other methods have been used to detect clusters of road traffic collisions. For example Dai (2012) used SatScan to identify clusters of pedestrian crashes with injuries compared to crashes without injuries.[32] Although interesting this method was not used as we wanted to explore the whole spatial pattern of collisions in a before-and-after type of comparison, not just pinpoint the statistically significant cluster in a case-control study. Recently, applications using network kernel density estimates were developed to take into account the road network in collision density and cluster analysis. [33-36]. However, the network methods were not used for this study as the location of PMVC points along the road lines already influence the pattern seen on the resulting maps. Preliminary analyses using NKDE (not shown here) suggested that it is was not suitable to detect patterns at larger scale such as the present study area.

A second step in the exploration of the change in the spatial pattern before and after PCS installation was estimated by: 1) calculating simple point pattern density for pre-post PCS and non-PCS collisions and; 2) subtracting the pre-PCS density map from the post-PCS density map using the raster calculator. Simple point patterns densities were preferred to KDE to examine the changes in spatial patterns in order to avoid smoothing of the density function.[37] Point density maps were created using a search radius of 24 pixels and 30-meter cells for: 1) PCS collisions that occurred pre-PCS installation 2) PCS collisions that occurred post-PCS installation 3) Non-

PCS collisions that occurred pre-PCS installation 4) Non-PCS collisions that occurred post-PCS installation.

The overlay of the two rasters (identical in their size and position) permits the subtraction of one layer to the other and highlights areas of higher or lower point density, pre-post. Since those values of the difference were normally distributed, a simple z score was used to test significance (PCS mean -.031, SD 2.47, non-PCS -.688, SD 3.06).[37] Again, the definition of a "hot spot" relies mostly on subjective decisions related to threshold (Hashimoto, 2016). Accordingly, only raster values of +/- 3 standard deviations significant at the 5 percent level were mapped to identify major changes in spatial patterns.

RESULTS

From November 20, 2006 to January 6, 2011 there were 2,155 countdown signals installed at signalized intersections. There were 145 PCS excluded where there were less than 6 months between traditional traffic signal installation, and an additional 146 PCS excluded where there were no collisions either before or after the intervention period, resulting in a total of 1,864 intersections included in the analyses.

A flow chart demonstrating the sample used for these analyses is presented in Figure 2. There were 31,636 PMVC from 2000-2013, with a total of 16,725 PMVC excluded. There were 4,284 PMVC excluded related to location; 4,055 collisions occurring on private property, in a parking lot or lane and 229 with missing location codes. There were 12,441 PMVC exclusions related to the date of the collision; 7,447 PMVC during the defined installation period (2006-2009), 4,514 prior to the defined 4 year pre installation period, 344 before a traditional signal was installed, 133 as there was less than 6 months between the installation of the PCS and the traditional signal and 3 that occurred on the same day of PCS installation. Therefore, there were 14,911 PMVC included in the overall analysis. There was a secular trend of reduction in PMVC post PCS installation at both PCS locations and non-PCS locations, with more of a reduction at non-PCS locations (22% versus 1%).

Of the 14,911 collisions, 6,167 (41.4%) had no/minimal injuries, 7,080 (47.5%) had minor injuries requiring a visit to the emergency department, 1,418 (9.5%) had major injuries requiring admission to the hospital and 244 (1.6%) were fatalities. No specific weight by severity was given to collisions in the density calculation.

Of 7,194 non-PCS collisions, 3,395 (47.2%) were located at midblock and 3,799 (52.8%) were located at intersections. The majority of midblock collisions occurred where there were no crossing controls (3,605, 94.9%). The largest proportion of non-PCS collisions at intersections occurred at stop signs (1,460, 43.0%), followed by areas with no controls (1,412, 41.6%).

For the age stratified analysis, 482 collisions were excluded due to missing age information. There was a reduction in collisions post installation at PCS locations for children, but an increase in adults and older adults. There was a reduction in collisions at non-PCS locations for all age groups.

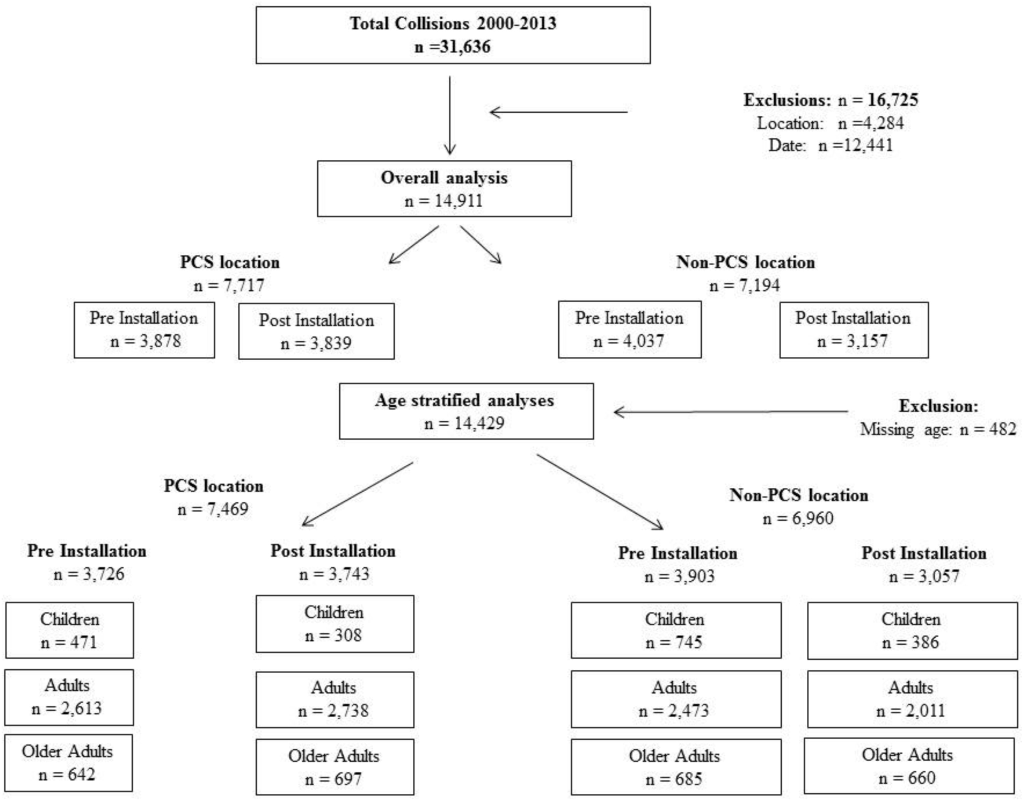

FIGURE 2 Sample flowchart

Point density analysis

Figure 3 illustrates the kernel density estimates for all PMVC. The greatest density of PMVC at PCS intersections for all ages was observed in the downtown pre-amalgamated city, with dispersion throughout the city along major arterials. Non-PCS PMVC had a similar pattern, with lower numbers of PMVC densities than PCS sites. Child PMVC were dispersed throughout the city. Adult PMVC were focused in the pre-amalgamated city. Although older adult PMVC also tended to be focused in the pre-amalgamated city, they were more dispersed throughout the city compared to younger adults.

Figure 4 illustrates the differences in the PMVC point density pre and post PCS installation. There were some specific areas that had increased numbers of PMVC with PCS installation in the pre-amalgamated city including the northeast border of the city and scattered in the east end. Much of the downtown area had a lower collision point density at PCS intersections, post PCS installation. There was an obvious pattern of reduction in the number of non-PCS collisions after PCS installation throughout the city, with only a few higher locations north of the East/West expressway at the north part of the city, and in the pre-amalgamated city. There was a consistent pattern of reduction in both PCS and non-PCS locations over the whole study area, but also along a major arterial (St. Clair Avenue) at the north-west pre-amalgamated border.

Figure 5 illustrates the differences in the PMVC point densities pre and post PCS installation by age group. In children, it appeared that there was some improvement everywhere with PCS installation. Improvements were more evident at non-PCS sites, except just east of the pre-amalgamated city border which is a high density low-income residential apartment complex.

In adults, there was no obvious pattern of improvement with the installation of PCS; there were some locations where PMVC were reduced and others where they increased. In the pre-amalgamated City of Toronto increases were noted in the south along the waterfront and in central-west areas, reductions were evident, downtown. In the inner suburbs, there were some increases in the north, the northeast and just northwest of the pre-amalgamated city boundary. There was a more consistent pattern of reduction in the non-PCS locations for adults, except in the south part of the pre-amalgamated city along waterfront and just north of the major northern east/west expressway in the northern part of the city.

The installation of PCS seemed to have less of an effect on the spatial distribution of PMVC both at PCS and non-PCS locations for older adults. There were no real patterns evident, with both scattered increases and decreases throughout the city.

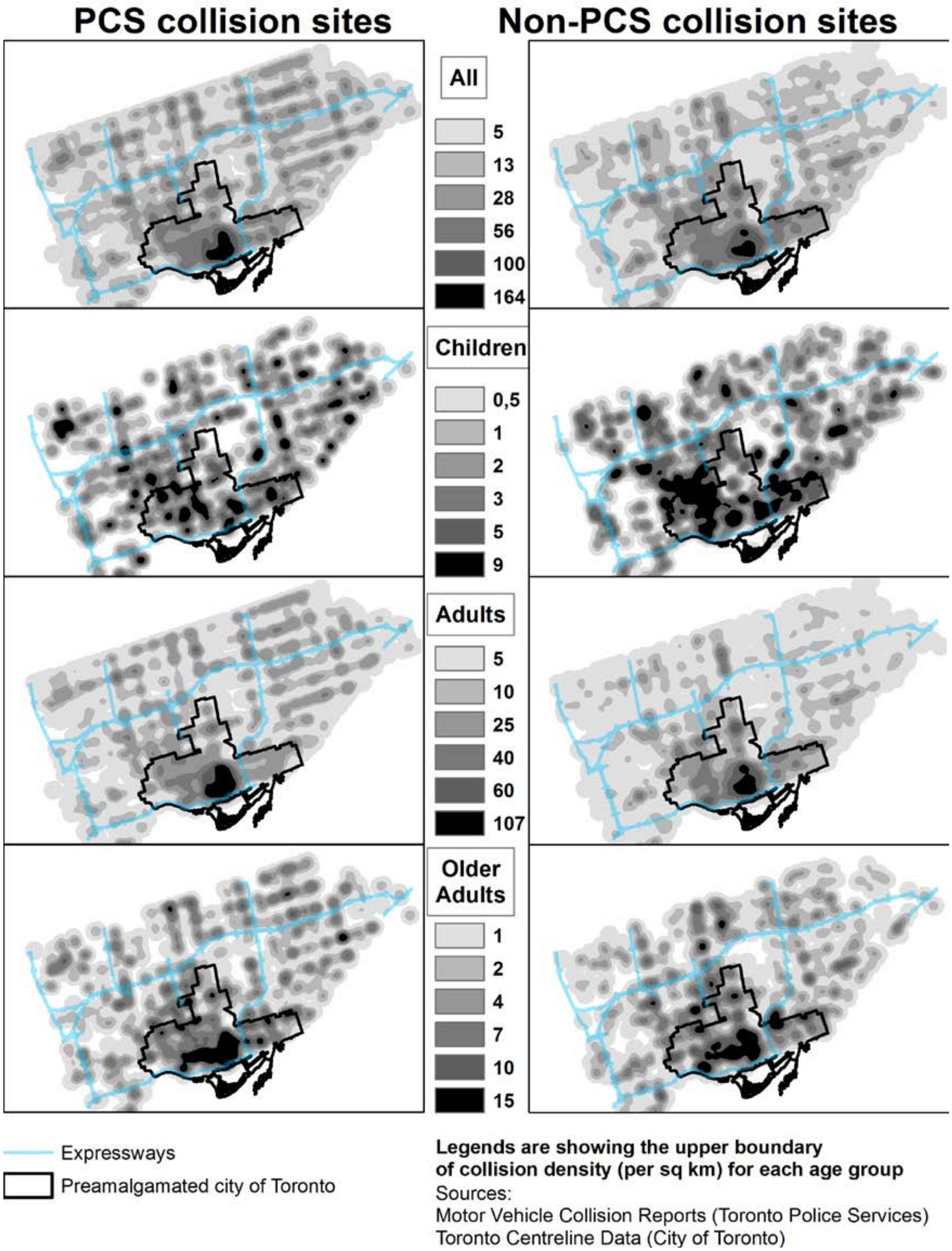

FIGURE 3 Kernel-density estimates (collision/km^2) for collision locations (2002-05, 2009-13.

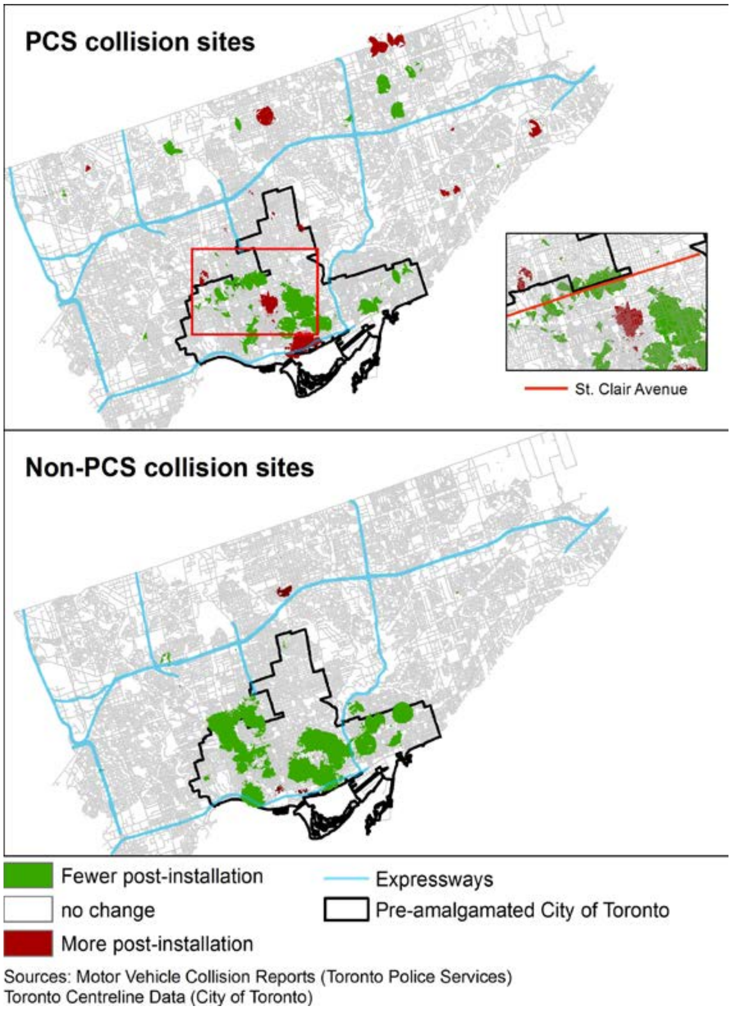

FIGURE 4 Significant change in PMVC density comparing before and after PCS installation (raster values of +/- 3 standard deviations significant at the 5 percent level)

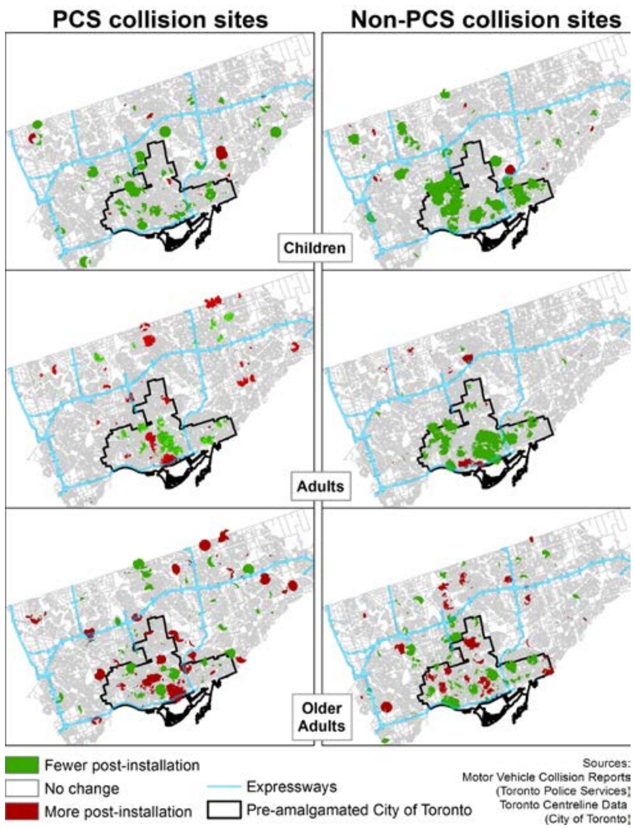

FIGURE 5 Significant change in PMVC density before and after PCS installation period by age group (raster values of +/- 3 standard deviations significant at the 5 percent level)

DISCUSSION

This exploratory study compared point densities of PMVC prior to and after a period of PCS installation. Some PCS locations had more PMVC after installation of the PCS, particularly in adult and older adult pedestrians. Increased adult pedestrian PMVC were concentrated downtown, whereas older adult pedestrian PMVC increases occurred throughout the city following no spatial pattern. There was a reduction in children's PMVC at both non-PCS and PCS locations, with a more consistent reduction at non-PCS locations.

Our previous study conducted in the City of Toronto, found an increase in PMVC rates overall after installation at PCS locations after controlling for temporal trends over the study period, season and baseline PMVC rates.[14] The current study is built on our previous work, by examining the spatial distribution of PMVC related to PCS installation and suggests that: 1) the installation of PCS may result in increased PMVC, since non-PCS locations showed more consistent reductions, and; 2) the effect of PCS varies by age and location, with some sites showing increased PMVC and others showing decreases.

If PCS safety effectiveness varies within a city, then it follows that effectiveness will certain vary across cities, resulting in the discrepant findings in the literature.[14],[15-17] Studies reporting decreased collisions with PCS installation include those with limited numbers of intersections, potentially biased by regression to the mean effects due to their design[15 16] and studies that have not controlled for pre-intervention PMVC rates or seasonal effects.[17] The strongest spatial patterns were most evident in adults, who represent the largest number of PMVC. Areas where PCS increased PMVC should be further investigated to see if changes in signal timing, or vehicle turning restrictions, could yield the desired safety benefits. Pedestrians may misuse the information from a PCS to cross the street quickly, rather than to use the information to cross safety. We regularly observe adults initiating crossings, by running if needed, with inadequate time remaining on the PCS. This results in pedestrians being in the intersection when the countdown runs down to 0. Children may not behave similarly especially when accompanied. Older adults may not be able to complete a crossing, even using all the time available.[38 39] Therefore, it is likely and to be expected that PCS effectiveness varies by age.

The built environment and simultaneous co-interventions may have had an effect on the study findings. For example, a consistent reduction in PMVC was demonstrated along St. Clair

Avenue, which is a major east/west roadway at the north-west border of the pre-amalgamated city (see Figure 4). The installation of a dedicated streetcar right-of-way installation overlapped with the PCS intervention period at this location (2005-2010). This right-of-way installation was related to a 50% decrease in PMVC rates.[40] Therefore, reductions in PMVC at both PCS and non-PCS locations along this roadway could be attributed at least in part to the streetcar right of way co-intervention. It is possible that the roadway redesign and the PCS installation had synergistic positive effects on safety, which is something to be considered when planning targeted roadway safety interventions.

The overall reduction in PMVC in children at both PCS and non-PCS locations could also be an indicator of the reduction in walking mode share in children over time in Toronto. The majority of children's exposure to traffic occurs on the trip to and from school, and there has been a reported reduction in children walking to school over the last 20 years. A recent Metrolinx report indicated a reduction in walking to school mode share in 11-13 year old children in Toronto from 59% - 44.5% between 1986 and 2011.[41] Therefore, the reduction in both PCS and non-PCS locations may be an indicator of a reduction in children's exposure to traffic.

Another limitation of this study is related to the lack of real-time, routinely collected data available in Toronto at specific intersections and roadways related to vehicle speed and vehicle and pedestrian volume.[14] Vehicle volume modeling and pedestrian volume modeling are based on counts that are done approximately every two years at any given location, so there is insufficient data to include exposure variables in collision models. Regardless of the lack of exposure data, this study provides interesting information regarding the absolute numbers of pedestrian morbidity, and points to the necessity of preventive measures. There are also limitations related to the use of police-reported data, with the underreporting of PMVC injuries, particularly in children.[42-46] However, there was no indication that there would be a difference in police reporting pre and post PCS installation at either PCS or non-PCS locations that could potentially bias study results.

The study strengths included large, population-based datasets of PMVC and PCS installations that occurred throughout the city that we were able to stratify by age. Secular trends were accounted for by comparing PMVC at PCS intersections versus non-PCS PMVC.

The main finding from this study demonstrates that the effects of PCS on PMVC may vary by location and age as was evident in the significant differences in point pattern densities. For adults, the spatial distribution suggests strong area effects where either the road environment can be improved for pedestrians, or the signal timing or turning restrictions can be changed. For older adults, the lack of spatial patterning in PMVC may mean that traffic signals provide insufficient time for some road users to cross, and that older pedestrian travel patterns expose them to danger throughout the city. The age and location effects of PCS need to be fully understood to consistently improve pedestrian safety.

COMPETING INTERESTS: None to declare

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CONTRIBUTORS

Linda Rothman, Andrew Howard and Marie Soleil Cloutier were responsible for the conceptual framework and design, analysis and interpretation, and writing and critical editing of the manuscript. Alison Macpherson and Sarah Richmond contributed to the interpretation and critical editing of the manuscript. All authors approved the final version of the article to be published.

Key Messages

What is already known on this subject

- Pedestrian countdown signals (PCS) have been installed in many cities over the last 15 years.
- Evidence regarding PCS effectiveness has been inconclusive

What this study adds

- PCS may increase PMVC in some locations and for some road users, especially adults and older adults.
- Non-PCS locations showed more consistent crash reductions after PCS installation.
- PCS effects vary within a city, and the age and location effects need to be understood in order to consistently improve pedestrian mobility and safety.

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