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Identifying street design elements associated with vehicle-to-pedestrian collision reduction at intersections in New York City

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ABSTRACT

Objective: We evaluated associations between the installation of eleven street design elements, between 2007 and 2015, and subsequent changes in vehicle-to-pedestrian collisions in New York City.
Methods: Collision data were from Accident Location Information System in the New York State Department of Transportation. Safety improvement projects at 118 intersections were reviewed and their implemented street design elements were identified. First, we assessed potential regression-to-the-mean effects using historic trends of pedestrian collision count at the intersection project locations. Second, we used a two-group pretest-posttest design to assess individual element's associations with pedestrian collision reduction after installations. Pedestrian collision count and pedestrian- and vehicle-based pedestrian collision rates were examined. Third, regression trees were used to classify the intersections with design elements as independent variables for the target variables of collision outcomes, to identify street design element combinations associated with pedestrian collision reductions.
Results: Treatments with pedestrian refuge island or pedestrian plaza had reductions in pedestrian collision count and pedestrian-based collision rate while their comparisons had no changes. Treatments with pedestrian refuge island had a larger reduction in pedestrian collision when combined with lane removal or narrowing. Treatment with curb extension or pedestrian plaza had reductions in vehicle-based pedestrian collision rate while their comparisons had no changes. Other studied elements showed no, small, or insignificant associations with post-project pedestrian collision reductions.

1. Introduction

In the U.S., 5376 pedestrians were killed by vehicle crashes in 2015. In the last decade pedestrian fatalities have fluctuated, however the pedestrian fatality percentage of total traffic-related fatalities has continuously increased from 11% in 2006 to 15% in 2015 (National Center for Statistics and Analysis, 2017). Pedestrian risks have large geographic variances. One study analyzed pedestrian deaths adjusted by the number of people who walk to work in the 104 largest metro areas between 2005 and 2014 and estimated that the most dangerous area had a pedestrian risk more than 20 times higher than the safest area (Smart Growth America, 2017b). City- or region-level transportation policies and street designs may affect the risk of pedestrian collisions (Ewing and Dumbaugh, 2009).

Many cities have adopted pedestrian safety strategies. As of 2015, 8 large U.S. cities have passed a Vision Zero policy, aiming at no fatalities or serious injuries in street traffic (Fleisher et al., 2016). And, a total of 1232 “Complete Streets” policies have been adopted by 2016 in the U.S. to restructure car-dominant transportation networks into safer, multimodal, pedestrian-centered networks (Smart Growth America, 2017a). With an increased interest in local municipalities’ street safety projects, the National Association of City Transportation Officials published *The Urban Street Design Guide* providing a standardized manual on pedestrian-centered streets, street design elements, and intersections (National Association of City Transportation Officials, 2013).

As cities develop and implement pedestrian safety projects, it is necessary to monitor and evaluate their effectiveness. For example, New York City first adopted *Vision Zero Action Plan* in 2014 which recommended the completion of 50 safety improvement projects per year and listed 20 specific street design elements such as pedestrian safety (refuge) island, curb extension, parking lane widening, and traffic signal alteration (New York City Department of Transportation, 2014). The city has been publishing annual reports which update completed projects and evaluate their effectiveness in terms of city-level statistics. New York City Department of Transportation (NYC DOT) reports project- or site-level changes in pedestrian collisions or pedestrian fatalities. However, such brief reports may not be sufficient for scientific

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conclusions and it is needed to examine the effectiveness with rigorous research methods (Retting et al., 2003; New York City Department of Transportation, 2017a).

There are academic studies which have examined the safety effect of individual pedestrian safety countermeasures such as high-visibility crosswalks, raised medians (King et al., 2003), road diets (Persaud and Lyon, 2010; Chen et al., 2013), and pedestrian refuge islands (King et al., 2003; Li and Fernie, 2010). However, many studies examined treatments without making comparisons, adjusting pedestrian traffic volume changes, or addressing selection bias in a quasi-experimental study design or regression-to-the-mean effects (Retting et al., 2003; Chen et al., 2013). Failing to address such issues, particularly the regression-to-the-mean issue, may lead to overestimation of treatment effects, when a study design uses repetitive measurements (Barnett et al., 2004). For example, if a transportation agency selects project sites for treatment at hotspots where collision counts are unexpectedly increasing, this may result in selection bias. In addition, short-term high collision counts may decrease to long-term average in the following years (regression-to-the-mean effect) (Srinivasan et al., 2016). It is recommended that a pretest-posttest design should control potential confounding factors as regression-to-the-mean effects, long-term collision trends, and pedestrian traffic volume changes, with a comparison group (Elvik, 2002; Fitzpatrick and Park, 2010).

Safety improvement projects usually adopt multiple street design elements together at one intersection. For example, curb extensions are usually implemented with pedestrian refuge islands or median alteration. Certain elements may work better when other elements are implemented together systematically than when they are installed separately. For example, a study in Florida suggested that combining advanced yield lines and lead pedestrian intervals together produced greater safety improvement than implementing them separately, although it examined only 4 intersection cases (Turner, 2000). Most prior studies focused on single street design element's independent effect without considering multiple design elements' combination effect. To redesign safer intersections, we need to understand interactions between street design elements for safety and study their combinations.

The aim of this study was to test if street design elements which were intended to improve pedestrian safety at intersections, implemented in New York City between 2007 and 2015, individually and combined with other elements, were associated with longitudinal reductions in vehicle-to-pedestrian collisions.

2. Methods

2.1. Data

We used point-level collision data received from Accident Location Information System (ALIS) in the Safety Program Management and Coordination Bureau, Department of Transportation, NY, in July 2017 (NYS DOT, 2017). The data covered all vehicle collisions reported and geocoded by police and Department of Motor Vehicles (DMV) offices, to December 31, 2016. We filtered the data on the vehicle body type, selecting all collisions that involved a pedestrian and identified vehicle-to-pedestrian collision data points. Finally, we selected vehicle-to-pedestrian collision points within the study area, New York City. In this study, a pedestrian collision is defined as a vehicle-to-pedestrian collision.

In June and July 2017, we obtained planning documents on New York City's Safety Improvement projects which were intended to improve pedestrian safety, published on the NYC DOT website (New York City Department of Transportation, 2017a). Project documents were manually reviewed and matched to intersection project GIS data, which included intersection points, downloaded from the NYC DOT data feed (New York City Department of Transportation, 2017b). This process yielded safety improvement intersection location GIS data with the projects' detailed information. As of January 2018, documents were available for projects completed between 2007 and 2016. The current study included projects completed through the end of 2015 so that we were able to collect at least 1 year of pedestrian collision data coverage after the completion of all projects.

2.2. Street design elements in projects

Using project documents, GIS data, and Google Street View's historical imagery before and after the projects, two trained researchers examined each project and identified street design elements implemented in the projects. The first researcher initially coded elements and the second validated the coding results. Using the design categories in the National Association of City Transportation Officials' *Urban Street Design Guide* (National Association of City Transportation Officials, 2013), we first identified and categorized a list of 11 street design elements which were associated with pedestrian safety and implemented in the study projects. The list included curb extensions (CE), high-visibility crosswalks (HC), median alteration (MA), pedestrian buffer (BU), pedestrian refuge islands (PI), pedestrian plazas (PLZ), bicycle lanes (BL), parking rearrangements (PA), turning bay alterations (TN), lane removal or lane narrowing (LR), and traffic signal alteration (TS). Table 1 shows the elements and descriptions. Finally, each project was coded with the presence or absence of the elements. For example, when a project had a curb extension (CE) yet no pedestrian island (PI), it was coded as CE = 1 and PI = 0.

2.3. Collision count

Pre- and post-project pedestrian collision counts were calculated at individual intersection locations. First, for each location, we selected pedestrian collision points whose straight-line distances were ≤ 50 feet from intersection center points. The distance was selected from prior studies examining pedestrian collision at street intersections (Schneider et al., 2004; Miranda-Moreno et al., 2011). The distance threshold was shown to successfully match collisions with intersections. Second, pre-project collisions were selected within a 3-year pre-project time window. The 3-year time window length was chosen to avoid bias from short-term statistics or potential regression-to-the-mean effects (Sharma and Datta, 2007), in addition to an assumption that collision counts older than 3 years may not represent current conditions and changes associated with treatments (Hauer et al., 2002). The 3-year time window ends 1 year before the project's reported completion date. For example, if the project completion date is 09/01/2015, its 3-year pre-project time window starts on 09/01/2011 and ends on 08/31/2014. The 1-year tolerance was chosen to safely avoid possible pedestrian travel interruptions during project construction. Most projects did not

Table 1
Street design elements implemented in Safety Improvement intersection projects.

Code	Description
CE	Curb extension (or bulb-out or neck-down leading to "shortened crosswalk")
HC	High-visibility crosswalk (or relevant crosswalk modification)
MA	Median alteration (striped median, planters, or widened existing median)
BU	Buffer for pedestrians or bicyclists
PI	Pedestrian refuge island (new or expansion of median to form a new pedestrian island)
PLZ	Pedestrian plaza (or public space more than a curb extension)
BL	Bicycle lane (excludes shared bicycle lanes or sharrows)
PA	Parking rearrangement (parking lane, angled parking change, or parking space change)
TN	Turning bay (or turning lane) alteration
LR	Lane removal or lane narrowing (or through-lane removal)
TS	Traffic signal alteration (new traffic signal, new traffic signal pole, or traffic signal phasing change, including bike/pedestrian signals)

have exact construction start dates reported in project documents or in the GIS data. Third, post-project collisions were identified and counted within a post-project time window starting from 1 day after the project's reported completion date. The post-project time window length was between 1 and 3 years, depending on the length between the project's completion date and the collision data coverage end point (December 31, 2016). Finally, we calculated pedestrian collision count, adjusting the counts by the length of time window in years. Pedestrian collision count, $\mathrm{C}(i,\ T)$, for i-th intersection for the time point T (T_0: the pre-project time and T_1: the post-project time) is defined as below.

For $t_j \in W_{i,T}$ where $j = \{1,\ 2,\ 3,\ \ldots\}$

$$\mathrm{C}(i,\ T) = \frac{\sum_j \mathrm{N}(i,\ t_j)}{\sum_j l(t_j)} \tag{1}$$

where $W_{i,T}$ is a time window, t_j is a time interval split by calendar years within $W_{i,T}$ and the start and end points of $W_{i,T}$, $l(t_j)$ is the length of t_j in years or fractional, and finally, $\mathrm{N}(i,\ t_j)$ is the count of pedestrian collisions at the i-th intersection location occurred within t_j. For example, an i-th project completed on 07/01/2009, W_{i,T_0} is [07/01/2005, 06/30/2008], includes time intervals (t_j) of [07/01/2005, 12/31/2005], [01/01/2006, 12/31/2006], [01/01/2007, 12/31/2007], and [01/01/2008, 06/30/2008], and their $l(t_j)$ are 0.5, 1, 1, and 0.5 years, respectively. The change in pedestrian collision count before and after the project completion was calculated as $\mathrm{C}(i,\ T_1) - \mathrm{C}(i,\ T_0)$.

2.4. Pedestrian and vehicle volume index

We estimated pedestrian activity volume at each intersection location for each year between 2005 and 2016, using NYC DOT's historical bi-annual pedestrian count data at 114 locations (New York City Department of Transportation, 2017b). The historical pedestrian count data measured short-duration peak-hour pedestrian counts twice per year: one set in May including two periods (7–9 am and 4–7 pm) on a weekday and one period (12–2 pm) on a weekend day and another set in September having the same time periods, yielding a total of six count measurements per year. Average counts per year per location were calculated. Next, we estimated pedestrian counts at the study intersection locations, using a universal kriging with exponential semivariogram functions of straight-line distance between pedestrian count points and project intersection points, following steps in a prior study (Selby et al., 2013). The skewed distribution of pedestrian counts was normalized with Box-Cox transformation (Collins, 1991). This process produced $P_{i,\ y}$ pedestrian count estimate at the i-th intersection in the calendar year y (y = 2005, …, 2016). Finally, we created pedestrian volume index, $PI_{i,y}$, using the year 2005 as a baseline, to estimate relative trends in pedestrian activity volume levels in the study area over time. Because the observed pedestrian counts were from short-periods, not interpretable to a 24-hour count, we used the relative index.

$$PI_{i,y} = \frac{P_{i,y}}{P_{i,\,2005}} \tag{2}$$

For vehicle volume estimation, we used annual average daily traffic (AADT) downloaded from New York State's Open Data Website (New York Open Data, 2016). Using the same kriging method above, AADT over project intersection points were calculated as $V_{i,y}$ for each year. Vehicle volume index, $VI_{i,y}$, is defined as using the year 2005 as a baseline.

$$VI_{i,y} = \frac{V_{i,y}}{V_{i,\,2005}} \tag{3}$$

2.5. Collision rate

We defined $\mathrm{PR}(i,\ T)$, pedestrian-based pedestrian collision rate, and $\mathrm{VR}(i,\ T)$, vehicle-based pedestrian collision rate, at the i-th intersection location for T time window in the below.

For $t_j \in W_{i,T}$ where $j = \{1,\ 2,\ 3,\ \ldots\}$

$$\mathrm{PR}(i,\ T) = \frac{\sum_j \frac{\mathrm{N}(i,\ t_j)}{PI_{i,\mathrm{Y}(t_j)}}}{\sum_j l(t_j)} \tag{4}$$

$$\mathrm{VR}(i,\ T) = \frac{\sum_j \frac{\mathrm{N}(i,\ t_j)}{VI_{i,\mathrm{Y}(t_j)}}}{\sum_j l(t_j)} \tag{5}$$

where $\mathrm{Y}(t_j)$ is the calendar year to which t_j belongs. The change in pedestrian collision rate before and after the project completion was calculated as $\mathrm{PR}(i,\ T_1) - \mathrm{PR}(i,\ T_0)$ for pedestrian-based rate and $\mathrm{VR}(i,\ T_1) - \mathrm{VR}(i,\ T_0)$ for vehicle-based rate, respectively.

2.6. Comparison group

To compare collision counts and rates between the treated intersections with projects (treatment intersections) and their nearby intersections without safety projects (comparison intersections), we selected a matched comparison intersection to each of the 118 treatment intersections, as the nearest one in terms of geographic distance and pedestrian collision level history before projects started, chosen from outside of safety project areas. First, we identified exclusion areas from which we excluded comparison intersection selections. We compiled all relevant street safety improvement projects available from the NYC DOT web GIS database (New York City Department of Transportation, 2017b), including enhanced crossings and Vision Zero priority intersections, as the exclusion area. Intersections that were not on the compiled exclusion GIS geometries and not on open spaces were initially selected. The intensive exclusion was intended to select comparisons that were untreated for sure during the study period, at the risk of excluding potentially comparable comparison candidates. Second, for each treatment intersection, we identified comparison candidates consisting of the 300 nearest neighboring intersections in terms of straight-line distance, as comparison candidates. Third, pedestrian collision counts in T_{-2}, T_{-1}, and T_0 were measured at those candidate intersections. Finally, we chose the candidate having the smallest Euclidean difference to the treatment in terms of pedestrian collision count at the three time points.

2.7. Analysis

First, we examined long-term pedestrian collision trends at treatment and comparison intersections, to assess potential regression-to-the-mean effects or treatment selection bias. The trend of pedestrian collision count before pre-project times is particularly important. If pedestrian collision counts increased significantly and unexpectedly from T_{-2} or T_{-1} (explained below) to T_0, the observed pedestrian collision count may need to be adjusted for the regression-to-the-mean effects. If NYC DOT systematically selects treatment locations from hotspot intersections where there were increasing pedestrian collision counts, there should be significantly more pedestrian collision counts at T_0 than preceding times. To determine if such phenomena were present, we compared pedestrian collision counts over multiple time windows using paired t-tests (Barnett et al., 2004), assuming that the between-time differences were independent of one another and normally distributed. Pedestrian collision counts were measured within two time windows before project: (i) time window ≥7 and < 10 years before the project completion (T_{-2}); and (ii) time window ≥4 and < 7 years before the project completion (T_{-1}). In addition, correlation tests were conducted on pedestrian collision counts between T_{-2} and T_{-1} and between T_{-1} and T_0, to test if there were potential selection bias before the project locations were chosen (Barnett et al., 2004; Srinivasan et al., 2016). Intersections without available old pedestrian collision data were excluded from the comparison and correlation analysis.

Second, to test individual street design elements' association with pedestrian collisions, we grouped treatment intersections by street design elements and compared pedestrian collision count and pedestrian- and vehicle-based rates at T_0 and T_1 within the groups using paired *t*-tests. Changes of their matched comparison intersections were also examined.

Third, to examine different effects of combinations of street design elements, we classified the treatment intersections into group nodes of certain combinations of design elements, using regression trees with recursive partitioning (Chang and Wang, 2006). Regression trees were used because of potential multicollinearity between predictors (street design elements) and straightforward interpretation of results (Karlaftis and Golias, 2002). The target variables were changes in pedestrian collision outcomes. Predictor variables were the presence or absence of street design elements (presence = 1; absence = 0). Means of pedestrian collision outcomes within group nodes were calculated. Statistical significance level was set to $p = 0.05$. All data processing and analyses were conducted using *R* 3.4.1 (R Core Team, Vienna, Austria) and *rpart* package (Therneau and Atkinson, 2017). Regression trees were fitted using the *rpart* function in the package without controlling parameters and cross-validation.

3. Results

Between 2005 and 2016, we obtained 118,199 pedestrian collisions in New York City from the ALIS database. Fig. 1(A) shows total pedestrian collision count change by year in the city. It peaked at 2013, declined until 2015 by 2192 collisions, and rebounded again in 2016. Fig. 1(B) shows pedestrian count trends from 114 pedestrian count locations. At the city level, AADT gradually decreased as shown in Fig. 1(C).

We obtained 260 project documents from the NYC DOT website and manually matched to 118 intersection points. Street design elements implemented in intersections were identified. On average, the intersection projects implemented 4.1 street design elements (SD = 2.2).

Table 2 shows changes of pedestrian collision counts over time. Among treatment and comparison intersections, there were no significant short-term changes before projects completed. The differences in pedestrian collision count between times were approximately normally distributed. Pedestrian collision counts did not also change significantly over time before project when treatment and comparison intersections were examined together (data not shown in the table). Correlation coefficients between pedestrian collision counts at T_{-2} and T_{-1} and between T_{-1} and T_0 were 0.75 and 0.78, respectively, suggesting a low possibility of the regression-to-the-mean effect. In overall, we did not find a significant short-term, correlated change among the study intersections and determined not to adjust regression-to-the-mean effects or selection bias in the analysis.

Table 3 shows frequency of the street design elements. PI was the most prevalent design element, found in 80 intersections, followed by TS (n = 63) then CE (n = 59). On average, after projects were completed, pedestrian collision count decreased by 0.31 (30% reduction) among the treatments and decreased by 25 (28.4% reduction) among the comparisons. Table 3 shows changes in pedestrian collision count after project completion of individual elements. On average, intersections with PI and PLZ had significant reductions (-0.39 and -0.44, respectively) while their comparisons had no significant changes ($p < 0.05$). Treatments with MA and PA did not significantly change while their comparisons had significant reductions. As for other elements, treatment and comparison intersections had the same directions of changes or no significant changes over time.

Changes in pedestrian-based pedestrian collision rates, shown in Table 4, had a similar pattern. Both treatments and comparisons had decreased collision rates after project completion. Treatments with PI and PLZ had significant decreases while their comparisons had no significant changes over time. Intersections with MA and PA did not significantly change while their comparisons had significant reductions. As for other elements, treatments and comparisons had no differences in terms of the change directions or change significance levels. When vehicle-based pedestrian collision rates were examined, treatments with CE and PLZ had significant reductions while their comparisons had no significant changes (Table 4). In overall, treatments and comparisons had no significant changes in vehicle-based collision rate.. Due to the changes only for two design elements, we did not establish a regression tree for vehicle-based rate.

In total, the treatment intersections had 44 different combinations of the presences and absences of street design elements. Table 5 shows the top 19 prevalent combinations that had the frequency of 2 or more. The most frequently found combination was the intersections with the presences of PI and LR and the absences of other elements (n = 15). The second most frequent combination included the presence of CE, PI, TN, and TS and absences of other elements (n = 13). The top 7 most prevalent combinations cover more than half of the treatment intersections (n = 61).

Fig. 2 shows the established regression tree (R1) for the target variable of change in pedestrian collision count, yielding 6 terminal nodes partitioned by 5 splitters of street design elements (CE, BL, PI, TS, and LR). Three terminal nodes had decreased pedestrian collision counts while the other three had increased pedestrian collision counts after project completion. For each node, the mean of pedestrian

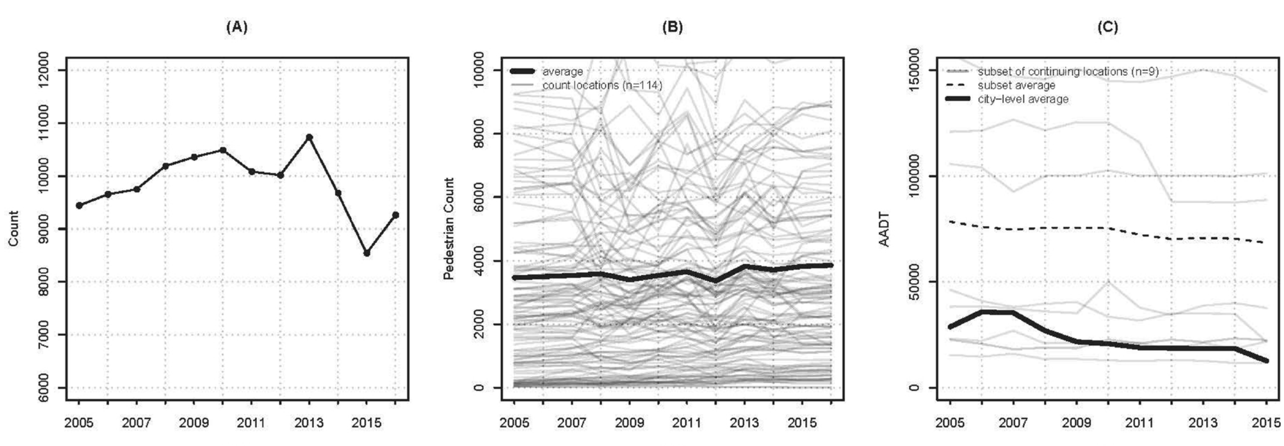

Fig. 1. Trends of collisions and traffic volume.
(A) City-level vehicle-to-pedestrian collision count by year, annual total in New York City; (B) Pedestrian count by year, count measured at 114 pedestrian count locations; and (C) AADT by year, averages of 9 locations (where AADT were available every year) and of all locations in New York City.

Table 2
Vehicle-to-pedestrian collision count changes over time.

Time	N	Treatment [count/year]					Comparison [count/year]				
		Mean	Min	Max	SD	Difference (P^*)	Mean	Min	Max	SD	Difference (P^*)
T_{-2}	47	0.79	0.00	3.33	0.82		0.70	0.00	3.67	0.81	
T_{-1}	84	0.92	0.00	4.67	1.07	T_{-2} to T_{-1}: +0.13 (.823)	0.77	0.00	3.00	0.76	T_{-2} to T_{-1}: +0.07 (.247)
T_0	118	1.05	0.00	6.33	1.39	T_{-1} to T_0: +0.13 (.672)	0.88	0.00	6.00	1.15	T_{-1} to T_0: +0.11 (.909)

T_{-2}: time window ≥7 and < 10 years before the project completion.
T_{-1}: time window ≥4 and < 7 years before the project completion.
T_0: time window ≥1 and < 4 years before the project completion.
* P-values are from paired t-tests comparing vehicle-to-pedestrian counts between two time windows.

Table 3
Vehicle-to-pedestrian collision count changes before and after project completion.

Design elements		Vehicle-to-pedestrian collision counts per year							
		Treatments				Comparisons			
Type	N	Before (T_0)	After (T_1)	Change* (%)	P	Before (T_0)	After (T_1)	Change* (%)	P
All	118	1.05	0.73	−0.31 (−30.0)	.007	0.88	0.63	−0.25 (−28.4)	.004
CE	59	1.32	0.73	−0.59 (−44.8)	< .001	1.07	0.62	−0.45 (−41.9)	< .001
HC	52	0.72	0.45	−0.42 (−45.4)	.039	0.73	0.47	−0.26 (−35.1)	.010
MA	49	1.01	0.68	−0.32 (−32.5)	.082	0.82	0.50	**−0.31** (−38.3)	.038
BU	20	0.52	0.42	−0.10 (−19.0)	.391	0.50	0.52	0.02 (3.7)	.882
PI	80	1.03	0.61	**−0.39** (−39.3)	.004	0.80	0.60	−0.19 (−24.0)	.071
PLZ	12	0.67	0.18	**−0.44** (−72.7)	.017	0.61	0.33	−0.28 (−45.5)	.218
BL	17	0.76	0.61	−0.16 (−20.7)	.282	0.71	0.63	−0.08 (−11.2)	.631
PA	46	1.00	0.70	−0.27 (−27.2)	.153	0.78	0.50	**−0.28** (−35.9)	.030
TN	52	1.42	0.89	−0.50 (−35.8)	.014	1.20	0.73	−0.47 (−39.3)	.005
LR	54	1.07	0.74	−0.33 (−30.7)	.089	0.84	0.72	−0.12 (−14.5)	.308
TS	63	1.19	0.76	−0.43 (−36.0)	.013	0.99	0.59	−0.40 (−40.6)	.004

T_0: time window ≥1 and < 4 years before the project completion.
T_1: time window > 0 and ≤1–3 years after the project completion.
* Significant changes ($p < 0.05$) only either (not both) among treatments or comparisons are shown in bold.

collision counts of the node members' matched comparisons was calculated for a reference. Node 3 had the largest difference between treatments and comparisons (difference = 0.69). Node 6 shows that collisions rather increased among treatment intersections without CE and PI. Fig. 3 shows the regression tree (R2) for the target variable of change in pedestrian-based pedestrian collision rate, having 7 terminal nodes with 6 splitters (CE, BL, PI, TN, TS, and LR). Node 7 had the largest difference between treatments and comparisons (0.54). Treatments without CE and PI had an increase in pedestrian-based collision rate. Node 4 had the second largest difference (0.51).

Table 6 shows the presences or absences of all street design elements in each node. MA and PI were mostly present in Node 2 in R1 and Node 3 in R2.

4. Discussion

The current study used a two-group pretest-posttest design to assess pedestrian collision reduction at 118 intersections in New York City. The study adjusted pedestrian collision counts at the intersections with pedestrian and vehicle volume estimates because they may affect the risk of collision (Leden, 2002; Lee and Abdel-Aty, 2005; Elvik, 2009). The current study suggests that pedestrian refuge island and pedestrian plaza were consistently associated with a relatively large reduction of pedestrian collisions. Pedestrian collisions and their associations with street design elements (Tables 3 and 4) will be useful for urban planners and traffic engineers to estimate future projects' potential safety improvement effects. The presented approach will be useful to monitor intersection-level pedestrian traffic safety levels.

When pedestrian collision count and pedestrian-based collision rate examined, both treatments and comparisons had reduced collision outcomes in overall (decreased by about 30% in both count and rate). It is because more than 70% of the studied projects were completed in 2012 or after, when collision count decreased at the city level (Fig. 1(A)). Treatment elements, specifically focusing on pedestrian's physical space as PI, PLZ, CE, and HC, showed significant safety improvement. Treatments with PI or PLZ had more significant and larger reductions than their comparisons. Treatments with CE or HC had larger reductions than their comparisons although the comparisons also had significant collision reductions. The findings are generally consistent with previous studies on pedestrian refuge islands, or expanded

Table 4
Pedestrian- and vehicle-based vehicle-to-pedestrian collision rate changes before and after project completion.

Design elements		Vehicle-to-pedestrian collision rate (pedestrian-based)								Vehicle-to-pedestrian collision rate (vehicle-based)							
		Treatments				Comparisons				Treatments				Comparisons			
Type	N	Before (T_0)	After (T_1)	Change* (%)	P	Before (T_0)	After (T_1)	Change* (%)	P	Before (T_0)	After (T_1)	Change* (%)	P	Before (T_0)	After (T_1)	Change* (%)	P
All	118	0.93	0.67	−0.26 (−28.1)	.016	0.79	0.56	−0.23 (−29.1)	.004	1.25	1.33	0.08 (6.6)	.742	1.16	1.10	−0.06 (−4.9)	.724
CE	59	1.12	0.57	−0.55 (−48.9)	< .001	0.92	0.54	−0.39 (−41.8)	< .001	1.57	1.04	−**0.53** (−33.8)	.013	1.46	1.09	−0.37 (−25.2)	.091
HC	52	0.81	0.46	−0.35 (−43.4)	.007	0.66	0.44	−0.23 (−34.4)	.015	1.29	1.10	−0.19 (−14.6)	.507	1.20	1.09	−0.11 (−9.2)	.710
MA	49	0.91	0.67	−0.24 (−26.0)	.190	0.74	0.45	−**0.28** (−38.6)	.041	1.11	1.21	0.10 (8.8)	.765	1.00	0.92	−0.08 (−8.0)	.776
BU	20	0.50	0.43	−0.07 (−13.6)	.543	0.49	0.53	0.04 (7.4)	.780	0.57	0.73	0.16 (28.7)	.630	0.49	0.72	+0.23 (+45.9)	.300
PI	80	0.84	0.52	−**0.32** (−38.2)	.005	0.70	0.52	−0.18 (−25.6)	.058	1.23	1.10	−0.13 (−10.6)	.558	1.11	1.17	+0.06 (+5.6)	.773
PLZ	12	0.60	0.17	−**0.43** (−72.1)	.017	0.61	0.34	−0.27 (−43.9)	.255	0.85	0.18	−**0.66** (−78.4)	.037	0.85	0.50	−0.34 (−40.6)	.364
BL	17	0.75	0.60	−0.15 (−20.5)	.280	0.69	0.62	−0.07 (−10.4)	.685	0.80	0.96	0.17 (21.1)	.683	0.74	0.91	+0.17 (+22.3)	.543
PA	46	0.86	0.70	−0.16 (−18.9)	.397	0.67	0.42	−**0.25** (−37.7)	.025	1.22	1.37	0.15 (12.0)	.689	1.02	0.92	−0.10 (−9.9)	.731
TN	52	1.27	0.82	−0.45 (−35.5)	.026	1.07	0.63	−0.44 (−41.4)	.004	1.64	1.64	0.00 (0.1)	.998	1.59	1.50	−0.09 (−5.8)	.768
LR	54	0.95	0.75	−0.20 (−21.4)	.266	0.74	0.63	−0.11 (−14.5)	.299	1.33	1.60	0.27 (20.5)	.585	1.12	1.13	+0.00 (+0.2)	.994
TS	63	1.01	0.65	−0.36 (−35.2)	.016	0.87	0.51	−0.36 (−41.6)	.005	1.47	1.55	0.08 (5.1)	.861	1.25	0.92	−0.33 (−26.1)	.178

* Significant changes ($p < 0.05$) only either (not both) among treatments or comparisons are shown in bold.

Table 5
Frequency of intersection projects with combinations of street design elements.

Combination Number	Street design Elements*											Frequency**
	CE	HC	MA	BU	PI	PLZ	BL	PA	TN	LR	TS	
1	0	0	0	0	1	0	0	0	0	1	0	15
2	1	0	0	0	1	0	0	0	1	0	1	13
3	1	1	1	0	0	0	0	1	0	1	1	8
4	0	0	0	0	1	0	0	0	0	0	0	7
5	1	1	1	1	1	1	1	0	0	1	1	6
6	0	1	1	1	0	0	0	1	0	0	0	6
7	0	1	1	0	1	0	0	1	1	1	1	6
8	1	1	1	0	1	0	1	1	1	1	1	5
9	1	0	1	0	1	0	0	1	1	0	1	3
10	1	0	1	0	1	0	0	0	0	1	0	3
11	0	1	0	0	0	1	0	0	1	0	1	3
12	0	0	1	0	1	0	0	1	1	1	0	3
13	0	0	0	1	0	0	1	0	0	0	1	3
14	1	1	0	0	0	0	0	1	0	0	1	2
15	1	0	0	0	0	0	0	0	1	0	0	2
16	0	1	0	0	1	1	0	1	1	0	0	2
17	0	0	1	0	1	0	0	0	0	0	1	2
18	0	0	1	0	0	0	0	0	1	0	1	2
19	0	0	0	1	0	0	0	1	0	1	0	2

* 1 = presence; 0 = absence of street design elements.
** 25 combinations with the frequency of 1 are not shown.

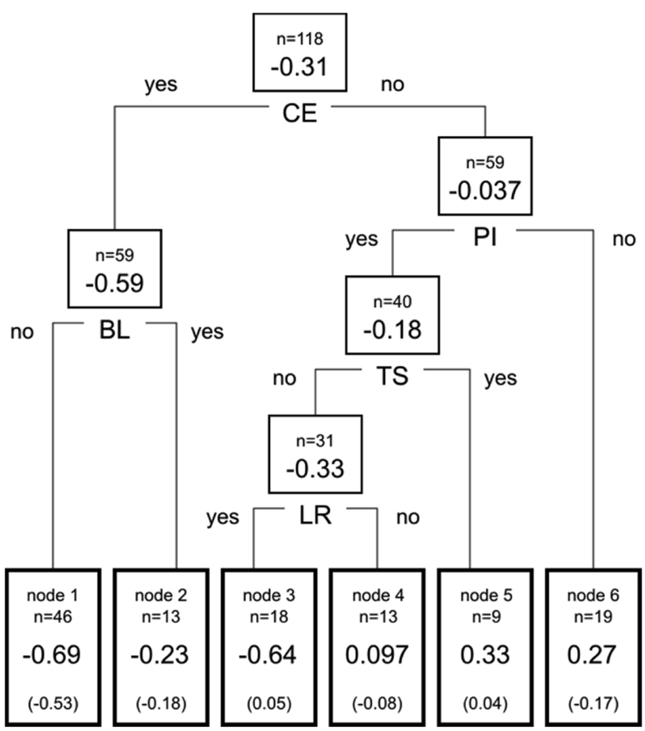

Fig. 2. Regression tree on vehicle-pedestrian collision count (R1).
Size and mean of node (mean of the matched comparisons in parenthesis).

islands (King et al., 2003; Retting et al., 2003; Li and Fernie, 2010), curb extensions or curb redesign (King et al., 2003; Bella and Silvestri, 2015), and high-visibility crosswalks or textured crosswalks (King et al., 2003, Chen et al., 2013), although CE and HC in the current study appeared to make a small difference. One unexpected finding is that treatment with new or altered BU, BL, and LR had no or smaller safety improvement than their comparisons. Treatments with TN and TS had even smaller decreases in pedestrian collision than their comparisons. A study in New York City found that pedestrian collision decreased with pedestrian phasing (some TS) but increased with left-turn bay (TN) and signal installation (some TS) (Chen et al., 2013). A more detailed classification and characterization of elements may clarify specific associations with safety improvement. It is noteworthy that treatments with MA or PA did not have significant changes in pedestrian collision count and pedestrian-based collision rate while their nearby comparisons had reduced collision outcomes. One possible explanation is that such treatments may involve new street rearrangements and increase visual complexity for drivers, increasing collision risks for pedestrians (Edquist et al., 2012).

It should be noted that when pedestrian collision count were adjusted by vehicle volume index, only treatments with CE and PLZ had significant changes. PI, which showed relative safety improvement in terms of collision count and pedestrian-based collision rate, was no longer significantly associated with vehicle-based collision rate reductions. The vehicle-based pedestrian collision rate could be interpreted as collision risk factor as a function of vehicle traffic volume. As for those design elements, after project completion, vehicle traffic may be significantly reduced and pedestrian collision risks may be reduced accordingly as a consequence. Causality directions are not clear. The relationships among pedestrian and vehicle volume and collision could have non-linear relationships (Gårder, 2004; Lee and Abdel-Aty, 2005). The mechanism by which the design elements affect vehicle traffic and pedestrian behavior, and eventually safety, should be further studied.

A unique contribution of the study is to classify combinations of street design elements with the respect to the longitudinal pedestrian collision reduction. The established regression trees for the pedestrian collision count and for the pedestrian-based pedestrian collision rate had the same classification structure except that the tree for the pedestrian-based pedestrian collision rate had an additional splitter of TN. In both trees, treatments having both PI and LR yet no CE and no TS, had substantially large collision decreases (by 0.64 in count and by 0.53 in rate), compared to their comparisons' change (nearly 0 in both count and rate). Overall, when PI was combined with LR (n = 40), there were significant collision reductions (by 0.45 in count and by 0.35 in rate) while their nearby comparisons had nearly no changes. These significant decreases were larger than those of treatments with PI yet no LR (by 0.33 in count and by 0.30 in rate). PI may be associated with higher safety improvement when combined with lane removal, lane narrowing, or road diet.

The regression trees, shown in Figs. 2 and 3, indicate that 19 intersections, although they had some other treatments, were not associated with pedestrian collision reduction when they had neither CE nor

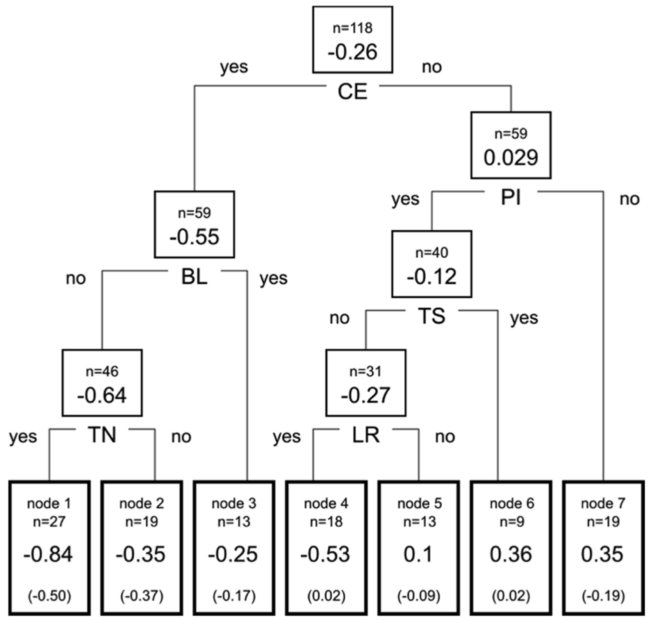

Fig. 3. Regression tree on pedestrian-based vehicle-pedestrian collision rate (R2).
Size and mean of node (mean of the matched comparisons in parenthesis).

PI. Such treatments without CE and PI had rather increased collisions than their comparisons. Both design elements are designed to actively protect pedestrians from vehicles by encouraging motorists' safe driving behaviors (Huang and Cynecki, 2000; Bella and Silvestri, 2015). Street design changes without such active and physical pedestrian protection may not necessarily result in safety improvement.

In the current study, we determined that treatment selection bias or the regression-to-the-mean problem were not evident after reviewing historic collision trends over 9 years at each intersection location, while some studies strongly suggest to control the problem that may be a potential confounding factor in pretest-posttest study designs (Elvik, 2002; Persaud and Lyon, 2007; Srinivasan et al., 2016). However, at the studied intersection locations, the collision level was stable before the projects started, suggesting that potential regression-to-the-mean effects were likely minimal or negligible (Goldenbeld and van Schagen, 2005). A study on traffic safety in New York City discussed that locations of safety improvement projects may be selected based on a city-wide comprehensive transportation improvement plan and, if so, the potential regression-to-the-mean effects may not be of a concern (Chen et al., 2013). A road safety study in Norway found that treatment locations were chosen by multiple reasons, not just by accident records, suggesting that we need to be careful about regression-to-the-mean effect assumptions (Elvik, 2004). New York City implemented many transportation safety projects and adopted a city-wide transportation safety plan, *Vision Zero Action Plan*, in 2014 and intersection projects were part of the comprehensive plan.

Pedestrian safety at the studied treatment intersections could be enhanced even further in the future if more pedestrians are attracted to the locations. Studies found safety in numbers as pedestrian collision risks decreased with increased pedestrian traffic flows (Elvik, 2009; Murphy et al., 2017). Projects improving pedestrian safety, such as Complete Streets projects, have shown to increase street users and to promote street activities over time (Brown et al., 2016; Jung et al., 2017). At the city's pedestrian count monitoring locations, yearly pedestrian count averages have consistently increased. Long-term, continuous monitoring is needed over treatment locations, measuring pedestrian activities and safety statistics.

Regression trees have competing (primary) splitters and surrogate splitters, which requires careful interpretations. Table 6 shows patterns of design elements while no strong patterns among non-splitter were evident. The regression tree method selects best splitters in terms of split fit improvement for each split (Therneau and Atkinson, 2017). In the study, selected splitters had more than 47% larger fit improvement than competing splitters, except for BL (30% larger than its second primary splitter of TS) in R1 and BL (14% larger than its second primary splitter of TN).

The quantitative approach of the study has limitations of subjective coding and street design element simplification. Although street design elements were coded and cross-validated by two trained researchers, their decisions may be subjective. To produce more objective and reproducible coding results, the researchers consulted with visual examples in the National Association of City Transportation Officials' *Urban Street Design Guide* (National Association of City Transportation Officials, 2013). Some elements may be further classified into multiple ones (e.g., new traffic signal or new traffic signal pole). Depending on its size, shape, or locational context, the same element may have different impacts on safety. However, the main objective of the study is to find overall design elements associated with pedestrian collision reduction. Detailed qualitative and context-aware studies are needed.

Following studies are needed to monitor collisions over longer periods after project completion. Under the collision data availability to

Table 6
Street design elements in terminal nodes.

Node #	N	Change	Presence of street design elements [%]**										
			CE	HC	MA	BU	PI	PLZ	BL	PA	TN	LR	TS
R1: Tree with pedestrian collision count													
1	46	−0.69	100.0*	43.5	34.8	0.0	60.9	0.0	0.0*	37.0	58.7	30.4	71.7
2	13	−0.23	100.0*	84.6	**100.0**	46.2	**92.3**	53.8	100.0*	46.2	46.2	84.6	84.6
3	18	−0.64	0.0*	0.0	16.7	0.0	100.0*	0.0	0.0	16.7	16.7	100.0*	0.0*
4	13	0.097	0.0*	38.5	0.0	7.7	100.0*	15.4	0.0	38.5	15.4	0.0*	0.0*
5	9	0.33	0.0*	66.7	88.9	11.1	100.0*	0.0	0.0	66.7	77.8	66.7	100.0*
6	19	0.27	0.0*	52.6	47.4	63.2	0.0*	15.8	21.1	47.4	36.8	26.3	52.6
R2: Tree with pedestrian-based pedestrian collision rate													
1	27	−0.84	100.0*	22.2	14.8	0.0	85.2	0.0	0.0*	18.5	100.0*	3.7	77.8
2	19	−0.35	100.0*	73.7	63.2	0.0	26.3	0.0	0.0*	63.2	0.0*	68.4	63.2
3	13	−0.25	100.0*	84.6	**100.0**	46.2	**92.3**	53.8	100.0*	46.2	46.2	84.6	84.6
4	18	−0.53	0.0*	0.0	16.7	0.0	100.0*	0.0	0.0	16.7	16.7	100.0*	0.0*
5	13	0.10	0.0*	38.5	0.0	7.7	100.0*	15.4	0.0	38.5	15.4	0.0*	0.0*
6	9	0.36	0.0*	66.7	88.9	11.1	100.0*	0.0	0.0	66.7	77.8	66.7	100.0*
7	19	0.35	0.0*	52.6	47.4	63.2	0.0*	15.8	21.1	47.4	36.8	26.3	52.6

* Selected splitters in the regression tree.
** Non-splitters with high presence (> 90%) are shown in bold.

December 31 2016, we determined to examine projects with post-project collision data > 1 year, to include more cases with various street design elements. For example, the sample size for projects with CE increased to 59 by including 22 recent projects although they had collision data 1–2 years. Among projects with CE, the significance of reduction in pedestrian collisions did not change when the recent projects were excluded. Short study periods are often selected although they may produce unstable results. For example, a study reviewed 18 traffic safety studies and found that 4 of them had one year as their study periods and most studies had temporal analysis units of 1 year or shorter (Cai et al., 2016). Because there is an increasing interest in pedestrian safety, our early analysis on recent cases would inform researchers and policy makers.

The current study used primarily pedestrian collision count and secondarily rates to adjust pedestrian or vehicle traffic volume. Because no observed traffic data were available at study intersections, we used estimated data which may be affected by estimate errors. We generated bootstrap samples (Efron and Tibshirani, 1986), using kriging estimates and kriging standard errors of pedestrian counts, to test if pedestrian-based collision rates were consistently reduced after project completion when estimation errors adjusted. It appeared that 48.4% of the treatment intersections had a reduction at a 95% confidence interval, from a 1000 bootstrap sample, while 45.8% had a reduction from the study sample, yielding relatively robust results.

On average, comparison intersections had lower pedestrian collision outcomes than treatment intersections. For the comparison selection, we identified non-treatment areas by excluding areas where relevant street safety improvement projects were implemented, shown in the NYC DOT GIS database archive. The intensive exclusion may limit comparison candidates. For example, a nearby intersection, which could be comparable to a treatment, was excluded for the comparison if it was involved with an enhanced crossing or Vision Zero priority project at any time during the study period. Because there may be many safety-related intersection projects implemented in New York City, we intended to select untreated, eligible comparisons for sure. However, this safe selection method may exclude some potential intersections that could be more comparable to a treatment than others. In another study in New York City, treatments had higher pedestrian and bicyclist collisions than comparisons (Chen et al., 2013), possibly caused by an intensive comparison selection within the study site's unique context. As additional information, descriptive statistics on pedestrian volume index at treatment and comparison intersections locations before and after project completion are provided (Supplementary File 1). Tracking the built environment changes for the 11 years of the study period was not available for all the studied intersections. Due to the unavailability of these data, we did not use the built environment or street characteristics in comparison group selection. Instead, we focused on the geographic distance and pedestrian collision count level difference between treatment and comparison.

The current study has other potential limitations, mostly data availability issues. First, as widely discussed, pedestrian collision data from police and DMV offices might be underreported or include misclassified data (Noland et al., 2017). Second, we did not include land use context or the built environment around intersections in the analysis. Context may be important to pedestrian and street activities (Ewing and Dumbaugh, 2009; Chen et al., 2015), however, the built environment in the proximity of an intersection may have a small direct effect on pedestrian collision frequency (Miranda-Moreno et al., 2011).

5. Conclusion

The quantified reduction of pedestrian collisions be useful to design future intersections for pedestrian safety. Pedestrian refuge islands and pedestrian plazas were associated with reductions in post-project pedestrian collision count and pedestrian-based collision rate. Pedestrian collision reduction associated with pedestrian refuge islands were increased when combined with lane removals or narrowing. When pedestrian collision rates were adjusted by vehicle traffic volume, curb extensions and pedestrian plazas were associated with collision reduction. Other elements showed small, no, or insignificant changes in pedestrian collision reductions.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aap.2018.10.019.

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