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Left-turn phase: Permissive, protected, or both? A quasi-experimental design in New York City

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ABSTRACT

The practice of left-turn phasing selection (permissive, protected-only, or both) varies from one locality to another. The literature evidence on this issue is equally mixed and insufficient. In this study, we evaluate the safety impacts of changing left-turn signal phasing from permissive to protected/permissive or protected-only at 68 intersections in New York City using a rigorous quasi-experimental design accompanied with regression modeling. Changes in police reported crashes including total crashes, multiple-vehicle crashes, left-turn crashes, pedestrian crashes and bicyclist crashes were compared between before period and after period for the treatment group and comparison group by means of negative binomial regression using a Generalized Estimating Equations (GEE) technique. Confounding factors such as the built environment characteristics that were not controlled in comparison group selection are accounted for by this approach. The results show that the change of permissive left-turn signal phasing to protected/permissive or protected-only signal phasing does not result in a significant reduction in intersection crashes. Though the protected-only signal phasing does reduce the left-turn crashes and pedestrian crashes, this reduction was offset by a possible increase in over-taking crashes. These results suggest that left-turn phasing should not be treated as a universal solution that is always better than the permissive control for left-turn vehicles. The selection and implementation of left-turn signal phasing needs to be done carefully, considering potential trade-offs between safety and delay, and many other factors such as geometry, traffic flows and operations.

1. Introduction

Left-turning vehicles at intersections encounter conflicts of various sources. Left-turn crashes are one of the most frequently occurring collision types at intersections: based on the twenty-year (1989–2008) history of crashes at intersection in New York City, left-turn crashes rank the third, following rear-end and right-angle crashes, and represent 9.5% of all intersection crashes reported (New York City Department of Transportation, 2009). Furthermore, the severity of the injury and the likelihood of fatality of left-turn crashes tend to be grave and high because of the relatively high travel speeds of vehicles involved and the angle of impact (Wang and Abdel-Aty, 2008).

Left-turn signal phasing is a frequently applied treatment to intersections with substantial left-turning traffic (Agent and Deen, 1979; Stamatiadis et al., 1997; Al-Kaisy and Stewart, 2001). Left-turning movements at signalized intersections are usually controlled by traffic signals in three ways: permissive-only, protected-only, and protected/permissive. According to the *Manual on Uniform Traffic Control Devices* (MUTCD), the permissive-only type provides no exclusive phasing for left-turn traffic – left-turning vehicles make turns on a green signal indication after yielding to pedestrians and opposing traffic, if any. A left-turn phase can be either protected-only or protected/permissive: the protected-only type provides an exclusive phasing for left-turn traffic and allows vehicles to make left turns only when a left-turn green arrow signal indication is displayed; the protected/permissive type combines the permissive-only and protected-only left-turn phases in the same cycle, and vehicles are allowed to make left-turns either on a green arrow indication (protected-only phase) or on the circular green (permissive-only phase), during which they must yield to the opposing traffic.

There may be trade-offs between safety and the smooth progression of traffic when deciding whether a left-turning phase

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shall be installed. On one hand, left-turn signal phases facilitate left-turning traffic and may improve the safety of left-turning movements at intersections. On the other hand, the addition of a protected left-turn signal phase will usually result in reduced green time available for through traffic and longer total cycle lengths, which will reduce the capacity of an intersection by increasing stops and delays (Agent and Deen, 1979; Agent, 1987). Sometimes in order to reduce delays and increase capacity at a signalized intersection, permissive left-turn phasing is used as an alternative to protected phasing (Agent, 1987).

In practice, the decision on the choice of left-turn phasing at signalized intersections greatly depends on local context (Lalani et al., 1986; Zhang et al., 2008). As a low-cost safety countermeasure, left-turn signal phasing (protected/permissive or protected-only mode) has been popular with many traffic engineers (Federal Highway Administration, 2009). In South Florida, for example, the protected left turn phasing is favored over the permissive type and is applied at most intersections (Ewing, 2011). On the other hand, some other agencies may be in favor of permissive phasing considering that the protected left turn phases require more green time and they result in long delays for through movements and poor progression. Phoenix, for example, once had permitted left turn movements at nearly every intersection (Ewing, 2011).

Findings from the literature on this question – whether permissive, protected-only, or both shall be applied to an intersection – are mixed. While some studies found that left-turn phasing – protected-only or permissive/protected – reduced left-turn crashes and total intersection crashes (Agent and Deen, 1979; Agent, 1987; Gibby et al., 1992; Shebeeb, 1995; Stamatiadis et al., 1997), other studies showed that left-turn phasing was ineffective in reducing left-turn crashes or total intersection crashes (Perfater, 1983), or in some cases, even increased total intersection crashes (Upchurch, 1991; Box and Basha, 2003; Srinivasan et al., 2008). Hauer's review of 20 studies on the safety impacts of left-turn phasing concluded that there is insufficient and contradictory evidence on whether or not left-turn phasing will have significant impacts on crashes (Hauer, 2004).

Using a rigorous study design, the purpose of this research is to evaluate the safety effectiveness of left-turning signal phasing installed at 68 intersections in New York City (NYC) where the permissive left-turn phasing was replaced by the protected/permissive or protected-only left-turn phasing. For most of the treated locations, the change in left-turn phasing was also accompanied with the addition of a left turn lane. This study advances the existing practice of safety evaluation by adopting a rigorous before and after quasi-experimental design comprising a treatment group and a comparison group. Given that the treated locations are often not randomly selected, the quasi-experimental design is the strongest possible one in evaluation studies (Shadish et al., 2002; Chen et al., 2011a,b, 2012a,b). To further control possible neighborhood-level confounding factors, the study also employed negative binomial models. A Generalized Estimating Equations (GEE) method (Zeger and Liang, 1986) was used to account for correlations between repeated measures – crashes in the before and after periods.

2. Method

Methodologically, the current studies are deficient to conclude whether the addition of a special phase for left-turns reduces crashes or not. Many of the early studies used simple cross-sectional comparisons of crash rates for different types of left-turn phasing (Gibby et al., 1992; Shebeeb, 1995; Stamatiadis et al., 1997; Box and Basha, 2003), and in some, only simple before–after comparisons were conducted (Agent and Deen, 1979; Perfater, 1983; Agent, 1987). A more rigorous quasi-experimental design that involves a treatment group and a comparison group and compares crashes before and after the installation of the left-turn phase is preferred (Krizek et al., 2009). Srinivasan et al. (2008) studied the effect of replacing permissive phasing with protected/permissive or protected-only phasing by using the Empirical Bayes (EB) method, in which a reference group was selected and a before–after comparison was conducted. However, the conclusion of that study was that the results cannot be taken as definitive due to the small sample sizes – the study had only 1 intersection for replacing permissive phasing with protected/permissive phasing, 2 intersections for replacing permissive with protected-only phasing, and 3 intersections for replacing protected/permissive with protected-only phasing.

Few existing studies account for differences in settings. A few studies (Agent, 1987; Stamatiadis et al., 1997) account for site characteristics (such as number of lanes, signal display and signing, speed, and traffic composition) at the intersections, however, no built environment characteristics were accounted for. Recent studies suggest that the built environment is correlated with crashes and injuries (Ewing and Dumbaugh, 2009). Therefore, to correctly identify the safety effect of left-turn phasing in reducing crashes, a preferred study design should entail comparing before and after crashes for both the treatment group (with left-turn phasing) and the comparison group (without left-turn phasing), while accounting for differences in the built environment.

Police-reported intersection crashes including total crashes, multiple-vehicle crashes (vehicle-vehicle collisions), and left turn crashes (involved left-turning vehicles) were studied. Each intersection was associated with two observations: crashes within a 5-year period prior to the treatment and crashes within a 2-year period after the treatment. A crash is a relatively rare event, thus, including a longer 5-year before period allows us to capture a more stable trend prior to the treatment. On the other hand, the selection of a shorter after period than the before period allows us to include more treatment sites: crash data is only available until 2008, thus implementing a 5-year after-treatment period would mean that only treatments installed prior to 2003 can be evaluated and yet, more than one third of the intersections in the treatment group were treated with protected-only or permissive/protected left-turn phasing after 2003. The difference in the before- and after-period is controlled by an offset variable in the model.

This study involves a two-stage design. In the first stage, we identified a comparison group of signalized intersection without any treatments during the same study period but sharing intersection-level characteristics comparable to those in the treatment group comprising 68 intersections in NYC where their permissive phasing was changed to protected/permissive or protected-only between 2000 and 2007. In the second stage, we applied negative binomial regression models with the GEE method to the dataset comprising observations in the before and after periods for both treatment group and comparison group. The effectiveness of the installation of permissive and protected-only phasing in reducing crashes is evaluated through the coefficients estimated from the model.

2.1. Stage one – comparison group selection

In the first stage, we generated a comparison group comprising similar intersections but without the treatment. The selection of the comparison group was based on several intersection-level factors that have been found to have significant effects on crashes: control type (signalized or not) (Poch and Mannering, 1996), the number of intersection legs (Milton and Mannering, 1998; Harkey et al., 2008), one-way or two-way on the major road, and number of lanes on the major road of the intersection (Harkey et al., 2008). Since the intersections in the treatment group were all signalized and the major roads were all two-way, non-treated intersections with similar characteristics (signalized and two-way major roads) were selected in the comparison group. The distributions of the other two characteristics – the number of legs and the number of lanes on the major roads – were also controlled in the selection of the comparison group. The geographical distribution (e.g., five boroughs of NYC, as shown in Fig. 1) of the locations in the comparison group was further controlled to resemble the distribution of those in the treatment group.

In the ideal case, traffic volume shall also be used to select the comparison group. However, data on traffic volume was not available to the research team. We apply two checks in this study to account for this volume effect, or more precisely, the exposure effect. First, in the selection of the comparison group, the application of the above-described segment- and intersection-level characteristics is to account for the exposure effect to some extent. Second, in stage two where we apply to a negative binomial GEE model, we include both socio-demographic and land use related variables. Though these variables do not fully explain the exposure effect from traffic volume, recent research has demonstrated a strong correlation between built environment variables and safety (Ewing and Dumbaugh, 2009). We note that these efforts may still not be able to account for the full effect of volume. Thus, we discuss the implications in Section 4.

The change of left-turn phasing from permissive to protected/permissive and/or protected-only was completed over a period of 8 years (from 2000 to 2007), and thus the before period and the after period are different for intersections treated in different years. As an example, the 5-year before period and the 2-year after period for signals installed in 2005 are 2000–2004 and 2006–2007, respectively, while those corresponding to signals installed in 2006 are 2001–2005 and 2007–2008, respectively. For this reason, a treatment group was first divided into multiple subsets defined by the year of installation. Then, for each subset, a set of untreated locations were selected by applying the frequency matching technique (Chen et al., 2011a,b) to resemble the joint distribution of those selected matching variables (signalized, two-way on major roads, number of legs, and number of lanes on major roads) as well as the geographical distribution (in five boroughs of NYC) of the treatment group. After each subset was identified with a corresponding set of untreated intersections, those untreated intersections were combined into a single comparison group.

Since many of the treated intersections are on parts of long corridors whereas those in the comparison group selected are more likely to be scattered throughout the city, we also manually selected those intersections along streets that are parallel to those in the treatment group and added them to the comparison group. These procedures resulted in a comparison group of 991 intersections, corresponding to 68 intersections in the treatment group. The distributions of the matching variables in the treatment group and the comparison group are shown in Table 1.

Stage two – negative binomial models with GEE method

In the second stage regression models were applied to further control those factors, for example, built environment characteristics, that cannot be controlled when selecting the comparison group but are potentially associated with crashes (Ewing and Dumbaugh, 2009). Negative binomial regression models were used due to over-dispersion of the crash data.

To account for correlation within observations collected on the same location at two time points (before and after period), the generalized estimating equation (GEE) methodology with an exchangeable correlation structure was applied. An exchangeable correlation structure assumes that the within-subject correlation is the same across all time periods.

The model is specified below:

$$\begin{aligned} y_{\mathrm{it}} &= \exp(\alpha + 1 \times \log(\mathrm{year}_t) + \mathbf{X}^{(s)} + \boldsymbol{\beta} + \mathbf{X}^{(n)}\boldsymbol{\gamma} \\ &\quad + a_1(\mathrm{PP\_T1}) + a_2(\mathrm{PO\_T1}) + b(\mathrm{CG\_T1}) + c(\mathrm{If\_TG})) \\ &= \mathrm{year}_t \times \exp(\alpha + \mathbf{X}^{(s)}\boldsymbol{\beta} + \mathbf{X}^{(n)}\boldsymbol{\gamma} + a_1(\mathrm{PP\_T1}) + a_2(\mathrm{PO\_T1}) \\ &\quad + b(\mathrm{CG\_T1}) + c(\mathrm{If\_TG})) \end{aligned} \tag{1}$$

where, y_{it} is the expected crash count at site i during time t (before or after period); year_t is the number of years during time t (5 years

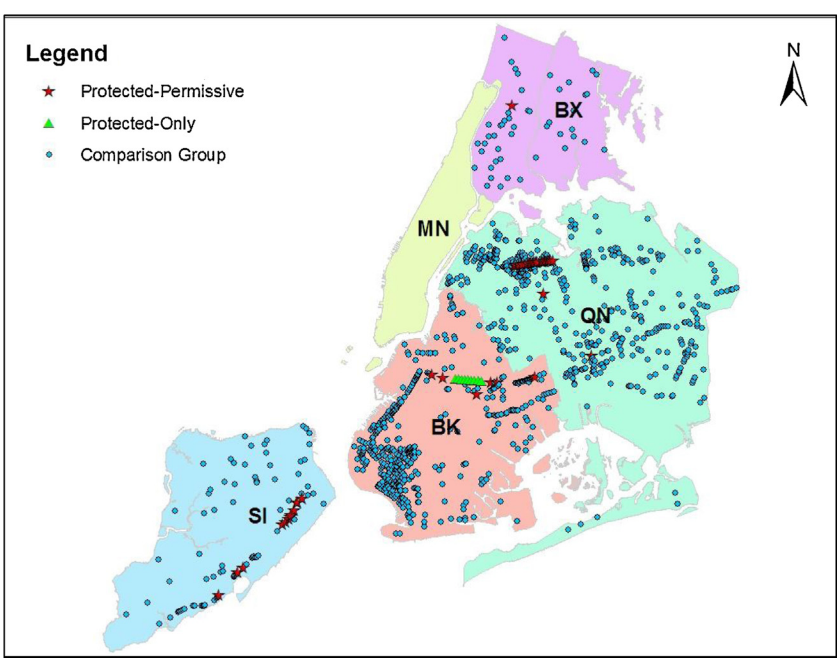

Fig. 1. Geographical distribution of treatment and comparison intersections in New York City.

Table 1
Distributions of matching variables.

Control variables	Values	Treatment group	Comparison group
Borough	Manhattan	0 (0%)	0 (0%)
	Bronx	1 (1%)	47 (5%)
	Brooklyn	15 (22%)	430 (43%)
	Queens	38 (56%)	433 (44%)
	Staten island	14 (21%)	81 (8%)
Number of legs	3-leg	3 (4%)	15 (2%)
	4-leg	63 (93%)	971 (98%)
	5 or more	2 (3%)	5 (1%)
Number of lanes (on major road)	1-lane	25 (37%)	264 (27%)
	2-lane	16 (24%)	405 (41%)
	3-lane	11 (16%)	145 (15%)
	4-lane	12 (18%)	161 (16%)
	5 or more	4 (6%)	16 (2%)

for pre-treatment period and 2 years for post-treatment period); $\mathbf{X}^{(s)}\boldsymbol{\beta}$ are site-level covariates with coefficient β; $\mathbf{X}^{(n)}\boldsymbol{\gamma}$ are neighborhood-level covariates with coefficient $\boldsymbol{\gamma}$; PP_T1 is equal to 1 if the data point comes from a location in the treatment group (where the signal phase was changed from permissive to protected/permissive) post-treatment and 0 otherwise, and the coefficient for this variable is a_1; PO_T1 is equal to 1 if the data point comes from a location in the treatment group (where the signal phase was changed from permissive to protected-only) post-treatment and 0 otherwise, and the coefficient for this variable is a_2; CG_T1 is equal to 1 if the data point comes from an un-treated location in the comparison group post-treatment and 0 otherwise, and the coefficient for this variable is b; If_TG is equal to 1 if the data point comes from a treated location (where signal phases were changed from permissive to protected/permissive or protected-only) and 0 otherwise, and the coefficient for this variable is c.

The difference between the before (5-year) and the after period (2-year) was accounted for in the model by the offset variable (year$_t$), whose coefficient is restricted to 1, assuming that the crash frequency is proportional to the number of years it is counted.

The model includes two sets of independent variables that may potentially affect crash frequencies: neighborhood-level and site-level covariates. Table 2 shows the list of explanatory variables and their sources. At the neighborhood level (calculated as census tract level), it is hypothesized that higher exposure and more conflicts are associated with more crashes (Ewing and Dumbaugh, 2009). We used daytime population density, retail density, percentage of different age groups (under 21, 21–65, or above 65), motorized or non-motorized mode shares in the neighborhood (census tracts) to account for the exposure of vehicular traffic and pedestrians. Daytime population density was calculated as the number of residents plus employment minus the number of people who live and work in the same census tract (to remove double counting) divided by the total census tract area; and retail density was calculated as the floor area of retail land use divided by total census tract area. These two variables measure the density of people who live, work, and shop in the neighborhood. Site-level covariates include the number of legs at an intersection and the number of lanes on the major road of an intersection.

It is possible that the before crashes in the treatment group are significantly more than those in the comparison group, leading to a potential regression-to-mean effect. Therefore, in addition to the explanatory variables included in Table 2, we included in the model a dummy variable "If_TG", representing the treatment group. This dummy variable is used to capture the effect of the difference in crashes between the treatment group and comparison group. A positive coefficient of this dummy variable means that the before-period crashes of the treatment group are significantly more than those of the comparison group and a negative coefficient suggests otherwise.

The coefficients of variables "PP_T1", "PO_T1" and "CG_T1", that is, "a_1,a_2, and b" in Eq. (1), are of our primary interest. If the coefficient for variable "PP_T1" is estimated to be negative, it means that crashes in the after period are expected to be less than those in the before period in the treatment group (PP) where the permissive signal phase was changed to protected/permissive left-turn phasing; a positive coefficient suggests otherwise. Similarly, for variables "PO_T1" and "CG_T1", negative coefficients indicate crash reductions and positive coefficients imply crash increases in the treatment group (PO), when signal phases were changed from permissive to protected-only, and in the comparison group (CG) over the same period.

The contrast between the two coefficients ($a_1 - b$) represents the difference in the change in crash frequencies from the pre-treatment to the post-treatment period for the treatment group (PP, where the permissive signal phase was changed to protected/permissive left-turn phasing) versus that for the comparison group (CG). In order to test if the difference of the two coefficients is statistically significant at 5% level, the model can be transformed by replacing "PP_T1" and "CG_T1" with Z_1 and P_1 as in Eq. (2):

$$y_{it} = \text{year}_t \times \exp(\alpha + \mathbf{X}^{(s)}\boldsymbol{\beta} + \mathbf{X}^{(n)}\boldsymbol{\gamma} + d_1(Z_1) + e_1(P_1) + a_2(\text{PO\_T1}) + c(\text{If\_TG})) \quad (2)$$

where $Z_1 = (\text{PP\_T1} - \text{CG\_T1})/2, P_1 = (\text{PP\_T1} + \text{CG\_T1})/2$

Table 2
List and categories of potential explanatory variables.

Category	Variables	Data source
Roadway geometry	Number of ways (legs) at the intersection	NYCDOT
	Number of travel lanes on the major road	
Socio-demographic	Daytime population density (1000 per sq mi)	US census 2000
	Median household income ($1000)	
	Percentage of Asian population (%)	
	Percentage of Black population (%)	
	Percentage of population age between 21 and 65 (%)	
	Percentage of population age under 21 (%)	
	Percentage of population age above 65 (%)	
Mode share	Percentage of commuting by auto (%)	US census 2000
	Percentage of commuting by public transportation (%)	
	Percentage of commuting by bicycling (%)	
	Percentage of commuting by walking (%)	
Land use	Residential land use density (floor area, sqft/sqft)	NYCDCP
	Commercial land use density (floor area, sqft/sqft)	
	Retail land use density (floor area, sqft/sqft)	
Transportation	Percentage of roadway miles that is one-way (%)	NYCDOT
	Percentage of roadway miles that is truck route (%)	
	Percentage of roadway miles with parking lane (%)	
	Subway ridership in the census tract (1000)	
	Subway station density (number per sq mi)	
	Bus stop density (number per sq mi)	

Note: NYCDOT: New York City Department of Transportation.
NYCDCP: New York City Department of City Planning.

Similarly, the contrast between the two coefficients $(a_2 - b)$ represents the difference in the change in crash frequencies from the pre-treatment to the post-treatment period for the treatment group (PO, where permissive signal phase was changed to protected-only left-turn phasing) versus that for the comparison group (CG). In order to test if the difference of the two coefficients is statistically significant at 5% level, the model can be transformed by replacing "PO_T1" and "CG_T1" with Z_2 and P_2 as in Eq. (3):

$$y_{it} = \text{year}_t \times \exp(\alpha + \mathbf{X}^{(s)}\boldsymbol{\beta} + \mathbf{X}^{(n)}\boldsymbol{\gamma} + d_2(Z_2) + e_2(P_2) + a_1(\text{PP\_T1}) + c(\text{If\_TG})) \quad (3)$$

where $Z_2 = (\text{PO\_T1} - \text{CG\_T1})/2, P_2 = (\text{PO\_T1} + \text{CG\_T1})/2$

The coefficient of Z_1 (Eq. (2)) is the difference of the two coefficients associated with "PP_T1" and "CG_T1": $d_1 = a_1 - b$. If d_1 is significant and negative, it points to the effectiveness of treatment – changing from permissive to permissive/protected-only phasing reduces crashes. If it is insignificant, it suggests that this treatment has no effect on crashes. Similarly, the coefficient of Z_2 (Eq. (3)) is the difference of the two coefficients associated with "PO_T1" and "CG_T1": $d_2 = a_2 - b$. If d_2 is significant and negative, it suggests the effectiveness of the treatment – protected-only left-turn signal phasing reduces crashes.

3. Results

We first compared before and after crashes of all types, including total crashes, multiple-vehicle crashes, left-turn crashes, pedestrian crashes and bicyclist crashes for the treatment group (59 intersections with protected/permissive left turn phasing and 9 intersections with protected-only left turn phasing) and the comparison group. Given the potential trade-offs in safety impacts (Srinivasan et al., 2008), we also included rear-end collisions and over-taking collisions to understand the impacts of left-turn signal phasing on other types of vehicle collisions. The results are shown in Table 3.

Over time, crash reduction was experienced by both treatment group and comparison group, reflecting a city-wide downward trend in crashes. The magnitudes of crash reductions vary between groups. For total crashes, the reduction (in the average number of crashes per intersection per year) in the comparison group was less (35%) than that in the treatment group (42%). For vehicle collisions, the two groups experienced similar reductions (38% for the treatment group versus 37% for the comparison group). The reduction in left-turn crashes was, 30% for the treatment group versus 36% for the comparison group. The reduction in rear-end collisions in the comparison group was less (37%) than that in the treatment group (41%), while the reduction for over-taking collisions in the comparison group was higher (70%) than that in the treatment group (64%). The reduction in pedestrian crashes was, 40% for the treatment group versus 25% for the comparison

Table 3
Comparison of crashes in the treatment group and comparison group.

Crash type	Group[a]	Before (5 years)	After (2 years)	Average crashes (per intersection per year)		
		Sum	Sum	Before	After	% Change
Total crashes	CG (991)	13174	3322	2.66	1.72	−35%
	TG (68)	2447	564	7.2	4.15	−42%
	PP (59)	1901	465	6.44	4.29	−33%
	PO (9)	546	99	12.13	5.5	−55%
Multiple-vehicle crashes	CG (991)	10686	2618	2.16	1.36	−37%
	TG (68)	2038	474	5.99	3.74	−38%
	PP (59)	1553	388	5.26	3.58	−32%
	PO (9)	485	86	10.78	4.78	−56%
Left-turn crashes	CG (991)	1258	301	0.25	0.16	−36%
	TG (68)	261	64	0.77	0.54	−30%
	PP (59)	207	59	0.7	0.58	−17%
	PO (9)	54	5	1.2	0.28	−77%
Rear-end collisions	CG (991)	2698	663	0.54	0.34	−37%
	TG (68)	619	138	1.82	1.08	−41%
	PP (59)	451	105	1.53	0.97	−37%
	PO (9)	168	33	3.73	1.83	−51%
Over-taking collisions	CG (991)	1110	127	0.22	0.07	−70%
	TG (68)	206	29	0.61	0.22	−64%
	PP (59)	157	22	0.53	0.19	−63%
	PO (9)	49	7	1.09	0.39	−64%
Pedestrian crashes	CG (991)	1663	499	0.34	0.25	−25%
	TG (68)	262	58	0.77	0.46	−40%
	PP (59)	232	54	0.79	0.49	−38%
	PO (9)	30	4	0.67	0.22	−67%
Bicyclist crashes	CG (991)	514	115	0.1	0.06	−44%
	TG (68)	83	14	0.24	0.11	−55%
	PP (59)	68	12	0.23	0.11	−52%
	PO (9)	15	2	0.33	0.11	−67%

[a] CG: comparison group (991 intersections); TG: treatment group (68 intersections, combination of subgroup PP and PO); PP: subgroup of treatment group comprising intersections where signal phases were changed from permissive to protected/permissive (59 intersections); PO: subgroup of treatment group comprising intersections where signal phases were changed from permissive to protected-only (9 intersections).

group; and the reduction in bicyclist crashes was 55% for treatment group versus 44% for the comparison group.

A much greater reduction can be observed for the protected-only phasing than the permissive/protected phasing – 77% reduction in left-turn crashes for the former as opposed to 17% reduction for the latter. A similar trend is observed in our study for other crash types, though at a less degree. Intersections with protected-only phasing experienced 55% and 56% reductions in total crashes and multiple-vehicle crashes, respectively, as compared to 33% and 32% reductions for intersections with permissive/protected phasing. Intersections with protected-only phasing experienced 67% reductions in pedestrian and bicyclist crashes, as compared to 38% and 52% reductions for intersections with permissive/protected phasing. Similarly, protected-only phasing experienced a 51% reduction in rear-end collisions corresponding to a 37% reduction with protected/permissive phasing. For over-taking collisions, on the other hand, the two types (protected-only and protected/permissive left-turn phasing) experienced similar reductions – 63% versus 64%, and both are less than the reduction in the comparison group (70%).

The results of the five models (total crashes, multiple-vehicle crashes, left-turn crashes, pedestrian crashes and bicyclist crashes) are shown in Table 4. On the role of the built environment, our results conform to those in the literature (Ewing and Dumbaugh, 2009). Variables measuring the exposure of travelers, for example, daytime population density, retail density, percentages of commuters by auto, bus stop density, were all found to be positively correlated with crashes. Variables such as the percentages of 4-leg intersections, roadways with parking, and truck routes in the census tract were included to measure conflicts at the intersection (Ewing and Dumbaugh, 2009). The results suggest that areas with a higher percentage of roadways with parking and more 4-leg intersections are associated with more crashes. We also examined census tract-level social effects, for example, population of different ethnic groups, and found that census tracts with a higher percentage of black or Asian population have more crashes, a finding consistent with the existing literature (Chen et al., 2012a,b).

The coefficients of the dummy variable "If_TG" for the three crash types – total crashes, multiple-vehicle crashes, left-turn crashes, pedestrian crashes and bicyclist crashes are all positive and significant at 5% level (p-value <0.0001), confirming the potential existence of the regression to the mean effect.

As shown in Table 4, the difference between "a_1" and "b", that is, "$a_1 - b$", is positive for total crashes, multiple-vehicle crashes and left-turn crashes, suggesting an increase in the crashes in the treatment group after the change of left-turning signal phase from permissive to protected/permissive. The difference is negative for pedestrian and bicyclist crashes. However, the coefficients are insignificant at 5% level for all five crash types.

The difference between "a_2" and "b", that is, "$a_2 - b$", is negative for total crashes, multiple-vehicle crashes, left-turn crashes,

Table 4
Estimates of the model coefficients and effectiveness.

Covariates	All crashes		Multi-veh crashes		Left-turn crashes		Pedestrian crashes		Bicyclist crashes	
	Est. (S.E.)	p.	Est. (S.E.)	p.	Est. (S.E.)	p.	Est. (S.E.)	p.	Est. (S.E.)	p.
Intercept	−3.6 (0.6)	<.0001	−3.5 (0.6)	<.0001	−7.7 (0.9)	<.0001	−5.4 (0.8)	<.0001	−3.4 (0.5)	<.0001
Site-level covariates (intersection)										
Number of legs	0.6 (0.1)	<.0001	0.6 (0.1)	<.0001	0.9 (0.2)	<.0001	0.3 (0.2)	0.0429		
Number of lanes on major road	0.2 (0.03)	<.0001	0.2 (0.03)	<.0001	0.3 (0.04)	<.0001	0.2 (0.04)	<.0001	0.1 (0.05)	0.0053
Neighborhood-level covariates (census tract)										
Log(daytime population density)	0.1 (0.05)	0.0443	0.06 (0.05)	0.1942			0.5 (0.08)	<.0001	0.3 (0.1)	0.0033
Percent of Black population	0.009 (0.001)	<.0001	0.01 (0.001)	<.0001	0.01 (0.002)	<.0001			0.006 (0.002)	0.0006
Percent of Asian population	0.01 (0.002)	<.0001	0.01 (0.002)	<.0001	0.02 (0.004)	<.0001				
Percent of commuter by auto	0.004 (0.002)	0.0694	0.008 (0.002)	0.0002	0.01 (0.003)	<.0001			-0.02 (0.004)	<.0001
Retail density	0.008 (0.006)	0.1437								
Percent of roadway with truckroute			0.003 (0.003)	0.2658						
Percent of roadway with parking	0.008 (0.003)	0.0084			0.008 (0.005)	0.1014	0.007 (0.004)	0.0541		
Percent of 4-leg intersections			0.004 (0.002)	0.0187						
Bus stop density	0.002 (0.0007)	0.006	0.002 (0.0007)	0.0051	0.004 (0.001)	0.0042	0.003 (0.0009)	0.001	0.003 (0.001)	0.0032
Dummy variables										
If from treatment group in the after period ($a1$)	−0.4 (0.07)	<.0001	−0.4 (0.08)	<.0001	−0.2 (0.2)	0.2377	−0.5 (0.1)	0.0001	−0.8 (0.3)	0.0171
If from treatment group in the after period ($a2$)	−0.7 (0.2)	0.0001	−0.7 (0.2)	0.0002	−1.4 (0.3)	<.0001	−1.2 (0.4)	0.0065	−1.2 (0.6)	0.0389
If from comparison group in the after period (b)	−0.4 (0.03)	<.0001	−0.5 (0.03)	<.0001	−0.5 (0.07)	<.0001	−0.3 (0.05)	<.0001	−0.6 (0.1)	<.0001
If from treatment group (c)	0.8 (0.09)	<.0001	0.8 (0.1)	<.0001	0.9 (0.1)	<.0001	0.8 (0.1)	<.0001	0.6 (0.1)	<.0001
Effectiveness										
Estimate of the difference: $a_1 - b$	0.03 (0.08)	0.7182	0.1 (0.08)	0.2396	0.3 (0.2)	0.0727	−0.3 (0.2)	0.0607	−0.2 (0.3)	0.5247
Estimate of the difference: $a_2 - b$	−0.2 (0.2)	0.1701	−0.2 (0.2)	0.2023	−0.9 (0.3)	0.0012	−1.0 (0.4)	0.0336	−0.6 (0.6)	0.2868

Note: a: the coefficients of these dummy variables are estimated using Eq. (1).
PP: subgroup of treatment group comprising intersections where signal phases were changed from permissive to protected/permissive;
PO: subgroup of treatment group comprising intersections where signal phases were changed from permissive to protected-only;
TG: treatment group (combination of PP and PO).
CG: comparison group.
b: the estimate of the effectiveness of changing from permissive to protected/permissive left-turn signal phasing, by using Eq. (2).
c: the estimate of the effectiveness of changing from permissive to protected-only left-turn signal phasing, by using Eq. (3).

pedestrian crashes and bicyclist crashes – crashes decreased more in the treatment group than in the comparison group, suggesting a decrease in crashes in the treatment group after the change of left-turning signal phase from permissive to protected-only. However, only the coefficient for left-turn crashes and pedestrian crashes are significant at 5% level.

4. Discussions

In 2009, New York City Department of Transportation published a new street design manual that established guidelines for various components of street design, including road geometry, street furniture and lighting. This new street design manual is the culmination of many years' effort on the part of NYCDOT that has been implementing engineering and traffic calming measures to smooth traffic and reduce crashes of all types. Under this background, we conducted a safety evaluation of 13 different traffic calming measures implemented in the city from 2001 to 2007 and left-turn phase change is one of the 13 evaluated.

We find that changing from permissive to protected-only phasing significantly reduces left-turn crashes and pedestrian crashes, a finding consistent with many existing studies (Agent and Deen, 1979; Upchurch, 1991; Gibby et al., 1992; Stamatiadis et al., 1997; Box and Basha, 2003). The likely reason: this signal phasing separates left-turning movements from the opposing traffic and crossing pedestrian completely, and thus reduces conflicts between the left-turning and opposing vehicles as well as the conflicts between the left-turning vehicle and crossing pedestrians. Left-turn crashes were not fully eliminated by the protected signal phasing, because there are other collision patterns, such as those between vehicles making left-turns, between left-turning vehicles and free right-turning vehicles, or those between left-turning and crossing traffic when one of which was against signal. A study of left-turn crashes by Wang and Abdel-Aty (2008) found that left-turn phasing may not be effective in reducing these other collision patterns.

On the other hand, the effect of left-turn phasing on reducing total crashes and multiple-vehicle crashes proves insignificant. Furthermore, when the protected-only phasing is combined with the permissive, there is an unexpected increase (though insignificant) in three types of crashes (total crashes, multiple-vehicle crashes and left-turn crashes). While Srinivasan et al. (2008) argued that the introduction of a protected left-turn phase will tend to increase mostly rear-end crashes, we found an increase in over-taking crashes after the installation of left-turn signal phasing (as shown in Table 3). This may be explained by the situation that vehicles making left-turns would probably overtake other through traffic in their rush to turn within the protected left turn phase and avoid the long wait when missing it. The reduced green time and the resulting increased queues may also contribute to the increase in over-taking crashes.

One limitation that the study has is its inability to directly incorporate traffic volume due to data unavailability. Within the context of this study (in New York City), one possibility is that the volume changes from before to after treatment are likely minimal, in which case, not accounting for volumes has no impact on the study results. The reason for the minimal change is primarily that it is a highly urbanized area with a significant amount of congestion. In a recent study conducted by New York City Department of Transportation, the overall traffic in New York City grew about 0.5% in the 10-year period from 2000 to 2010 (New York City Department of Transportation, 2012).

Another possibility is that traffic volumes at treatment sites may decrease over time as compared to those at the comparison sites, since most of the left-turn phasing treatments were accompanied with left-turn lanes, which are typically obtained by reducing or narrowing the existing travel lanes. If this were true, it will actually further support our conclusion that changing permissive phasing to protected-only or protected/permitted does not always lead to safety benefits.

With the study area being in New York City, we discuss a few issues related to external validity: how well will the findings from the study hold in other localities? We argue that four salient characteristics of the study likely support potential applicability in certain other localities. First, we note (Table 1) that the majority of the treatments (99%) were implemented in Brooklyn, Queens, and Staten Island. Without Manhattan that has a population density of nearly 70,000 people per square miles, these three boroughs are quite comparable to many places on the east coast in terms of land use patterns and people's demographics. The second notion relates to the use of the relatively large sample of treatments (68 in total) as compared to what is available in the existing literature. Everything else being equal, the larger sample size potentially accounts for more variations in settings and outcomes, thus mitigating the threats to external validity. Third, the use of a quasi-experimental design with corresponding before and after observations for both treatment group and comparison group (Section 2.1) helps eliminating factors that affect NYC as a whole. Last, five different types of outcomes (all crashes, multi-vehicle crashes, left-turn crashes, pedestrian crashes, and bicyclist crashes) were examined and the results are quite consistent throughout. This helps reduce the possibility that the study results may only be applicable to one type of outcomes.

We also want to note the potential limitations in applicability. At a national scale, the three boroughs where the treatments were implemented still represent highly urbanized areas in the US, which is still a small proportion. Consequently, the direct transferability of the results to many places in the US is not advisable and more studies are required. In sum, our key message is that though left-turn phasing (in particular, protected only) can be potentially highly effective in, for example, reducing left-turn crashes, it is not always a better option than permissive only phasing.

5. Conclusions

In conclusion, our study results show that protected left-turn phasing can be effective in reducing left-turn crashes as well as pedestrian crashes. Thus, in dense urban environments where there are a large number of left-turn crashes and many pedestrians, protected left-turn phasing is an effective solution. However, it may be compromised by an increase in other types of crashes and traffic delay at intersections. These results suggest that left-turn phasing should not be treated as a universal solution that is always better than the simple permissive control for left-turning vehicles.

Left-turn phasing must be carefully selected and implemented by considering the trade-offs between safety and delay, as well as many other factors – the literature shows that various factors, such as crash experience, traffic flow at the intersections, and intersection geometry, need to be considered (Agent and Deen, 1979; Stamatiadis et al., 1997). In addition to left-turn signal phasing, several other means can be used to accommodate left-turn movements at signalized intersections. As noted earlier, left-turn signal phasing usually includes geometric improvements, such as addition of left turn lanes or left turn bays. However, these treatments have their own pros and cons and thus the implied impacts on safety and traffic need to be studied.

Our study also demonstrated that characteristics of the built environment should be included in safety studies. Built environment attributes have been largely disregarded in existing studies assessing the effect of left-turn phasing. Because there had been a city-wide downward trend in crashes, a simple before-and-after comparison is insufficient in the evaluation of the effectiveness of left-turn phasing in reducing crashes. Our two-stage approach offers a number of advantages over simple before–after or comparison group analysis by further controlling those built environment factors, quantifying their impacts on crashes and accounting for repeated measures at the same location using GEE method.

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