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Article

Safety Effects of Protected Left-Turn Phasing at Signalized Intersections: An Empirical Analysis

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Abstract: Left-turn crashes occur frequently at signalized intersections and often lead to severe injuries. This problem can be addressed through the implementation of protected left-turn signals. This gives left-turning vehicles the right to enter the intersection free from conflict with opposing drivers and pedestrians. The present study analyses the effect of this measure on crash occurrence. The study included 103 signalized intersections with left-turn signals in highways in Flanders, Belgium, of which 33 received only changes in the signal control and 70 also received additional changes. The effect on traffic safety is analyzed through an Empirical Bayesian before-and-after study on crashes, in which general trend effects and regression-to-the-mean are controlled. On the 33 intersections that received only changes in the signal control, the number of injury crashes decreased significantly (−46%, 95% CI (−36%; −55%)) during the after-period. This was mainly attributable to a decrease in left-turn crashes: −60%, 95% CI (−39%; −74%). The number of rear-end injury crashes did not change significantly after the implementation of a protected left-turn signal. A larger effect was identified for more severe crashes (involving serious injuries and fatalities) as compared with crashes resulting in lighter injuries: −66%, 95% CI (43%; −80%). Furthermore, the effect of left-turn phasing on the number of injured car occupants, cyclists, moped riders and motor cyclists was examined, and favorable effects were found for each of these groups.

Keywords: before-and-after study; crash; protected left turn; signalized intersection; traffic safety

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1. Introduction

Intersections are dangerous spots on roadway networks. Although the installation of traffic signals can help to separate traffic flows, some problems remain, for example, left-turn crashes (in countries driving on the right hand side). Left-turn crashes can be defined as crashes between left-turning vehicles and opposing through-traffic. These crash types are often severe, possibly due to the relatively high traveling speeds of the involved vehicles and the angle of impact [1]. The safety problems encountered by turning left are often addressed through some sort of left-turn protection. This protection eliminates conflicts because left-turning vehicles do not need to yield to opposing through-traffic. Generally, three types of left-turn phasing can be distinguished: permitted, protected only and protected/permitted signal phasing. In the most basic, "permissive", mode, a green signal permits vehicles to turn left as traffic allows. The principle of a "protected" signal phasing is that left-turning vehicles only get a green signal if the opposing traffic gets a red light. In case of a combined protected/permitted signal phasing, there are two phases: one "protected" phase and also a "permitted" phase in which left-turning is allowed, although drivers in opposite directions face green lights. The advantages of protected/permitted left-turn control compared with other systems are believed to be an increased left-turn capacity and reduced delay [2,3].

A number of studies analyzed the traffic safety effects of the implementation of left-turn phasing at signalized intersections. In 2004, Hauer [4] published an on-line literature review on left-turn protection, safety, delay and guidelines of signal phasing. Based on a narrative review of 12 published US studies (three before-and-after studies, eight cross-sectional studies and one study that combined the two approaches), Hauer reported an estimated overall 70% decrease in the number of left-turn crashes for the conversion of signals from permitted- and protected/permitted-phased to protected-phased. However, the conversion from permitted to protected/permitted did not show an effect on left-turn crashes or on other crashes.

More recently, Lyon *et al.* [5] analyzed the impact of flashing advance-green and left-turn green-arrow signals on injury and fatal left-turn crashes (crashes involving at least one left-turning vehicle) and left-turn side-impact crashes (crashes involving one vehicle turning left and one going straight through from the opposite direction). They studied 35 intersections in the city of Toronto through an empirical Bayesian before-and-after analysis: 15 intersections with flashing advanced green signals (*i.e.*, protected/permitted phasing) and 20 with green-arrow signals (protected phasing). In total, the number of left-turn crashes decreased by 16% (p = 0.04), and the number of left-turn side impacts decreased by 19% (p = 0.02). Srinivasan *et al.* [6] analyzed three sites at which the permitted left-turn phase was replaced by a protected/permitted phase. The study showed very little change in crashes involving at least one left-turning vehicle or in total crashes. The authors, however, stated that the results could not be taken as definitive because of the small sample size. Furthermore, eight sites were analyzed at which a permitted phase was replaced by a protected phase. The number of left-turn crashes decreased significantly (by 97.9%) and the total number of crashes decreased insignificantly (by 2.5%). Because a decrease in the left-turn crashes was found but no effect was found on the total number of crashes, the authors concluded that there must have been an increase in non-left-turn crashes. They hypothesized that this could have been attributable to an increase in rear-end crashes. A more recent study by these authors [3] partially confirmed this assumption. They analyzed 59 intersections in Toronto and 12 intersections from North Carolina that were converted from permitted left-turn phasing to protected/permitted left-turn phasing. They found a significant (14%) decrease in the number of crashes between left-turn vehicles and through-vehicles from the opposing direction. Furthermore, they found a 7.5% increase in the number of rear-end crashes; however, this result was not significant.

It can thus be concluded that the implementation of protected left-turn signals has been reported to result in quite large decreases in the number of left-turn crashes. However, the available literature appears to be relatively old and the number of scientifically published evaluation studies, which are almost exclusively North American, all in all, is still limited. There is a need, therefore, for a further validation and exploration of the effects of various types of signal phasing. Moreover, only a few studies so far have used research designs, such as well-controlled before-and-after studies, for the evaluation of the effects of protected left-turn signals on the number of crashes.

In the present study, the safety effect of the installation of protected left-turn signals was examined through a before-and-after study, controlling for effects of trends and regression to the mean. In addition to the effect on left-turn crashes, the effect on rear-end crashes was studied, since little is known about the impact on these crash types. In addition, the effect on the most severe crashes (*i.e.*, fatal and serious injury crashes) was analyzed separately, since this has not yet been studied in previous peer-reviewed research. Furthermore, the effect on casualty level was examined in order to analyze the effects on various road-user categories (cyclists, moped riders, motorcyclists and car occupants).

2. Method

2.1. Study Design

The traffic safety effect was analyzed through a before-and-after study on crash occurrence. This method compares the number of crashes before the implementation of the measure with the number of crashes after the implementation. It is the study design most commonly used to evaluate the effectiveness of a traffic safety measure [7,8]. It is, however, important to control for confounding variables that can affect the number of crashes and whose effects can thus be mixed up with the effects of the measure being evaluated [7]. Both the regression-to-the-mean (RTM) phenomenon and long-term trend effects were controlled for in the present study. The RTM effect was controlled through the use of a lag period. This is the period after the years that were used to select the sites for treatment (on the basis of their crash records) but before the moment that the treatment was implemented. This lag period can be used as an unbiased estimate of the true crash rate before the treatment is applied, and instead of comparing the crashes after the treatment with those before, the crashes from after the treatment can be compared with the lag period [9]. General trend effects are controlled through the inclusion of a comparison group of locations that is comparable to the treated locations (see description in Sections 2.2 and 2.3).

Especially for severe crashes, there is a chance that the observed number of crashes at a treated location in the before or after-period will equal zero. Intuitively, the presence of zero crashes is not very likely to be a correct long-term average because it would indicate "perfect" safety. In order to solve this problem and increase the precision of the estimates, an empirical Bayes estimation was executed for the crash frequencies during the before- and after-periods. For both the before- and after-periods, a weighted average based on the joint use of the observed number of crashes at that location and the average number of crashes that occurred at all treated locations was used. The formula for the before-period can be written as follows:

$$L_{estimated,before} = w \times \lambda_{before} + (1 - w) \times K_{l,before} \quad (1)$$

where $L_{estimated,before}$ = the estimated number of crashes at the treated location, L, during the before-period; w = the weight (between 0 and 1) that is given to the average number of crashes at the treated locations; λ_{before} = the average number of crashes that occurred at the treated locations during the before-period; 1 − w = the weight given to the crashes at the treated location, L; and $K_{l,before}$ = the observed number of crashes that occurred at the treated location, L, during the before-period where:

$$w = \frac{1}{1 + \lambda_{before} / k_{before}} \quad (2)$$

and k is the inverse value of the over-dispersion parameter [10].

The over-dispersion parameter is written as follows:

$$k_{before} = \frac{\frac{Var(x)_{before}}{\lambda_{before}} - 1}{\lambda_{before}} \quad (3)$$

where $Var(x)_{before}$ is the empirical variance of the crashes that occurred at the treated locations during the before-period.

The same formulas are used for the after-period.

The result per location is expressed as an index of effectiveness (θ_l), which indicates the proportion of crashes that remain after the measure has been taken:

$$\theta_l = \frac{L_{estimated,after} / L_{estimated,before}}{C_{after} / C_{before}} \quad (4)$$

where, C_{before} = number of crashes in the comparison group during the before-period and C_{after} = number of crashes in the comparison group during the after-period.

The evaluation of each location separately has only limited significance. Therefore, a fixed effects meta-analysis was carried out, which resulted in one overall effect estimate and more statistically reliable outcomes [11]. Every location within the meta-analysis receives a weight, which is the inverted value of the variance. Subsequently, locations at which many crashes occurred are given higher weights:

$$w_l = \frac{1}{s_l^2} \quad (5)$$

And

$$s_l^2 = \frac{1}{L_{estimated,before}} + \frac{1}{L_{estimated,after}} + \frac{1}{C_{before}} + \frac{1}{C_{after}} \quad (6)$$

Supposing that the measure is executed at n different places, the weighted mean index of effectiveness of the measure over all places, θ, is as follows:

$$\theta = \exp\left[\frac{\sum_{l=1}^{n} w_l \times \ln(\theta_l)}{\sum_{l=1}^{n} w_l}\right] \tag{7}$$

The estimation of a 95% CI is as follows:

$$\theta_{\text{below limit}} = \exp\left[\frac{\sum_{l=1}^{n} w_l \times \ln(\theta_l)}{\sum_{l=1}^{n} w_l} \pm 1.96 \times \frac{1}{\sqrt{\sum_{l=1}^{n} w_l}}\right] \tag{8}$$

2.2. Treated and Comparison Sites

The study included 103 signalized intersections with left-turn signals in highways in Flanders, Belgium, of which 33 received only changes in the signal control and 70 received additional changes, such as resurfacing the road, changes in cycle facilities, the installation of red light cameras and the construction of traffic islands. At the majority of the intersections, protected-only signals were installed. A small number were equipped with protected/permitted signals.

At the time of the study, geographical located crash data were available up to 2010. In order to have at least one year of crash data available during the after-period, only the intersections that were adapted up until 2009 were included. The left-turn phasing was implemented at four locations in 2004, 24 locations in 2005, 16 locations in 2006, 28 locations in 2007, 17 locations in 2008 and 14 locations in 2009.

The comparison group, which was used to control for general trend effects, included all crashes at signalized intersections in Flanders. The treated locations were excluded from this group. This group of comparison sites provided a good indication of the general crash trend at locations similar to the treated locations but where no left-turn phasing was implemented during the research period.

2.3. Crash Data

At the moment of the study, Flemish geo-coded crash data were available up to 2010. In order to exclude the period during which the black spots were selected on the basis of crash counts (1997–1999) and thus to control for RTM, only crashes from 2003 onwards were selected. All crashes within a radius of 100 m from the intersection center were selected. This was done to make sure that every accident that possibly could have been influenced by the presence or absence of the measure under investigation was included. The before-period varied across locations but amounted to 3.7 years on average; the after-period amounted to 3.3 years on average. Two groups of crash data were included: (1) all injury crashes; (2) severe injury crashes, which included crashes with severely injured persons (every person who required more than 24 h of hospitalization as a result of a crash) as well as crashes with fatally injured persons (every person who died within 30 days after the crash as a consequence of the crash). Furthermore, two types of crashes were distinguished: left-turn crashes and rear-end crashes. In addition to the analyses of the crash levels, an analysis of the level of casualties was carried out, and the effect on each of the road user categories was examined. Table 1 shows the descriptive statistics for the crashes from the treated locations, with a distinction between the before and after-periods.

Table 1. Number of crashes at the treated locations before and after conversion to left-turn protection.

Crash Type	Before Conversion			After Conversion		
	Min	Max	Mean (st. dev.)	Min	Max	Mean (st. dev.)
Injury crashes	0	45	10.98 (8.45)	0	31	6.79 (5.73)
Left-turn crashes	0	13	2.38 (2.44)	0	9	1.19 (1.62)
Rear-end crashes	0	29	3.45 (4.26)	0	12	2.74 (2.62)
Severe crashes	0	8	1.67 (1.71)	0	4	0.58 (0.86)

Similarly, crash information was collected for the comparison group locations. The annual averages of crashes for the total comparison group were 1913 injury crashes, 420 left-turn crashes, 500 rear-end crashes and 204 severe crashes. For any given intersection, the before and after period in the comparison group was the same as for the research group. An example to illustrate this: if an intersection was converted in 2007, the before period consisted of crashes from 2003 until 2006 while the after period consisted of crashes from 2008 to 2010. Consequently, the same before and after periods from the comparison group data were used. Logically, this means that the average before and after period for the comparison group data was the same as for the research locations: 3.7 and 3.3 years respectively. The year of the conversion itself was excluded from the data.

3. Results

Table 2 shows the results of the effects on the crash numbers. In total, the number of injury crashes decreased by 37% after the implementation of a left-turn signal. The intersections at which only a left-turn signal control was implemented showed a decrease of 46%; at the intersections with additional measures (see description in 2.2), a decrease of 32% was found. Furthermore, a subdivision was made according to crash type. Left-turn crashes decreased by 50% as a result of the implementation of left-turn signals. The results were more favorable for intersections that received a protected left-turn signal only (−60%) than for intersections that received additional measures (−45%). The number of rear-end crashes showed no significant differences from before to after the measure.

Furthermore, the effect of the replacement of a permitted phase with a protected phase on severe crashes was measured. At all treated intersections, the number of severe crashes decreased by 59%. A decrease of 66% was found at the intersections at which only a protected left-turn signal was installed; at the intersections with additional measures, this was a decrease of 55%.

In addition to the analysis on crash level, an analysis on the level of casualties was executed. Through this method, it was possible to determine whether this measure had a favourable effect on each of the road-user categories. Table 3 shows the mean number of injured road users per year, both for the treated group and for the comparison group. The treated group included all 103 intersections because the number of casualties was too low to make separate analyses for the 33 intersections at which only a left-turn signal control was applied; the comparison group included all road users injured at signalised intersections in Flanders, except for those injured at the treated sites. The rightmost column shows the relative change, which is the odds ratio of the change in the number of crashes from the before-period to the after-period in the treated group, along with the change in the crash frequencies from the before-period to the after-period in the comparison group. A favorable effect was found for all road user categories, and the results for all categories were comparable. The number of injured car occupants decreased by 47%, injured cyclists decreased by 43%, injured moped riders decreased by 39% and injured motorcyclists decreased by 37%. The numbers of injured pedestrians and truck drivers were too low to perform any meaningful analysis on them (on average, there were 5.75 injured pedestrians and 4.5 injured truck drivers per year).

Table 2. Effect on crashes (index of effectiveness (95% CI)).

Crash Type	Left-Turn Signal Control Only (33 sites)	Left-Turn Signal Control + Additional Measures (70 sites)	All intersections (103 sites)
Injury crashes	0.54 (0.45; 0.64) *	0.68 (0.60; 0.77) *	0.63 (0.57; 0.70) *
Left-turn crashes	0.40 (0.26; 0.61) *	0.55 (0.42; 0.72) *	0.50 (0.40; 0.63) *
Rear-end crashes	1.01 (0.73; 1.39)	0.94 (0.77; 1.16)	0.96 (0.80; 1.14)
Severe crashes	0.34 (0.20; 0.57) *	0.45 (0.31; 0.65) *	0.41 (0.30; 0.55) *

Note: * significant at the level $p \leq 0.05$.

Table 3. Effect on casualties.

Road User Category	Number of Injured Road Users						Odds Ratio
	Treated Group (Average per Intersection)			Comparison Group (All Intersections)			
	Before	*After*	*Difference (%)*	*Before*	*After*	*Difference (%)*	
Car occupants	2.35	1.32	−43.80	1130	1193	+5.59	**0.53**
Moped riders	0.27	0.15	−44.09	210	193	−8.05	**0.61**
Cyclists	0.44	0.28	−36.64	313	350	+11.58	**0.57**
Motorcyclists	0.16	0.12	−25.18	95	113	+18.40	**0.63**

4. Discussion

The results for the 33 intersections can be seen as the most valid as they reflect the best estimate for the effect on locations on which the only measure has been the one that was targeted to be evaluated, *i.e.*, installation of protected left-turn signals. The results show a clear decrease in the number of injury crashes (−46%) and an even stronger decrease in the number of severe crashes (−66%). A separate analysis of left-turn injury crashes indicated that this effect was mainly attributable to a decrease in the number of these crashes (−60%). This decrease in the number of left-turn crashes corroborates the results found in earlier studies [3−6]. Previous research further concluded that, in addition to the favorable effect on left-turn crashes, adverse effects were also present and should be examined in a more in-depth manner [6]. Therefore, the present study also analyzed the effect on rear-end crashes. However, we did not find meaningful effects since the best estimate was a slight, but insignificant, increase of 1%. This is slightly different from the results of Srinivasan *et al.* [3], who studied the effect of the replacement of a permitted left-turn signal with a protected/permitted left-turn signal and found an insignificant increase in the number of rear-end crashes (+7.5%) for all sites together, but a significant increase (+9%) at intersections with only one treated approach. Furthermore, we analyzed the effect on fatal and serious injury crashes, which showed greater decreases (−66%) than all injury crashes. Because of the sparse nature of severe crashes, it was impossible to separately analyze the effect of left-turn and rear-end crashes for this subgroup. An analysis of casualty level also showed favorable effects not only for motorized vehicles but also for the number of injured cyclists.

Furthermore, it was found that the effects were slightly higher at intersections at which only a left-turn signal control was implemented, whereas the decrease was less high at intersections where additional modifications were executed. We think this difference might be attributable to some ex-ante differences between the selected locations; thus, there was some selection bias in the treatment group. The initial problem was perhaps more complicated at intersections at which, later on, several measures were implemented, which could have been exactly the reason why the multiple measures were implemented. On the contrary, at intersections at which only protected left-turn signals were installed, the initial problem might have been more straightforwardly attributable to crashes with left-turning vehicles. The available data did not allow for checking this hypothesis. Although the results for the 33 intersections and the additional 70 intersections do not differ substantially, we believe that the results for the 33 intersections could be seen as more valid as they reflect the best estimate for the effect on locations on which the only measure has been the one that was targeted to be evaluated.

One limitation of the present study is that no distinction could be made according to the number of treated legs. Srinivasan *et al.* [4], for example, found higher decreases in the left-turn crashes at intersections where a protected/permitted left-turn signal was implemented at more than one leg (−21%) than at intersections with only one treated approach (−7.5%). Additionally, more limited increases in rear-end crashes were found at intersections with more than one treated approach (+5%) than at intersections with one treated approach (+9%). Such a comparison was not possible in the present study. It is noteworthy that, at the majority of the treated intersections, a left-turn signal was installed at two legs of the main road, *i.e.*, the road with the highest traffic intensity. Furthermore, it was not possible to analyze whether the implementation of a left-turn signal control had a particular effect on traffic exposure and, therefore, some indirect effect on safety. No data were available to compare traffic volumes in the before- and after-periods. However, there is little reason to believe that such a volume effect would be substantial. General changes in traffic volume (*i.e.*, trend changes that not only occur at the treated intersections) were accounted for by using a comparison group [7].

5. Conclusions

Based on the results, the following conclusions can be drawn:

1. Converting permitted to protected left-turn signal control at intersections had a significant and substantial effect on the number of crashes. The results show:
    - a decrease of 46% (95% CI (−36%; −55%)) in the number of crashes with at least one person injured;
    - a decrease of 66% (95% CI (−43%;−80%)) in the number of crashes with at least one person killed or severely injured.

These findings are in line with what has been found in previous studies.

2. Detailed analyses demonstrate a clear favorable effect on left-turn crashes (−60%, 95% CI (−39%; −74%)), but no effect on rear-end crashes.
3. The general favorable effect is found for each road user category: car occupants, cyclists, moped riders and motorcyclists.

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Conflicts of Interest

The authors declare no conflict of interest.

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