THE TRAFFIC SAFETY EFFECT OF PROTECTED LEFT-TURN PHASING AT SIGNALIZED INTERSECTIONS

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Key words: before and after study, crash, left turn, permitted, protected
Word Count: 2735

ABSTRACT

Background Left-turn crashes occur frequently and often lead to severe injuries. This problem can be addressed through the implementation of a protected left-turn signal. This gives vehicles turning left the right to enter the intersection free from conflict with opposing drivers and pedestrians. The present study analyzes the effect of this measure on the crash occurrence.

Methods The study includes 103 signalized intersections in Flanders-Belgium, at which a protected/permitted or a protected only left-turn signal control was implemented. The traffic safety effect is analyzed through a before and after comparison of the crashes, in which general trend effects and regression-to-the-mean are controlled.

Results The number of injury crashes decreased significantly with 37% (95% CI [0.57; 0.70]) during the after period, which was particularly attributable to a decrease in left-turn crashes (-50%). The number of rear-end injury crashes did not change significantly after the implementation of a protected(/permitted) left-turn signal. A larger effect was identified for more severe crashes (involving serious injuries and fatalities), compared with crashes with lighter injuries. Furthermore it was examined what effect the left-turn phasing had on the number of injured car occupants, cyclists, moped riders and motor cyclists and favourable effects were found for each of these groups.

Conclusions The implementation of protected/permitted and protected only left-turn signals at signalized intersections is an effective measure in the context of traffic safety.

INTRODUCTION

Intersections are dangerous spots in the roadway network. Although the installation of traffic signals can help to separate the traffic flows, still 21% of the fatalities at intersections occurred at signalized crossroads in Flanders in 2011[1]. Left-turn crashes, which are defined as crashes between left turning vehicles with opposing through traffic, occur frequently at these intersections. These crash types are prone to be severe, possibly due to the relatively high conflicting speeds of involved vehicles and the angle of impact[2]. The safety problems encountered by left turning are often addressed through some sort of left-turn protection. This protection eliminates conflicts, as left turning vehicles do not need to yield to opposing through traffic. Generally two types of left-turn phases can be distinguished: protected only and protected/permitted signal phasing. The advantages of protected/permitted left-turn control is the increased left-turn capacity and the reduced delay[3, 4]. However, there are still conflicts between left turns and opposing through traffic during the permitted phase.

A number of studies analyzed the traffic safety effects of the implementation of left-turn phasing at signalized intersections. Hauer[5] applied a literature review of 14 studies from several countries. He found a decrease of 70% in the number of left-turn crashes for the conversion of signals from permitted and protected/permitted phased to protective phased. No effect was identified for the other crashes. The conversion from permitted to protected/permitted did not show any effect, not on left-turn crashes, nor on other crashes.

Lyon et al.[6] analyzed the impact of flashing advance-green and left-turn green-arrow 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 opposing approach). They studied 35 intersections in the city of Toronto: 15 intersections with flashing green and 20 with green-arrow. The priority worked at one or more approaches during certain periods of the day. In total the number of left-turn crashes decreased with 16%, the number of left-turn side impacts decreased with 19%. Srinivasan et al.[7] analyzed three sites at which the permitted left-turn phase was replaced by a protected/permitted phase. The study showed very little changes in the crashes involving at least one left turning vehicle or in the total crashes. The authors however stated that the results cannot 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 with 97.9%, the total number of crashes decreased non-significantly with 2.5%. Since a decrease was found in the left-turn crashes, but no effect was found in the total number of crashes, the authors stated that there must have been an increase in non-left-turn crashes. They thought this was possibly attributable to an increase in rear-end crashes, but that further research was necessary to examine this in an in-depth manner. A more recent study of these authors[4] partially confirmed this presumption. 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 decrease of 14% in the number of crashes between left-turn vehicles and through vehicles from the opposing approach. Furthermore they found an increase of 7.5% in the number of rear-end crashes, which was not significant.

In the present study the traffic safety effect of the replacement of a permitted left-turn phase by (1) a protected/permitted left-turn phase and (2) a protected only left-turn phase was examined. Through a before- and after study the effect on injury crashes and on crashes with fatal and serious injuries was examined, and a distinction was made between left-turn crashes and rear-end crashes. Furthermore the effect on casualty-level was examined in order to analyze the effect on the different road user categories.

METHODS

Study design

The traffic safety effect is analyzed through a before and after study of the crash occurrence. This method compares the number of crashes before the implementation of the measure with the number of crashes after the implementation and is the most commonly used study design to evaluate the effectiveness of a traffic safety measure[8, 9]. It is however important to control for confounding variables that can affect the number of crashes and thus whose effects can be mixed up with the effects of the measure being evaluated[8]. Both the regression-to-the-mean (RTM) phenomenon and long term trend effects were controlled for in the present study. The RTM effect is controlled through the use of a lag period. This is the period after the years which were used to select the sites for treatment (on the basis of their crash record) and before the moment the treatment was implemented. The 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 with before, the crashes can be compared from after with the lag period[10]. General trend effects are controlled through the inclusion of a comparison group of locations which are comparable to the treated locations (see description below).
There is a chance that, especially for the severe crashes, the observed number of crashes at a treated location in the before or after period equals zero. Intuitively, the presence of a zero level of crashes is not very likely to be a correct long term average as it would be equal to a ‘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 in the before and after period. Both for the before and after period not the observed number of crashes is used, but per location a weighted average is calculated 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 together. The formula for the before period can be described as next:

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

Where:
$L_{estimated,before}$= 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} = average number of crashes that occurred at the treated locations during the before period
1-w= the weight that is given to the crashes at the treated location L
$K_{l,before}$= 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[11].

$$\text{Over dispersion parameter}_{before} = \frac{\frac{Var(x)_{before}}{\lambda_{before}} - 1}{\lambda_{before}} \quad (3)$$

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. This method was also applied and described in a previous study[12].

The result is expressed in an index of effectiveness which indicates the proportion of crashes that remains after the measure has been taken. The percentage reduction in crashes is thus calculated as 100 × (1−"index of effectiveness"). Furthermore the chance effects were controlled through the use of a 95% confidence interval.

Treated and comparison sites

The study included 103 signalized intersections with permitted left-turn signals at highways in Flanders, Belgium, from which 25 were replaced by protected/permitted left-turn phasing and 78 by protected only left-turn phasing.

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 gives a good indication of the general crash trend at locations that are similar to the treated locations, but where no left-turn phasing was implemented during the research period.

Crash data

At the moment of the study, Flemish geo-coded crash data was 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 were selected. All crashes in a radius of 100 m around the intersection centre were selected. The before period amounted on average to 3.7 years; the after period to 3.30 years. Two groups of crash data were included: (1) all injury crashes; (2) severe injury crashes which included crashes with severely injured persons (every person that needed more than 24 hours of hospitalization as a result of a crash) and fatally injured persons (every person that 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 on the crash level, an analysis on the level of casualties was carried out, and the effect on each of the road user categories was examined.

RESULTS

Table 1 shows the results of the effects on the crash numbers. In total, the number of injury crashes decreased with 37% after the implementation of a left-turn signal. The intersections at which a protected/permitted signal was implemented showed a decrease of 32%; at the intersections with a protected only signal a decrease of 38% was found. Furthermore a subdivision was made according to the crash type. The left-turn crashes decreased with 50% as a result of the implementation of left-turn signals. Similar results were found for protected/permitted left-turn signals (-46%) and protected only left-turn signals (-52%). The number of rear-end crashes showed no significant differences from before to after the measure, not for protected/permitted signals, nor for protected only signals.

Furthermore it was analyzed what effect the replacement of a permitted phase by a protected(/permitted) phase had on severe crashes. At all treated intersections the number of severe crashes decreased with 59%. A decrease of 65% was found at the intersections with protected/permitted signals, at the protected only signals this decrease was 57%.

Table 1. Effect on crashes (index of effectiveness [95% CI])

	Protected/permitted (25 sites)	**Protected only** (78 sites)	**All intersections** (103 sites)
Injury crashes	0.68 [0.56; 0.83]*	0.62 [0.54; 0.69]*	0.63 [0.57; 0.70]*
Left-turn crashes	0.54 [0.34; 0.85]*	0.48 [0.37; 0.63]*	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	0.35 [0.19; 0.66]*	0.43 [0.30; 0.60]*	0.41 [0.30; 0.55]*

In addition to an 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 2 shows the mean number of injured road users per year, both for the treated group and for the comparison group which included all injured road users at signalized intersections in Flanders, except for 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 to the after period in the treated group, with the change in the crash frequencies from the before to the after period in the comparison group. A favourable effect was found for all road user categories, for which the results were close to each other. The number of injured car occupants decreased with 47%, injured cyclists decreased with 43%, for moped riders and motorcyclists this was -39% and -37% respectively. The number of pedestrians and truck drivers was too low to make any analyzes (on average 5.75 injured pedestrians per year and 4.5 injured truck drivers).

Table 2. Effect on casualties

Road user category	**Mean number of injured road users per intersection**						**Odds ratio**
	Treated group			**Comparison group**			
	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**

DISCUSSION

The present study analyzed the traffic safety effect of the implementation of a protected/permitted and a protected only left-turn signal at signalized intersections in Flanders. The study found highly favourable results, with a strong decrease in the total number of injury crashes (-37%). A separate analysis of the left-turn injury crashes indicated that this effect was mainly attributable to a decrease in these left-turn crashes (-50%). Although the impact strongly differs between the different studies, previous research also found favourable effects on the number of left-turn crashes[4-7]. Previous research furthermore concluded that next to the favourable effect on left-turn crashes, also adverse effects were present and that this should be examined in a more in-depth manner[7]. The present study therefore also analyzed the effect on rear-end crashes, but did not find adverse effects as the best estimate was a slight, though far from significant decrease of 4% with a 95% CI [-20%; +14%]. This is slightly different from Sinivasan et al.[4], who studied the effect of the replacement of a permitted left-turn signal with a protected/permitted left-turn signal and found a non-significant increase in the number of rear-end crashes of 7.5%, but a significant increase of 9% at intersections with only one treated approach. Furthermore the effect on fatal and serious injury crashes was analyzed, which showed greater decreases (-59%) compared to the injury crashes. Because of the low number of severe crashes, it was impossible to separately analyze the effect of left-turn and rear-end crashes. However, it can be expected that this decrease was mainly attributable to a decrease in left-turn crashes. An analysis on casualty-level also showed favourable effects, not only for motorized vehicles, but also for the number of injured cyclists.

No strong differences were found according to the type of left-turn signal control. Intersections with protected/permitted left-turn phasing showed similar effects than intersections with

protected only left-turn phasing. This is different compared to previous research, which found more favourable effects for protected only signals compared to protected/permitted signals [4, 5, 7]. This could be explained by the type of traffic control of the protected/permitted left-turn signals at the Flemish highways. Next to the green light which is displayed during both the permitted and the protected phase, also a green arrow is displayed during the protected phase. This means that drivers clearly know when they can turn left protected, and thus it can be expected that they wait until the green arrow illuminates, especially at busy moments.
It should be noted that at some intersections additional measures were implemented next to the left-turn signals. Examples are: resurface of the road, changes in cycle facilities and construction of traffic islands. However, the main measure at each intersection was the implementation of left-turn signals and related measures, such as lengthening of left-turn lanes. It can thus be stated that the effects from the present study were mainly attributable to the implementation of left-turn signal control.
A limitation of the present study is that no distinction was 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%) compared to 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%) compared to intersections with one treated approach (+9%). Such comparison was not possible in the present study. However, at the majority of the treated intersections a left-turn signal was installed at the two legs of the main road, i.e. the road with the highest traffic intensity.
Another limitation is that all crashes in a radius of 100 m around the intersection centre were selected. Subsequently also crashes were selected that were not related to the crashes that are targeted through the installation of left-turn signals. However, since these crashes were selected both in the before and the after period and no specific efforts were made in order to tackle other types of crashes, we can expect that the effects were mainly attributable to crashes related to left turning.

CONCLUSIONS

- Left-turn protection had a significant and substantial effect on crashes
    - decrease of 37% [0.57; 0.70] in the number of injury crashes
    - decrease of 59% [0.30; 0.55] in the number of severe crashes
- Favourable effect on left-turn crashes, no effect on rear-end crashes
- Similar results for protected/permitted signals and protected only signals
- Favourable effect for every road user category (car occupants, cyclists, moped riders and motorcyclists)

KEY MESSAGES

What is already known on the subject

- Left-turn crashes occur frequently and often lead to severe injuries
- The implementation of a protected left-turn signal results in strong decreases in the number of left-turn crashes

What this study adds

- The present study found highly favourable results both for all injury crashes and for the subgroup of the more severe fatal and serious injury crashes
- Favourable effects were mainly attributable to the decrease in left-turn crashes, no adverse effects on rear-end crashes were found
- Similar results were found at intersections with protected/permitted left-turn phasing and with protected only left-turn phasing.
- An analysis on casualty level showed favourable effects for car occupants, cyclists, moped riders and motorcyclists.

Acknowledgements
We would like to thank the Ministry of Mobility and Public Works, Roads and Traffic Agency for their support on the data gathering. This research was partly funded by a grant from the Research Foundation Flanders (FWO). The content of this paper is the sole responsibility of the authors.

Contributors
EDP and SD conceived and designed the study, and gathered the data. EDP and SVH carried out the statistical analyses and its interpretation under the supervision of SD and GW. EDP and SD constructed, and edited the manuscript. All authors approved the final version.

Competing interests None

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