

THE EFFECT OF COMBINED SPEED AND RED LIGHT CAMERAS ON SAFETY

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ABSTRACT

Combined speed and red light cameras are a widely implemented enforcement measure. Previous research already examined the effect of red-light cameras, however the effect of combined speed and red light cameras on severe crashes has not been examined thoroughly. This study evaluates the traffic safety effect of combined speed and red light cameras at 253 intersections in Flanders-Belgium that were installed between 2002 and 2007. The adopted approach was an empirical Bayes method. The evolution in the number of crashes at the investigated locations was compared with the evolution in a comparison group of locations. These analyses show a non-significant increase of 5-9% in the number of injury crashes. For the severe crashes, with serious and fatal injuries, a decrease of 14-18% was found. A distinction between side and rear-end crashes showed a significant increase of 44% in the number of rear-end crashes, but a non-significant decrease of 6% in the number of side collisions. The decrease for the severe crashes was mainly attributable to the effect on side-collisions, for which a significant decrease of 24% was found. Furthermore ANOVA-analyses showed combined speed and red light camera equipped intersections outside the urban area yield more favorable results, compared to intersections inside the urban area. From this study can be concluded combined speed and red light cameras have a favorable effect on traffic safety, especially on severe crashes. Future research should however examine the circumstances of rear-end crashes and how these can be handled.

INTRODUCTION

Red light running is an important offence, mainly involving side crashes with often severe consequences (1). To counteract this problem a limited number of measures can be taken, for example: re-timing of signal phasing, variable warning signs in the approach of signalized junctions and detection systems for automatic regulation of green phases (2). As this is often not sufficient, traffic light signalized intersections are equipped with red light cameras. These systems detect vehicles through two closely spaced inductive loops, embedded in the pavement at the limit line. To analyze red light running, the system compares the information of the vehicle speed at the stop line with the signal phase. In case of an offence, two photographs are taken: one when the vehicle is crossing the stopping line and one to determine whether or not the vehicle continues through the intersection. Next to this, cameras often control driven speed, through calculation of the time which the vehicle passes the two loops. In Flanders, which covers about 5000km regional roads (roughly the upper category of roads, motorways excluded), more than 400 intersections are equipped with one or more fixed combined speed and red light camera (SRLC) since 2002. All of these cameras are photo radar units mounted in boxes. The decision to install a camera is mainly based on the crash history of the intersection.

Different past studies examined the effectiveness of red light cameras. However, most of these studies analyzed the effect of cameras that only determine red light running, but no excessive speed. Although results can differ according to the applied methodology, it is generally found that red light cameras reduce the frequency of side collisions, and increase the number of rear-end collisions. A meta-analysis of Erke (1), including five studies from the United States, showed a non-significant increase of 13% in the number of injury crashes. A distinction between side and rear-end crashes showed an increase of 43% for the rear-end collisions and a decrease of 10% in the side collisions. Only the result of the rear-end collisions was significant at the 5% level. Shin and Washington (3) more profoundly examined the side-collisions and analyzed the differential effect on right-angle and left-turn crashes. They applied an Empirical Bayes-analysis at 14 intersections in Arizona, and found a decrease of 20% in angle crashes, which was only significant at the 20% level. Furthermore a decrease of 45%, significant at the 5% level was found for left-turn crashes. On the contrary, the rear-end crashes increased significantly with 41%. Persaud et al. (4) examined the effectiveness of 132 red light cameras in the United States, and found a significant decrease of 16% in the number of side crashes and an increase in the number of rear-end crashes of 24%. Furthermore they studied spill-over effects from red light cameras equipped intersections to neighboring intersections without red light cameras, and performed a separate analysis by using untreated signalized intersections. This study showed modest spillover effects on right-angle crashes, and found no difference in the rear-end crashes.

Budd, Scully and Newstead (5) studied the effect of combined speed and red light cameras with accompanying warning signs at 77 locations in Victoria. They found a decrease in casualty crashes of 26% at the researched intersection. Furthermore they found a significant decrease of 44% in right angle and right turn crashes. For the rear-end crashes no significant change from before to after was found. Also no significant difference in effect on all injury crashes and severe crashes was found.

STUDY DESIGN

Present study aims to examine the traffic safety effect of all SRLCs in Flanders, through a before-after comparison of the crash rates. For these crash rates a distinction is made according to the severity of the crash, with at one hand all injury crashes, which are all crashes with at least a slightly injured person. On the other hand the more severe crashes are separately analyzed, which are crashes with serious injuries and fatalities. Also the effect on rear-end collisions and side collisions was separately analyzed, to examine whether also here a difference could be determined. Furthermore a distinction was made according to the characteristics of the location, to analyze whether effectiveness differed according to the localization inside or outside urban area, number of lanes, maximum speed limit, presence of a median and whether or not other cameras are nearby. Next to the crash level, also an analysis on the level of casualties was executed, and the effect on each type of road users (car occupants, moped rider, motor cyclists, cyclists, pedestrians, truck drivers) was examined.

The effect of the installation of combined speed and red light cameras is analyzed through a comparison of the crash rates from before to after, taking into account different confounding variables. Ideally the Empirical Bayes method should be used, which is widely accepted as the best standard in the evaluation of traffic safety measures (6, 7, 8, 9). Through this method the observed number of crashes after treatment is compared with the expected number had there been no treatment. This 'expected' number is based on the number of crashes before treatment with correction for extraneous factors. Such correction is necessary, as besides the effects of the treatment itself, a range of other factors will have had an effect on traffic safety. Those confounding factors are regression to the mean, general crash trend, coincidence of the occurrence of crashes and general changes in traffic volumes (10). In current research two methods were applied, both based on the empirical Bayes method, which however differ in the extent they control for RTM.

DATA

In order to make an analysis of the crash rates possible, next conditions have to be fulfilled:

- a geographical localization of the crashes around the camera;
- date (year) the camera was installed and put into use;
- information about other measures executed at the intersection during the research period.

Important to emphasize is that the unit of evaluation is not the SRLC, but the intersection with SRLCs. The number of the SRLCs at these intersections varies along the intersections from one to four cameras. From the total of 408 SRLC equipped intersections, 253 are included in this research. Sixty locations were excluded, since they were installed after 2007. Localized crash data are available for Flanders up to and including 2008. Using a before-and-after study, at least one year of crash data after the installation of the SRLC is necessary. Subsequently only cameras installed up to 2007 inclusive could be evaluated. Next to this, four intersections were excluded as no date of installation was available. Moreover, eight locations were put out of use before 2008, mainly due to problems with the inductive loops, which were also excluded. From six locations no information concerning local measures was received, which subsequently could not be taken up. For 77 locations all necessary information was available, but it was not possible to exclude the effect of other traffic safety measures, as these measures were implemented the year right before, after or during the year the SRLC was installed. Finally 253 locations were selected, for which the isolated effect of the installation of a SRLC could be examined.

For the comparison group a selection of all crashes in Flanders was executed, which gives a good estimation of the general trend. To analyze whether this group was comparable with the research group, the odds ratio for the crash rates from the years of the before period were calculated. The odds ratio is the ratio of the change in the number of crashes in the research group, compared to the change in number of crashes in the comparison group. The odds ratio of two consecutive years is:

$$\text{Odds ratio} = \frac{R_t/R_{t-1}}{C_t/C_{t-1}} \quad [1]$$

With:

R_t = the number of crashes in the research group in year t

R_{t-1} = the number of crashes in the research group in year t-1

C_t = the number of crashes in the comparison group in year t

C_{t-1} = the number of crashes in the comparison group in year t-1

The overall score of this calculation showed an odds ratio of 0.99. This can be considered to be an indication of a good comparability between research group and comparison group (8).

Crash data for Belgium are available until 2009 (Federal Public Service Economy, department Statistics), however geo-coded crash data are only available from 1996 until 2008 (Ministry of Mobility and Public Works, Roads and Traffic Agency). The crash data are gathered by the police through a crash form, and digitally reported. Afterwards these data are controlled by the Federal Public Service Economy, and supplemented with data of deaths 30 days (injured who died within 30 days after the crash) provided by the public prosecutor. Based on the information about the place the crash occurred, a geo-coding is executed by the Ministry of Mobility and Public Works. In the present study, all crashes within a radius of 50 meter around the intersection centre were included.

The research period ran from 2000 until 2008, meaning that, as the first cameras were installed in 2002, for any location at least two years of data in the before period and one year of data in the after period were available. On average, the before period amounted 3.13 years, the after period 3.7 years.

METHODOLOGY

To examine the effectiveness, first the effect per location is examined. Afterwards the results of different locations are combined through a meta-analysis, in order to examine the overall effectiveness of those locations.

Analysis per Location

Empirical Bayes-estimate

The EB estimate for the number of crashes on the research locations in the before period was made as follows:

$$L_{\text{before, RTM}} = w * \lambda_{\text{before}} + (1-w) \left(\sum_{t=1}^{T_{\text{before}}} L_t \right) \quad [2]$$

With:

$L_{\text{before, RTM}}$ = estimated number of crashes during the before-period in location L with control for RTM

λ_{before} = mean number of crashes at all research locations during the before period

T_{before} = length of period before the measure

L_t = number of crashes at location L in year t

The weight (w) can be calculated through next equation:

$$w = \frac{1}{1 + \lambda_{before} / k_{before}} \quad [3]$$

With k is an over dispersion parameter per unit of length (11, 12), calculated from locations where only after 2008 a camera was installed.

This formula can however not be considered as a good method to control for RTM, as no comparison group was included. In order to analyze whether the RTM effect influenced the result, a crash prediction model was used in order to control for RTM (13). This crash prediction model was based on 600 dangerous spots in Flanders. All of these spots were intersections, through which this model could be handled to control for RTM in the analyses of SRLC's. Here a formula, slightly different than formula [2] was applied, based on Hauer et al. (14):

$$L_{before, RTM} = w * (\mu_{M,before} * km_L * T_{before}) + (1-w)(\sum_{t=1}^{t_{before}} L_t) \quad [4]$$

With:

$L_{RTM,before}$ = estimated number of crashes during the before-period in location L, after control for RTM

$\mu_{M,before}$ = average number of crashes per year calculated from the model, based on the Flemish black spot dataset

The dependent value of the model was the number of crashes, based on crash rates of 2000-2003. This period is located after the selection of the black spots, for which crash rates from 1997-1999 were taken into account, and which subsequently led to exclusion of the effect of RTM. Furthermore this period is located before measures were implemented, as the first locations were adapted in 2004. Here a model is used which estimates the number of injury crashes and severe crashes through traffic volumes at major and minor roads of the intersection:

$$E_{injury}(\lambda) = e^{-1.7131} Q_{Maj}^{0.3231} Q_{Min}^{0.2463} \quad [5]$$

$$E_{severe}(\lambda) = e^{-3.2138} Q_{Maj}^{0.3327} Q_{Min}^{0.2009} \quad [6]$$

Where

$E(\lambda)$ = expected annual number of crashes (dependent variable), with E_{injury} are all crashes with injured, and E_{severe} are all crashes with severe injuries and fatalities

Q_{maj} = traffic volume at major road

Q_{min} = traffic volume at minor road

e = natural logarithm = 2.718

More information concerning the measurements on which this model is based, can be found in De Ceunynck et al. (13).

The weight can be calculated through next equation:

$$w = \frac{1}{1 + (\mu_{C,before} * T) / k_{before}} \quad [7]$$

With k is an over dispersion parameter per unit of length (12, 13), which is also calculated through the model.

Control for Crash Trend

To control for trend effects, the crash rates from the before and after period in the comparison group, that consist of all injury crashes in Flanders, are taken into account.

The control for crash trend can be expressed through an odds ratio:

$$Eff = \frac{L_{after} / L_{before, RTM}}{C_{after} / C_{before}} \quad [8]$$

L_{after} = number of crashes on location L during the after period

$L_{before, RTM}$ = number of crashes on location L during the before period, after correction for regression to the mean

C_{after} = number of crashes in the comparison group during the after period

C_{before} = number of crashes in the comparison group during the before period

With a 95% confidence interval (CI):

EFF, below limit = $\exp[\ln(EFF) - 1.96 * s_L]$

EFF, above limit = $\exp[\ln(EFF) + 1.96 * s_L]$ [9]

And a standard deviation of the location (s_L) as the root of the variance (s_L^2):

$$s_L^2 = \frac{1}{L_{after}} + \frac{1}{L_{before,RTM}} + \frac{1}{c_{after}} + \frac{1}{c_{before}} \quad [10]$$

Control for Zero Counts in the After Period

When one of the factors in formula [8] becomes zero, the calculation of the variance (formula [10]) becomes impossible. Also the calculation of the index of effectiveness (formula [8]) is impossible when the denominators equal zero. Elvik (15) described these zero counts as a problem for three reasons. He stated it is highly implausible that the true long-term mean number of accidents at any location is zero. Secondly zero counts suggest that a safety treatment could be either a hundred percent crash reduction (if there was a positive count before and a zero count after) or an infinite increase in the number of crashes (if there was a zero count before and a positive count after), both of which are highly implausible. Thirdly, zero counts have to be adjusted when in a meta-analysis a statistical weight is to be assigned to each result. To solve this problem, an EB-estimate is also made for the crash rates for the after period like proposed by Elvik (14). Therefore formula [2] is also applied on data from the after period.

Meta-Analysis

Next to the individual evaluation per location, the total effect across different locations can be calculated by means of a fixed effects meta-analysis, which results in one overall effect estimate and in more statistically reliable results (16). Every location within the meta-analysis gets a weight, which is the inverted value of the variance. Subsequently locations at which many crashes occurred, are given a higher weight.

$$w_l = \frac{1}{s_l^2} \quad [11]$$

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

$$\text{Overall index of effectiveness} = \exp \left[\frac{\sum_{l=1}^n w_l \ln(EFFI)}{\sum_{l=1}^n w_l} \right] \quad [12]$$

The estimation of a 95% confidence interval is

$$95\% \text{ CI} = \exp \left[\frac{\sum_{l=1}^n w_l \ln(EFFI)}{\sum_{l=1}^n w_l} \pm 1.96 * \frac{1}{\sqrt{\sum_{l=1}^n w_l}} \right] \quad [13]$$

Comparative Analysis According to Characteristics

Through formula [12] different locations with similar characteristics can be taken together to count the overall effect. However, it cannot be said whether some structural variation in the effectiveness exists according to some characteristics of the locations. Therefore an ANOVA(Analysis of variance)-analysis in SPSS is used, in order to determine whether significant differences between the means of two or more groups of intersections exist, for example the comparison of the index of effectiveness of locations inside and outside the urban area. Three conditions must be fulfilled before the ANOVA-test can be applied. At first all groups need to have a normal distribution. As this is not always the case, the logarithms functions of the obtained odds ratios are used. Secondly, all groups need to include at least five observations. A third condition is that the dispersion of groups is sufficiently equal. To control for this, the 'Levene's Test for equality of variance' is used. When this test is significant, the dispersion is not sufficiently equal and a non-parametric test can be applied. When this test also shows no sufficient equal dispersion, the results cannot be interpreted.

Excluding Local Measures

Using a comparison group, the trend effect and subsequently the implementation of other traffic safety measures on a wider scale is taken into account. However this formula does not control for more locally implemented measures. Therefore responsible authorities for all intersections with SRLCs were asked to give information whether other measures were executed during the research period. Examples of those measures are: installation of traffic lights, changes in turn lanes, changes in infrastructure for pedestrians or cyclists, resurface of the road, conversion to conflict free traffic lights and restriction of maximum speed limit. To make sure only the effect of the installation of SRLCs was examined, the effect of these measures were excluded through adaptation of the research period. When the measures were implemented before the camera was installed, the before period started from the year after the measure was completed. When a measure was applied after the installation, the after period was shortened until the year before the measure was implemented. However in certain situations it was not possible to exclude those other treatments. This was the case when for example the measure was implemented during the same year the camera was installed, or during the year right before or after the installation. For these locations, a separate meta-analysis was executed, and the overall effect of all these measures together was examined.

RESULTS

Table 1 shows the results of the meta-analyses. The best estimate of the overall effect on injury crashes of the 253 locations for which the isolated effect of SRLCs could be evaluated (i.e. all the locations for which the possibly confounding effect of other measures could be eliminated), is a non-significant increase of 5%, when RTM is not explicitly controlled. A significant increase of 9% was found, when RTM is controlled through a crash prediction model. An analysis of the crashes with fatal and serious injuries showed a decrease of 14%, significant at the 10% level. Using the crash prediction model, a significant decrease of 18% was found. As previous research showed SRLCs have a different effect on side collisions, compared with rear-end collisions, also this research examined the effect on both crash types. However it was not possible to explicitly control for RTM, as no separate crash prediction model for side and rear-end crashes was available. An analysis of the side collisions showed a non-significant decrease of 6% in the number of injury crashes. For the severe side crashes a decrease of 24% was found, significant at the 5% level. The opposite effect was found for rear-end crashes, for which the total number of injury crashes increased with 44%. For the severe rear-end crashes it was not possible to execute an analysis, as the number of crashes in the research group was too low, with an average of 12 crashes per year.

At 77 locations it was not possible to analyze the isolated effect of SRLCs, because other measures were implemented during the same year the camera was installed, or during the year right before or after the installation. The majority of these measures included a restriction of the speed limit and the application of a new pavement. The locations with multiple measures showed a significant decrease in the number of injury crashes of 24 to 28%, dependent on the method which was used to control for RTM. For the number of severe crashes a non-significant decrease of 12% to 19% was found.

TABLE 1 Results of meta-analyses (Index of effectiveness, [95% CI])

	Research group to control for RTM		Model to control for RTM	
	All injury crashes	Severe crashes	All injury crashes	Severe crashes
SRLCs (253 locations)	1.05 [0.98; 1.12]	0.86 [0.73; 1.02]*	1.09 [1.03; 1.16]	0.82 [0.70; 0.96]**
Side crashes	0.94 [0.85; 1.03]	0.76 [0.59; 0.98]**		
Rear-end crashes	1.44 [1.29; 1.62]**			
SRLCs + other measures (77 locations)	0.72 [0.63; 0.81]**	0.88 [0.64; 1.21]	0.76 [0.67; 0.86]**	0.81 [0.59; 1.09]

*significant at the 90% confidence interval

** significant at the 95% confidence interval

In order to reveal whether certain intersections are more effective compared to other, a distinction was made according to the characteristics of the locations. Because of the contrast in effects between side and rear-end collisions, those were separately analyzed. It was examined whether significant differences were present according to the localization inside or outside urban areas, the presence of other cameras and the number of lanes, the presence of a median and the maximum speed limit at the main road. The road with the highest road category was selected as main road. When plural roads had the same road category, the roads were ordered according to the traffic volume. Results of these analyses are given in table 2. A difference was found according to the localization inside or outside the urban area, which was significant for the side collisions ($F=11.388$, $df=1$; $p=0.001$) and nearly significant for rear-end crashes ($F=2.973$; $df=1$; $p=0.086$). A decrease of 18% in the number of side crashes was found for locations outside the urban area, while a non-significant increase of 14% was found for locations inside the urban area. For the rear-end crashes the increase is more limited for SRLCs outside the urban area (33%) compared to locations inside urban areas (70%). Secondly, intersections with at least one road with a median showed a higher decrease in the number of side collisions compared to intersections without roads with a median. This difference was nearly significant ($F=3.126$; $df=1$; $p=0.079$). Intersections with a median showed a significant decrease of 15% in the number of side collisions, whereas the locations without a median showed no significant difference. Whether or not other SRLC equipped intersections are in the vicinity of the research location, also showed significant differences for the side collisions ($F=11.809$; $df=1$; $p=0.001$). In line with the general definition of the Flemish Government, a distinction is made between cameras that have no or one other camera within a radius of 1500m, and locations with two or more cameras. For junctions with two or more intersections with cameras within 1500m a non-significant increase was found, whereas intersections with no or only one intersection with a SRLC in a radius of 1500m showed a significant decrease of 18% in side crashes. For rear-end crashes no significant difference was found according to presence of other SRLC equipped

junctions. According to the number of lanes and the maximum speed limit no significant difference was found, not for side crashes, nor for rear-end crashes.

TABLE 2 Results (F-value, Df, p-value) of ANOVA-analyses in order to compare the effectiveness of SRLC according to Characteristics of the Intersection; and the Results of the Meta-Analyses (Index of Effectiveness [95%CI])

Characteristic	F-value	Df	p	Side crashes				Rear-end crashes			
				Meta-analysis		F-value	Df	p	Meta-analysis		
Inside /outside urban area	11.388	1	0.001	Inside:	1.14 [0.98; 1.33]	2.973	1	0.086	Inside:	1.70 [1.39; 2.08]**	
				Outside:	0.82 [0.72; 0.93]**				Outside:	1.33 [1.16; 1.53]**	
Number of lanes	1.245	2	0.290	1:	0.89 [0.73; 1.08]	0.390	2	0.678	1:	1.42 [1.10; 1.84]**	
				2:	0.93 [0.83; 1.05]				2:	1.44 [1.26; 1.66]**	
Presence of median	3.126	1	0.079°	None:	0.85 [0.73; 0.98]**	0.357	1	0.551	None:	1.33 [1.12; 1.59]**	
				Present:	1.02 [0.89; 1.16]				Present:	1.53 [1.31; 1.77]**	
Maximum speed limit	2.088	3	0.102	50:	1.06 [0.87; 1.28]	0.321	3	0.810	50:	1.57 [1.22; 2.02]**	
				70:	0.97 [0.83; 1.14]				70:	1.44 [1.19; 1.76]**	
				90:	0.83 [0.71; 0.97]**				90:	1.38 [1.16; 1.64]**	
Other intersections within 1500m	11.809	1	0.001	0 or 1:	0.82 [0.72; 0.93]**	0.495	1	0.482	0 or 1:	1.34 [1.16; 1.55]	
				≥2:	1.11 [0.96; 1.29]				≥2:	1.61 [1.35; 1.93]**	

** significant at the 95% confidence interval

° Nearly significant, but variance not sufficiently equal. Non parametric test (Kruskall-Wallis) also showed a nearly significant result: $\chi^2=2.99$; $df=1$; $p=0.084$

Next to the crashes, also an analysis on the level of casualties was executed. Table 3 shows the mean number of injured road user per year per location, both for the research group and for the comparison group, that consist of all injured people in road crashes in Flanders. Column 7 shows the relative change, which is the odds ratio of the change in crashes from the before to after period in the research group with the change in crashes from the before to after period in the comparison group. These results show only for cyclists a result lower than one, which indicates a higher decrease in the research group compared to the comparison group. For all other road users (car occupants, moped riders, motorcyclists, pedestrians), the relative change was close to, however slightly higher than one. The number of injured truck drivers was too low to make any analyses.

TABLE 3 Mean Number of Injured per Year per Location, Before and After the Installation of a SRLC, Subdivided to Type of Road User

Type of road user	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
	Mean number of injured road users per year per location						Relative change
	Research group			Comparison group			
	before	after	% difference	before	after	% difference	
Car occupants	2.37	2.00	-16	11577.81	9602.86	-17	1.02
Moped riders	0.33	0.27	-18	2313.05	1766.19	-24	1.08
Cyclists	0.40	0.36	-9	2284.70	2659.22	+16	0.78
Motorcyclists	0.14	0.14	+7	1062.51	1065.20	+0.003	1.07
Pedestrians	0.09	0.11	+23	701.59	831.02	+18	1.04

DISCUSSION

In line with research concerning red light cameras, the installation of combined speed and red light cameras led to a clear increase in rear-end, and a non-significant decrease in the number of side crashes with injured. In addition to this, current research examined the effect on fatal and serious injury crashes, for which an overall decrease of 14-18% was found. This was mainly due to a decrease in side crashes with serious injuries and fatalities. Furthermore it was clearly shown that rear-end crashes mainly lead to less severe crashes, as almost no severe rear-end crashes occurred. Analyses that examined the effect of the installation of SRLC together with other measures, for example change in maximum speed limit or resurface of the road, showed the overall effect on injury crashes is higher, compared to the isolated effect of the installation of SRLC.

A distinction according to the characteristics of the intersection showed locations with a median have a stronger effect on the number of side collisions compared to locations without a median, for which the difference was nearly significant. A possible explanation is that roads with a median have a higher traffic volume and consequently more crosswise movements. The installation of a SRLC can influence these movements, and subsequently all possible crashes that occur due to these movements. Another possible explanation is the presence of a median creates an illusion of continuity and protection, which can lead to less attention of drivers for possible conflicts with transverse traffic, and subsequently to more red light running and excessive speed. Both offences can be handled through the installation of SRLCs. However, next to these possible explanations, also an omitted variable bias could have occurred. Possibly the presence of a median correlates with other unknown variables, such as traffic volume and infrastructural characteristics, which are not taken into account in current analyses.

Furthermore also differences were found according to the presence of other SRLC equipped intersections in the vicinity of the research location. Where one would expect a spill-over effect when different SRLC equipped intersections are near to each other, the analyses showed the opposite, and found the decrease of side collisions was more limited when other intersection with SRLC were nearby. This is a remarkable result and possibly other factors could have had an effect, such as type of road, traffic volume and type of road users. A comparison of locations that have two or more SRLC equipped intersections in the vicinity, further mentioned as clustered SRLCs, with locations that have only one or no other neighboring intersections with SRLC, showed a significant difference in the number of lanes ($\chi^2=11.415$; $df=1$, $p=0.001$). For clustered locations comparatively more intersections with two lanes (80%) than one lane are present, compared with single locations, where 59% of the locations have two lanes. Also a significant difference was found according to the maximum speed limit ($\chi^2=11.125$; $df=2$; $p=0.011$), with clustered locations generally have a lower speed limit (50 and 70 km/h), whereas more single locations have a higher speed limit (90km/h). Next to this, significant differences were found according to localization inside or outside urban area ($\chi^2= 25.083$; $df=1$; $p<0.001$), with 46% of the clustered locations are located outside the urban area compared to 76% of the single locations. Also this could have had an important effect, as analyses showed locations outside the urban area have a significantly higher effect on side collisions compared to locations inside the urban area.

Next to a more limited effect on side crashes at locations inside urban areas, also a higher increase in the number of rear-end crashes was found in urban areas, compared to rural areas. An analysis of all crashes, without a distinction according to type of crash, also found a significant difference ($F=14.376$; $df=1$; $p<0.001$), with a more favorable traffic safety effect for locations outside the urban area. Outside urban areas the crashes decreased non-significantly with 6%, whereas inside urban areas this number significantly increased with 27%. The possible reason of this result should be examined more profoundly through future research, however it can be expected that the traffic flow is a possible cause.

At the level of casualties, only for cyclists a decrease was found, whereas for the other road users (car occupants, moped riders, motor cyclists, pedestrians) the analyses showed no clear difference in the number of injured. A possible explanation can be found in the distinction between side and rear-end collisions. The increasing number of rear-end collisions will logically only appear between drivers of a motorized vehicle, which can explain why for these types of road users generally an increase was found in the number of injured.

One of the restrictions of this study is that it was not possible to analyze whether the decrease in side collisions was mainly due to a decrease in red light running or to a restriction of driven speed. Current research shows results which are in line with previous studies that evaluated the sole effect of red light cameras on red light running. However, future research could help to get more detailed information about which behavioral indicators are affected to which extent by the installation of SRLCs. A detailed analysis can not only give more information about excessive speed and red light running, but can also make a distinction between two types of side collisions that occur as a consequence of red light running, that is right-angle and left-turn crashes.

Another restriction is that there were no data concerning the frequency and duration of operation of the cameras. It was not possible to study the relationship between the intensity of use and the effectiveness. A more profound research of this relationship could be interesting. For example road users could be asked how high they think the chance is they are controlled when passing an intersection with a SRLC, and to what extent this differs according to the location.

The comparison group includes all crashes in Flanders, which as a consequence also includes the crashes that occurred at the research locations. This could lead to an underestimation of the effect, as the trend effect will partially be influenced by the installation of the cameras. However the selected crashes at SRLC's consist on average of 3.06% of all crashes in Flanders, which will have a limited effect on the general trend and subsequently on the result.

In line with studies that mainly examined the effect of red light cameras (1), this study found a remarkable significant increase of 44% in the number of rear-end crashes. Though these bring about less severe consequences (17), future research can help to develop measures, in order to tackle this unintended effect. E.g. measures could be assessed that are intended to harmonize drivers behavior at intersections in a way that avoids rear-end crashes. Elements that could play a role in explaining the effects on rear-end crashes are driven speed before the collision and the phase of the traffic light at the moment of the collision. The hypothesis is that most rear-end collisions occur at orange phase, and it causes vehicles to brake abruptly and unexpectedly. Also an analysis of the psychological processes that play a role in the behavior of road users at the moment they are subjected to unmanned camera surveillance, could give more information. Furthermore it could be examined to what extent also the analysis of the speed has an influence on the occurrence of rear-end crashes.

CONCLUSIONS

- (1) The installation of SRLCs brought about a slight increase of 5-9% in the number of injury crashes. For the number of fatal and serious injury crashes, a decrease of 14-18% was found.
- (2) The increase found for the injury crashes can mainly be attributed to an increase in the number of rear-end crashes (44%), whereas the decrease in the severe crashes is largely the consequence of a decrease in the severe side crashes (24%).
- (3) SRLC outside the urban area showed a higher effect compared to inside the urban area. Outside the urban area a significant decrease of 18% in the number of side collisions was found, in contrary to a non-significant change inside urban areas. Furthermore the increase in the number of rear-end crashes was more limited at intersections outside the urban area (+33%) compared to inside (+70%).

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