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Red light cameras revisited. Recent evidence on red light camera safety effects

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ABSTRACT

The aim of this paper is to update the most recent published evidence on road safety estimates of recent red light camera (RLC) and speed/red light camera studies (SRLC).

A literature search was carried out on RLC studies in the period 2013–2017 which, after screening, identified 18 recent studies on red light cameras (RLCs) and speed/red light cameras (SRLCs). The methodology and results of these studies were further examined and summary safety estimates were derived and compared to earlier meta-analysis summary estimates.

The primary conclusion is that the new safety estimates from this paper show a 12% decrease of total crashes and confirm the general tendency of RLCs to reduce right angle crashes while at the same time increasing rear-end crashes. However, comparing the developments over time, the review reveals that safety estimates tend to increase with time (the safety effects of the most recent studies are the greatest). Also safety estimates suggest more positive effects with SRLCs than with RLCs. Most of recent studies indicate that spillover effects are present and can be quite substantial.

1. Introduction

Red light running is a worldwide road safety problem and is associated with very serious, high injury crashes. In the USA alone 811 people were killed in crashes that involved red light running in 2016 and a further 137,000 persons were estimated to have been injured (IIHS, 2018a, 2018b). In London, UK, 19% of all crashes occur at signal-controlled intersections, and to address red light running related- safety problems, red light cameras were installed at 300 of these intersections (Kennedy and Sexton, 2009). In the city of Christchurch, New Zealand, red light running accounted for 35% of all injury crashes at signalised intersections (Koorey et al., 2017).

In a Dutch study using crash and exposure data at 50 km/h signalised intersections, it was estimated that red light running by road users (drivers, cyclists or pedestrians) was associated with an increased crash risk of 10 to 15 times higher than when complying to red lights (Aarts et al., 2016).

Studies into red light violation rates show that the rate per 1000 vehicles varies between 1.3 and 5.3 in the USA and Australia (Attawi, 2014). Similar European figures are not available. Although this paper focuses on red light cameras which are intended to influence red light running by car drivers, the red light running problem is not restricted to car drivers. For cyclists and pedestrians, high rates of red light running have been observed in different large-size cities worldwide (cyclists: Pai and Jou, 2014; Richardson and Caulfield, 2015; pedestrians: Dommes et al., 2015; Rosenbloom, 2009).

Red light cameras (RLCs) are one of several possible countermeasures against red light violations. Other measures include improved signal timings, transverse rumble strips, advance warning signing (McGee et al., 2003). In terms of behavioural effects, RLCs have demonstrated to have a strong and immediate effect on red light running behaviour. Studies on the effects of RLCs on red light running indicate that the installation of RLCs reduces red light running (Chin & Hague, 2012; Chai et al., 2015; McCartt and Hu, 2013; Polders et al., 2015a,b), whereas the removal of RLCs increases red light running (Porter et al., 2013). In several simulation and observational studies indications were found as to the extent that red light running violations led to increased traffic conflict situations (Chai et al., 2015; Polders et al., 2015a,b; Chin and Haque, 2012).

Recently two meta-analyses have been carried out to assess the effectiveness of RLCs in term of crash reduction. The first was conducted by Høye (2013) and is an update of work done by Erke (2009) and the second a meta-analysis by Perkins et al. (2017). The Høye analysis revealed that the placement of RLCs caused a non-significant increase of

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6% for all crashes, a non-significant decrease of 13% for injury crashes, a significant decrease of 33% for right-angle injury crashes and a significant increase of 39% for rear-end crashes.

For total crash numbers, the Perkins et al. meta-analysis indicates somewhat more favourable safety estimates than Høye (all crashes: −2% (NS) versus +6% (NS); right angle crashes −24% (Sign.) vs. −13% (NS); rear-end crashes: +19% (Sign.) versus +39% (Sign.); red light running crashes: −47% (NS) vs. -7% (NS)). Injury crashes estimates were not comparable since Høye excluded fatal crashes and Perkins included them.

These two meta-analyses cast some doubt on the extent to which red light cameras are effective in improving overall safety. Although RLCs have been found to reduce right angle crashes, they have at the same time been found to increase rear-end crashes. Also, the meta-analyses are far from conclusive about the evidence on spillover effect of RLCs. Spillover effects have been defined as the effects of RLCs on behaviour and safety at non-camera equipped intersections in the same area (Retting et al., 2003; Shin and Washington, 2007). Høye (2013) reported weak overall evidence for spillover effects and Perkins et al. (2017) conclude that results on spillover are inconsistent.

This paper aims to update the evidence on the safety effectiveness of RLCs by reviewing 18 recent RLC studies which were not included in earlier meta-analyses by Erke (2009) and Høye (2013), and of which 6 were included in Perkins et al. (2017). It focuses on answering the following questions:

- How do (summary) safety estimates of recent studies compare to earlier summary estimates?
- What do estimates of spillover from recent studies indicate about the strength or consistency of this effect?
- How do safety estimates in recent studies depend on intersection characteristics?

2. Method

A literature study was done to obtain recent RLC studies and after review pooled estimates of safety effects were generated.

As part of the SafetyCube reviewing process on road safety measures (Aigner-Breuss et al., 2017), the literature on RLCs was searched for in the international database Scopus on 16 December 2016 to identify studies that appeared after Høye (2013) and which included estimates of crash reduction. In view of this, the literature was searched over the period 2012–2016 (Goldenbeld, 2017). The literature review and subsequent coding of basic study features and results was part of the European road safety project SafetyCube (Filtness et al., 2016). The search for RLC studies used the following combination of key words: TITLE-ABS-KEY ("red light camera" AND (safety OR crash OR accident)) AND PUBYEAR > 2011. SafetyCube used a two stage process to select papers, firstly the abstracts, and reference lists of 30 hits were screened for potential relevance, and 13 crash studies were retained for detailed review. This was completed in 2016 and the studies were coded and integrated into the SafetyCube Decision Support System (DSS). For the purpose of this paper, the SafetyCube search was updated in February 2018. The updated search resulted in the identification of 8 additional studies, 6 of which were published in 2017. This meant that a total of 21 recent studies published between 2013 and 2017 were selected to be included in this review of RLC safety effects. None of these studies were included in the Høye meta-analysis (2013) and 6 had been included in the Perkins et al. review (2017).

In order to obtain pooled estimates of safety effects of recent studies, a limited meta-analysis was deployed using a JASP open source statistics program. Percentage changes in crashes were expressed as odds ratios. A random effects model was applied to log odds ratios and corresponding confidence intervals. Log odds results were recalculated to odds ratios in order to facilitate understanding.

Only studies with similar camera enforcement strategies (red light camera or speed/red light camera), with similar methodology in terms of deriving the estimates (Empirical Bayes) and with similar crash type outcomes were included. Furthermore the studies had to be methodologically sound and include the correct statistical information to facilitate analysis. Based on this 3 studies were excluded from the meta-analysis (summary estimates), Wong (2014) because of confounding camera operations with changes in signal timings and deficient enforcement procedures, Vanlaar et al. (2014) because of inconsistent results, and Lee et al. (2016) because of insufficient reported information and also possible implementation issues. Care was taken to identify studies with possible overlap (interdependence) in data. Several studies were identified that contained possible overlap: for Florida: Ahmed and Abdel-Aty (2015) and Wang et al. (2015); for Chicago: Mahmassani et al. (2017) and Lord and Geedipally (2014); for Texas, Ko et al. (2012, and 2017). In cases with possible overlap only one study was chosen (the more comprehensive one).

3. Results

3.1. Study characteristics

Table 1 describes the main characteristics of the 18 recent studies reporting on RLC safety effects. This summary compares the studies and shows the analysis method, types of crashes being studied, whether they control for regression-to-the mean and whether estimates are derived for spillover effects. None of the 18 recent studies were included in an earlier Erke (2009) or Høye (2013) meta-analysis, and 6 (AECOM, 2014; Ahmed and Abdel-Aty, 2015; Llau et al., 2015; Ko et al., 2013; Pulugurtha and Otturu, 2014) were included in the Perkins et al. review (2014).

The main methodology for estimating the safety effects of red light cameras was a before-after Empirical Bayes (EB) method with a reference (or control) group, with 14 of 18 the selected studies using this method. The actual number of crashes after the implementation of a measure are compared to the number of crashes that would be expected in the absence of treatment, based on the number of crashes prior to implementing the measure and correcting for various static and dynamic site characteristics that are associated with crash occurrence (Hauer, 1997). There is evidence that the regression-to-the mean effects can be quite substantial in road safety research and that the EB method is a very effective tool for accounting for this effect (Persaud and Lyon, 2007).

3.2. Estimates of crash effects

3.2.1. General safety effects following the introduction of RLC

The overall crash effects reported by the 18 selected studies is shown in Table 2. Looking at effects on total crash numbers, favourable safety estimates are found in three Canadian studies (Abdulsalam et al., 2016; AECOM, 2014; Contini and El-Basyouny, 2016) ranging from eight to twentyfive percent reduction of crashes. The USA studies show more varied safety estimates, with favourable safety estimates ranging from thirteen to thirtyfour percent crash reduction in three studies (Maina et al., 2016; Schattler et al., 2017) and unfavourable estimates ranging from one to seventeen percent increase in crashes in three other studies (Claros et al., 2017; Pulugurtha & Otturu, 2014; Wong, 2014). A study in South Korea shows a large negatieve effect with a fifty-one percent increase in crashes (Lee et al., 2016). The USA-based studies in general confirm that RLCs reduce right angle crashes but at the same time increase rear-end crashes and other types of crashes, complicating the estimate of the net safety effect (Ahmed and Abdel-Aty, 2015; Claros et al., 2016; Lord and Geedipally, 2014; Pulugurtha and Otturu, 2014; Wong, 2014). One European study (De Pauw et al., 2014) and two Canadian studies (AECOM, 2014; Abdulsalam et al., 2016) also confirmed this pattern: a significant increase in rear-end crashes combined with significant decrease in severe side crashes (De Pauw et al.,

Table 1
Study characteristics of red light camera and speed/red light camera studies.

First author, year, location	Method	Treat-ment	Time period	Number intersections		Crash types in study	Control RTM	Estimate spillover
				RLC	Refe-rence			
USA studies								
Ahmed, 2015, Florida	Before-after EB	RLC	2006-2008 vs. 2009-2011	25	50	LT/RA/RE crashes	Yes	Yes
Claros et al., 2016, Missouri	Before-after EB	RLC	2007-2011	24	35	All/RA/LT for levels fatal/fat + injury/PDO	Yes	No
Hu, 2017, USA states	Poisson regression	RLC	1992-2014	N.R.	N.R.	Fatal crashes	No	No
Ko, 2013, Texas	Before-after EB	RLC	2007-2010	254	66	RLR cr. All/RE/RA	Yes	No
Ko, 2017, Texas	Before-after EB	RLC	2007-2010	48	66	RLR cr. All/RE/RA	Yes	Yes
Llau, 2015, Florida	Before-after EB	RLC	2008-2010 vs. 2011-2012	20	40	All injury/RLR injury/ RE/RA-Turn	Yes	No
Lord, 2014, Chicago	Before-after EB	RLC	2005-2007 vs. 2010-2012	90	59	KABC-all/-RE/-RA-Turning/KABC-Other	Yes	No
Mahmassani, 2017, Chicago	Before-after EB	RLC	2005-2007 vs. 2010-2012	85	103	KABC crashes	Yes	Yes
Maina, 2016, Virginia Beach	Before-after EB, CMF	RLC	2008 vs. 2010	13	No	All crashes	Yes	No
Pulugurtha, 2014, Charlotte	Before-after EB	RLC	1997-2010	32	32	LT/RA/RE/SS/RT	Yes	No
Wang, 2015, Florida	Time series, monthly CMFs	RLC	2003-2013	19	95	All/Fat + Injury crashes	No	No
Schattler et al., 2017, Illinois	Before-after EB	RLC	2005-2015	41	No	All, RA-RLR crashes	Yes	No
Jiang, 2017, Illinois[1]	Before-after EB	RLC	2005-2015	41	60	RA, RE crashes	Yes	Yes
Outside USA								
Abdusalam, Canada, 2016,	Propensity score matching	SRLC	1999-2013	30	88	All/RE/RA/TM/Fatal/Non-fatal/PDO	Partial	No
AECOM, 2014, Canada, Alberta,	Before-after EB	SRLC	1995-2008	76	141	All/Severe/RE/ RA/ PDO	Yes	Yes
Contini, 2016, Canada, Edmonton	Before-after EB	SRLC	2006-2013	50	93	All/Severe/RE/RA/PDO	Yes	Partially
Daniels, 2017, Belgium	Cost-benefit analysis	SRLC	2000-2008	–	–	Safety benefit calculated over all severity levels	Not relevant	Not relevant
De Pauw, Belgium, 2014	Before-after EB	SRLC	2000-2008	253	All roads outside	All-injury/all-severe/ RA-injury/RA-severe/RE-injury	No	No

Abbreviations: EB = Empirical Bayes; CMF = Crash Modification Factor; KABC = Killed or Injury level A, B or C; RLC = Red light camera.
SRLC = Speed/red light camera.
Crash types:
HO = Head on; LT = Left turn; NR = Not reported; RA = Right angle; RE = Rear end, RLR = Red light running; RT = Right turn; SS = Sideswipe; TM = Turning movement.
[1]This study only concerns spill-over effect on adjacent intersections; results are described in Section 3.3.

Table 2
Red light camera effect estimates in studies appearing after Høye, 2013 meta-analysis (all estimates statistically significant at $p < 0.05$ unless reported as non-significant (NS).

First author, year, location		Total crashes		Fatal crashes	Right angle (side) crashes		Rear-end crashes		RLR-related crashes		
		All	Injury		All	Injury	All	Injury	All	Injury	Fatal
USA studies											
Ahmed, 2015 Florida	Target A.	–	–	–	−24,1%[a]	−25,8%[b]	+325%	+408%[b]	–	–	–
	All A.	–	–	–	−15,7%[a]	−13,4%[b]	+174%	+234%[b]	–	–	–
Claros,2017, Missouri		+1,6% NS	−7,4%[b] NS	–	−11,6% NS	−14,5% NS	+16,5%	−10,9% NS	–	–	–
Hu, 2017, USA		–	−14,2%[b]	−14,2%	–	–	–	–	–	–	−21,3%
Ko, 2013, Texas		–	–	–	–	–	–	–	−20%	–	–
Ko, 2017, Texas		–	–	–	–	–	–	–	−37%	–	–
Llau, 2015, Florida	1 yr.	–	−19,1%	–	−3,2%[a]	–	+40,2%	–	–	−24,3%	–
	2 yr.	–	−12,2% NS	–	+13,6%[a]	–	+50,7%	–	–	−17,2%	–
Lord, 2014, Chicago		–	+5% NS	–	–	−15%[a]		+22%	–	–	–
Mahmassani, 2017, Chicago		–	−16%	–	–	−32%[a]		+14% NS		–	–
Pulugurtha, 2014, Charlotte		+1,5%NS	–	–	–	–	–	–	–	–	–
Wang, 2015, Florida		−12,8%	−34,8%[c]	–	–	–	–	–	–	–	–
Wong, 2014, Los Angeles		+17%	+22%	–	+24%[b]	–	+34%	–	−12% NS	–	–
Maina, 2016, Virginia Beach		−15,4%	–	–	–	–	–	–	–	–	–
Schattler et al., 2017, Chicago		−34,4%	–	–	−66,9%[d]	–	–	–	–	–	–
Outside USA											
Abdulsalam, 2016, Canada		−16%	−8%	−72%	−39%	–	+42%	–	–	–	–
AECOM, 2014, Canada		−8,4%	−32,4%[c]	–	−37,7%	–	+7,7%	–	–	–	–
Contini, 2016, Canada		−25,5%	–	–	−33,4%	–	−107%	–	–	–	–
De Pauw, 2014, Belgium		–	−14%[c]	–		−24%[c]	–	+44%	–	–	–
Lee, 2016, South Korea		+50,8%	+52,5%	+2% NS	+31,1%	+33,1%	–	–	–	–	–

[a]angle and turning (Ahmed angle and left turn); b including fatal; c severe; d red light running related.
A. = approaches; NS = not significant at $p < 0.5$.

2014). In contrast, one Canadian study found that speed/red light cameras even tended to reduce rear-end crashes (Contini and El-Basyouny, 2016).

One American study indicated relatively unfavourable safety results of RLCs (Pulugurtha and Otturu, 2014). In exploring their unfavourable safety results, Pulugurtha & Otturu found that RLC enforcement programs were especially not effective in reducing crashes at signalised intersections with high traffic volumes (≥ 40.000 vehicles/day), high annual numbers of rear-end crashes (≥ 20) or high annual numbers of sideswipe crashes (≥ 5).

The study by Hu and Cicchino (2017) uses fatal crashes as the main outcome which is the best outcome indicator for road safety. The study included roughly four times as many cities with RLC programs as an earlier study by Hu et al. (2011) and it used a better method that accounted for trends in fatal crash rates and unemployment rates over time within cities. The study found that the fatal crash rate at signalized intersections was significantly reduced by 14.2% in cities with active cameras programs compared to the rate that would have been expected without cameras. The lower crash rates for RLC-equipped intersections in this study - when applied to all 57 cities, as well as to 22 cities that started and ended camera programs - translated into 1296 lives saved during the years the cameras were operational (IIHS, 2017). Economically, this would translate in a reduction of associated lifetime comprehensive costs (economic and quality-of-life valuations) of about 11,8 billion dollars in the same period (based on applying cost estimates of Blincoe et al., 2015 to the estimated fatality reduction).

Three Canadian studies (Abdulsalam et al., 2016; AECOM, 2014; Contini and El-Basyouny, 2016) tend to show somewhat larger crash reductions for comparable crash categories (injury, right angle, rear-end) than found in the USA studies (Ahmed and Abdel-Aty, 2015; Claros et al., 2016; Lord and Geedipally, 2014; Pulugurtha and Otturu, 2014). An obvious explanatory factor could be that the Canadian studies are concerned with combined speed/red light cameras (SRLCs) that target both speeding and red light violations whereas the USA studies are concerned with cameras that detect only red light violations. Other factors could also play a role.

3.2.2. *Safety effects after deactivation of red light cameras*

Not only are there studies reporting the effect of installing RLCs, there are a number of studies that have focused on effects following the removal/decommissioning of RLCs. In several USA cities or jurisdictions RLC programs have been stopped for legal, political, or financial

Table 3
Estimated safety effect after deactivation of RLC programs.

Study, year, location	Method	Total crashes		RLR-related crashes		
		All	Fatal	All	Fatal	Injury
USA studies (first author, year)						
Hu, 2017, 14 cities analysis (which ended RLC programs in 2010-2014)	Poisson regression modelling	–	+16,1%	–	+30,1%	–
Hu, 2017, 19 cities analysis (which ended RLC programs 2006-2014)	Poisson regression modelling	–	+8,4%	–	+17,9%	–
Ko, 2017, *after deactivation* (RLR crashes)	Before- after EB	–	–	+20%	–	+10%[a]
Pulugurtha, North Carolina, Charlotte, 2014, *after termination cameras*	Before-after EB	−37,5%	–	–	–	–

[a]including fatal.

reasons (Pulugurtha and Otturu, 2014; Hu and Cicchino, 2017; Ko et al., 2017). These results are summarised in Table 3.

A 2014 study in 14 large USA cities (> 200.000 pop.) which had terminated their RLC program, Hu and Cicchino (2017) found that the annual rate of fatal RLR crashes after the cameras were turned off was 30.1% higher than what would have been expected had cameras not been turned off (statistically significant effect). The annual rate of all fatal crashes at signalised intersections in the cities where cameras were turned off was 16.1% higher than what would have been expected with cameras on (statistically significant effect). In a similar analysis by Hu & Cicchino in 19 cities (14 studies that turned off cameras 2010–2014; 5 that turned off cameras in 2005–2008), the annual rates of fatal RLR crashes and all fatal crashes at signalised intersections after cameras were turned off were respectively 17.9% and 8.4% higher than would have been expected had cameras been on (both results not significant).

Ko et al. (2017) estimated that RLC deactivation led to a statistically significant increase of 23% in all right-angle RLR crashes. They further estimated that deactivating the RLC systems would increase all RLR crash types by 20% (also significant). However, the effect on serious injury crashes was markedly less. The safety effect of deactivation was estimated to increase all fatal/injury RLR crashes by 10% (although not statistically significant). The average safety effect of the RLC deactivation on right-angle fatal/injury crashes indicated an increase of 13% (also not significant).

Contrary to the above results which suggest that RLC deactivation increases crashes, Pulugurtha and Otturu (2014) reported that total crashes were reduced after the termination of RLC operations in North Carolina. However, it should be pointed out that this study includes many locations where RLCs were placed at intersections with high proportions of rear-end crashes, conditions not suited to RLC placement.

3.2.3. Pooled summary estimates

The results for the selected studies were used to derive pooled safety effectiveness estimates. Pooled estimates were generated with JASP meta-analysis where effect estimates where entered as log odds ratios. Since red light cameras (RLCs) and speed/red light cameras (SRLCs) are considered different safety treatments, their safety effects were calculated and reported separately.

The estimates were calculated for studies with similar camera types (either RLC or SRLC), similar effect estimates and similar safety outcomes and compared to the results of earlier meta-analyses by Erke (2009); Høye (2013) and Perkins et al. (2017) (Table 4).

In Table 4 statistical significance is indicated by the confidence intervals, with intervals including zero-value indicating a non-significant tendency. The pooled estimates calculated for the most recent studies reviewed in this paper reveal that RLCs tend to reduce total crashes by 12%, total right angle crashes by 24%, and tend to increase rear-end crashes by 32%. The recent estimate for all crashes (−12%) is far different and more favourable from those of earlier reviews by Erke (+15%), Høye (+6%) and Perkins et al. (−2% estimate). In terms of all rear-end crashes all meta-analyses show significant increases with effects ranging from +19 to +43% with pooled estimates from the most recent studies showing a 32% increase. Looking at injury crashes, RLCs tend to reduce right angle injury crashes by 29% and tend to increase rear-end injury crashes by 14%. The latest effect estimates for right angle injury crashes, rear-end crashes, and rear-end injury crashes are similar to those of Høye (2013). The recent effect estimates for right angle crashes, both injury and all crashes, are similar to those of Perkins et al. (2017).

Comparing the safety estimates among Erke, Høye, and Perkins, the estimates for total crashes, injury crashes right angle crashes, and rear end crashes tend to become more favourable with each more recent review. The most recent estimates indicate a more favourable effect on all crashes (−12%) than estimates from earlier reviews (+15% to −2%), and a safety effect on right angles crashes that is identical to the most recent Perkins (−24%) review and, again, more favourable than the older reviews (−10%, −13%). Also, the current estimate on right angle injury crashes (−29%) is close to those in two earlier reviews (−29%; −33%), and more favourable than the oldest review (-6%). In conclusion, there seems to be a tendency towards more favourable RLC safety estimates when summary estimates include more recent studies.

The summary safety effects estimated for recent studies on SRLCs are even more favourable than for RLCs. SRLCs tend to reduce total crashes by 17%, injury crashes by 25%, right angle crashes by 37%, and rear-end crashes by 2%. The Erke, Høye and Perkins et al. studies do not distinguish between RLCs and SRLCs; so the effect estimates cannot be compared.

3.2.4. Summary

Fig. 1 presents a schematic overview of the main results reported in recent studies and the steps in deriving the revised road safety effects of RLCs and SRLCs presented in this paper.

3.3. Spillover effects

Spillover effect is the effect of a RLC installation on crashes at non-equipped signalised intersections in the surrounding area. Recent American and Canadian studies (Ahmedand Abdel-Aty, 2015; AECOM, 2014; Mahmassani et al., 2017; Contini and El-Basyouny, 2016; Ko et al., 2017; Jiang and Ouyang, 2017) suggest that the spillover effect can be large and should be accounted for in effect studies.

In an analysis spanning 10 years, AECOM (2014) estimated a significant spillover effect of 10,7% reduction in the total number of expected crashes at RLC intersections. However, the researchers could not rule out the possibility that other safety-related interventions (such as engineering improvements, safety campaigns etc.) may have contributed to this crash reduction effect.

In Orange county, Florida, Ahmed and Abdel-Aty (2014) examined the spillover effects on 50 adjacent non-RLC intersections. They found that there was a statistically significant spillover effect for angle and left-turn crashes (respectively −11% and -8% for all and for serious injury crashes) and no effect to an insignificant effect on rear-end crashes (−1% for all crashes and -8% for serious injury crashes). In order to analyse the safety impact of the RLC programme, the researchers also performed a spatial analysis of crashes. They found a notable reduction in the density of right angle and left-turn crashes throughout the county indicating spillover benefits.

In the Chicago city area, Mahmassani et al. (2017) found a 8% reduction in crashes at RLC installations without accounting for spillover effect. Correcting for a maximum spillover effect the overall reduction was estimated in the model to be 10% in the affected area. The estimates for right angle and turn crashes indicated rather large spillover reduction effects: the estimated decrease was 13% excluding any spillover effect, and 32% including a maximum possible spillover effect, and 19% including a corrected spillover effect. However, for rear-end crashes the possible effect of spillover was minimal: the increase of rear-end crashes was estimated to be 13% without the spillover effect, and 14% with either maximum or corrected spillover included.

In another study in the Chicago area, Jiang and Ouyang (2017) concluded that the crashes at adjacent non RLC intersections were reduced significantly, with right angle crashes reduced by 31,7% and rear-end crashes by 26,1%. The researchers attributed this reduction to spill-over, but did not rule out the possibility of other influences (changed traffic or weather conditions).

In a study on activation and deactivation of RLC at 48 intersections in Houston, Ko et al. (2017) examined spillover effects at intersections in the surrounding area. After deactivation of RLC, there were rather surprisingly increases of RLR crashes of 28% for all crash types, 27% for right-angle crashes, and 48% for rear-end crashes. Analysing fatal/injury crashes at nearby non-treated intersections in the period following deactivation of the RLC at treated intersections, the fatal/injury rear-

Table 4
Summary effect estimates recent studies and meta-analyses by Høye (2013) and Perkins et al. (2017). 95% confidence intervals between parentheses.

Crash type	Camera type	Recent studies 2014-2017 Studies included	Recent studies 2014-2017 Summary estimates	Erke, 2009 Studies 1988-2007 Summary estimates	Høye, 2013 Studies 1988-2011 Summary estimates	Perkins et al. 2017 Studies 1988-2015 Summary estimates
Total crashes	RLC	Claros et al., 2016 Lord 2014 Maina 2016 Schattler et al., 2017 Wang 2015	−12% (−26;+3)	+15% (−3;+38)	+6% (−4; +17)	−2% (-9;+7) −1% (-8;+6)[a]
	SRLC	AECOM, 2014 Contini 2016	−17% (−33;+1)	–	–	–
Injury crashes	RLC	–	–	+13% (−10;+43) (fatal not included)	−12% (−27; +5) (fatal not included)	−20% (−32;-5) −18% (−29;-5)[a] (fatal included)
	SRLC	AECOM, 2014 De Pauw 2014	−25% (−41;−5)	–	–	–
Total right angle crashes	RLC	Ahmed and Abdel-Aty, 2015 Claros et al., 2016 Llau 2015 Schattler 2017	−24% (−51;+17)	−10% (−31;+19)	−13% (−27; +3)	−24% (−35; −10)
	SRLC	AECOM, 2014 Contini 2016	−37% (−41; −33)	–	–	–
Right angle injury crashes	RLC	Ahmed 2015 Claros 2016 Mahmassani 2017	−29% (−36; −21)	−6% (−24;+16)	−33% (−48; −12)	−29% (−42; −14)
	SRLC	–	–	–	–	–
Total rear end crashes	RLC	Ahmed 2015 Claros 2016 Llau 2015	+32% (+14;+53)	+43% (+20;+70)	+39% (+20; +60)	+19% (+9;+31)
	SRLC	AECOM, 2014 Contini 2016	−2% (−19;+18)	–	–	–
Rear-end injury crashes	RLC	Ahmed 2015 Claros 2016 Mahmassani 2017	+14% (−11;+46)	+15% (−2;+36)	+19% (+3; +39)	−1% (−20;+23)
	SRLC	–	–	–	–	–

[a]Imputed CL = extra effects estimated by including studies with imputed confidence levels.

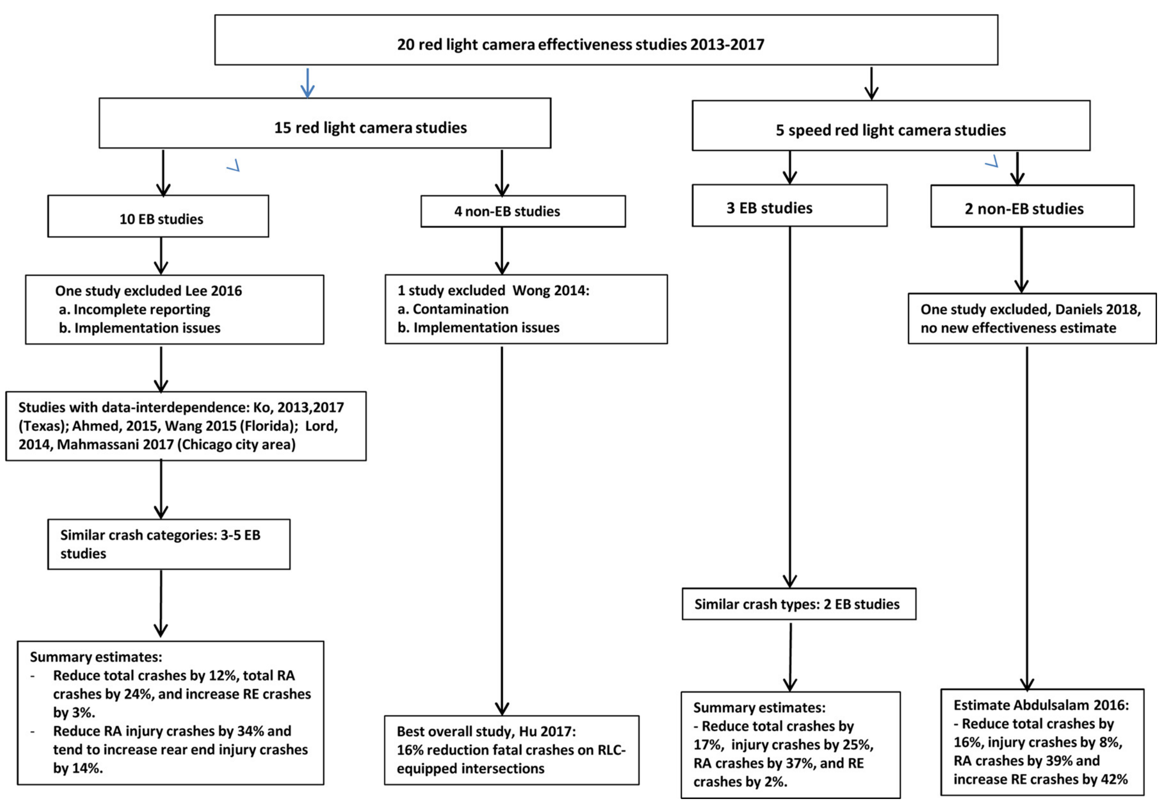

Fig. 1. Overview of steps in study selection, and summary estimates of studies.

end crashes decreased by 44%. However, all-severity rear-end crashes went up by 48% at the same intersections.

In a study on speed/red light cameras in Edmonton, Contini and El-Basyouny (2016) looked at spillover from camera-equipped approaches to non-camera equipped approaches at the same intersections. For angle crashes they found evidence for spillover to non-camera approaches: a significant decrease in angle crashes at non-camera approaches (-80% non-signed approaches; −35% signed approaches). In the same study, there was no evidence for spillover for other types of crashes.

Two recent studies report inconclusive or weak evidence for spillover. A study Wong (2014) finds inconclusive evidence for spillover. However, the RLC program studied by Wong suffered from weak judicial follow-up of red light sanctions. In a study in Winnipeg Canada, Vanlaar et al. (2014) also found little evidence for spillover. The only finding suggestive of spillover was that rear-end crashes tended to increase at non-camera intersections (25% increase at $p = 0.051$), an example of a negative spillover. The analyses showed that other intersections without cameras in Winnipeg did not experience a comparable significant decrease in right-angle crashes, nor did they experience an increase in rear-end crashes. However, in general the crash results of this study were not consistent.

In conclusion, of 8 recent studies that report on spillover effects, 2 indicated inconclusive or weak evidence for spillover, and 6 indicate significantly positive spillover effects (i.e. reductions in crashes at non-camera equipped intersections or approaches after installing RLCs, or).

3.4. Intersection characteristics

The geometric and traffic characteristics of signalised intersections may significantly impact on the efficacy of RLCs. This section provides the results of studies that have reported specifically these impacts and effects.

Pulugurtha and Otturu (2014) analysed RLC camera data from thirty-two signalised intersections in the city of Charlotte, North Carolina. They estimated that the road safety benefits/crash reduction of RLCs were higher if cameras were deployed at signalised intersections with ADTs below 40,000 vehicles, with fewer than 20 rear-end crashes per year or with fewer than 5 sideswipe crashes per year.

A relationship between RLC safety benefits and crash characteristics of intersections is also suggested by Ko et al. (2013), (2017). In two separate studies in Houston, Texas, Ko et al. found higher safety benefits in the second study when compared to the first (37% vs. 20% reduction of RLR crashes). There were about 2 more RLR crashes per 10,000 vehicles per year at the intersections in Houston than the ones used in Ko et al. (2013). As a result, according to the authors, the RLC installation at the intersections with greater RLR crash rates led to more safety benefits than might be expected from the earlier study.

In an analysis of SRLC at 50 intersections in Edmonton, Canada, Contini and El-Basyouny (2016) found that three intersection characteristics had an impact on the safety performance of speed/red light cameras; namely the number of lanes, the presence of a separate right turn lane and the speed limit. Intersections equipped with SRLC and a speed limit of 50 or 60 km/h had larger crash reductions than those with a speed limit of 70 km/h. SRLC- intersections with separate right turn lanes had significant reductions in collisions, while intersections without separate right turn lanes did not. The difference was largest for right angle crashes which showed a 50% reduction in crashes at intersections with separated right turn lanes. Intersections which did not have separate right turn lanes showed a small non-significant increase. However, the presence of a separate right turn lane was not positive for rear-end crashes; the crash reductions were larger at intersections that did not have right turn separation (26% vs 13%). Regarding the intersection size, the study found that SRLC-intersections with 5–7 approach lanes had greater collisions reduction for almost all collision types. Again the difference was greatest for right angle crashes which showed a 54% decrease in crashes at large (4+ lanes) intersections compared to a 28% decrease at smaller intersections (< 4 lanes).

In the Chicago area, Mahmassani et al. (2017) studied the relationship between intersection characteristics and safety benefits of RLCs. The model results suggest that RLC installation was most effective at intersections with high number of right angle and turn crashes per AADT. Locations with long cycle lengths or high number of lanes were more likely to show safety benefits. The model results suggest that it even would be counterproductive to install cameras at locations that have a history of high numbers of rear-end crashes. Also, locations with high crossing traffic volumes, a 2 s all red period (instead of 1 s) or with left turn bays were not recommended for camera installation since these locations were already relatively safe and RLCs would have lower impact.

4. Discussion

The results of recent RLC studies, published between 2013–2017, most of which were not included in the meta-analyses by Høye (2013) and Perkins et al. (2017), indicate that RLCs are associated with a 12% decrease in crashes and they confirm the general trend that RLCs reduce right angle crashes but simultaneously tend to increase rear-end crashes. A pooled estimate of all the most recent studies reveals that RLCs tend to reduce total right angle crashes by 24%, right angle injury crashes by 29% and tend to increase rear-end crashes by 3% and rear-end injury crashes by 14%. The reduction figures for right angle injury crashes, rear-end crashes, and rear-end injury crashes are quite similar to those of Høye (2013). The reduction estimate for right angle crashes is similar to that of Perkins et al. (2017) and more favourable than those by Erke (2009) or Høye (2013). The estimated safety effect for total crashes, a reduction by 12%, tends to be more favourable than earlier estimates by Erke, Høye or Perkins et al. The contrast in safety estimates between our estimates - mostly covering accident data 2005–2015 - and the initial Erke review which mostly covered accident data before 2005, is substantial.

The finding that RLC safety estimates in subsequent reviews tend to become more favourable may be related to two sorts of factors: firstly factors that are related to some variations across studies in terms of methods or studied samples (e.g. included jurisdictions and differences in intersection populations). However, part of the explanation may also be that RLC programs in the past decade may have performed better than in earlier decades. This seems plausible on account of two developments. First, the new generation of digital red light camera systems in the last decade has higher capacity, reliability, and precision than the old wet-film systems in previous decades improving the processing time and the fast issuance of tickets (e.g. DoT New York City, 2009). Second, the various experiences with the implementation of RLC camera systems has led to the identification of various strengths and weaknesses in RLC camera programs (e.g. California State Auditor, 2002; Solomon et al., 2014), and to the dissemination of further knowledge and of guidelines (e.g. Eccles et al., 2012; McGee and Eccles, 2005; FHWA, 2005). In an optimistic vein, one could argue that the possible weaknesses of the first series of RLC programs may have been avoided in latter RLC programs.

In this paper the effects of red light cameras (RLC) and speed/red light cameras (SRLCs) have been separated since these are two clearly different measures with the speed option likely to have a larger effect because of the dual role for enforcement. The results confirm this showing SRLCs to have more positive effects by reducing total crashes by 17%, injury crashes by 25%, right angle crashes by 37%, and rear-end crashes by 2%. Recent Canadian studies (Abdulsalam et al., 2016; AECOM, 2014; Contini and El-Basyouny, 2016) into SRLC effects tend to show somewhat larger safety benefits than the USA studies. Basically, the safety effects of SRLCs may be better than RLCs because speeding itself may be a key factor in the red light running problem. However, certainly other factors may also play a role. There have been some indications from the studied research that proper implementation of RLC programs in USA can be difficult. Problems that may have limited the impact include deficient prosecution of red light violations (Wong, 2014), intersection layout, prevailing crash rates (Pulugurtha and Otturu, 2014)) and improper settings of signal timing (Yang et al., 2013).

Deriving a net safety effect from RLC deployment is complicated since they generally have a positive impact on right angle crashes but a negative impact on rear-end crashes. There is clear evidence that rear-end crashes are associated with less severe injury than right-angle crashes (Council et al., 2005; Tay and Rifaat, 2010; Polders et al., 2015a,b; Ye et al., 2008). Even though RLCs may increase rear-end crashes, the net safety effect is likely to be positive. For example, Shin and Washington (2007) estimated that the RLCs at 14 intersections in Scottsdale generated favourable crash benefits on all intersection approaches (836,000 USD) and on camera-equipped target approaches (684,000 USD), despite an estimated significant increase of 41% in rear-end crashes at those intersections.

Of course an increase of rear-end crashes should not be simply accepted as a collateral damage of RLCs. The negative effects on rear-end crashes should be avoided. Intersections with high rates of rear-end crashes should not be selected for camera instalment. Furthermore, rear-end crashes should be mitigated by introducing reductions in intersection approach speed, making cameras highly conspicuous, posting advance warning signs, and/or optimising signal phasing.

Many recent studies were unable to provide an estimate of the safety effect of RLC on fatal and/or serious injuries. Often fatal or severe injury crashes at intersections represent relatively low numbers and do not provide enough statistical power for separate analysis. As an exception to this was the study by Hu and Cicchino (2017) which combined data from several USA cities and has used fatal crashes as main outcome. It is perhaps the most convincing recent demonstration that, at least in large cities, RLC programs tend to have a strong overall net safety effect, with an overall estimate of nearly 1300 lives saved in 79 cities during the period of red light camera enforcement. By providing evidence that RLC programs both decreased fatal crashes after RL programs were activated and increased fatal crashes after termination, the study provides consistent evidence that the RLC-programme may well be the main causative mechanism and not some unobserved other factor.

For Europe, a favourable net safety effect is suggested by a recent benefit-to-cost ratio of 3.7 for RLC suggesting that economic benefits will be almost fourfold the costs within a span of 10 years of time (Daniels et al., 2017).

5. Study limitations and future research needs

The present study has some limitations. First, although we paid attention to earlier meta-analyses, earlier RLC studies (studies before 2013) were not separately studied or used in pooled effect estimates. Second, due to study difference in crash definitions and effect estimates, the results of only a limited number of recent studies could be aggregated to obtain (meta-analytic) pooled summary estimates of safety effects. Third, the pooled estimates were not corrected for possible biases, such as publication bias.

High quality research into RLC or SRLC effectiveness can help to improve camera operations and to support further public funding of this measure. When a controlled randomised trial is not possible the Empirical Bayes method is likely the best available method to study effectiveness. Care should be taken that this method is soundly applied (e.g. Persaud et al., 2007). One specific concern is that the EB method is still vulnerable to bias from site selection when an entry criterion is used and when the characteristics of the treatment and control groups are dissimilar (Lord and Geedipally, 2014; Kuo and Lord, 2013; Lord and Kuo, 2012). Another concern is that in American RLC studies the development of local SPFs do not follow general AASHTO guidelines (Claros et al., 2017), which require SPFs based on data from 100 to 200 intersections with similar geometry, operations, and safety-related traits; the total group of intersections requires at least 300 crashes per year and preferably more than 3 years of crash data. To our knowledge, Claros et al. (2016) is the (only) USA study that has used calibrated SPF from the Highway Safety Manual.

One aspect of study quality is whether studies control for spillover. Although the Høye meta-analysis has not found strong spillover effects, 6 recent USA/Canada-studies indicate that spillover effects do occur and can be substantial (AECOM, 2014; Ahmed and Abdel-Aty, 2015; Contini and El-Basyouny, 2016; Ko et al., 2017; Mahmassani et al., 2017; Jiang and Ouyang, 2017). More research is needed to exactly determine the nature and size of spillover effects as the literature is not yet conclusive.

Future studies into the safety effect of RLC should report the true public health impacts by distinguishing injury types and specifying fatalities and/or seriously injured. Where possible, future studies should elaborate the complex interrelationships between intersection characteristics (design, traffic volume, signal phasing), violation behaviours (red light running related to speeding, to smart phone use, platooning etc.), adjudication of violations, and crash development, so that further (local) guidelines or advice for successful implementation can be suggested. An example of such research is illustrated in a paper by Mahmassani et al. (2017) where a detailed analysis enabled the development of a comprehensive remedial strategy.

6. Final conclusions

- Recent summary estimates indicate that RLCs tend to reduce total crashes by 12%, total right angle crashes by 24%, right angle injury crashes by 29%, and tend to increase rear-end crashes by 32% and rear-end injury crashes by 14%. These results confirm the tendency of RLCs to reduce right angle crashes while at the same time increasing rear-end crashes.
- Over time, the estimated safety results of RLCs have tended to become more favourable. This evolution may have several causes, some of which may be related to improved knowledge and routines for red light camera systems management.
- The safety estimates of speed/red light camera studies tended to be more favourable than those of red light camera studies. SRLCs tend to reduce total crashes by 17%, injury crashes by 25%, right angle crashes by 37%, and rear-end crashes by 2%.
- Although earlier meta-analyses have not found strong or consistent support for spill-over effects, 6 of 8 recent USA/Canada-studies indicated that spillover effect do occur and can be quite substantial.
- Further research is needed to understand why cameras in different settings produce different results and on how the apparent increase in rear-end crashes can be mitigated.

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References

Aarts, L.T., Loenis, B.J.C., Dijkstra, A., Deden, N.Y., Noorloos, R., 2016. Risicofactoren nader onderzocht: 50km/uur-kruispunten. Report 2016-17. Institute for Road Safety Research SWOV, The Hague.

Abdulsalam, A.J., Easa, S., Rowlands, D., Halim, A.E., El, Abd, Halim, A.O., 2016. Framework for safety and economic evaluation of red-light cameras at signalized intersections: application of propensity score matching method. Int. J. Civil Environ. Sci. 1, 1–9.

AECOM, 2014. Intersection Safety Device Program – Red-light Camera Analysis. AECOM, Markham, Ontario.
Ahmed, M.M., Abdel-Aty, M., 2015. Evaluation and spatial analysis of automated red-light running enforcement cameras. Transp. Res. Part C 50, 130–140.
Aigner-Breuss, E., Kaiser, S., Usami, D.S., Reed, S., Weijermars, W., 2017. Inventory of Road User Related Risk Factors and Safety Measures, Deliverable 4.4 of the H2020 Project SafetyCube. IFSTTAR, Paris.
Attawi, A.M., 2014. Characteristics of red light running violations in urban areas in Tabuk, Kingdom of Saudi Arabia. IATSS Res. 37, 119–123.
Blincoe, L.J., Miller, T.R., Zaloshnja, E., Lawrence, B.A., 2015. The Economic and Societal Impact of Motor Vehicle Crashes, 2010. (Revised) (Report No. DOT HS 812 013). National Highway Traffic Safety Administration, Washington, DC.
California State Auditor, 2002. Red Light Camera Programs: Although They Have Contributed to a Reduction in Accidents, Operational Weaknesses Exist at the Local Level. California State Auditor, Sacramento.
Chai, C., Wong, Y.D., Lum, K.M., 2015. Safety impacts of red light cameras at signalized intersections based on cellular automata models. Traffic Inj. Prev. 16, 374–379.
Chin, H.C., Haque, Md.M., 2012. Effectiveness of red light cameras on the right-angle crash involvement of motorcycles. J. Adv. Transp. 46, 54–66.
Claros, B., Sun, C., Edara, P., 2017. Safety effectiveness and crash cost benefit of red light cameras in Missouri. Traffic Inj. Prev. 18, 70–76.
Contini, L., El-Basyouny, K., 2016. Lesson learned from the application of intersection safety devices in Edmonton. Accid. Anal. Prev. 94, 127–134.
Council, F.M., Persaud, B.N., Eccles, K.A., Lyon, C., Griffith, M.S., Zaloshnja, E., Miller, T., 2005. Implementing red light camera programs: guidance from economic analysis of safety benefits. Transp. Res. Rec. 1922, 38–43.
Daniels, S., Aigner-Breuss, E., Kaiser, S., Goldenbeld, C., Katrakazas, C., Schoeters, A., Ziakopoulos, Usami D.S., Bauer, R., Papadimitriou, E., Weijermars, W., Rodriguez Palmeiro, A., Talbot, R., 2017. Economic Evaluation of Road User Related Measures. Deliverable 4.3 of the H2020 Project SafetyCube. IFSTTAR, Paris.
De Pauw, E., Daniels, S., Brijs, T., Hermans, E., Wets, G., 2014. To brake or to accelerate? Safety effects of combined speed and red light cameras. J. Safety Res. 50, 59–65.
Dommes, A., Granié, M.-A., Cloutier, M.-S., Coquelet, C., Huguenin-Richard, F., 2015. Red light violations by adult pedestrians and other safety-related behaviors at signalized crosswalks. Accid. Anal. Prev. 80, 67–75.
Eccles, K.A., Fiedler, R., Persaud, B., Lyon, C., Hansen, G., 2012. Automated Enforcement for Speeding and Red Light Running. Prepared for National Cooperative Highway Research Program (NCHRP). Transportation Research Board of the National Academies, Washington, D.C.
Erke, A., 2009. Red light for red-light cameras? A meta-analysis of the effects of red-light cameras on crashes. Accid. Anal. Prev. 41, 897–905.
FHWA, 2005. Red Light Camera Systems. Operational Guidelines. The Federal Highway Administration, US Department of Transportation, Washington.
Filtness, A., Thomas, P., Talbot, R., Quigley, C., Papadimitriou, E., Yannis, G., Theofilatos, A., Aigner-Breuss, E., Kaiser, S., Machata, K., Weijermars, W., Van Schagen, I., Hermitte, T., 2016. The Application of Systems Approach for Road Safety Policy Making, Deliverable 8.1 of the H2020 Project SafetyCube. IFFSTAR, Paris.
Goldenbeld, Ch, 2017. Red Light Cameras, European Road Safety Decision Support System, Developed by the H2020 Project SafetyCube. Retrieved from www.roadsafety-dss.eu on 27-03-2018. .
Hauer, E., 1997. Observational Before-After Studies in Road Safety. Pergamon, Oxford, UK.
Høye, A., 2013. Still red light for red light cameras? An update. Accid. Anal. Prev. 55, 77–89.
Hu, W., McCarttt, A.T., Teoh, E.R., 2011. Effectts of red light camera enforcement on fatal crashes in large U. S. cities. Safety Res. 42, 277–282.
Hu, W., Cicchino, J.B., 2017. Effects of turning on and off red light cameras on fatal crashes in large U.S. cities. J. Safety Res. 61, 141–148.
IIHS, 2017. Red light running. Camera Enforcement Works to Curb This Dangerous Behavior. Insurance Institute for Highway Safety, Washington Retrieved March 27th 2018 at: http://www.iihs.org/iihs/topics/t/red-light-running/qanda.
IIHS, 2018a. Turning Off Red Light Cameras Costs Lives, New Research Shows. Retrieved April 4th 2019 at:. IIHS News, July 28. Insurance Institute for Highway Safety, Washington. http://www.iihs.org/iihs/news/desktopnews/turning-off-red-light-cameras-costs-lives-new-research-shows.
IIHS, 2018b. New Guidelines for Automated Enforcement Programs Emphasize Safety Amid Rise in Red-light-running Crash Deaths. Retrieved April 1st 2019 at:. https://www.iihs.org/iihs/news/desktopnews/new-guidelines-for-automated-enforcement-programs-emphasize-safety-amid-rise-in-red-light-running-crash-deaths.
Jiang, Z., Ouyang, Y., 2017. Spill-over Effect and Economic Effect of Red Light Cameras. Research Report No. FHWA-ICT-17-006. Illinois Center for Transportation, Urbana-Champaign.
Kennedy, J., Sexton, B., 2009. Literature Review of Road Safety at Traffic Signals and Signalised Crossings. PPR436. Transport Research Laboratory, Wokingham, UK.
Ko, M., Geedipally, S., Walden, T., 2013. Effectiveness and site selection criteria for red light camera systems. Transp. Res. Rec. 2327, 53–60.
Ko, M., Geedipally, S.R., Walden, T.D., Wunderlicht, R.C., 2017. Effects of red light running camera systems installation and then deactivation on intersection safety. J. Safety Res. 62, 117–126.
Koorey, G., Fowler, M., Wilke, A., Mackie, H., 2017. Factors Influencing Red Light Running – A Christchurch Investigation. Paper Presented at Australasian Transport Research Forum 2017 Proceedings 27–29 November 2017, Auckland, New Zealand. Australasian Transport Research Forum, Auckland.
Kuo, P.-F., Lord, D., 2013. Accounting for site-selection bias in before-after studies for continuous distributions: characteristics and application using speed data. Transp. Res. Part A Policy Pract. 49, 256–269.
Lee, S.H., Lee, Y.D., Do, M., 2016. Analysis on safety impact of red light cameras using the Empirical Bayesian approach. Transp. Lett. 8, 241–249.
Llau, A.F., Ahmed, N.U., Khan, H.M.R.U., Cevallos, F.G., Pekovic, V., 2015. The impact of red light cameras on crashes within Miami–Dade County, Florida. Traffic Inj. Prev. 16, 773–780.
Lord, D., Geedipally, S.R., 2014. . Safety Effects of the Red-Light Camera Enforcement Program in Chicago, Illinois. Research report prepared for the Chicago Tribune, College Station, TX. .
Lord, D., Kuo, P.-F., 2012. Examining the effects of site selection criteria for evaluating the effectiveness of traffic safety improvement countermeasures. Accid. Anal. Prev. 47, 52–63.
Mahmassani, H.S., Schofer, J.L., Johgnson, B.L., Verbas, O., Elfar, A., Mittal, A., Ostojic, M., 2017. Chicago red light enforcement. Best Practices and Program Road Map. Northwestern University. The Transportation Center, Evanston.
Maina, E.V., Ford, A., Robinson, M., 2016. Estimating the safety benefits of red light cameras at signalized intersections in urban areas case study: the City of Virginia beach. Int. J. Transp. Eng. 3, 45–54.
McCartt, A.T., Hu, W., 2013. Effects of Red Light Camera Enforcement on Red Light Violations in Arlington County, Virginia. Insurance Institute for Highway Safety, Arlington.
McGee, H., Eccles, K., 2005. Field Guide for Inspecting Signalized Intersections to Reduce Red-Light Running. Institute of Transportation Engineers, Washington DC.
McGee, H., Eccles, K., Clark, J., Prothe, L., O'Connell, C., 2003. Making Intersections Safer: A Toolbox of Engineering Countermeasures to Reduce Red-Light Running. Institute of Transportation Engineers, Washington DC.
Pai, C.-W., Jou, R.-C., 2014. Cyclists' red-light running behaviours: an examination of risk-taking, opportunistic, and law-obeying behaviours. Accid. Anal. Prev. 62, 191–198.
Perkins, C., Steinbach, R., Edwards, P., Beecher, D., Hess, S., Aeron-Thomas, A., Cohn, E., Kakar, S., 2017. Red Light Enforcement Cameras to Reduce Traffic Violations and Road Traffic Injuries. College of Policing and the Economic and Social Research Council (ESRC), London.
Persaud, B., Lyon, C., 2007. Empirical Bayes before–after safety studies: lessons learned from two decades of experience and future directions. Accid. Anal. Prev. 39, 546–555.
Polders, E., Daniels, S., Hermans, E., Brijs, T., Wets, G., 2015a. Crash patterns at signalized intersections. Transp. Res. Record: J. Transp. Res. Board 2514, 105–116.
Polders, E., Cornu, J., De Ceunynck, T., Daniels, S., Brijs, K., Brijs, T., Hermans, E., Wets, G., 2015b. Drivers' behavioral responses to combined speed and red light cameras. Accid. Anal. Prev. 81, 153–166.
Porter, B.E., Johnson, K.L., Bland, J.F., 2013. Turning off the cameras: red light running characteristics and rates after photo enforcement legislation expired. Accid. Anal. Prev. 50 (1104), 1111.
Pulugurtha, S.S., Otturu, R., 2014. Effectiveness of red light running camera enforcement program in reducing crashes: evaluation using "before the installation", "after the installation", and "after the termination" data. Accid. Anal. Prev. 64, 9–17.
Retting, R.A., Ferguson, S.A., Hakkert, A.S., 2003. Effects of red light cameras on violations and crashes: a review of the international literature. Traffic Inj. Prev. 4, 17–23.
Richardson, M., Caulfield, B., 2015. Investigating traffic light violations by cyclists in Dublin City Centre. Accid. Anal. Prev. 84, 65–73.
Rosenbloom, T., 2009. Crossing at a red light: behaviour of individuals and groups. Transp. Res. Part F 12, 389–394.
Schattler, K., Vadlamudi, N., Riemann, A., 2017. Safety Evaluation of Red Light Running Camera Intersections in Illinois. FHWA-ICT-17-005. Illinois Center for Transportation, Urbana-Champaign.
Shin, K., Washington, S., 2007. The impact of red light cameras on safety in Arizona. Accid. Anal. Prev. 39, 1212–1221.
Solomon, H., Izadpanah, P., Brady, M., Hadayeghi, A., 2014. Montreal, QuebecSo You're Considering a red Light Camera Program? Lessons and Insights from over a Decade of Camera Operation in South and Central Ontario, Paper Prepared for Presentation at the Road Safety Policy Development – Past, Present, Future Session of the 2014 Conference of the Transportation Association of Canada2014. So You're Considering a red Light Camera Program? Lessons and Insights from over a Decade of Camera Operation in South and Central Ontario, Paper Prepared for Presentation at the Road Safety Policy Development – Past, Present, Future Session of the 2014 Conference of the Transportation Association of Canada.
Tay, R., Rifaat, S.M., 2010. Factors contributing to the severity of intersection crashes. J. Adv. Transp. 41, 245–265.
Vanlaar, W., Robertson, R., Marcoux, K., 2014. An evaluation of Winnipeg's photo enforcement safety program: results of time series analyses and an intersection camera experiment. Accid. Anal. Prev. 62, 238–247.
Wang, J.-H., Abdel-Aty, M.A., Park, J., Lee, C., Kuo, P.-F., 2015. Estimating safety performance trends over time for treatments at intersections in Florida. Accid. Anal. Prev. 80, 37–47.
Wong, T., 2014. Lights, camera, legal action! The effectiveness of red light cameras on collisions in Los Angeles. Transp. Res. Part A Policy Pract. 69, 165–182.
Yang, Q., Han, L.D., Cherry, C.R., 2013. Some measures for sustaining red-light camera programs and their negative impacts. Transp. Policy 29, 192–198.
Ye, X., Pendyala, R.M., Al-Rukaibi, F.S., Konduri, K., 2008. A joint model of accident type and severity for two-vehicle crashes. Paper Presented at 87th Annual Meeting of the Transportation Research Board, Washington, DC.