Effectiveness and Site Selection Criteria for Red Light Camera Systems

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The objective of this paper is to evaluate the safety effectiveness of automated traffic enforcement systems, that is, red light cameras, installed at 254 signalized intersections in 32 jurisdictions in Texas. In addition, criteria for site selection were evaluated to provide analytical resources for camera installation. A before–after study by the empirical Bayesian methodology was performed to remove the regression-to-mean bias during the evaluation of treatments. The results indicate significant decreases in the incidences of all types of red light running (RLR) crashes and right-angle RLR crashes by 20% and 24%, respectively. A significant increase of 37% for rear-end RLR crashes was discovered. The study results suggest that a significant safety benefit for red light cameras is achieved if intersections have four or more RLR crashes per year or have two or more RLR crashes per 10,000 vehicles. Red light cameras show counterproductive results if intersections experience fewer than two RLR crashes per year or have one crash per 10,000 vehicles per year.

Intersections deserve special attention because they provide an important role in the safety and operation of highways. According to NHTSA, approximately 733,000 people were injured at more than 2.3 million reported intersection-related crashes in 2008. It was estimated that 165,000 people were injured by red light running (RLR) at signalized intersections. In Texas in 2008, more than 12,000 crashes occurred because of RLR violations (*1*). To improve intersection safety related to RLR violations, automated photographic traffic signal enforcement systems, also known as red light cameras (RLCs), have been installed at signalized intersections.

A before–after study that uses a naïve, comparison group, or empirical Bayesian (EB) method can be used to evaluate the safety effectiveness of RLC systems. However, naïve and comparison group methods suffer from the limitation of regression-to-the-mean (RTM) bias. This bias exists because the method predicts the number of target crashes expected at the treatment site on the basis of the crash numbers only from during the before period. RTM means that a possible tendency exists for a fluctuating characteristic of the treatment site to return to a typical value during the period after an extraordinary value has been observed (*2*). The EB method can be used to remove the RTM bias during the evaluation of treatments. The EB method estimates the safety benefits at treated sites on the basis of comparison with other reference sites with similar traits.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2327, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 53–60.
DOI: 10.3141/2327-07

The primary objective of this study was to determine RLC system effectiveness at reducing motor vehicle crashes at signal-controlled intersections by use of an EB methodology. The secondary objective of this study was to analyze the criteria used for the selection of intersections for RLC treatment. Treatment intersections are usually selected on the basis of high crash frequencies, high rates of RLR violations, high traffic volumes, or high crash rates. However, these higher values do not always correspond to greater numbers of RLR crashes (*3*). In addition, the researchers of this study are not aware of any study that has documented the evaluation criteria for the selection of sites for RLC treatment.

BACKGROUND

A large amount of previous work has provided meaningful results on the impact of RLC treatment on intersection safety. For instance, Ng et al. reported the results of their evaluation that was conducted at 42 camera-treated and nontreated intersections in Singapore (*4*). Each of the nontreated intersections used for comparison had a configuration similar to that of the treated intersections. The study findings indicated a 7% reduction in all crash types and an 8% reduction in right-angle (RA) crashes after RLC systems were used. Winn evaluated the effectiveness of RLC systems by considering six treatment sites and six nontreatment sites in Glasgow, Scotland (*5*). Crash data were collected for 3 years before treatment and 3 years after treatment. The study results indicated a 62% reduction in injury crashes in association with active RLC treatments.

In Texas, Walden, in his first study, used a naïve before–after study to analyze the effectiveness of RLCs at 56 intersections and concluded that their use resulted in a 30% decrease in crashes of all types and a 43% decrease in RA crashes (*6*). Rear-end (RE) RLR-related crashes increased by 5%. In 2011, Walden et al. evaluated the effectiveness of RLCs at 296 intersections in 39 communities in Texas by the comparison group method and concluded that crashes of all types and RA crashes decreased by 26% and 19%, respectively, although RE crashes increased by 44% (*7*). Even though all the studies cited above concluded that RLC systems are effective in reducing crash frequency, they did not consider either the spillover effect (i.e., the change in drivers' behavior at the intersections without RLCs but near intersections with RLC systems) or the RTM bias in their analyses.

Some studies have controlled for the spillover effect. Retting and Kyrychenko analyzed the effects of RLC systems by considering 29 months of before-and-after crash data from approximately 125 intersections (including 11 intersections with RLCs) in the city of Oxnard, California (*8*). The researchers selected three similarly sized cities that did not implement RLCs for comparison. These comparison cities were located more than 100 mi from Oxnard to control for the spillover effect. The study results indicated that

TABLE 1 Summary of Research Studies Evaluating RLCs

Study	Number of Sites	Method	Crash Reduction Percentage[a] (crash type)	Notes
Ng et al. (*4*)	42 treated sites 42 nontreated sites	CG method	7 (all types) 8 (RA)	No control for RTM and spillover effect
Winn (*5*)	6 treated sites 6 nontreated sites	CG method	62 (injury)	No control for RTM and spillover effect
Walden (*6*)	56 treated sites	Naïve comparison	30 (all types) 43 (RA) −5 (RE)	No control for RTM and spillover effect
Walden et al. (*7*)	296 treated sites (39 communities)	CG method	26 (all types) 19 (RA) −44 (RE)	Partial control for RTM and spillover effect
Retting and Kyrychenko (*8*)	125 sites (11 treated sites)	Generalized linear regression model	7 (all types) 32 (RA) −3 (RE)	Control for RTM and spillover effect, but the results are based on citywide effects and not just effects at RLC sites
Hu et al. (*9*)	14 cities with treatment 48 cities without treatment	Poisson regression analysis	35 (fatality rate) for cities with treatment 14 (fatality rate) for cities without treatment	Control for RTM and spillover effect, but the results are based on citywide effects and not just effects at RLC sites
Washington and Shin (*10*)	24 treated sites	CG method	42 (angle) 10 (LT) −51 (RE)	
		EB method	20 (angle) 45 (LT) −41 (RE)	Control for RTM and spillover effect
Persaud et al. (*11*)	132 treated sites (7 jurisdictions)	EB method	25 (RA) −15 (RE)	Control for RTM
Hallmark et al. (*12*)	4 treated sites 5 nontreated sites	Bayesian method	20 (all types) at treated sites −7 (all types) at nontreated sites	Control for RTM

NOTE: CG = comparison group.
[a]Negative values represent increases in crashes after the treatment.

crashes of all types and RA crashes at the signalized intersections within the treated city were significantly reduced by 7% and 32%, respectively. Although the finding was not significant, the study found that RE crashes increased by 3%.

Similarly, Hu et al. evaluated the citywide effects of enforcement with RLCs on per capita fatal crash rates (*9*). Poisson regression analysis was used to model fatal crash rates in 14 cities with RLC systems and 48 cities without such systems during the same period. The average annual rates of fatal RLR crashes were decreased by 35% for cities with treated intersections and 14% for cities without treatments. The crash reductions found by Retting and Kyrychenko (*8*) and Hu et al. (*9*) were not just due to the RLC installations but also resulted from citywide effects (*10*).

To address the RTM bias, some studies used the EB method in their evaluation. Washington and Shin analyzed crashes at 10 intersections in Phoenix, Arizona, and 14 intersections in Scottsdale, Arizona, equipped with RLC systems (*10*). Based on the comparison group method and using Phoenix data, the researchers found that angle and left-turn (LT) crashes decreased by 42% and 10%, respectively, but that RE crashes increased by 51%. Using data for Scottsdale and the EB method, the authors found that angle and LT crashes decreased by 20% and 45%, respectively, at the treated intersections, although RE crashes increased by 41%. The overall conclusions suggest that RLC installation had a positive influence on the reduction of angle and LT crashes and a negative influence on RE crashes.

Persaud et al. evaluated the effects of RLC treatments at 132 intersections in seven jurisdictions across the United States using the EB method (*11*). For individual jurisdictions, the evidence suggested that RA crashes decreased by 14% to 40% at six jurisdictions and increased by less than 1% at one jurisdiction. RE crashes increased by 7% to 38% at all jurisdictions. For all jurisdictions together, RA crashes were decreased by 25% and RE crashes were increased by 15%. Table 1 summarizes the research studies that evaluated the RLC treatment.

Among the studies that evaluated the effectiveness of RLC systems, some of them mentioned the criteria used for the selection of sites for RLC installation. In the study by Washington and Shin the cities of Phoenix and Scottsdale selected the intersections for RLC installation on the basis of high numbers of crashes of all types or RLR crash history and included citywide coverage (*10*). Hallmark et al. stated that the treatment intersections were selected on the basis of crash rates and intersection configurations and for intersections in which no future intersection improvements were planned (*13*).

None of the studies mentioned above analyzed the frequency of crashes or any specific criteria that were needed to warrant placement of RLC treatments at signalized intersections. The previous studies that evaluated the RLC treatments in Texas also suffered from the spillover effect and RTM bias. The study described here used the EB method to address the RTM bias and also presents criteria used to select the sites for treatment.

DATA COLLECTION

Crash information originated from electronic copies of stored crash records maintained in the Texas Department of Transportation Crash Records Information System database. Individual crash records were remotely accessed electronically through an interface with the Crash Records Information System and a search of the database by use of crash identification numbers assigned to each crash record. During the study period the researchers collected crash data at 245 intersections with RLC systems from 32 jurisdictions in Texas. The data were for periods from 1 to 4 years before (a total of 516 intersection years) and after (a total of 663 intersection years) camera installation.

In addition, crash and traffic data from 66 reference intersections without RLC systems were collected for the period from 2007 to 2010. The reference intersections were selected in such a way that they were located at least 2 mi away from the closest treatment intersection to minimize the spillover effect. All treatment and reference intersections were located in 32 jurisdictions in Texas. Table 2 provides the summary statistics for the variables collected at the intersections in the treatment and reference groups that were found to be significant in the statistical model. Other variables collected included lane width, shoulder width, yellow time, red time, channelization, and median width, among others.

The target (RLR) crashes are defined as those types of crashes that are likely influenced by RLCs. RLR crashes should include those crash events taking place inside the intersection in which one vehicle disregards the red signal, plus any intersection-related RE crash event occurring as a consequence of heavy braking in anticipation of a yellow signal turning to red while the units are traveling in the same approach direction. RLR crashes were identified on the basis of reports of one of the following factors, disregard of the stop or go signal or failure to yield the right-of-way during a turn on red.

In addition to the factors mentioned above, the researchers of this study reviewed crash narratives and diagrams to reconfirm whether crashes were related to RLR. Although the crashes occurred because of signal violations, they were not counted toward the target crashes when they occurred under the following conditions: (*a*) driving under the influence; (*b*) adverse weather conditions, such as icing on roadways; (*c*) a driver cut in front of traffic from a side lane; or (*d*) the presence of emergency vehicles. The exclusion of these crashes is based on law enforcement judgment from the belief that the installation of RLC systems will not affect crash occurrence under those conditions. The conditions considered in this study are similar to the ones mentioned by Washington and Shin (*10*).

After the RLC crashes were categorized at the treatment intersections, 2,781 and 2,597 RLR crashes of all types were reported during the before and after study periods, respectively. Of the crashes reported during the before study period, 2,609 and 116 crashes were categorized as RA and RE RLR crashes, respectively. In the after study period, 2,268 and 262 crashes were RA and RE RLR crashes, respectively. At the reference intersections, 432 crashes of all types, 229 RA crashes, and 106 RE RLR crashes were reported.

METHODOLOGY

A before–after study was used to evaluate the safety effectiveness of the RLCs. To overcome RTM bias in the selection process for the treatment intersections, the EB method was used. This method allowed the estimation of the safety benefits at treated sites by the use of information from reference sites. The expected crash frequency ($E[k|K]$) at a treated site was a result of the combination of the predicted crash count ($E[k]$) based on the reference sites with similar traits and the crash history (K) of that site. The expected crash frequency and its variance ($V[k|K]$) are shown in Equations 1 and 2.

$$E[k|K] = w \cdot E[k] + (1 - w) \cdot K \tag{1}$$

$$V\left[k|K\right] = \left(1 - w\right) \cdot E\left[k|K\right] \tag{2}$$

where w is a weight between 0 and 1, and it is calculated as

$$w = \frac{1}{1 + \dfrac{V\left[k\right]}{E\left[k\right]}} \tag{3}$$

The parameter $E[k]$ is estimated from the safety performance functions (SPFs) developed by use of a negative binomial regression (also known as Poisson gamma) model under the assumption that

TABLE 2 Summary Statistics for Treatment and Reference Intersections

Intersection Type	Variable	Min.	Max.	Mean	SD	Sum
Treatment	RLR crashes					
	Before					
	All types	0	162	11	17	2,781
	RA	0	161	11	16	2,609
	RE	0	11	0.48	1.14	116
	Study period (year)	1	4	2.1	0.56	516
	After					
	All types	0	187	10.6	18.15	2,597
	RA	0	185	9.29	17.77	2,268
	RE	0	13	1.08	1.96	262
	Study period (year)	1	4	2.7	0.84	663
	ADT^a_{maj}	1,300	158,000	31,212	17,647	—
	ADT^a_{min}	950	52,000	15,998.11	9,067.03	—
Reference	RLR crashes					
	All types	0	23	6.55	5.80	432
	RA	0	20	3.47	4.48	229
	RE	0	8	1.61	1.68	106
	ADT^a_{maj}	5,750	64,914	23,884.28	9,779.68	—
	ADT^a_{min}	2,080	29,885	15,628.86	7,901.30	—

NOTE: Min. = minimum value; max. = maximum value; SD = standard deviation; — = no data.
[a] ADT_{maj} and ADT_{min} are the average daily traffic for major and minor approaches at intersections, respectively.

the covariates in SPFs represent the main safety traits of the reference sites (*10*). The procedure used for the before–after study with the EB method is described below.

Step 1. Develop SPFs

SPFs are developed by the use of crash, traffic, and geometric data from the reference sites and the negative binomial regression models for RLR crashes of all types and RA and RE RLR crashes. The negative binomial regression model is the most common type of model used by transportation safety analysts to model traffic crashes. This model is preferred over other mixed-Poisson models because the gamma distribution is the conjugate of the Poisson distribution. The negative binomial regression model has the following model structure: the number of crashes for a particular ith site and time period t (Y_{it}), when it is conditional on its mean (μ_{it}), is Poisson distributed (Po) and independent over all sites and time periods.

$$Y_{it}|\mu_{it} \sim \text{Po}(\mu_{it}) \qquad i = 1, 2, \ldots, i \text{ and } t = 1, 2, \ldots, t \tag{4}$$

The mean of the Poisson distribution is structured as

$$\mu_{it} = f(X;\beta)\exp(e_{it}) \tag{5}$$

where

$f(.)$ = function of the covariates (X),
β = vector of unknown coefficients, and
e_{it} = model error independent of all the covariates.

Although different functional forms were tried, the best-fit functional forms used for each crash type in this study are as follows:

$$E[k]_{\text{all types}} = e^{\beta_0} \cdot N \cdot \left(\frac{\text{ADT}_{\text{min}}}{\text{ADT}_{\text{maj}} + \text{ADT}_{\text{min}}}\right)^{\beta_1} \tag{6}$$

$$E[k]_{\text{RA}} = e^{\beta_0} \cdot N \cdot \left(\frac{\text{ADT}_{\text{min}}}{\text{ADT}_{\text{maj}} + \text{ADT}_{\text{min}}}\right)^{\beta_1} \tag{7}$$

$$E[k]_{\text{RE}} = e^{\beta_0} \cdot N \cdot (\text{ADT}_{\text{maj}} + \text{ADT}_{\text{min}})^{\beta_1} \tag{8}$$

where

β_i = vector of unknown coefficients (to be estimated) (i = 0, 1),
N = number of years of crash data,
ADT_{maj} = average daily traffic (ADT) for the major approach at the intersection,
ADT_{min} = ADT for the minor approach at the intersection,
RA = RA crashes, and
RE = RE crashes.

Step 2. Predict Expected Number of Crashes and Calculate Observed Number of Crashes

On the basis of Equation 1, predict the expected number of crashes (π) at a particular ith site with the following equation:

$$\hat{\pi}_i = E\left[\hat{k}_i|K_i\right] = \hat{w}_i \cdot E\left[\hat{k}_i\right] + (1 - \hat{w}_i) \cdot K_i \tag{9}$$

The estimate of w ($\hat{w}$) in Equation 9 can be calculated as follows:

$$\hat{w}_i = \frac{1}{1 + \alpha \cdot E\left[\hat{k}_i\right]} \tag{10}$$

where α is the overdispersion parameter of a negative binomial regression model. The expected number of crashes in the after period and their variances for a group of sites had the treatment not been implemented at the treated sites are given as

$$\hat{\pi} = \sum_{i=1}^{n} \hat{\pi}_i \tag{11}$$

where n represents the total number of sites in the treatment group, and $\hat{\pi}$ is the expected number of crashes at all treated sites during the after period had there been no treatment. This step is not required when the safety effect is assessed at each jurisdiction level.

For a treated site, the crashes in the after period are influenced by the implementation of the treatment. The safety effectiveness of a treatment is known by comparison of the actual number of crashes with the treatment with the expected number of crashes without the treatment. The number of crashes observed in the after period (λ) for a group of treated sites is given as follows:

$$\hat{\lambda} = \sum_{i=1}^{n} L_i \tag{12}$$

where L_i is the crash frequency during the after period at site i. The estimate of λ is equal to the sum of the observed number of crashes at all treated sites during the after study period. This step is not required when the safety effect is assessed at each jurisdiction level.

Step 3. Estimate var[$\hat{\lambda}$] and var[$\hat{\pi}$]

On the basis of the assumption of a Poisson distribution, the estimate of the variance of λ [var($\hat{\lambda}$)] is assumed to be equal to L. The estimate of the variance of $\hat{\pi}$ can be calculated from the equation as follows:

$$\text{var}\left[\hat{\lambda}_i\right] = L_i \tag{13}$$

$$\text{var}\left[\hat{\lambda}\right] = \sum_{i=1}^{n} \text{var}\left[\hat{\lambda}_i\right] \tag{14}$$

$$\text{var}\left[\hat{\pi}_i\right] = (1 - \hat{w}_i) \cdot E\left[\hat{k}_i|K_i\right] = (1 - \hat{w}_i) \cdot \hat{\pi}_i \tag{15}$$

$$\text{var}\left[\hat{\pi}\right] = \sum_{i=1}^{n} \text{var}\left[\hat{\pi}_i\right] \tag{16}$$

Step 4. Estimate $\hat{\delta}$ and $\hat{\theta}$

The change in safety (δ) and the index of effectiveness (θ) are defined as the difference and the ratio of the safety with the treatment to what it would have been without the treatment, respectively. These parameters give the overall safety effect of the RLC treatment and are given by

$$\hat{\delta} = \hat{\pi} - \hat{\lambda} \tag{17}$$

$$\hat{\theta} = \frac{\left(\frac{\hat{\lambda}}{\hat{\pi}}\right)}{\left(1 + \frac{\text{var}(\hat{\pi})}{\hat{\pi}^2}\right)} \tag{18}$$

If $\hat{\delta}$ is greater than 0 and $\hat{\theta}$ is less than 1, then the treatment has a positive safety effect. In addition, the percent decrease in the number of target crashes due to the treatment is calculated as $100(1 - \hat{\theta})$.

Step 5. Estimate var[$\hat{\delta}$] and var[$\hat{\theta}$]

The estimated variance and the standard error (SE) of the estimated safety effectiveness are given by

$$\text{var}\left[\hat{\delta}\right] = \hat{\pi} + \hat{\lambda} \tag{19}$$

$$\text{var}\left[\hat{\theta}\right] = \frac{\hat{\theta}^2 \cdot \left[\frac{\text{var}(\hat{\lambda})}{\hat{\lambda}^2} + \frac{\text{var}(\hat{\pi})}{\hat{\pi}^2}\right]}{\left[1 + \frac{\text{var}(\hat{\pi})}{\hat{\pi}^2}\right]} \tag{20}$$

$$\text{SE}\left[\hat{\theta}\right] = \sqrt{\text{var}\left[\hat{\theta}\right]} \tag{21}$$

The 95% confidence interval for $\hat{\theta}$ is calculated as $\hat{\theta} \pm 1.96$ SE [$\hat{\theta}$]. If the confidence interval contains the value 1, then no significant effect has been observed at the 5% level.

RESULTS OF ANALYSIS

This section of the paper provides the results of the evaluation of the effectiveness of RLCs at the intersections by the EB method. In addition, the results of the evaluation of the site selection criteria for RLC treatments are also provided.

Safety Evaluation of RLCs

Table 3 summarizes the estimation results for all types of RLR crashes and RA and RE RLR crashes. The coefficients were combined with Equations 6 to 8 to obtain the mean for each crash type. The variables that have an absolute *t*-statistic value greater than 2.0 were included only in the final model. The *t*-statistics indicate a test of the hypothesis that the coefficient value is equal to 0.0. Those *t*-statistics with an absolute value that is greater than 2.0 indicate that the hypothesis can be rejected, with the probability of error in this conclusion being less than .05. In general, the trend for each variable is logical and intuitive. The estimation results suggest that with an increase in total traffic flow, the numbers of RE crashes at the intersection increase. At the same time, as the proportion of the volume on the minor approach increases, the numbers of RLR crashes of all types and RA RLR crashes increase.

Table 4 summarizes the change in safety (δ) due to the installation of RLCs by jurisdiction and crash type. A value of δ greater than 1 implies that the treatment is effective for crash reduction at a jurisdiction. Of 32 jurisdictions, δ was greater than 1 at 18 jurisdictions for all types of RLR crashes and 20 jurisdictions for RA RLR crashes. For the RE RLR crash type, only five jurisdictions had δ values greater than 1. Table 4 also summarizes the index of effectiveness by jurisdiction and crash type. Twenty-eight jurisdictions showed reductions in RLR crashes of all types and RA RLR crashes after RLC installation. For RE RLR crashes, 18 jurisdictions showed crash reductions at the treatment intersections.

Table 5 presents the average safety effect of the RLC enforcement systems at 32 jurisdictions in Texas. Table 5 shows that about 933 crashes were reported annually during the after study period. The results of the analysis show that if the treatment had not been installed, the expected number of crashes per year would have been 1,166 during the after study period. Thus, the safety effect is positive and one can expect to see about 233 fewer crashes per year with the implementation of RLC systems. The average safety effect of the systems was estimated to be a decrease in RLR crashes of all types by 20%. The standard deviation of this estimate of the average safety effect is 3%. At the 95% confidence interval, this result is statistically significant, and one may expect a decrease in crashes from 13% to 27%. Table 5 also shows that for RA RLR crashes, about 812 crashes were reported annually and one would have expected 1,070 crashes had the treatment not been installed. Thus, a reduction of about 258 crashes per year is expected with the treatment.

The average safety effect of RLC enforcement on RA crashes shows that, at the 5% level, RA crashes significantly decreased by 24%. Contrary to crashes of all types and RA crashes, an increase in RE crashes after the implementation of RLCs was observed. Overall, about 95 RE crashes were reported annually, and one would have expected about 68 crashes had there been no treatment. Thus,

TABLE 3 Estimates of SPFs for Reference Intersections

Variable	All Type RLR Crashes	RA RLR Crashes	RE RLR Crashes
Constant (β_0)	1.4256 (0.379)	1.5697 (0.638)	−11.3326 (3.387)
$AADT_{maj} + AADT_{min}$ (β_1)	—	—	0.9848 (0.319)
$\frac{AADT_{min}}{AADT_{maj} + AADT_{min}}$ (β_1)	0.978 (0.371)	1.8295 (0.645)	—
Dispersion parameter (α)	0.7274 (0.171)	1.3907 (0.343)	0.3844 (0.213)
Log likelihood	−191.4	−150.8	−108.9
AIC	388.8	307.6	223.9
BIC	395.3	314.1	230.5

NOTE: Values in parentheses represent SEs. AIC = Akaike information criterion; BIC = Bayesian information criterion; — = no data.

TABLE 4 Safety Effects by Jurisdiction

City	$\hat{\delta}$ All	$\hat{\delta}$ RA	$\hat{\delta}$ RE	$\hat{\theta}$ All	$\hat{\theta}$ RA	$\hat{\theta}$ RE
Amarillo	5.1 (5.20)	4.9 (5.08)	0.4 (1.19)	0.65 (0.23)	0.64 (0.23)	0.38 (0.43)
Arlington	10.2 (8.75)	5.2 (8.45)	3.9 (1.96)	0.74 (0.16)	0.84 (0.19)	0.02 (0.05)
Austin	12.8 (13.2)	11.0 (12.9)	0.3 (1.52)	0.85 (0.12)	0.86 (0.12)	0.54 (0.46)
Baytown	7.3 (6.02)	6.2 (5.76)	1.6 (1.26)	0.63 (0.20)	0.65 (0.21)	0.04 (0.11)
Bedford	0.9 (1.97)	0.5 (1.85)	0.6 (0.79)	0.47 (0.36)	0.55 (0.41)	0.10 (0.26)
Burleson	0.4 (5.51)	0.8 (4.21)	–1.8 (3.03)	0.92 (0.29)	0.85 (0.34)	1.28 (0.64)
Cedar Hill	3.5 (4.17)	3.5 (3.93)	–0.2 (1.33)	0.62 (0.26)	0.58 (0.26)	0.91 (0.77)
College Station	1.9 (2.81)	0.1 (2.02)	0.9 (1.70)	0.52 (0.31)	0.69 (0.47)	0.42 (0.38)
Coppell	1.3 (2.70)	1.4 (2.31)	–0.1 (1.10)	0.60 (0.36)	0.49 (0.34)	0.88 (0.87)
Corpus Christi	1.1 (6.30)	3.5 (5.17)	–3.4 (3.25)	0.90 (0.27)	0.72 (0.26)	1.68 (0.80)
Dallas	33.7 (19.1)	33.9 (18.3)	1.0 (3.51)	0.82 (0.08)	0.81 (0.08)	0.75 (0.36)
Diboll	–4.1 (2.42)	–0.5 (0.91)	–3.4 (2.14)	4.07 (2.26)	2.14 (1.79)	4.86 (2.78)
Duncanville	9.2 (4.20)	8.2 (4.08)	1.1 (1.06)	0.29 (0.15)	0.31 (0.16)	0.06 (0.16)
El Paso	–0.4 (10.1)	14.7 (8.90)	–12.0 (4.75)	0.98 (0.18)	0.67 (0.14)	2.95 (1.17)
Farmers Branch	1.4 (4.00)	1.8 (3.54)	0.4 (1.80)	0.76 (0.33)	0.67 (0.33)	0.59 (0.46)
Fort Worth	12.6 (7.65)	12.7 (7.46)	0.8 (1.68)	0.62 (0.16)	0.61 (0.16)	0.41 (0.35)
Garland	–0.2 (4.04)	–0.5 (3.93)	0.8 (1.12)	0.93 (0.39)	0.97 (0.42)	0.17 (0.26)
Grand Prairie	2.5 (4.37)	3.4 (4.00)	–0.3 (1.92)	0.71 (0.29)	0.60 (0.27)	0.88 (0.60)
Haltom City	–1.1 (3.44)	–1.3 (3.11)	–0.5 (1.24)	1.08 (0.50)	1.16 (0.57)	1.32 (1.13)
Houston	101.0 (26.9)	109.0 (26.6)	–4.5 (3.89)	0.75 (0.05)	0.73 (0.05)	1.56 (0.69)
Humble	–0.5 (3.67)	1.9 (2.93)	–2.6 (2.01)	0.98 (0.43)	0.56 (0.32)	3.74 (2.21)
Irving	0.6 (1.61)	0.4 (1.33)	0.1 (0.86)	0.48 (0.42)	0.44 (0.43)	0.57 (0.76)
Jersey Village	4.4 (7.37)	5.0 (6.24)	–3.0 (3.60)	0.82 (0.21)	0.74 (0.22)	1.47 (0.62)
Killeen	–0.1 (3.14)	0.9 (2.42)	–0.8 (2.04)	0.90 (0.45)	0.63 (0.40)	1.12 (0.72)
Lufkin	–0.4 (6.08)	–0.2 (4.67)	–1.9 (3.28)	0.97 (0.29)	0.95 (0.35)	1.29 (0.59)
Mesquite	–1.4 (1.88)	–1.6 (1.55)	0.5 (0.68)	1.64 (1.04)	2.99 (1.97)	0.14 (0.35)
North Richland Hills	8.8 (4.29)	6.8 (3.62)	1.2 (1.96)	0.33 (0.16)	0.29 (0.17)	0.43 (0.34)
Plano	21.4 (11.8)	23.1 (11.1)	–2.9 (3.50)	0.72 (0.12)	0.67 (0.12)	1.40 (0.64)
Richardson	0.7 (4.71)	2.8 (4.15)	–1.3 (2.17)	0.87 (0.33)	0.66 (0.28)	1.38 (0.84)
Roanoke	–1.8 (2.86)	–2.2 (2.40)	–0.5 (1.21)	1.32 (0.68)	1.79 (1.01)	1.53 (1.30)
Sugar Land	1.2 (4.45)	1.4 (4.08)	–0.1 (1.36)	0.84 (0.31)	0.80 (0.32)	0.91 (0.81)
Terrell	0.1 (1.77)	0.7 (1.29)	–0.4 (1.24)	0.70 (0.53)	0.30 (0.34)	1.31 (1.11)

NOTE: Values in parentheses represent SEs.

26 more RE crashes occurred annually at the treatment intersections since RLC installation. The average safety effect of RLC systems on RE crashes is estimated to be an increase in crashes by 37%. This result is significant at the 95% confidence level.

Site Selection Criteria

In addition to the results on the effectiveness of RLR enforcement systems, the researchers conducted evaluations of the safety effect at intersection groups categorized by (*a*) the number of RLR crashes per year, (*b*) ADT from all approaches, and (*c*) crash rates (number of RLR crashes per 10,000 vehicles per year). The categorization was based on the data collected during the before study period. These evaluations were used to provide information on the criteria used for the selection of sites for RLC installation. Table 6 summarizes the safety effectiveness by the different selection criteria.

The results indicated that if the intersections have less than two crashes per year in the before period and they are selected for the treatment, then RLR crashes of all types and RA RLR crashes increase by 49% and 28%, respectively, because of the RLC enforcement systems. If the intersections with greater than or equal to two and less than four crashes per year are selected, then one can expect decreases in crashes of all types and RA crashes of 18% and 29%, respectively. If the intersections have four or more crashes per year, then crashes of all types and RA crashes are significantly decreased by 23% and 29%, respectively. For the change in safety (δ), reductions of 205 RLR crashes of all types and 260 RA RLR crashes at

TABLE 5 Average Safety Effects for All Treatment Intersections

RLR Crash Type	$\hat{\lambda}$	$\hat{\pi}$	$\hat{\delta}$	$\sigma[\hat{\delta}]$	$\hat{\theta}$	$\sigma[\hat{\theta}]$
All RLR	932.8	1,165.64	232.8	44.82	0.8	0.03
RA RLR	812.4	1,069.99	257.6	42.46	0.76	0.03
RE RLR	94.8	68.39	–26.4	11.62	1.37	0.19

TABLE 6 Safety Effects by Site Selection Criteria

Criterion	Variable	Category		
		<2	2–4[a]	≥4
RLR crashes (number of crashes/year)	All			
	θ	1.49 (0.22)*	0.82 (0.09)	0.77 (0.03)*
	δ	−32	23	205
	Number of intersections[b]	70	61	114
	Changes per intersection[c]	−0.5	0.4	1.8
	RA			
	θ	1.28 (0.22)	0.71 (0.09)*	0.71 (0.03)*
	δ	−17	37	260
	Number of intersections[b]	70	61	114
	Changes per intersection[c]	−0.2	0.6	2.3
		<15,000	15,000–25,000[a]	≥25,000
Traffic volume (number of vehicles/day)	All			
	θ	0.71 (0.07)*	0.93 (0.07)	0.82 (0.04)*
	δ	58	20	105
	Number of intersections[b]	56	89	100
	Changes per intersection[c]	1.0	0.2	1.0
	RA			
	θ	0.73 (0.07)*	0.89 (0.07)	0.78 (0.04)*
	δ	48	30	119
	Number of intersections[b]	56	89	100
	Changes per intersection[c]	0.9	0.3	1.2
		<1	1–2[a]	≥2
RLR crash rate (number of crashes/year/ 10,000 vehicles)	All			
	θ	1.13 (0.14)	0.78 (0.07)*	0.71 (0.03)*
	δ	−16	48	245
	Number of intersections[b]	95	72	78
	Changes per intersection[c]	−0.2	0.7	3.1
	RA			
	θ	1.11 (0.14)	0.86 (0.08)	0.73 (0.04)*
	δ	−12	28	186
	Number of intersections[b]	95	72	78
	Changes per intersection[c]	−0.1	0.4	2.4

NOTE: Values in parentheses represent SEs.
[a]First number in the range is inclusive and second number is exclusive.
[b]Number of intersections in the group.
[c]Change in number of crashes per intersection. Negative values represent increases in crashes after treatment.
$*p < .05$.

114 intersections are found. Thus, if the intersections with four or more RLR crashes are selected for treatment, then the reduction is about two crashes per intersection. At the same time, if intersections with less than two crashes are selected, then a counterproductive result is observed.

The traffic volume (average of ADT_{maj} and ADT_{min}) during the before study period was evaluated as the next criterion. Intersections were categorized into three groups: (*a*) those with less than 15,000 vehicles per day, (*b*) those with at least 15,000 but no greater than 25,000 vehicles per day, and (*c*) those with 25,000 vehicles per day or greater. In the first group, with intersections with less than 15,000 vehicles per day, RLR crashes of all types and RA RLR crashes significantly decreased by 29% and 27%, respectively, after the implementation of the RLC systems. The second group of intersections showed that RLR crashes of all types decreased by 7% and RA crashes decreased by 11%. The third group showed significant decreases in both crashes of all types and RA crashes by 18% and 22%, respectively. No specific trends in the safety effectiveness of RLC systems appeared to be observed when ADT rates changed, even though safety benefits were apparent.

The third criterion used for site selection was the RLR crash rate (i.e., the number of RLR crashes per 10,000 vehicles per year). If intersections with crash rates of less than one were selected for RLC installation, RLR crashes of all types crashes increased by 13% and RA RLR crashes increased by 11%. If the intersections with crash rates of greater than or equal to one but less than two were selected, RLR crashes of all types crashes decreased by 22% and RA RLR crashes decreased by 14%. For the third group of intersections, which had crash rates greater than or equal to two, RLR crashes of all types decreased by 29% and RA RLR crashes decreased by 27%; both of these values were significant. These findings equate to reductions in three crashes of all types and two RA crashes per intersection after the treatment.

CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the safety effectiveness of RLC systems with data collected at 245 intersections in 32 jurisdictions in Texas. Using the same data and a naïve before–after method, Walden concluded that RLC systems have a positive impact on intersection safety (*6*). Walden et al. recently evaluated the safety effectiveness of RLC systems using the same data and a before–after study with a comparison group method and indicated a significant decrease in RLR crashes of all types of 26.4% (*7*). However, the results in both studies are subject to possible RTM bias because these two methods predict the expected number of target crashes at a site only on the basis of the before-period crash frequency.

This study made use of the EB method to control for the RTM bias and concluded that the RLC treatment played a positive role in reducing RLR crashes of all types and RA RLR crashes at the signalized intersections and had a negative impact on RE RLR crashes. The results of this study indicate significant decreases in RLR crashes of all types and RA RLR crashes by 20% and 24%, respectively, but a significant increase in RE RLR crashes by 37%. Although the EB method provides precise estimates, this method cannot be easily applied to all RLC research because of the requirement for large amounts of data.

This study used reference intersections located at least 2 mi away from the treated intersections to control for the spillover effect from RLC systems. However, no research study has specified the minimum distance required to eliminate the spillover effect. Retting and Kyrychenko used a distance of more than 100 mi from the treatment intersections to control for the spillover effect in their analysis (*8*). Thus, the authors of the present study recommend that additional work be conducted to determine the exact minimum distance from the treated intersections for the selection of reference intersections.

The results of this study were consistent with those of previous studies. For RLC installation, the *Highway Safety Manual* uses a crash modification factor of 0.74 for RA crashes and a crash modification factor of 1.18 for RE crashes (*14*). These crash modification factors mean that RLCs would typically be expected to reduce RA crashes by 26% and increase RE crashes by 18%.

This paper also evaluated criteria for the selection of sites for the implementation of RLC systems. Intersections are selected for the treatment on the basis of crash history, traffic volume, or crash rate. However, no specific guidelines on when the implementation of RLC systems is warranted exist. The results of this study demonstrate that RLC systems have a significant and positive impact when intersections with greater than or equal to four crashes per year or a crash rate of two crashes per 10,000 vehicles per year are selected for the treatment. It is expected that those intersections will have a reduction of about two or more RLR crashes per year after the RLC installation. If the intersections with less than two RLR crashes per year or a crash rate of less than one are selected, then a negative safety impact should be expected after the treatment.

This study also considered ADT to be one of the criteria for the selection of sites. The study results show that no specific trend in safety occurs with a change in traffic volume. The research by Walden et al. showed that more RLR violations occurred during morning and afternoon peak hours (8 to 10 a.m. and 4 to 6 p.m., respectively) when RLCs were not installed (*7*). When RLCs were active, more violations occurred between 12 and 3 p.m. As a result of this study, it is recommended that ADT not be the only criterion considered for site selection. Additional research is needed to determine if traffic violations can be used as a single criterion for the selection of sites for treatment. Further work is recommended to examine the effect of RLC systems on injury severity outcomes and as well on economic and health benefits.

REFERENCES

1. *Red Light Cameras on State Highways,* Texas Department of Transportation, Austin, 2011. http://www.txdot.gov/safety/red_light_cameras.htm. Accessed Feb. 12, 2012.
2. Hauer, E. *Observational Before–After Studies in Road Safety.* Pergamon Press, Elsevier Science Ltd., Oxford, United Kingdom, 1997.
3. *Guidance for Using Red Light Cameras.* NHTSA, FHWA, 2003.
4. Ng, C. H., Y. D. Wong, and K. M. Lum. The Impact of Red Light Surveillance Cameras on Road Safety in Singapore. *Road and Transport Research,* Vol. 6, No. 2, 1997, pp. 72–81.
5. Winn, R. *Running the Red and Evaluations of Strathclyde Police's Red Light Camera Initiative.* Scottish Central Research Unit, Glasgow, Scotland, 1995. http://www.scotland.gov.uk/cru/resfind/drf7-00.htm. Accessed Aug. 1, 2011.
6. Walden, T. D. *Evaluation of Photographic Traffic Signal Enforcement Systems in Texas.* Traffic Operations Division, Texas Department of Transportation, Austin, Aug. 2010. http://ftp.dot.state.tx.us/pub/txdot-info/trf/red_light/tti_evaluation.pdf. Accessed May 1, 2012.
7. Walden, T. D., S. Geedipally, M. Ko, R. Gilbert, and M. Perez. *Evaluation of Automated Traffic Enforcement Systems in Texas.* Traffic Operations Division, Texas Department of Transportation, Austin, Aug. 2011. http://ftp.dot.state.tx.us/pub/txdot-info/trf/red_light/auto_traffic.pdf. Accessed May 1, 2012.
8. Retting, R. A. and S. Y. Kyrychenko. Reductions in Injury Crashes Associated with Red Light Camera Enforcement in Oxnard, California. *American Journal of Public Health,* Vol. 92, No. 11, 2002, pp. 1822–1825.
9. Hu, W., A. T. McCartt, and E. R. Teoh. Effects of Red Light Camera Enforcement on Fatal Crashes in Large U.S. Cities. *Journal of Safety Research,* Vol. 42, No. 4, 2011, pp. 277–282.
10. Washington, S., and K. Shin. *The Impact of Red Light Cameras (Automated Enforcement) on Safety in Arizona.* Report 550. University of Arizona, Tucson, 2005.
11. Persaud, B. N., F. M. Council, C. Lyon, K. A. Eccles, and M. Griffith. Multijurisdictional Safety Evaluation of Red Light Cameras. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1922,* Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 29–37.
12. Hallmark, S., M. Orellana, E. J. Fitzsimmons, T. McDonald, and D. Matulac. Red Light Running in Iowa: Automated Enforcement Program Evaluation with Bayesian Analysis. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2182,* Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 48–54.
13. Hallmark, S., N. Oneyear, and T. McDonald. *Evaluating the Effectiveness of Red Light Running Camera Enforcement in Cedar Rapids and Developing Guidelines for Selection and Use of Red Light Running Countermeasures.* InTrans Project 10-386. Center for Transportation Research and Education, Iowa State University, 2011.
14. *Highway Safety Manual.* AASHTO, Washington, D.C., 2011.

The Traffic Law Enforcement Committee peer-reviewed this paper.