Safety effectiveness and crash cost benefit of red light cameras in Missouri

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ABSTRACT
Objective: Red light cameras (RLCs) have generated heated discussions over issues of safety effectiveness, revenue generation, and procedural due process. This study focuses on the safety evaluation of RLCs in Missouri, including the economic valuation of safety benefits. The publication of the national Highway Safety Manual (HSM; American Association of State Highway and Transportation Officials) in 2010 produced statistical safety models for intersections and spurred the calibration of these models to local conditions.
Methods: This study adds to existing knowledge by applying the latest statistical methodology presented in the HSM and more current data. Driver behavior constantly changes due in part to driving conditions and the use of technology. The safety and economic benefit evaluation was performed using the empirical Bayes method, which accounts for regression to the mean bias. For the economic benefit evaluation, the KABCO crash severity scale and crash cost estimates were used. A total of 24 4-leg urban intersections were randomly selected from a master list of RLCs in Missouri from 2006 to 2011. Additionally, 35 comparable nontreated intersections were selected for the analysis.
Results and Conclusions: The implementation of RLCs reduced overall angle crashes by 11.6%, whereas rear-end crashes increased by 16.5%. The net economic crash cost benefit of the implementation of RLCs was $35,269 per site per year in 2001 dollars (approximately $47,000 in 2015 dollars). Thus, RLCs produced a sizable net positive safety benefit that is consistent with previous statistical studies.

Introduction
Automated enforcement systems such as red light cameras (RLCs) have generated heated discussions over issues of transportation safety, economics, and laws. The objective of implementing RLCs at signalized intersections is to reduce red light running violations and the resulting crashes. This article reviews the RLC literature and examines RLC programs in Missouri.

Several studies have evaluated the effect of RLCs on red light running frequency in cities such as Fairfax, Virginia (Retting et al. 1999a), and Oxnard, California (Retting et al. 1999b), in the United States and in other countries including Singapore, Great Britain, Australia, The Netherlands, and Canada (Retting et al. 2003). The results of these studies indicate that the safety benefit of automated enforcement is a reduction in the number of red light violations between 40 and 50% and spillover effects to non-RLC-equipped intersections (Retting et al. 2003). Associated with the reduction in violations is a decrease in crash frequency. Several studies reported exaggerated and statistically biased estimates of the effectiveness of RLCs. Some of these studies lacked methodological rigor and statistical significance, which fueled the counterargument against the benefits of RLCs. It was not until 2005 when a federally funded study, conducted by nationally recognized safety experts, produced better information on RLC effectiveness (Council, Persaud, Eccles, Lyon, and Griffith 2005; Council, Persaud, Eccles, et al. 2005; Persaud et al. 2005). The study included significant data from 7 jurisdictions and rigorous statistical methods. The implementation of RLCs was found to have an overall positive effect on safety. Furthermore, recent studies in North Carolina, Virginia, and Arizona supported the findings of the national study (Miller et al. 2005; Pulugurtha and Otturu 2014; Shin and Washington 2007). Pulugurtha and Otturu (2014) found that RLCs had beneficial safety effects at intersections over a period of time after the automated enforcement was terminated. Hu et al. (2011) examined aggregated per capita fatal crashes in 99 large U.S. cities and found that RLCs were associated with statistically significant reductions in city-wide rates of fatal red light running crashes. The most recent meta-analysis of RLCs conducted in 2013 reported that on average there was an increase in total crashes by 6%, a decrease in right-angle crashes by 13%, and an increase in rear-end crashes by 40%. Injury right-angle crashes decreased by 33%, and injury rear-end crashes increased by 19% (Høye 2013). Høye (2013) highlighted red light camera program studies that did not control for selection bias and reported right-angle crash reductions up to 2 times larger than other studies. The meta-analysis only included studies that controlled for regression to the mean and publication bias.

When individual intersection performance is analyzed in addition to aggregate performance, it is possible to examine the appropriateness of RLC use at an individual sites. Council,
Persaud, Eccles, Lyon, and Griffith (2005) performed an exploratory analysis with net economic crash effects and found that RLCs were most effective when sites

- were highly publicized with public information programs;
- enforced higher fines;
- had one or more left turn protected phases;
- had shorter signal lengths and inter-green periods;
- had reduced major road speed limit;
- had a high proportion of traffic in the major road;
- had a high ratio of right-angle to rear-end crashes.

Despite general guidance on site selection for RLC treatment (Council, Persaud, Eccles, Lyon, and Griffith 2005), there is no specific quantitative measure or methodological procedure to determine best candidate locations. Therefore, the cumulative experience of RLC programs from different jurisdictions provides a good historical database of RLC site characteristics. With more recent data in Missouri and rigorous statistical methods, this study contributes to the existing knowledge with updated safety estimates for furthering the study of RLCs. Specifically, this new study added significant variables that were omitted from previous studies, manually reviewed individual crash reports based on intersection functional areas, and used recent data from the past decade that captured changes in vehicular technology and driver behavior; for example, the use of portable devices such as smart phones in vehicles. The labor-intensive crash review process was important, because crash locations in an electronic database may not distinguish a non-intersection-related crash that just happened to occur near an intersection.

A commonly used argument against the use of RLCs is that rear-end crashes are increased while reducing right-angle crashes. However, the severity of angle crashes and rear-ends are very different; thus, there is a need for an overall crash cost analysis (Council, Persaud, Eccles, Lyon, and Griffith 2005). In terms of economic benefits of RLCs, crash costs can be quantified using aggregated economic costs across crash types and severity levels, including material and life losses. RLCs were found to have a net economic benefit of approximately $38,000 per site per year in 2001 dollars (Council, Persaud, Eccles, Lyon, and Griffith 2005; Council, Persaud, Eccles, et al. 2005).

In the state of Missouri, the implementation of RLCs has not been studied rigorously. Public perception in Missouri has been based mainly upon media coverage and court decisions. Only a few other states have applied rigorous techniques that accounted for sampling bias and regression to the mean. This article presents the first RLC evaluation that used the Highway Safety Manual (HSM; American Association of State Highway and Transportation Officials [AASHTO] 2010) methodology, including a comprehensive safety evaluation and crash cost-benefit analysis using the empirical Bayes method (Hauer 1997). In this study, the safety performance functions (SPFs) of the HSM were all calibrated to Missouri conditions. In contrast, various studies (Miller et al. 2006; Persaud et al. 2005; Pulugurtha and Otturu 2014; Shin and Washington 2007) developed their own SPFs with limited data sets instead of calibrating functions from the HSM; the development of local SPFs is desirable but also complicated. Current guidance to develop jurisdiction-specific SPFs requires 100 to 200 intersections; these intersections have to be similar in geometry, operations, and safety-related traits. The total group of intersections requires at least 300 crashes per year and more than 3 years of crash data. In addition, the level of effort for data collection and preparation per SPF may be as high as 1,050 technical staff hours (Srinivasan et al. 2013). The calibration of SPFs from the HSM is a supported alternative when limited data and resources are available. The benefit of the HSM approach is the inclusion of many factors via crash modification factors (CMFs). Thus, the HSM considers factors such as pedestrians, alcohol establishments, schools, bus stops, signal control type, left turn phasing, right turns, and even lighting, whereas some previous SPFs included only a few variables such as amber duration and the number of lanes. The inclusion of more information regarding the surrounding intersection area could result in more accurate crash prediction by accounting for more confounding factors. Another contribution of this article is the use of much more recent data (2006–2011) compared to previous studies such as Persaud et al. (2005; 1995–2000), Miller et al. (2006; 2000–2005), Shin and Washington (2007; 1998–2003), and Pulugurtha and Otturu (2014; 1998–2006). The use of more recent data captures the technological and driver behavioral changes in the past decade including the recent proliferation of mobile devices and the associated distracted driving problems.

**Methodology**

**Site selection**

The first RLC installed in Missouri was in the city of Arnold in 2005, and many municipalities followed suit. In building a data sample, a master list of locations with RLCs across the state was first developed. From the list, facilities were randomly selected and validated to obtain a consistent sample. The sampling criteria consisted of 4-leg intersections, urban locations, no influence from other facilities, and crash data availability. A total of 24 intersections were selected for this study. The HSM recommends a sample of 20–40 sites for safety evaluations (AASHTO 2010). Additionally, 35 comparable intersections with no RLC treatment were selected to estimate crashes by type (right angle and rear end). The periods of analysis consisted of 2 years before and 2 years after RLC implementation. The crash data were collected from the Missouri State Highway Patrol database.

**Data collection**

The data collection included intersection geometry, signal control operation, traffic volume, surrounding features, and crash data. The data were collected using tools such as aerial photographs, the Missouri traffic volume database, and the Missouri State Highway Patrol crash records database. The geometry required for the analysis was the number of left/right turn lanes and the length of pedestrian crossings. The traffic volume was the annual average daily traffic (AADT) for every year of analysis. The AADT was collected for each leg of the intersection for each year of analysis. Because pedestrian volume counts were not available, estimates of crossing volumes were determined based on the general level of pedestrian activity.
provided by the HSM (AASHTO 2010). Pedestrian accessibility, businesses, public transportation, population density, and other factors are used to determine pedestrian activity. The signal control operations were collected for left turn signal phasing type (permissive, protective/permissive, and protected) and right turn on red restriction. It was important to identify educational facilities, bus stops, and alcohol sale establishments in the area (within 1,000 feet of the center of the intersection), because they significantly influence crashes (AASHTO 2010; Harwood et al. 2008). These facilities were located using address coordinates in combination with aerial imaging and navigation (Google Earth). The crash data were collected using the functional area of the intersections as illustrated in Figure A1 (see online supplement) for the before and after periods. All crashes that occurred in the shaded functional area shown in Figure A1 were included. The functional area of an intersection was determined on a case-by-case basis because each intersection has different geometric and operational features that may prolong queues up to different distances from the intersection.

**Safety evaluation**

Crashes are random events that fluctuate over time at any given site. In previous safety evaluation practice, crash frequency (crashes/year) over a short period of time was used to quantify the frequency of crashes at roadway facilities. Although this is a fair estimate, it is not completely accurate. As illustrated in Figure A2 (see online supplement), short-term average crashes may not accurately describe expected average crash frequency. Short-term crash rates may differ significantly from the long-term estimates. This difference is magnified in locations in which a small number of crashes are observed, so variations in crash frequency represent an even larger fluctuation in relation to the expected crash frequency. Therefore, it would be difficult to identify high, average, or low crash frequencies at a site using short-term crash rates (AASHTO 2010).

In the case of treatments such as RLCs, it is difficult to determine whether changes in crash frequency are due to changes in site conditions or natural fluctuations. There is a tendency, called *regression to the mean* (RTM), which dictates that a period with comparatively high crash frequency will likely be followed by a comparatively low crash frequency or vice versa (low crash frequency followed by a high-frequency period; Hauer 1996). Because sites are often selected for treatments based on short-term trends in the observed data, RTM bias is introduced (selection bias). The effect of this bias is significant while evaluating treatment effectiveness. When using conventional before-and-after studies to evaluate safety treatments, the perceived effectiveness is an overestimate of the actual treatment effectiveness. Figure A3 (see online supplement) illustrates graphically the regression to the mean effect and the difference between actual and perceived effectiveness.

Treated sites that were selected for improvement due to an unusually high number of red light running violations and crashes suffer from a selection bias that can result in high RTM in safety effectiveness evaluations. The empirical Bayes method, as applied in this study, accounts for RTM and provides unbiased estimates.

**Empirical Bayes for safety effectiveness**

The main purpose of the empirical Bayes method is to determine an unbiased expected crash frequency in the after period had the treatment not been implemented (Hauer 1997). The predicted crashes are obtained using the prediction methodology of the HSM (AASHTO 2010) using SPF, CMFs, calibration factors (C), and crash type distribution (D) by facility and severity type. All of these functions and factors account for local site characteristics, refining the prediction of crashes. The crash type distribution for angle, rear-end, and other crashes was determined using the 35 comparable sites. Additional crash data were collected for these sites, and crashes were classified according to type (angle, rear end, and other) to determine their incidence over the total. Because the HSM prediction models were developed by Harwood et al. (2007) with data form other states (Minnesota and North Carolina), the use of calibration factors for Missouri was required. The calibration factors for the state of Missouri were taken from Sun et al. (2013). To obtain calibration factors, the observed crashes in Missouri were compared with the predicted crashes from the model—calibration factor is the ratio of observed over predicted crashes. The SPF and CMFs for 4-leg signalized urban intersections from the HSM were considered (AASTHO 2010). Equation (1) shows the general form of the prediction methodology. The base model SPF has an additional parameter called overdispersion (k), which forms the basis for the application of the empirical Bayes method.

\[
N_{\text{pred}} = D_i \times C_j \times N_{\text{spf}} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_z)
\]  

(1)

where \(N_{\text{pred}}\) is the predicted crash frequency (crashes/year); \(D_i\) is the crash type distribution \((i = \text{all, right-angle, and rear-end crashes}); C_j,\) is the calibration factor according to local conditions for facility \(j; N_{\text{spf}}\) is the predicted crash frequency for site type SPF (crashes/year); and \(CMF_z\) is the crash modification factor specific to a site type characteristic \(z\).

The expected crash frequency \((N_{\text{exp,b}})\) in Eq. (2) is then clated at the weighted average \((w)\) of the observed crashes \((N_{\text{obs,b}})\) and the predicted crash frequency in the before period \((N_{\text{pred,b}})\) from Eq. (1). The weight \((w)\) is determined using the overdispersion parameter \((k)\) of the base SPF model.

\[
N_{\text{exp,b}} = w \times N_{\text{pred,b}} + (1 - w) \times N_{\text{obs,b}}.
\]  

(2)

where

\[
w = \frac{1}{1 + k \times N_{\text{pred,b}}}. \]  

(3)

The adjustment factor \((r)\) is introduced to account for variations between before and after periods. These variations include the durations of periods and traffic volume. Therefore, the factor is the ratio of the predicted crashes in the after period \((N_{\text{pred,a}})\) over predicted crashes in the before period \((N_{\text{pred,b}})\). Because the before and after periods were of the same duration, they cancelled each other out in the equation. Thus, the duration is not included in Eq. (4).

\[
r = \frac{N_{\text{pred,a}}}{N_{\text{pred,b}}}. \]  

(4)

Using Eq. (5), the expected crashes in the after period \((N_{\text{exp,a}})\) are then calculated by multiplying the adjustment factor
\( (r) \) by the expected crashes in the before period \( (N_{\text{exp},b}) \).

\[
N_{\text{exp},a} = r \times N_{\text{exp},b}.
\]  

(5)

The expected crashes in the after period \( (N_{\text{exp},a}) \) are then compared with the actual observed crash frequency in the after period \( (N_{\text{obs},a}) \). Equation (6) shows the comparison designated as \( OR' \):

\[
OR' = \frac{N_{\text{obs},a}}{N_{\text{exp},a}}.
\]  

(6)

uppotentially biased, it is adjusted using Eq. (7) to remove bias and account for regression to the mean using the variance of the expected crashes in the after period.

\[
OR = \frac{OR'}{1 + \frac{\text{Var}(N_{\text{exp},a})}{N_{\text{exp},a}}}.
\]  

(7)

where

\[
\text{Var}(N_{\text{exp},a}) = \left[ (r)^2 \times N_{\text{exp},b} \times (1 - w) \right].
\]  

(8)

The comparison (unbiased \( OR \)) of expected and observed crash frequency for the after period forms the basis for deriving the safety effectiveness, as shown in Eq. (9). The safety effectiveness is the measure of the treatment effectiveness at a site or group of sites after implementation. When crash frequency decreases after a treatment, the safety effectiveness is positive. When crash frequency increases, the safety effectiveness is negative.

\[
\text{Safety Effectiveness (\%)} = 100 \times (1 - OR).
\]  

(9)

**Empirical Bayes for crash cost benefit**

The change in crash costs over all treated facilities in a jurisdiction for specific crash types was estimated. Based on the method used for the safety effectiveness described previously, the empirical Bayes method measures the difference between net crash costs expected without treatment and observed with treatment in the after period. The cost modification factor \( (\theta_{\text{cost}}) \) is a measure quantifying the change in crash cost with the treatment (Council, Persaud, Eccles, Lyon, Griffith 2005; Council, Persaud, Eccles, et al. 2005):

\[
\theta_{\text{cost}} = \frac{\Lambda_{\text{cost},a}}{\Pi_{\text{cost},a}}.
\]  

(10)

\[
\text{Var}(\theta_{\text{cost}}) = \frac{\text{Var}(\Lambda_{\text{cost},a})}{\Lambda_{\text{cost},a}^2} + \frac{\text{Var}(\Pi_{\text{cost},a})}{\Pi_{\text{cost},a}^2},
\]  

(11)

where \( \theta_{\text{cost}} \) is the cost modification factor; \( \text{Var}(\theta_{\text{cost}}) \) is the variance in crash modification factor; \( \Lambda_{\text{cost},a} \) is the cost of crashes at treated sites in the after period; \( \Pi_{\text{cost},a} \) the expected cost of crashes in the after period over all treated sites had there been no RLC (after correcting for regression to the mean).

Additionally, the change in crash cost \( \Phi_{\text{cost}} \) and variance can be estimated in dollar costs:

\[
\Phi_{\text{cost}} = \Pi_{\text{cost},a} - \Lambda_{\text{cost},a}.
\]  

(12)

\[
\text{Var}(\Phi_{\text{cost}}) = \text{Var}(\Pi_{\text{cost},a}) + \text{Var}(\Lambda_{\text{cost},a}).
\]  

(13)

**Results**

The results section contains the details of the data collected, safety effectiveness, and crash cost benefit. Table 1 contains the data in which automated enforcement was implemented. The traffic volumes for the major road ranged from 13,000 to 60,000 (vehicles/day) and the minor road between 2,000 and 33,000 (vehicles/day) during the before period. The characteristics of turning lanes on approaching legs are listed, including the left and right turn lanes. Two types of signal control for left turns exist—permissive/protective and protected only. Pedestrian movements were not considered in previous research. In this study, 5 levels of pedestrian volume were considered as shown in Table 1. The maximum number of lanes pedestrians must cross to complete their movements was also considered. Several bus stops were common around the intersections, and in some cases there were up to 8 stops. Site 11 was the only intersection without any bus stops. Alcohol sale establishments were also common in the surrounding areas of the intersections. Site 9 was the only location without an alcohol sale establishment in the area.

The crash data for the before and after periods are shown in Figures 1 to 3. Total, angle, and rear-end crashes are shown individually. Figures 1 and 2 show that 11 and 16 sites experienced a reduction in observed crashes for total and angle crashes, respectively. On the other hand, there was an increase in rear-end crashes at 15 sites as shown in Figure 3. The changes in crashes between before and after periods were not large in magnitude.

It was important to determine the distribution of crashes (i.e., \( D \) in Eq. (1)) at nontreated facilities to accurately estimate the effect of the treatment by crash type. Therefore, an additional 35 nontreated comparison sites were used to determine crash distribution by type (e.g., angle, read end). Angle crash distribution refers to right-angle crashes or collisions between vehicles in converging directions (front-end and lateral crashes). In addition, the distribution of type of crashes was further identified by the severity categories of total (TOT), fatal and injury (FI), and property damage only (PDO). The results are shown in Table A1 (see online supplement).

The safety effectiveness results across all sites are shown in Table 2. The implementation of RLCs in Missouri resulted in a reduction in FI crashes by 7.4%, an increase in PDO crashes by 3.8%, and an increase in TOT crashes by 1.6%. Additionally, right-angle crashes were reduced across all severities, including 14.5% for FI. Rear-end crashes increased by 16.5% overall but decreased by 10.9% for FI crashes. These results are in agreement with previous studies (Høye 2013).

The economic benefit of RLCs was calculated using aggregated crash costs by crash types and severity levels. It involved placing a monetary value on crashes, including material and life losses. An adaptation of the empirical Bayes method was used for the economic estimates. The method accounts for regression to the mean (Council, Persaud, Eccles, Lyon, Griffith 2005; Council, Persaud, Eccles, et al. 2005). The analysis performed
### Table 1. Site data characteristics.

| No. | Enforcement date | Major road AADT | Minor road AADT | Turning lanes | Signal | Pedestrians | Establishments |
|-----|------------------|-----------------|-----------------|---------------|--------|-------------|----------------|
|     |                   | Approach with left turn | Approach with right turn | Approach pro/perm left | Approach protected left | Pedestrian volume | Maximum crossing lanes | Bus stops | School | Alcohol |
| 1   | 2/2/2008          | 17,337          | 15,782          | 4             | 3      | 3           | 7              | 4          | N      | 3       |
| 2   | 3/5/2009          | 30,296          | 11,491          | 4             | 4      | 0           | 4              | 3          | 8      | N       |
| 3   | 11/14/2007        | 28,357          | 5,473           | 2             | 0      | 2           | 0              | 5          | 5      | 0       |
| 4   | 11/28/2007        | 13,254          | 2,966           | 4             | 3      | 2           | 0              | 4          | 6      | 4       |
| 5   | 6/17/2008         | 24,793          | 6,667           | 3             | 1      | 3           | 6              | 6          | N      | 2       |
| 6   | 9/4/2009          | 29,944          | 14,364          | 4             | 3      | 0           | 4              | 3          | 7      | 1 N     |
| 7   | 3/9/2007          | 60,793          | 10,944          | 4             | 3      | 0           | 4              | 3          | 7      | 1 N     |
| 8   | 6/5/2008          | 39,121          | 12,205          | 4             | 3      | 4           | 0              | 4          | 7      | 8 Y     |
| 9   | 4/10/2008         | 19,134          | 4,746           | 3             | 0      | 2           | 0              | 4          | 5      | 3 Y     |
| 10  | 4/10/2008         | 29,171          | 9,529           | 3             | 3      | 2           | 1              | 3          | 5      | 3 Y     |
| 11  | 11/1/2011         | 29,559          | 6,946           | 4             | 4      | 4           | 0              | 5          | 5      | 0 N     |
| 12  | 10/27/2005        | 17,240          | 19,315          | 4             | 3      | 0           | 3              | 4          | 7      | 2 N     |
| 13  | 9/26/2008         | 24,019          | 18,749          | 4             | 4      | 0           | 4              | 4          | 8      | 2 N     |
| 14  | 3/16/2008         | 23,087          | 15,782          | 4             | 0      | 2           | 2              | 3          | 5      | 8 N     |
| 15  | 6/3/2009          | 27,068          | 15,608          | 4             | 4      | 0           | 4              | 4          | 7      | 7 N     |
| 16  | 2/5/2010          | 40,198          | 28,596          | 4             | 4      | 0           | 4              | 3          | 7      | 2 Y     |
| 17  | 9/4/2009          | 31,641          | 11,275          | 4             | 4      | 0           | 4              | 4          | 7      | 1 N     |
| 18  | 4/30/2009         | 21,586          | 19,487          | 4             | 3      | 0           | 4              | 4          | 7      | 6 Y     |
| 19  | 3/22/2010         | 30,162          | 9,057           | 4             | 3      | 0           | 2              | 3          | 7      | 4 N     |
| 20  | 2/11/2009         | 41,331          | 19,259          | 4             | 4      | 0           | 4              | 4          | 8      | 3 Y     |
| 21  | 3/5/2009          | 29,526          | 7,322           | 4             | 2      | 2           | 0              | 5          | 5      | 3 N     |
| 22  | 3/9/2007          | 24,707          | 32,975          | 4             | 4      | 0           | 4              | 4          | 7      | 7 N     |
| 23  | 10/5/2010         | 23,221          | 18,860          | 4             | 4      | 0           | 4              | 4          | 9      | 6 N     |
| 24  | 2/24/2008         | 15,782          | 16,909          | 4             | 3      | 4           | 0              | 4          | 9      | 8 N     |

Note. pro/perm = protected/permitted.

aLocations are not identified for due to data confidentiality (listed from 1 to 24).

bAverage AADT during before enforcement.

cEstablishments within 1,000 ft. from the center of an intersection.

dPedestrian volume 1 (3,200 ped/day), 2 (1,500 ped/day), 3 (700 ped/day), 4 (240 ped/day), and 5 (50 ped/day) (AASHTO 2010).

ePresence of educational establishment; Y = yes or N = no.

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**Figure 1.** Before and after total crashes.

**Figure 2.** Before and after angle crashes.
focused on crashes at urban intersections with speed limits equal to or less than 45 mph. Although there are crash costs for every individual KABCO severity scale (K = fatal; A, B, C = injury levels; O = no injury), fatal and injury crash costs were aggregated for this analysis as per common practice. This was done to limit the potential bias from fatal crashes that have large values but very few samples. The crash cost used were $64,468 for angle FI crashes, $44,687 for rear-end FI crashes, $91,917 for all FI crashes, $8,673 for angle PDO crashes, $11,463 for rear-end PDO crashes, and $7,068 for all PDO crashes (Council, Zaloshnja, et al. 2005). All crash values are in 2001 dollars.

The economic estimates of crash cost benefit results are presented in Table 3. RLCs in Missouri showed a positive net economic benefit of $35,269 per site per year in 2001 dollars (approximately $47,000 in 2015 dollars). It translated into an overall 5.0% economic crash benefit. The results are similar to the estimates from previous research (Council, Persaud, Eccles, Lyon, Griffith 2005; Council, Persaud, Eccles, et al. 2005).

### Table 3. Economic effects.

| Empirical Bayes estimates | Crash type       |               |               |               |
|---------------------------|------------------|---------------|---------------|---------------|
|                           | Right angle      | Rear end      | All           |               |
| Crash cost without RLC    | $8,220,077       | $11,080,705   | $33,960,325   |               |
| Crash cost after RLC      | $7,128,809       | $11,644,164   | $32,267,427   |               |
| Dollar crash cost benefit, all treated facilities | $1,091,268 | $-5563,459 | $1,692,898 |               |
| Dollar crash cost benefit by treated facility per year | $22,735 ($3,374) | $-11,739 ($3,779) | $35,269 ($6,433) |               |
| % Crash cost benefit      | 12.3% (1.8%)     | -5.1% (1.7%)  | 5.0% (0.9%)   |               |

a Crash cost ($SE) in 2001 dollar costs.
b Crash cost benefit% (SE %), all significant at the 95% confidence level. Negative values indicate an increase in costs.

### Discussion

RLC programs have been controversial over the years. RLC effectiveness has been questioned on different accounts such as research methodology, political pressure, revenues, and statutory authority. Despite the controversies, RLCs have been found to improve safety but exhibit certain trade-offs. The results of this study, using unbiased statistical methods, are in line with previous research. The Missouri results found a decrease in right-angle crashes by 11.6% and an increase in rear-end crashes by 16.5%. For FI crashes, there was a reduction in both right-angle and rear-end crashes of 14.5 and 10.9%, respectively. PDO crashes were reduced by 11.2% for angle crashes, but there was an increase of 23.1% in rear-end crashes. The results from the crash economic evaluation showed a net economic benefit of $35,269 per site per year in 2001 dollars (approximately $47,000 in 2015 dollars). This translated into a 5.0% overall economic crash cost benefit. At the disaggregate level, 11 sites experienced an overall crash reduction, and 16 sites experienced reductions in right-angle crashes. On the other hand, there was an increase in rear-end crashes at 15 sites. The main controlling factors in the data base were the major road AADT, speed limit, and left turn signal control.

Effective automated enforcement could be accomplished with the application of transportation safety research. The candidate intersections should be evaluated by considering geometric and operational features. The HSM methodology and the application of rigorous statistical methods such as empirical Bayes provide accurate estimates accounting for regression to the mean bias. Right-angle and rear-end crashes are 2 primary crash types of interest. The distribution of these types of crashes could be analyzed to identify facilities with abnormally high crash frequencies. It is important to consider measures of exposure, including speed limits and traffic volumes by movements (left/right turns and through movements).

The integration of automated enforcement should be closely related to local signal design, safety strategies, legislation, and driver behavior. RLC technology has developed into its own industry, a provider of a service rather than a provider of safety. Thus, a community would need to consider how RLCs could

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**Figure 3.** Before and after rear-end crashes.

**Table 2.** Aggregated RLC safety effectiveness results.

| Type                   | Severity | TOT     | FI      | PDO     |
|------------------------|----------|---------|---------|---------|
| All crashes            | −1.6% (3.9%, 0.6847) | 7.4% (7.3%, 0.3073) | −3.8% (4.5%, 0.4037) |
| Angle crashes          | 11.6% (6.6%, 0.0817)  | 14.5% (11.4%, 0.2034) | 11.2% (7.9%, 0.1550) |
| Rear-end crashes       | −16.5% (6.3%, 0.0088) | 10.9% (8.5%, 0.1997) | −23% (7.5%, 0.0019) |

a The results are safety effect % (SE %, P value), and negative values represent an increase in crashes.
fit into an overall traffic safety program. State legislatures could adopt guidelines promoted by federal agencies and uniform law committees to develop state statutes that would balance procedural safeguards with safety. The involvement of different stakeholders could contribute to the effective selection of sites and implementation of RLCs. As shown by Missouri data, judicious deployment of RLCs will help to reduce opposition and increase traffic safety at suitable signalized intersections.

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