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MARYLAND DEPARTMENT OF TRANSPORTATION
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RESEARCH REPORT

Evaluating the Impacts of Red Light Camera Deployment on Intersection Traffic Safety

Sung Yoon Park, Chien-Lun Lan, and Gang-Len Chang

Department of Civil & Environmental Engineering
University of Maryland-College Park
College Park, MD 20742

FINAL REPORT

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16. Abstract

Red-light cameras (RLC) are a popular countermeasure to reduce red-light running and improve intersection safety. Studies show that the reduction in side impact crashes at RLC intersections are often accompanied by no-change or an increase in the number of rear-end collisions. Part I of the study used crash data to evaluate twenty-seven RLC locations in Maryland. Part II conducted behavior observations at eight intersections to investigate if RLC impacts driver behavior, especially their responses to a yellow light. The eight intersections, two three-intersection clusters and two individual intersections, are in Montgomery and Prince George’s counties of Maryland. An intersection cluster includes a RLC intersection, and an upstream and a downstream non-RLC intersections for control comparisons. Findings indicate that a properly deployed RLC system can lead to the following impacts: (1) a reduction in side impact crashes; (2) changes in rear-end collisions depending on the local driving populations, (3) a reduction in aggressive driving behavior at the RLC and its downstream intersections; (4) more drivers reduce speeds when passing through a yellow phase, (5) more drivers choose to stop when encountering a yellow phase; and (6) less red-light-running vehicles.

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1. Introduction

Federal and state transportation agencies have devoted considerable resources over the past decades to education, engineering, enforcement, and deployment of safety strategies. Red-light cameras (RLC) are a popular countermeasure to reduce red-light running and improve intersection safety. The reduction in side impact crashes at RLC intersections, however, is sometimes accompanied by no-change or an increase in the number of rear-end collisions. In addition, whether multiple deployments of RLC in a traffic network can change driving habits (e.g., motorists drive less aggressively) remains to be determined. As transportation agencies continue to extend the use of RLC, it is imperative to rigorously review the past deployment results to identify effective designs at appropriate intersections and avoid undesirable effects.

1.1 Research Objectives

Previous research concluded that intersection crashes are the consequence of complex interrelations between engineering designs, signal controls, and behavioral discrepancies of local driving populations. Rather than generalize and be overly influenced by other research, it is necessary to collect location-specific data to evaluate the benefits/effectiveness of any deployed counter measure. The following objectives were set for this study:

- To assess the effectiveness of RLC systems in reducing various types of intersection crashes using location-specific data.
- To understand the impact of RLC systems on driver behaviors, including their approaching speeds and responses to the signal yellow phase.

1.2 Organization of this Report

The project consists of two parts. Part I evaluated the effectiveness of RLC deployments at 27 local intersections over the past decade, including a comparison with those findings in the literature with respect to reducing rear-end collisions and side-impact crashes. Based on the findings discussed in Part I, Part II investigated the impact that RLCs had on driver behaviors, especially their responses to the yellow phase.

Empirical observations of drivers at the upstream and downstream intersections at two RLC intersection clusters were conducted and potential differences in response to the presence of the RLC at these intersections were analyzed. A comparison of results and critical findings on the influence of the RLC on intersection safety constitutes the core of the project. The report is organized as follows.

Section 2 presents a literature review on the safety impacts of a RLC system, analyzing state-of-the-practice reports by public agencies and state-of-the-art publications in the research community. Key factors identified in the study scope of each RLC report and the changes in rear-end and side-impact crashes were given special attention.

The findings with respect to RLC's effectiveness were classified into four categories: reduction in both side-impact crashes and rear-end collisions; reduction in side-impact crashes only; reduction in rear-end collisions only; and no influence or a minor increase in rear-end collisions. Operational guidelines developed by both federal and state agencies were included in the review. The findings on the "spillover effect" of RLC deployment were also included in this section.

Section 3 presents the before-and-after study conducted at 27 RLC intersections in Maryland, which revealed similar inconsistent RLC effectiveness similar to what was reported in the literature. A discussion on critical factors contributing to either a reduction or increase in crash patterns was included.

Section 4 presents the results of field observations and the empirical analyses on the differences in traffic characteristics and driver responses to the yellow phase at the RLC-effective and ineffective intersections. Note that over 1,000 drivers were observed on their approaching speeds, acceleration/deceleration rates, and responses to the yellow phase at the two RLC intersection clusters and two additional individual RLC intersections. The comparison between key variables observed at RLC intersections and those at the neighboring intersections shed light on the inconsistent effects of the RLC program on traffic safety.

Section 5 summarizes the final research findings and some suggestions for additional traffic data to be included in the pre-deployment assessment and the development of a deployment guideline.

2. Review of Red-Light Camera Related Studies

2.1 Introduction

In light of the large body of literature on red-light camera (RLC) related issues, this section contains a review of primary studies on two pressing issues: guidelines for RLC deployment and the evaluation of the RLC program's effectiveness. The section first provides a concise description of the state of the practice by most responsible agencies in decision making. A summary of their implementation results follows, with a focus on the RLC program's effectiveness and potential outcomes. Suggested research on other critical issues is also covered in this section.

The Federal Highway Administration's (FHWA) RLC deployment guidelines serve as the basis for analyzing the state of the practice. Other practices or guidelines adopted by various state highway agencies or local jurisdictions are used to complement the FHWA guidelines. For convenience of reporting, this study classifies reports into the following categories:

Type-1: reduction in both side-impact crashes and rear-end collisions;
Type-2: reduction in side-impact crashes but not rear-end collisions;
Type-3: reduction in rear-end collisions but not side-impact crashes;
Type-4: reduction in neither type.

The robustness of field evaluation findings and sampling biases, are discussed at the end of this section.

2.2 Review of RLC Deployment Guidelines

Both FHWA and several states developed RLC deployment guidelines. Aside from some minor variations, most guidelines are consistent in principle and share the following common key steps:

Step-1: Establish the Program Objectives
The first step is to define, as clearly as possible, the objectives of the RLC program. Nearly all state guidelines require the the following tasks: collection of red-light-running data at a candidate site, investigation of contributing factors, and evaluation of potential benefits from the RLC installation. For example, poor signal visibility and insufficient yellow phase duration are often the contributing factors to red-light running. Such guidelines call for a rigorous review of signal and geometric designs first, and a comprehensive analysis of the driver compliance rate and other safety performance measures should follow. Proper engineering countermeasures must first be implemented, and the installation of RLCs is viewed as a last resort.

Step-2: Launch a Review Committee
After identifying a candidate RLC deployment site, the next step is to obtain approval from state authorities to proceed with the installation. Most states require local authorities to submit documents including crash counts at the proposed intersection and the results of an engineering study. The latter requirement serves to identify the contributing factors to red-light running.

Step-3: Initiate a Public Awareness Campaign
Once the RLC installation is justified and approved, the next step is to enhance public awareness of the RLC installation. A well-designed public awareness and information campaign helps motorists understand the safety issues at the intersection.

Step-4: Installation of Red Light Cameras

The actual RLC installation includes the following considerations:

- Cameras must be stored in a box and located at the top of 15-foot poles to shield them from environmental impacts and vandalism.
- One red-light camera can typically cover up to the three closest travel lanes.
- The RLC system includes a computer to process detected images, the induction-loop triggers, and the traffic light circuit to monitor the traffic signal and triggers.
- The camera will not be activated unless the signal turns to a red phase. If a vehicle is in the middle of the intersection when the signal turns red, the system shall not be activated.
- To activate the RLC system, the signal must be in the red phase, and a vehicle must cross the induction-loop triggers over a preset speed threshold.
- If a vehicle passes over both induction loop triggers relatively quickly after the signal turns to the red phase, the system will be activated, and the cameras shall take two photos of the vehicle: one showing the vehicle entering the intersection and the other capturing the vehicle in the middle of the intersection. The photos will clearly show the vehicle crossing the stop line during the red phase and continuing through the intersection.
- If a picture of the driver is required, the RLC system can take an additional photo of the vehicle from the front to capture an image of the driver.

Table 1 summarizes the key recommendations of the guidelines developed by federal and state agencies, including necessary next steps.

Table 1: A Summary of Key Steps Shown in the Available RLC Deployment Guidelines

Agency	Key steps
FHWA (2005)	*Step-1: Investigate intersection safety* Data may be obtained from the following sources: - crash statistics and investigation records maintained by law enforcement and traffic engineering agencies; - crash statistics maintained by insurance companies, if available; - counts of citations issued by law enforcement officers for red light running; - camera surveys of driver behavior at intersections, including counts of red light violations; - field observations of driver behavior at intersections, including speed surveys, by trained personnel; - complaints or other inputs from motorists and the general public. *Step-2: Execute an engineering study* An engineering study should be conducted to determine the factors contributing to red-light running and to identify appropriate countermeasures, including: - intersection engineering improvements; - traffic operations and signal control; - intersection geometry changes; - education; - traditional enforcement by law enforcement officers.

<table>
<tr><th>Agency</th><th>Key steps</th></tr>
<tr><td></td><td>Step-3: Implement red light camera program if other countermeasures are not effective on the sites
Key steps to successfully implement a red light camera system program include:
- early planning and startup;
- establish a steering committee;
- establish program objectives;
- identify the legal requirements;
- assess system procurement alternatives;
- establish a public awareness and information campaign;
- system planning such as building violations processing procedure;
- site selection based on accurate crash and red light violations data;
- install warning signs;
- establish traffic signal yellow times with Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD);
- select system and technologies;
- engineering design of red light camera systems;
- prepare and sign the red light camera system installation plans by an appropriately licensed engineer;
- red light camera system installation;
- on-going public information and education;
- operations and maintenance plan;
- on-going system assessment.</td></tr>
<tr><td>Alabama (2015)</td><td>Step-1: Identify red-light running problem
Identify and confirm the red-light-running safety problem, including:
- conduct an engineering analysis to identify the factors that may cause the problem;
- identify alternative countermeasures that could solve the problem
- select the most appropriate single or combined set of countermeasures;
- implement the countermeasures and monitor the solution to determine their effectiveness.

Step-2: Implement red light running camera if other countermeasures are not effective on the sites
All principal activities to be done at this step are identical to those specified in the FHWA’s guidelines.

Step-3: Submit the evaluation reports every year</td></tr>
<tr><td>Colorado (2016)</td><td>Step-1: Collect crash data over a minimum of (3) years of recent crash data

Step-2: Implementation of possible engineering countermeasures

Step-3: Provide optional supplemental information</td></tr>
</table>

Agency	Key steps
	Step-4: Analyze the supplemental red light violation data *Step-5: Summarize the final site selections for approval*
Delaware (2016)	*Step-1: Identify all candidate intersections* Identify candidate intersections for RLC, in the following manner: - rank all intersections (highest to lowest) by the total number of red-light running crashes using the most recent five years of available crash data; - eliminate unqualified intersections where it is unfeasible to install RLC; - improve all such intersections with signal reconstruction. *Step-2: Re-rank top-ranked intersections by approach based on a review of police reports* *Step-3: Evaluate if other types of engineering solutions are feasible to install and operate the RLC equipment* *Step-4: Submit the candidate locations for approval by the legislators*
Iowa (2013)	*Step-1: Provide the department a justification report* Conduct the following steps: - document existing traffic speeds, posted speed limits, traffic volumes, and intersection or roadway geometry; - document all applicable crash history, the primary crash types, crash causes, crash severity, and traffic violations—only crashes attributable to speeding or the running of a red light shall be included in this report; - compare crash data with other similar locations within the local jurisdiction, other jurisdictions, or larger metropolitan area; - identify the critical traffic safety issue(s). *Step-2: Provide a comprehensive list of countermeasures that may address the critical traffic safety issue(s), including documentation of the solutions or safety countermeasures that have been implemented along with those that have been considered but not implemented* *Step-3: Document all discussions held and actions taken with partnering agencies* Include the following: - those who have the resources to help reduce crashes attributable to speeding or the running of a red light; - report why the local jurisdiction believes automated enforcement is the best solution to address the critical traffic safety issue(s). *Step-4: Submit a request and a justification report to the appropriate*

Agency	Key steps
	district engineer department review Take the following steps: - notify the public and post the information on the department's website; - indicate the use of the automated enforcement to reduce red light running; - set up the minimum requirements for automated traffic enforcement systems; - post the permanent signs in advance of the locations where enforcement systems are in use. *Step-5: Perform periodic calibrations of automated traffic enforcement systems* *Step-6: Evaluate the effectiveness of RLC after the installation*
Florida (1998)	*Step-1: Site selection for installing the RLC* Selection based on: - traffic crash data; - traffic citation data; - law enforcement officer observations; - video surveys of violations. *Step-2: Execute a traffic engineering study (signed and sealed by a Florida licensed Professional Engineer)* *Step-3: Submit the request to FDOT for approval*
Louisiana (2010)	*Step-1: Submit potential permit location request* *Step-2: Submit engineering report* *Step-3: Complete red light running countermeasures* *Step-4: Implement red light running camera if other countermeasures are not effective on the sites*
Oregon (2015)	*Step-1: Provide the report to justify the RLC system, including a proper sight distance, and design of speed zones consistent with the Manual on Uniform Traffic Control Devices for Streets and Highways and ODOT's "Traffic Signal Policy and Guidelines"* *Stept-2: Ensure that the yellow and red clearance intervals are consistent with ODOT's "Traffic Signal Policy and Guidelines" or other jurisdiction's adopted policy* *Step-3: Ensure that the corridor progression timing does not contribute to red light running* *Step-4: Ensure the traffic signal timing is consistent with traffic volume, speed and specific intersection design elements*

Agency	Key steps
	Step-5: Implement the RLC system and concurrently provide a public information campaign and sign to inform drivers *Step-6: Provide safety and operations reports, based on the crash history, safety concerns, operations, and maintenance issues* *Step-7: Initiate public information campaigns, and implement the RLC program* *Step-8: Submit a biennial report to address the effect of using cameras on traffic safety, the degree of public acceptance, and the process of administration*
Virginia (2008)	*Step-1: Select the candidate intersections* Intersections should be based on: - the crash rate for the intersection, the rate of red-light violations; - the difficulty experienced by law-enforcement officers to apprehend violators; - the ability of law-enforcement officers to apprehend violators safely within a reasonable distance from the violation. *Step-2: Complete an engineering safety analysis* Base analysis on intersection geometric and signal data, traffic data, and crash and enforcement data. *Step-3: Submit the report for approval by the state department* *Step-4: Conduct a public awareness program* *Step-5: Provide public awareness campaigns and install a warning sign* *Step-6: Evaluate the photo enforcement system on a monthly basis*

2.3 Summary of Existing Evaluation Reports of RLCs

The review of RLC's safety in this study covered 16 states, including AZ (2005), CA (2002), DL (2015), FL (2014), IA (2007), LA (2010), MD (2007), NC (2004), NJ (2012), NY (2014), OR (2005), TN (2009), TX (2015), VA (2010), WA (2007), and WI (2006). Some findings reported in technical journals and studies conducted by cities were also included in this review. The safety impacts of the RLC deployment were classified into the following categories:

Type-1: reduction in both rear-end collisions and side-impact crashes (see Table 2)
Type-2: reduction only in side-impact crashes but not in rear-end collisions (see Table 3)
Type-3: reduction only in rear-end collisions but not in side-impact crashes (see Table 4)
Type-4: no significant impacts (e.g., insignificant increase or reduction) in both side-impact crashes and rear-end collisions (see Table 5)

It should be noted that the evaluation reports from WA (2007) and WI (2006) were not included the tables because they documented only the reduction of 24% and 35% in the total number of crashes respectively, without distinguishing the statistics between rear-end collisions and side-impact crashes.

These evaluation results shown in the tables showed that RLC deployments reduced both rear-end and side-impact crashes in 10 cities and one county, and only side-impact crashes in 28 cites, 5 counties and 10 papers. The reduction of only rear-end collisions were reported in one city by Cunningham and Hummer (2010). Evaluation studies from 21 cities and three counties showed no significant effect on reducing either type of intersection crash (Claros *et al.,* 2017).

These inconsistencies in the literature on the RLC effectiveness are likely attributed to the following factors:

- An inconsistent number of intersections selected for the evaluations: for example, the RLC evaluation conducted in Suffolk, New York (Popolizio, 1995) covers 104 intersections; however, a similar study in Davie, Florida focuses on only one intersection (Florida Department of Highway Safety and Motor Vehicles, 2014).
- An inconsistent number of years selected for the "before" and "after" periods for statistical comparison of crash patterns.
- Inconsistent methodologies adopted for before-and-after comparisons, including, but not limited to, Poisson regression, Empirical Bayesian, Naïve before-and-after tests, student t-test, and E-tests.
- Any significant change in critical safety factors during the target "before-and-after" periods.
- The behavioral discrepancies of the driving populations, especially with respect to their responses to the yellow phase under different traffic conditions at RLC intersections.

Of all the factors listed, the behavior of driving populations is likely to be the most critical one. Rigorous empirical studies to compare drivers' responses to the yellow phase at RLC and non-RLC intersections are essential to a better understanding of driver behavior.

2.4 Spillover Effects

When performing evaluations of RLC programs, this study took particular care in addressing two major issues. The first is the regression to mean effect, which is used to reflect the random nature of crashes. For example, an intersection experiencing a high crash frequency in one year, is more likely to have fewer crashes in the following years. Failing to account for such an effect may result in overestimating the actual RLC's safety impacts.

The second is the so called "spillover" or "halo" effect, a widely recognized RLC safety influence on nearby intersections by the traffic community. It is likely caused by jurisdiction-wide publicity of the presence of cameras and the fact that the general public does not know the exact RLC location (Persaud *et al.*, 2005). Many studies (Retting *et al.*, 1999a; Retting *et al.*, 1999b; Persaud *et al.*, 2005; Hobeika and Yaungyai, 2006; Martinez and Porter, 2006; Høye, 2013) confirmed that the spillover effect is significant and needs to be included in RLC performance evaluations.

For example, Persaud *et al.* (2005) adopted the empirical Bayesian method to estimate the spillover effect by calculating the difference between the expected number of crashes and the number of actual crashes reported in the after period at similar intersections without cameras near the monitored RLC intersections. Høye (2013) used meta-analysis to evaluate the spillover effect by comparing crash statistics from the non-RLC approaches of RLC intersections with those from nearby non-RLC intersections. Such studies consistently agreed upon the existence of the spillover effect.

2.5 Summary

Regardless of certain methodological deficiencies and potential poor data quality issues, the following conclusions were observed from the existing RLC evaluation studies:

- RLC-deployment in most scenarios helped reduce side-impact crashes.
- The impact on rear-end collisions could be either positive or negative, and the underlying reasons are yet to be investigated by the traffic community.
- For the RLC program to achieve the anticipated level of effectiveness, rigorous guidelines must be developed.
- Both regression to mean and the spillover effects should be considered in evaluations.

Table 2: List of Cities/Counties/Papers where RLC is Effective on both Rear-End and Side-Impact Crashes

Types of studies	City/County	State	Method	Before Period (Year)	After Period (Year)	Total Period (Year)	No. of int.	Effectiveness			
								Side-Impact	Left Turn	Rear End	Total (all kinds of crashes)
Reports	Brooksville (2014)	FL	Naïve Before & After Analysis	1	1	--	7	Y	--	Y	Y
	Clermont (2014)	FL	Naïve Before & After Analysis	1	1	--	4	Y	--	Y	Y
	Davie (2014)	FL	Naïve Before & After Analysis	1	1	--	1	Y	--	Y	Y
	Miami (2014)	FL	Naïve Before & After Analysis	1	1	--	50	Y	--	Y	N
	Pinecrest (2014)	FL	Naïve Before & After Analysis	1	1	--	4	Y	--	Y	Y
	Council Bluffs (2007)	IA	Comparison and Control	3	1	--	54[1]	Y	--	Y	Y
	Davenport (2007)	IA	Empirical Bayesian	3	2	--	45[1]	Y	--	Y	Y
			Comparison and Control	3	2	--	45[1]	Y	--	Y	Y
	Howard[2] (2007)	MD	Naïve Before & After Analysis	--	--	10	25	Y	--	Y	Y
	Portland (2005)	OR	Naïve Before & After Analysis	4	4	--	5	Y	--	Y	Y
	Knoxville (2009)	TN	Naïve Before & After Analysis	1	1	--	15	Y	--	Y	Y
	Austin (2015)	TX	Naïve Before & After Analysis	1.5	7	--	11	Y	Y	Y	Y

[1] Control site
[2] County

Table 3: List of Cities/Counties/Papers where RLC is Effective only on Side-Impact Crashes

Types of studies	Author/City /County	State	Method	Before Period (Year)	After Period (Year)	Total Period (Year)	No. of int.	Effectiveness			
								Side-Impact	Left Turn	Rear End	Total (all kinds of crashes)
Reports	Phoenix (2005)	AZ	Empirical Bayesian	3	2	--	10	Y	N	N	N
	Scottsdale (2005)	AZ	Empirical Bayesian	6 to 13	1 to 6	--	14	Y	N	N	Y
	San Diego (2002)	CA	Naïve Before & After Analysis	3	3	--	19	Y	--	N	N
	New Castle[1], Sussex[1], Newark, Elsmere, Dover, Seaford (2015)	DL	Naïve Before & After Analysis	3	9	--	30	Y	--	N	N
	Apopka (2014)	FL	Naïve Before & After Analysis	1	1	--	4	Y	--	N	N
	Boynton Beach (2014)	FL	Naïve Before & After Analysis	1	1	--	4	Y	--	N	N
	Campbellton (2014)	FL	Naïve Before & After Analysis	1	1	--	1	Y	--	N	Y
	Fort Lauderdale (2014)	FL	Naïve Before & After Analysis	1	1	--	14	Y	--	N	N
	Manatee[1] (2014)	FL	Naïve Before & After Analysis	1	1	--	6	Y	--	N	N
	New Port Richey (2014)	FL	Naïve Before & After Analysis	1	1	--	5	Y	--	N	N
	Ocoee (2014)	FL	Naïve Before & After Analysis	1	1	--	2	Y	--	N	Y
	Palatka (2014)	FL	Naïve Before & After Analysis	1	1	--	6	Y	--	N	N
	Palm Beach[1] (2014)	FL	Naïve Before & After Analysis	1	1	--	5	Y	--	N	N
	Sarasota (2014)	FL	Naïve Before & After Analysis	1	1	--	8	Y	--	N	N
	West Park (2014)	FL	Naïve Before & After Analysis	1	1	--	5	Y	--	N	Y
	Lafayette (2010)	LA	E-test	1	1	--	6	Y	--	N	-
	Greensboro (2004)	NC	Comparison and control	2.4	2.3	--	18 285[2]	Y	Y	N	Y
	Newark (2012)	NJ	Naïve Before & After Analysis	1	1	--	24	Y	--	N	N
	Suffolk[1] (2014)	NY	Naïve Before & After Analysis	3	0.16 to 3.33	--	104	Y	--	N	Y
	Amarillo (2015)	TX	Naïve Before & After Analysis	1.5	6	--	4	Y	N	N	Y
	Denton (2015)	TX	Naïve Before & After Analysis	1.5	6	--	2	Y	Y	N	Y

	Diboll (2015)	TX	Naïve Before & After Analysis	1.5	2	--	4	Y	N	N	N
	Frisco (2015)	TX	Naïve Before & After Analysis	1.5	6	--	4	Y	Y	N	Y
	Mesquite (2015)	TX	Naïve Before & After Analysis	1.5	6	--	7	Y	Y	N	Y
	Port Lavaca (2015)	TX	Naïve Before & After Analysis	1.5	4	--	6	Y	Y	N	Y
	Fairfax (2010)	VA	Empirical Bayesian	--	--	7	5	Y	--	N	Y
	Falls Church (2010)	VA	Empirical Bayesian	--	--	7	3	Y	--	N	N
	Vienna (2010)	VA	Empirical Bayesian	--	--	7	3	Y	--	N	Y
Published papers	Ahmed (2015)	--	Empirical Bayesian	3	3	--	25	Y	Y	N	--
	Council (2005)	--	Empirical Bayesian	--	--	9	132	Y	--	N	--
	Erke (2009)	--	Meta-analysis	--	--	--	--	Y	--	N	N
	Hadayeghi (2007)	--	Empirical Bayesian	--	--	5	447	Y	--	N	--
	Høye (2013)	--	Meta-analysis	--	--	--	--	Y	--	N	N
	Ko (2013)	--	Empirical Bayesian	--	--	1 to 4	254	Y	--	N	--
	Ng (1997)	--	Comparison and Control	3	3	--	42 42[2]	Y	--	N	Y
	Radalj (2001)	--	Naïve Before & After Analysis	--	--	5	58	Y	--	N	Y
	Retting (2002)	--	Regression	2.5	2.5	--	11	Y	--	N	Y
	Shin (2007)	--	Empirical Bayesian	--	--	--	60 to 156	Y	--	N	--

[1] County
[2] Control site

Table 4: List of Cities/Papers where RLC is Effective only on Rear-End Crashes

Types of studies	Author/City	State	Method	Before Period (Year)	After Period (Year)	No. of int.	Effectiveness		
							Side-Impact	Rear End	Total (all kinds of crashes)
Reports	Houston (2015)	TX	Naïve Before & After Analysis	3	1	50	N	Y	N
Published papers	Cunningham	--	Comparison and Control	5	4	14	N	Y	Y

Table 5: List of Cities/Counties/Papers where RLC Shows no Effectiveness or Negative Effects

Types of studies	Author/City /County	State	Method	Before Period (Year)	After Period (Year)	Total Period (Year)	No. of int.	Effectiveness			
								Side-Impact	Left Turn	Rear End	Total (all kinds of crashes)
Reports	Boca Raton (2014)	FL	Naïve Before & After Analysis	1	1	--	6	N	--	N	N
	Clewiston (2014)	FL	Naïve Before & After Analysis	1	1	--	2	N	--	N	N
	Jacksonville (2014)	FL	Naïve Before & After Analysis	1	1	--	23	N	--	N	N
	Lakeland (2014)	FL	Naïve Before & After Analysis	1	1	--	5	N	--	N	N
	Maitland (2014)	FL	Naïve Before & After Analysis	1	1	--	1	N	--	N	Y
	Miami Beach (2014)	FL	Naïve Before & After Analysis	1	1	--	5	N	--	N	N
	Miami Springs (2014)	FL	Naïve Before & After Analysis	1	1	--	1	N	--	N	N
	Orange[1] (2014)	FL	Naïve Before & After Analysis	1	1	--	26	N	--	N	N
	Orlando (2014)	FL	Naïve Before & After Analysis	1	1	--	5	N	--	N	N
	Osceola[1] (2014)	FL	Naïve Before & After Analysis	1	1	--	11	N	--	N	N
	Palm Coast (2014)	FL	Naïve Before & After Analysis	1	1	--	24	N	--	N	N
	Sunrise (2014)	FL	Naïve Before & After Analysis	1	1	--	7	N	--	N	N
	Tamarac (2014)	FL	Naïve Before & After Analysis	1	1	--	8	N	--	N	N
	Tampa (2014)	FL	Naïve Before & After Analysis	1	1	--	8	N	--	N	N
	West Miami (2014)	FL	Naïve Before & After Analysis	1	1	--	1	N	--	N	N
	Bedford (2015)	TX	Naïve Before & After Analysis	1.5	7	--	3	N	N	N	N
	Cleveland (2015)	TX	Naïve Before & After Analysis	1.5	6	--	3	N	Y	N	Y
	Garland (2015)	TX	Naïve Before & After Analysis	1.5	6	--	4	N	N	N	N
	Haltom City (2015)	TX	Naïve Before & After Analysis	1.5	5	--	3	N	N	N	N
	Richland Hills (2015)	TX	Naïve Before & After Analysis	1.5	4	--	2	N	N	N	N
	University Park (2015)	TX	Naïve Before & After Analysis	1.5	5	--	2	N	N	N	N
	Willis (2015)	TX	Naïve Before & After Analysis	1.5	6	--	3	N	N	N	N
	Arlington (2010)	VA	Empirical Bayesian	--	--	7	1	N	--	N	N
	Fairfax[1] (2010)	VA	Empirical Bayesian	--	--	7	13	N	--	N	Y
Published papers	Claros (2017)	--	Empirical Bayesian	2	2	--	24	N	--	N	N

[1] County

3. Before-and-After Comparison of the RLC's Effectiveness

3.1 Introduction

The purpose of the before-and-after comparison was to determine if the RLC deployments in Maryland had the same effect on side-impact crashes and rear-end collisions as reported in the literature and other states. Any discrepancy revealed may help traffic professionals to identify potential contributing factors to undesirable RLC effects (e.g., increasing rear-end collisions), and to design an effective intersection safety improvement program.

As previously stated, the dataset for the before-and-after comparison consisted of 27 RLC intersections with at least three years of in-operation period. Reliable crash records were available for each of those intersections for at least five years prior to its RLC deployment. Table 6 shows the list of intersections.

Table 6: List of RLC Intersections from Montgomery, Prince George's, and Howard Counties for Before-and-After Comparison

Montgomery County	
M1	MD 355 @ Cheltenham Dr.
M2	MD 124 @ Goshen Rd.
M3	Shady Grove Rd. @ Research Blvd.
M4	MD 355 @ Middlebrook Rd.
M5	MD 355 @ Halpine Rd.
M6	US 29 @ Fenton St.
M7	MD 355 @ Grosvenor Ln.
M8	MD 185 @ Knowles Ave.
M9	US 29 @ MD 193 EB (3-leg intersection with 3 RLCs)
M10	MD97 @ US 29 (4-leg intersection with 2 RLCs)
M11	US 29 @ Tech Rd. (4-leg intersection with 2 RLCs)
M12	MD 97 @ Nirbeck Rd. (Geometry change occurred between 2007-2012)
M13	MD 355 @ Montgomery Ln.
M14	MD 185 @ Randolph Rd.
M15	MD 650 @ Adelphi Rd. (Geometry change occurred at RLC leg)
Howard County	
H1	US 40 @ N. Ridge Rd.
H2	US 1 @ Corridor Rd.
Prince George's County	

P1	US 301 @ Gobernor Bridge Rd.
P2	MD 410 @ MD 450
P3	US 301@ Old Indian Head Rd.
P4	MD 410 @ 64th Ave.
P5	US 301 @ McKendee
P6	MD 212 @ Adelphi Rd.
P7	MD 410 WB @ Ager Rd.
P8	MD 223 @ Old Branch Rd.
P9	MD 301 @ Pointer Ridge Dr. (4-leg intersection with 2 RLCs)
P10	MD 458 @ Marlboro Pike. (4-leg intersection with 2 RLCs)

The collected crash data included not only the frequency of side-impact crashes and rear-end collisions but also their severity levels, classified as Property-Damage-Only (PDO), injury, and fatality.

To ensure the robustness of the findings, the study explored the following six time spans in the effectiveness comparison:

- Type-1: five years before and three years after implementation
- Type-2: three years before and three years after implementation
- Type-3: two years before and three years after implementation
- Type-4: five years before and two years after implementation
- Type-5: three years before and two years after implementation
- Type-6: two years before and three years after implementation

Note that by varying the time spans from the available five years before and three years after data period, the research team was able to assess the sensitivity in the comparison results. Definitive conclusions can then be reached if all findings are consistent across all six data sets. A side-by-side comparison of crash patterns between each candidate intersection's RLC leg and non-RLC legs was also conducted to further investigate the likelihood that the discrepancy in the crash pattern before-and-after the RLC deployment could be attributed to other factors such as volume increase or changes in the driving populations (e.g., new land developments).

3.2 Procedures for Before-and-After Comparisons

The intersection of MD 355 @ Halpine, Rockville was chosen to illustrate the comparison procedure. The evaluation summary using different data sets followed. An evaluation of the consistency of the results with respect to the crash patterns at the RLC and non-RLC legs at each intersection over various before-and-after periods was also included.

Comparison of the Total Crash Frequency

Figure 1 shows the geometric features of the MD 355 @ Halpine Road intersection, where the RLC was installed on the MD 355 southbound approach in August 2012. The crash data from 2007 to 2011 was patterns during the "before" period, and the data from 2013 to 2015 were considered the “after” period. The traffic volume was relatively stable over the selected before and after periods.

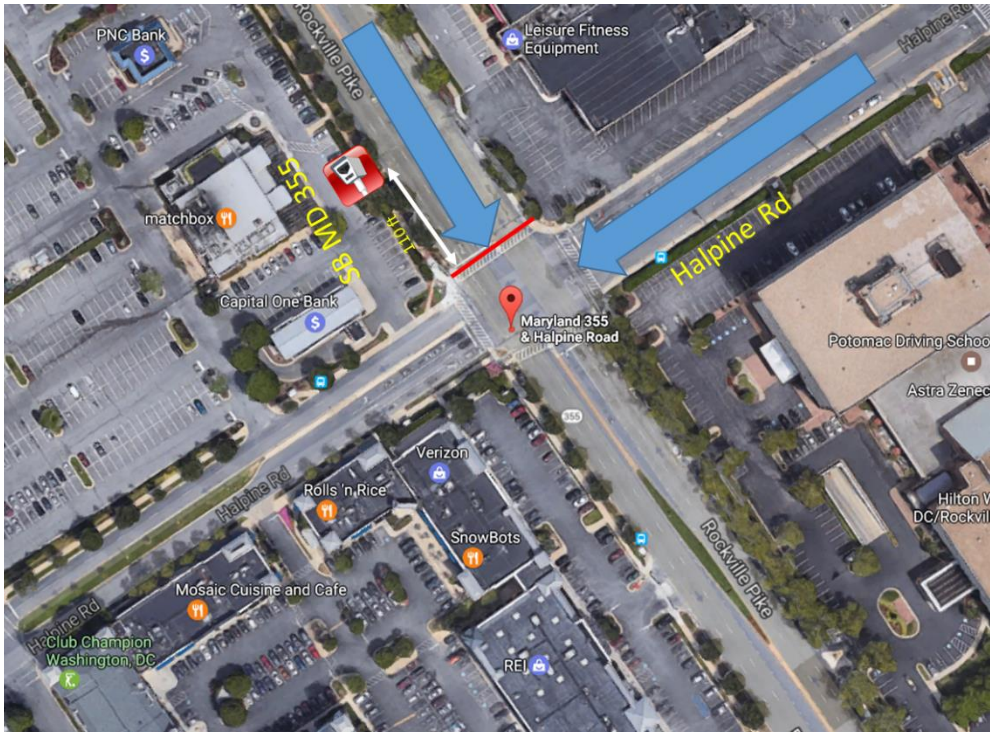


Figure 1: Geometric Features of the MD355@Halpine Intersection

Figure 2 shows the crash data at the RLC and non-RLC approaches during the before and after periods at the intersection of MD 355 @ Halpine Road using the actual annual frequency as the baseline measurement. It is obvious from the displayed patterns that the average crash frequency varied depending on the time span selected. For example, if the crash data from the two years before period was used as the baseline to compare to the three-year crash data in the after period, then the conclusion was either “no change” or “an increase” in the frequencies of side-impact crashes. A quite different conclusion, however, was reached if the crash data from the five years before period is used. For this reason, this study restructured the data from five years before and three years after installation into the six time span combinations.

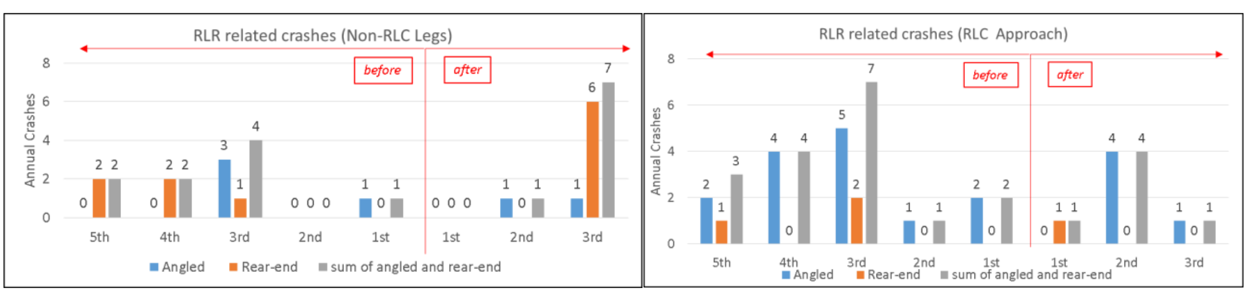
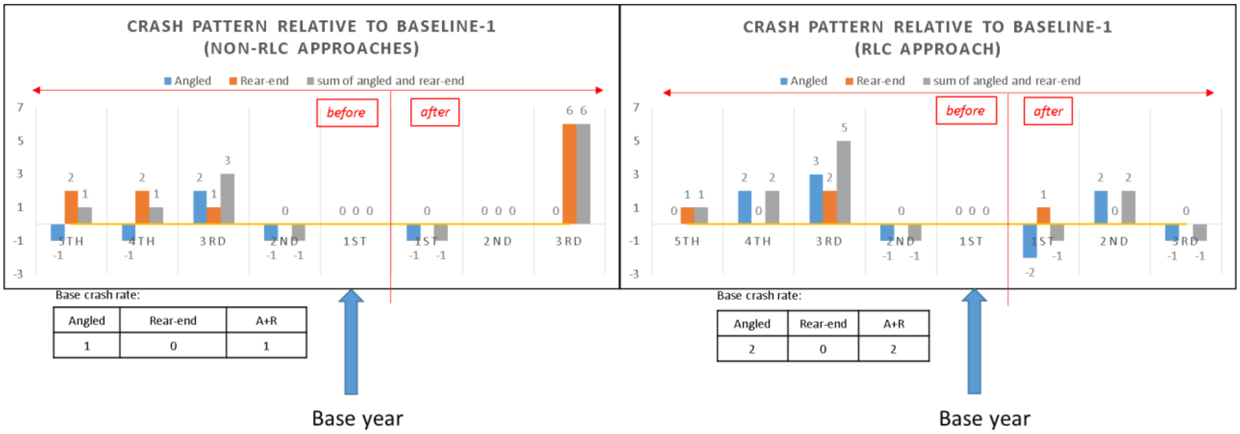


Figure 2: Frequency Distribution of Side-Impact Crashes and Rear-End Collisions during the Before-and-After Period at MD 355 @ Halpine Intersection

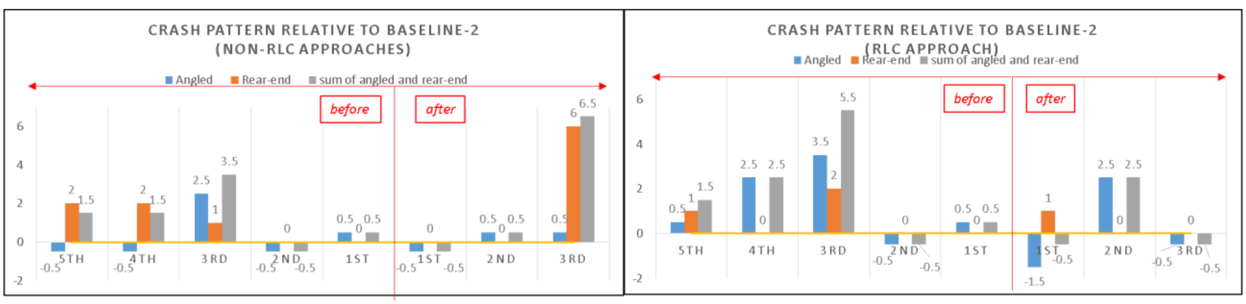
Figure 3 illustrates the frequency distribution of such crash data at the RLC and non-RLC approaches using the one year before period as the baseline. Figure 4 displays the same frequency distribution using the two years before period as the baseline. Figure 5 presents three years before period results.



Angled	Rear-end	A+R
1	0	1

Angled	Rear-end	A+R
2	0	2

Figure 3: Before-and-After Analysis of Crash Frequency at MD 355 @ Halpine Intersection (using the data in the year before the RLC deployment as the basis for comparison)



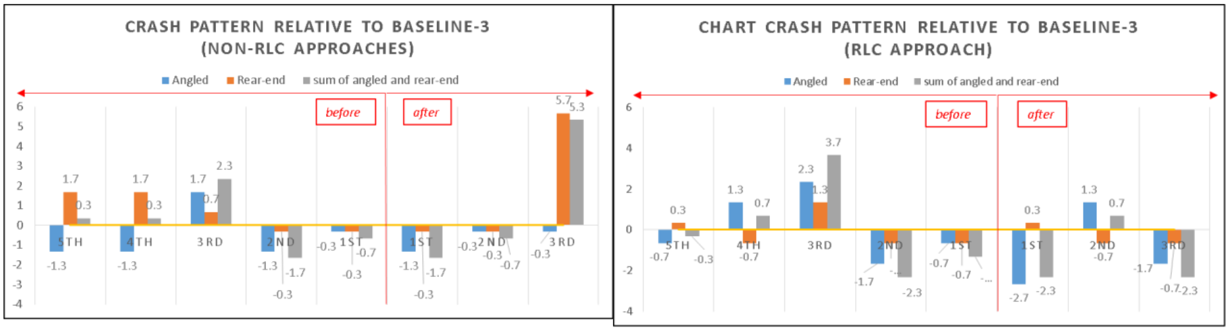
Base crash rate:

Angled	Rear-end	A+R
0.5	0	0.4

Base crash rate:

Angled	Rear-end	A+R
1.5	0	1.5

Figure 4: Before-and-After Analysis of Crash Frequency at MD 355 @ Halpine Intersection (using the average of two years before the RLC deployment as the basis for comparison)



Base crash rate:	Angled	Rear-end	A+R
	1.3	0.3	0.6

Base crash rate:	Angled	Rear-end	A+R
	2.7	0.7	3.4

Figure 5: Before-and-After Analysis of Crash Frequency at MD 355 @ Halpine Intersection (using the average of three years before the RLC deployment as the basis for comparison)

Comparison of the Frequency and Severity Levels

To further assess the impact of the RLC deployment on traffic safety, a before-and-after analysis on the severity levels was performed. The analysis procedures were identical to the before-and-after analysis on crash frequency. The crashes were classified as property-damage-only (PPO), injury and fatality severity levels.

Comparison of the Crash Patterns at Each Intersection's RLC and Non-RLC Approaches

Instead of using the total number of side-impact crashes or rear-end collisions at each intersection during the before-and-after period, it was essential to determine if any detected significant discrepancy was due to the presence of the RLC on the specific intersection approach. To investigate this critical issue, this study took the following steps:

- Step-1: classified the side-impact crashes and rear-end collisions at each intersection by whether they were on the RLC-leg or non-RLC legs;
- Step-2: conducted before-and-after comparison for the side-impact crashes on the RLC-leg;
- Step-3: conducted before-and-after comparison for the side-impact crashes on the non-RLC-legs;
- Step-4: performed a consistency comparison between RLC and non-RLC legs;
- Step-5: repeated the steps above to analyze the rear-end collision data and proceeded with the consistency comparison.

It is possible one may not be able to definitively attribute the reduction in crash frequency to RLC deployment if the data shows that the same changes in the crash patterns on both RLC and non-RLC legs. In contrast, one may view the presence of RLC as having a positive effect on reducing crashes if only the RLC-leg is shown to exhibit a statistically significant decreasing pattern during the target period of comparison.

3.3 Summary of the Before-and-After Comparison Results

Table 7 shows the before-and-after comparison results. The results for both side-impact crashes and rear-end collisions were consistent with those reported in the literature. At most intersections (24 out of 27), a reduction in frequency of side-impact crashes occurred after RLCs were deployed. Several intersections (i.e., three to nine, depending on the selected comparison time period), showed an increase in such crash patterns during the "after" period. Note that none of the existing studies offered any empirical evidence for such an inconsistency and most scholars assumed that behaviors of the driving populations are likely to be the main contributing factor.

The most interesting finding in Table 7 is that a significant increase in rear-end collisions occurred at 10 out of 27 of the intersections. Such negative effects were also observed in other states and were recognized by researchers in the traffic community. However, well-accepted hypotheses or behavioral theories to explain the inconsistencies have yet to be fully studied and deserve further discussion.

Table 7: Before-and-After Analysis of the RLC's Effects on the Crash Patterns under Different Periods

Length of Before | After	**Summary for Side-Impact and Rear-End Crashes (RLC legs only)**							
	Side-Impact Injury	**Side-Impact PDO**	**Side-Impact Injury**	**Side-Impact PDO**	**Side-Impact Injury**	**Side-Impact PDO**	**Side-Impact Injury**	**Side-Impact PDO**
	"Increase"	*"Increase"*	*"Decrease"*	*"Decrease"*	*"Increase"*	*"Decrease"*	*"Decrease"*	*"Increase"*
B:5-yr| A:3-yr	P3		H1AR, H2A, M1, M2A, M5, M6, M7, M8, M12, P2, P4, P8		M13R, P10		M3, M4A, M11A, M14, M15, P1, P5, P6R, P7, P9R	
B:3-yr| A:3-yr	M3, P3, P10		H1R, H2, M1, M2A, M5, M7, M8, P1, P4		M6, M13R, P8		M4, M12, M14A, M15, P2, P5, P6, P7, P9,M11A	
B:2-yr| A:3-yr	M3, M5, P3, P10		H1, H2A, M2A, M6, M8, M15, P1R, P4		M1, M7, M12, M13R, P8		M4R, M14R,M11A,P2, P5, P6, P7, P9R	
B:5-yr| A:2-yr	M9, P3		H1A, H2, M1, M2A, M3, M5, M6, M7, M8, P4A		M12, M13R, P8, P10		M4A, M10, M14, M15, P1, P2, P5, P6, P7, P9,M11	
B:3-yr| A:2-yr	M9, M12, P3		H1, H2, M2A, M5, M7, M8, P1, P4		M1, M3, M13R, P8, P10		M4, M6, M10, M14, M15, P2, P5, P6, P7, P9, M11A	
B:2-yr| A:2-yr	M5, P3		H1, H2A, M2A, M6, M8, P1, P4A		M1, M3, M7, M12, M13R, P8, P10		M4R, M9, M10, M14, M15, P2, P5, P6, P7, P9, M11A	

A: Side-impact crashes significantly at the 90% confidence level
R: Rear-End crashes significant at the 90% confidence level
AR: Both side-impact and rear-end crashes significant at the 90% confidence level.

Table 8 presents the results on the frequency of side-impact crashes classified by severity level. Note that the category of fatalities was not included in the analysis due to issues with sample size. The results showed that the deployment of a RLC had both positive and negative effects, not only on the frequency of side-impact crashes but also on the severity level of such crashes. For example, in the three years before and three years after comparison, there was a reduction in side-impact crashes that resulted in injury and property damage only (PDO) at 17 out of 27 intersections. Four of 27 intersections had an increase in PDO side-impact crashes but a reduction in injury side-impact crashes. Overall, the RLC deployment seems to have a positive effect on reducing the severity level of side-impact crashes. The above findings are tentative in nature and more empirical investigations on this issue should be conducted to reach more definitive conclusions.

Table 8: Before-and-After Analysis of the RLC's Effects on Side-Impact Crash Patterns by Severity Level

<table>
<tr><th rowspan="3">Length of Before | After</th><th colspan="8">Summary for Side-Impact Crashes of Different Severity Levels (RLC legs only)</th></tr>
<tr><th>Side-Impact Injury</th><th>Side-Impact PDO</th><th>Side-Impact Injury</th><th>Side-Impact PDO</th><th>Side-Impact Injury</th><th>Side-Impact PDO</th><th>Side-Impact Injury</th><th>Side-Impact PDO</th></tr>
<tr><th>"Increase"</th><th>"Increase"</th><th>"Decrease"</th><th>"Decrease"</th><th>"Increase"</th><th>"Decrease"</th><th>"Decrease"</th><th>"Increase"</th></tr>
<tr><td>B:5-yr|
A:3-yr</td><td colspan="2">P3</td><td colspan="2">H1^{I}, H2^{I}, M1, M2^{IP}, M4^{I}, M5, M8, M11^{I}, M15^{I}, P1, P5^{P}, P7, P9</td><td colspan="2">M6, P6, P8, P10^{I}</td><td colspan="2">M3, M7, M12, M13, M14, P2^{I}, P4</td></tr>
<tr><td>B:3-yr|
A:3-yr</td><td colspan="2">P3</td><td colspan="2">H1, H2^{I}, M1, M2, M4, M5, M7, M8, M11^{I} M12, M14^{I}, M15, P1, P5, P6, P7, P9</td><td colspan="2">M6, P8, P10^{I}</td><td colspan="2">M3, M13, P2, P4</td></tr>
<tr><td>B:2-yr|
A:3-yr</td><td colspan="2">M1, M12, P3</td><td colspan="2">H2^{IP}, M2, M4, M8, M11^{I}, M14, M15^{P}, P1, P5, P7, P9</td><td colspan="2">M5, M6, M7, P6, P8, P10^{I}</td><td colspan="2">H1, M3, M13, P2, P4</td></tr>
<tr><td>B:5-yr|
A:2-yr</td><td colspan="2">M9, M12, P3</td><td colspan="2">H1^{I}, H2, M2^{IP}, M3, M4^{I}, M5, M8, M10, M15, P5^{P}, P9</td><td colspan="2">M1, M6^{P}, P1, P6, P7, P8, P10^{I}</td><td colspan="2">M7, M11^{I} , M13, M14^{P}, P2^{I}, P4</td></tr>
<tr><td>B:3-yr|
A:2-yr</td><td colspan="2">M3, M9, P3</td><td colspan="2">H1, H2, M2, M4, M5, M10, M11^{I}, M15, P5, P7, P9</td><td colspan="2">M1, M6, M8, M12, P1, P6, P8, P10^{I}</td><td colspan="2">M7, M13, M14^{I}, P2, P4</td></tr>
<tr><td>B:2-yr|
A:2-yr</td><td colspan="2">M1, M3, M12, P3</td><td colspan="2">H2, M2, M4, M8, M9, M10, M11^{I}, M14, M15, P1, P4, P5, P7, P9</td><td colspan="2">M5, M6, M7, P6, P8, P10^{I}</td><td colspan="2">H1, M13, P2</td></tr>
</table>

I: Injury crashes significant at the 90% confidence level
P: PDO crashes significant at the 90% confidence level
IP: Both injury and PDO crashes significant at the 90% confidence level

Table 9 shows the comparison results on the frequency of rear-end collisions classified by severity level. Notably, all four categories of the before-and-after patterns contain approximately the same number of intersections, reflecting the similar inconsistent effects of the presence of RLC as in all the aforementioned analyses. For example, during the comparison period of five years before and three years after deployment, an increase in rear-end collisions occurred at six intersections, resulting in either PDO or injury, compared to a total of seven intersections that had a significant reduction in frequency for both severity levels. Although a total of seven intersections are classified in Table 9 as being associated with an increase in PDO, there was a reduction in injury caused by rear-end collisions. No conclusion on the effect of RLC deployment, either positively or negatively, on the frequency and severity of rear-end collisions can be reached.

Table 9: Before-and-After Analysis of the RLC's Effects on Rear-Collision Patterns by Severity Level

Length of Before | After	Summary for Rear-End Crashes of Different Severity Levels (RLC legs only)							
	Rear-end. Injury	**Rear-end. PDO**	**Rear-end. Injury**	**Rear-end. PDO**	**Rear-end. Injury**	**Rear-end. PDO**	**Rear-end. Injury**	**Rear-end. PDO**
	"Increase"	*"Increase"*	*"Decrease"*	*"Decrease"*	*"Increase"*	*"Decrease"*	*"Decrease"*	*"Increase"*
B:5-yr| A:3-yr	M4, M11[P], M14, P3, P5, P7		H1[I], M1, M2[I], M5, M6, M13, P8		H2[P], M12, M15[I], P2, P4[P]		M3, M7, M8[I], P1, P6[P], P9, P10	
B:3-yr| A:3-yr	M4, M11, M14, P7, P10		H1[I], M1, M2, M5, M7, M8, M13, P1, P8		H2[P], M6, M12, M15, P2, P3, P4		M3, P5, P6[P], P9	
B:2-yr| A:3-yr	M4[P], M14, P7, P10		M1, M2, M7, M8, M13, P1, P8		H2[P],M5, M6, M12, M15, P2, P3, P4		H1, M3, M11[P],P5, P6, P9[P]	
B:5-yr| A:2-yr	M9, M10, M11, M14, P5, P7		H1, M1, M2[I], M3, M13[P], P4[P], P8, P10		H2[P], M5, M6, M12, M15[P], P2		M4, M7, M8[I], P1, P3, P6, P9[P]	
B:3-yr| A:2-yr	M9, M10, M11, M14, P2, P6, P7		H1, M1, M2, M3, M13, P1, P4, P8		H2[P], M5, M6, M12, M15, P10		M4, M7, M8, P3, P5, P9	
B:2-yr| A:2-yr	M9, M10, M14, P2, P7		M1, M2, M3, M7, M8, P1, P3, P4, P8, P10		H2[P], M5, M6,M12, M15		H1, M4[P], M11, M13, P5, P6, P9	

I: Injury crashes significant at the 90% confidence level
P: PDO crashes significant at the 90% confidence level
IP: Both injury and PDO crashes significant at the 90% confidence level

Comparison of the Crash Patterns at the RLC and non-RLC Legs

To further verify that the identified changes in the before-and-after comparison were most likely due to the RLC deployment, as shown in Tables 10 and 11, this study investigated the side-by-side patterns of the RLC and non-RLC legs using the same analyses over the same time periods. In general, one may reasonably conclude that the RLC had a strong effect during the period of interest when there was a significant change in side-impact crashes or rear-end collisions at RLC legs only. Such a conclusion, however, must be subjected to further verification if the other approaches, not deployed with the RLC, also experienced the same changes in frequency of crash patterns.

Table 11 presents a side-by-side comparison of results for side-impact crashes at those intersections in Howard, Montgomery, and Prince George counties. Based on the distribution of positive and negative signs (which denote an increase or decrease from the before-and-after comparison) among all table cells, there were 96 out of the 150 pairs (i.e., 25 intersections x 6 tests) of the before-and-after comparisons that were consistent with the previous evaluation results of the RLC and non-RLC intersection legs.

Such empirical evidence appears to indicate that some factors, other than the RLC, were likely contributors to the changing crash patterns. Another hypothesis is that the presence of a RLC in one intersection approach may be causing a "spillover" effect for drivers from all other approaches. This study was able to discern a similar pattern from the results shown in Table 10 for the same set of intersections with respect to rear-end collisions, where 78 out of the 150 pairs of before-and-after analyses exhibit the consistent signs.

Table 10: Before-and-After Comparisons of the Rear-End Collision Pattern at RLC and Non-RLC Legs

Site index		Summary for Rear-End Crash at RLC and Non-RLC Legs					
		Before | After 5-yr | 3-yr	Before | After 3-yr | 3-yr	Before | After 2-yr | 3-yr	Before | After 5-yr | 2-yr	Before | After 3-yr | 2-yr	Before | After 2-yr | 2-yr
H1	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	-	-	-	-
H2	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	-	-	+	-
M1	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	+	-	+	+
M2	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	+	+	+	+
M3	***RLC***	+	+	+	-	-	-
	Non-RLC	+	+	+	+	+	+
M4	***RLC***	+	+	+	+	+	+
	Non-RLC	+	-	+	-	-	+
M5	RLC	-	-	+	-	-	+
	Non-RLC	+	+	+	-	-	-
M6	***RLC***	-	-	+	-	+	+
	Non-RLC	-	-	+	+	-	+
M7	***RLC***	-	-	-	-	-	-
	Non-RLC	+	+	+	-	-	-
M8	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	-	-	-	-
M9[c]	***RLC***	*NA*[b]	*NA*[b]	*NA*[b]	+	+	+
	Non-RLC	*NA*[b]	*NA*[b]	*NA*[b]	-	-	-
M10[c]	***RLC***	*NA*[b]	*NA*[b]	*NA*[b]	-	+	+
	Non-RLC	*NA*[b]	*NA*[b]	*NA*[b]	+	+	+
M11[d]	***RLC***	+	+	+	+	+	+
	Non-RLC	*NA*[a]	*NA*[a]	*NA*[a]	*NA*[a]	*NA*[a]	*NA*[a]

M12	RLC	-	+	-	-	+	-
	Non-RLC	-	-	-	-	-	-
M14	RLC	+	+	+	+	+	+
	Non-RLC	+	+	-	+	+	-
M15	RLC	+	+	-	+	+	+
	Non-RLC	+	+	-	-	+	+
P1	RLC	+	-	-	-	-	-
	Non-RLC	+	+	+	+	-	+
P2	RLC	-	+	+	+	+	+
	Non-RLC	-	-	-	-	-	-
P4	RLC	-	-	-	-	-	-
	Non-RLC	-	-	-	-	-	-
P5	RLC	+	+	+	+	+	+
	Non-RLC	+	+	+	+	-	-
P6	RLC	+	+	+	+	+	+
	Non-RLC	+	+	+	-	-	-
P7	RLC	+	+	+	+	+	+
	Non-RLC	-	-	-	-	-	-
P8	RLC	-	-	-	-	-	-
	Non-RLC	-	-	-	-	-	-
P9[d]	RLC	+	+	+	+	+	+
	Non-RLC	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]

1. "-" denotes the decreased crash rate after the RLC installation; "+" denotes the increased crash rate after the RLC installation;
2. "NA[a]" indicates the unavailability of crashes not involving vehicles from RLC legs (counted under "Non-RLC");
3. "NA[b]" denotes the unavailability of such comparison since there are different number of RLCs in-service during the first 2 years of the "after" and the 3rd year of the "after" (The crash data from the 3rd year of "after" need to use different comparison method);
4. "M9[c] / M10[c]" are the sites with multiple RLC installed but with different in-service date;
5. "M11[d]/ P9[d]" are the sites with no crashes observed from legs without RLC enforcement;
6. "RLC" summaries the crashes involving vehicles coming from the legs with RLC enforcement;
7. "Non-RLC" summaries the crashes not involving any vehicles coming from the legs with RLC enforcement;
8. Cells highlighted in yellow denotes the B/A difference significant at no less than 90% confidence level.

Table 11: Before-and-After Comparisons of the Side-Impact Crash Pattern at RLC and Non-RLC Legs

Site index		Summary for Side-Impact Crash at RLC and Non-RLC Legs					
		Before | After 5-yr | 3-yr	Before | After 3-yr | 3-yr	Before | After 2-yr | 3-yr	Before | After 5-yr | 2-yr	Before | After 3-yr | 2-yr	Before | After 2-yr | 2-yr
H1	RLC	-	-	-	-	-	-
	Non-RLC	-	-	-	-	-	-
H2	RLC	-	-	-	-	-	-
	Non-RLC	-	-	-	-	-	-
M1	RLC	-	-	+	-	+	+
	Non-RLC	-	-	-	-	-	-
M2	RLC	-	-	-	-	-	-
	Non-RLC	-	-	+	+	-	+
M3	RLC	-	+	+	-	+	+

	Non-RLC	-	+	+	+	-	-
M4	***RLC***	-	-	-	-	-	-
	Non-RLC	+	-	-	+	+	-
M5	***RLC***	-	-	+	-	-	+
	Non-RLC	-	-	+	-	-	-
M6	***RLC***	-	+	-	-	-	-
	Non-RLC	+	+	+	-	+	+
M7	***RLC***	-	-	+	-	-	+
	Non-RLC	+	+	+	-	-	-
M8	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	-	-	-	-
M9[c]	***RLC***	NA[b]	NA[b]	NA[b]	+	+	-
	Non-RLC	NA[b]	NA[b]	NA[b]	-	+	+
M10[c]	***RLC***	NA[b]	NA[b]	NA[b]	-	-	-
	Non-RLC	NA[b]	NA[b]	NA[b]	-	-	-
M11[d]	***RLC***	-	-	-	-	-	-
	Non-RLC	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]
M12	***RLC***	-	-	+	+	+	+
	Non-RLC	+	+	+	+	+	+
M14	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	+	-	-	+
M15	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	+	-	-	-
P1	***RLC***	+	-	-	-	-	-
	Non-RLC	+	+	+	+	-	+
P2	***RLC***	-	+	+	+	+	+
	Non-RLC	-	-	-	-	-	-
P4	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	-	-	-	-
P5	***RLC***	+	+	+	+	+	+
	Non-RLC	+	+	+	+	-	-
P6	***RLC***	+	+	+	+	+	+
	Non-RLC	+	+	+	-	-	-
P7	***RLC***	+	+	+	+	+	+
	Non-RLC	-	-	-	-	-	-
P8	***RLC***	-	-	-	-	-	-
	Non-RLC	-	-	-	-	-	-
P9[d]	***RLC***	+	+	+	+	+	+
	Non-RLC	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]	NA[a]

1. "-" denotes the decreased crash rate after the RLC installation; "+" denotes the increased crash rate after the RLC installation;
2. "NA[a]" indicates the unavailability of crashes not involving vehicles from RLC legs (counted under "Non-RLC");
3. "NA[b]" denotes the unavailability of such comparison since there are different number of RLCs in-service during the first 2 years of the "after" and the 3rd year of the "after" (The crash data from the 3rd year of "after" need to use different comparison method);

4. "M9c / M10c" are the sites with multiple RLC installed but with different in-service date;
5. "M11d/ P9d" are the sites with no crashes observed from legs without RLC enforcement;
6. "RLC" summaries the crashes involving vehicles coming from the legs with RLC enforcement;
7. "Non-RLC" summaries the crashes not involving any vehicles coming from the legs with RLC enforcement;
8. Cells highlighted in yellow denotes the B/A difference significant at no less than 90% confidence level.

3.4 Summary

Section 3 presented the results of several before-and-after crash analyses of 27 RLC intersections. Overall, the findings were consistent with those reported in the traffic literature, which confirms that the presence of RLC at an intersection can either increase or decrease side-impact crashes and rear-end collisions, depending on other contributing factors that have not yet been empirically verified by the traffic safety community. Even though there were discrepancies in the before-and-after evaluation results across 27 intersections, the general effects of the RLC deployment on traffic safety can be summarized below.

- There were significant reductions in side-impact crashes at most RLC intersections.
- Approximately equal percentage of RLC intersections had an increase or decrease in the rear-end collisions.
- A small percentage of RLC intersections seem to have an increase in both rear-end collisions and side-impact crashes.

Conceivably, the concerns about the use of RLC and their potential negative effects can be mitigated if the traffic safety community can identify those additional contributing factors that cause more rear-end collisions at some intersections. Initial efforts from this project to address this issue are presented in the next section.

4. Empirical Observations of Driver Characteristics at RLC-deployed Intersections

4.1 Design of Field Observation Plans

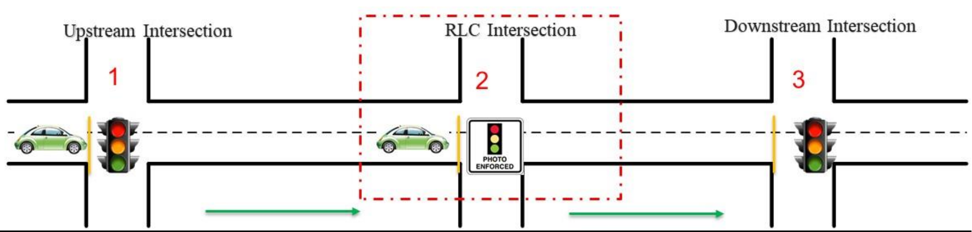
As discussed in the previous section, the before-and-after analysis of crash frequency at 27 Maryland RLC intersections showed that the rear-end collisions or side-impact crashes may be reduced, increased, or unchanged, despite the finding that fewer side-impact crashes and a slight increase in rear-end collisions were reported at many such intersections.

Such discrepancies of the effectiveness of RLC clearly show the need to better understand the influence of their presence on driving behaviors, such as driver responses when approaching the intersection or encountering the yellow phase. Measures of effectiveness (MOE), other than crash frequency, should also be considered when assessing the effectiveness of an RLC deployment. Therefore, this study extended the scope to include a two-stage field observation:

Stage-I: observations of driver behaviors at two RLC intersection clusters. Each cluster include a RLC intersection and its downstream and upstream intersections.

Stage-II: observations of driver behaviors at two additional RLC intersections to verify any findings from Stage-1 results.

A graphical illustration of the two selected sites for field observation in Stage-I is shown in Figure 6. The satellite image of the three intersections from Site 1 and their geographical relationship are also shown in Figure 7. Comparison of the traffic characteristics and driver behaviors from the upstream to the downstream intersections of RLC site offers the most direct measurement of their effect on the driving populations, including the possible “spillover effects” on neighboring intersections.



Data collection sites	Upstream	Red Light Camera	Downstream
Site 1: MD 650	Oakview Dr.	Adelphi Rd.	Northampton Dr.
Site 2: US 301	Frank Tippett Rd.	Rosaryville Rd. (Old Indian Head Rd.)	Fairhaven Ave.

Figure 6: Graphical Illustration of Field Data Collected in Stage-I

Figure 7: Overview of all Three Intersections in MD650 and their Geographical Relationships

Note that the Site 1 RLC intersection of MD 650 @ Adelphi Road was defined as "RLC-effective" to reflect its reduction in side-impact crashes (see Table 7). The Site 2 RLC intersection of US 301 @ Rosaryville Road (Old Indian Head Road) was defined as the "RLC-ineffective" intersection (no change or even a minor increase in side-impact crashes). The following is a list of key traffic characteristics and behavioral data collected from these two RLC intersection clusters:

- the speed of approaching vehicles during the green and yellow phases;
- speed evolution of each individual vehicle at distances of 100, 250, 400, and 550 feet from the intersection stop line;
- distance to the stop line when a driver decides to stop during a yellow phase;
- each individual driver's decision to stop or pass during a yellow phase, given the detected approaching speed and distance to the intersection;
- the speed, acceleration, or deceleration rate of each approaching vehicle when encountering a yellow phase;
- The number of vehicles crossing the intersection during the all-red and/or the red phase per cycle; and
- the time stamp during the yellow or the all-red/red phase when a "passing" vehicle traverses the intersection stop line.

Stage-II included two individual RLC intersections: MD 410 @ MD 450 and MD 97 @ MD 28. The former is a "RLC-effective" intersection experiencing a reduction in the side-impact crash frequency after the RLC deployment, while the latter is a "RLC-ineffective" intersection experiencing indiscernible changes in the pattern of side-impact crashes.

4.2 Empirical Findings Regarding the Effects of RLC Deployment

Although the collected driver behavioral data contained quite valuable information for various traffic engineering studies, the results discussed below include only those findings which are applicable to following vital questions:

- What are the likely effects of a RLC-deployment on traffic safety and driver behavior?
- Does the "spillover" effect from RLC-deployment actually exist?

- Is there a difference in traffic characteristics and driver responses to the yellow phase between RLC-effective and RLC-ineffective intersections?

Approaching Speed Distributions

Tables 12 to 15 show the speed distributions of vehicles approaching the RLC intersections, where aggressive drivers were defined as having an approaching speed of 10 mph over the posted speed limit. The following empirical findings were observed on the percentage of aggressive drivers:

- The percentage of aggressive drivers at the RLC-effective MD 650 intersection, 9.62%, is much lower than the percentage of 39.81% at the RLC-ineffective US 301 intersection.
- Similar pattern was observed at the MD 410 intersection (RLC-effective, 6.37%) and the MD 97 intersection (RLC-ineffective, 25.62%).
- The "spillover effect," reflected in the reduced percentage of aggressive drivers, is observed at the downstream intersections of both RLC-effective (i.e., from 9.62% to 7.77 % at the MD 650 intersection cluster) and RLC-ineffective sites (i.e., from 39.81% to 6.41% at the US 301 intersection cluster).
- The presence of RLC seemed to have no effect on moderate and conservative drivers, based on their percentages at the intersection clusters, as shown in Tables 12 and 13.

More observation is needed at additional RLC intersections to verify if the percentage of aggressive drivers is a valuable proxy measure to the effectiveness of RLC on reducing side-impact crashes.

Table 12: Distribution of Approaching Speeds at the MD 650 Intersection Cluster

MD 650 (effective in reducing side-impact crashes; speed limit: 40 MPH)					
% of vehicle	<40 mph	40 – 45 mph	45 – 50 mph	>50 mph	Average
Upstream (N = 202)	71.29%	14.85%	12.87%	0.99%	35.3
RLC (N = 104)	40.38%	36.54%	13.46%	9.62%	41.5
Downstream (N = 103)	36.89%	33.98%	21.36%	7.77%	41.9

*The number in each parenthesis denotes the sample size.

Table 13: Distribution of Approaching Speeds at the US 301 Intersection Cluster

US 301 (Ineffective in reducing side-impact crashes; Speed limit: 55 MPH)					
% of vehicle	<55 mph	55 – 60 mph	60 – 65 mph	>65 mph	Average
Upstream (N = 203)	25.12%	24.14%	30.54%	20.20%	59.1
RLC (N = 206)	19.9%	16.02%	24.27%	39.81%	61.5
Downstream (N = 457)	62.82%	19.23%	11.54%	6.41%	54.7

*The number in each parenthesis denotes the sample size.

Table 14: Distribution of Approaching Speeds at US 450

US 450 (effective in reducing side-impact crashes; speed limit: 45 MPH)					
% of vehicle	<45 mph	45 – 50 mph	50 – 55 mph	>55 mph	Average
RLC (N = 157)	27.39%	33.12%	33.12%	6.37%	47.26

*The number in each parenthesis denotes the sample size.

Table 15: Distribution of approaching speeds at MD 97

MD 97 (ineffective in reducing side-impact crashes; speed limit: 50 MPH)					
% of vehicle	<50 mph	50 – 55 mph	55 – 60 mph	>60 mph	Average
RLC (N = 203)	30.05%	22.66%	21.67%	25.62%	54.75

*The number in each parenthesis denotes the sample size.

Speed Change during the Yellow Phase

Table 16 presents the speed change statistics of moderate drivers when they progress through the intersection clusters. By comparing the percentage of drivers with speed changes when approaching the RLC and its downstream intersections, the following tentative conclusions can be made:

- The percentage of moderate drivers who reduced their speeds when passing the intersection during the yellow phase increased at the RLC intersections when comparing to the one at downstream intersections (13% at MD 650 versus 7% at its downstream intersection; 20% at US 301 versus 8% at its downstream intersection). It could be an evidence of the RLC deployment’s spillover effect.

- The percentage of moderate drivers who accelerated when passing the intersection during the yellow phase decreased at the RLC intersection when comparing to the one at downstream intersections (12% at MD650 versus 36% at its downstream intersection; 5% at US 301 versus 46% at its downstream intersection). It revealed the same empirical evidence of the spillover effect.
- Most of the moderate drivers (57% at MD 650 and 46% at US 310) tended to maintain a stable speed when passing an RLC-deployed intersection during the yellow phase, and this percentage increased at the downstream intersections (75% at MD 650 and US 310).

Further comparison of the speed change statistics for aggressive drivers at these intersection clusters revealed similar empirical evidence of the spillover effect at downstream intersections (see Table 17).

Table 16: Speed Changes during the Yellow Phase: Moderate "Passing" Drivers

Site	Intersection	Difference between the passing speed (at the stop line) and the approaching speeds (700ft)		
		< -5mph	Unchanged	> 5mph
MD650 (Effective)	Upstream	46 %	43 %	11 %
	RLC	7 %	57 %	36 %
	Downstream	13 %	75 %	12 %
US310 (Ineffective)	Upstream	9 %	56 %	35 %
	RLC	8 %	46 %	46 %
	Downstream	20 %	75 %	5 %

Table 17: Speed Changes during the Yellow Phase: Aggressive "Passing" Drivers

Site	Intersection	Difference between the passing speed (at the stop line) and the approaching speeds (700ft)		
		< -10 mph	Unchanged	> 5mph
MD650 (Effective)	Upstream	6.7 %	20 %	10 %
	RLC	29 %	36 %	7 %
	Downstream	30 %	60 %	0 %
US310 (Ineffective)	Upstream	0 %	89 %	11 %
	RLC	12 %	41 %	35 %
	Downstream	40 %	20 %	0 %

Responses to the Yellow Phase

Aside from affecting the speed of approaching vehicles, RLC deployment can also have an influence on a driver's decision when encountering a yellow phase. Table 18 shows the percentage of drivers who decided to stop based on their approaching speeds and distances from the RLC effective MD 650 intersection. As expected, the percentage increased with the distance from the intersection, but negatively correlated with the speed of approaching vehicles.

Table 19 presents a comparison between the RLC effective MD 650 intersection and its upstream intersection. Table 20 shows the same comparison between its downstream and upstream intersections.

Table 18: Percentage of Drivers Who Decide to Stop at the Yellow Phase at the MD 650

MD 650		Vehicle speed at the onset of Yellow (MPH)			
RLC Intersection (N = 168)		<35	35 ~ 45	45 ~ 55	>55
Vehicle's distance-to-stop-line at the onset of yellow (feet)	<100	6%	0%	0%	-
	100 ~ 200	29%	14%	17%	0%
	200 ~ 300	90%	76%	38%	0%
	300 ~ 400	100%	100%	50%	0%
	>400	100%	-	-	-

Table 19: Comparison of Drivers Who Decide to Stop at MD 650 and its Upstream Intersection

MD 650		Vehicle speed at the onset of Yellow (MPH)			
% (RLC – Upstream)		<35	35 ~ 45	45 ~ 55	>55
Vehicle's distance-to-stop-line at the onset of yellow (feet)	<100	0% (14)	0% (14)	0% (4)	-
	100 ~ 200	50% (8)	13% (16)	10% (10)	-
	200 ~ 300		7% (15)	17% (6)	-
	300 ~ 400	0% (3)	0% (3)	17% (2)	-
	>400	-	-	-	-

Table 20: Comparison of Drivers who Decide to Stop at the Downstream and Upstream Intersections of the MD 650 Intersection

MD 650		Vehicle speed at the onset of Yellow (MPH)			
% (Downstream – Upstream)		<35	35 ~ 45	45 ~ 55	>55
Vehicle's distance-to-stop-line at the onset of yellow (feet)	<100	7% (14)	0% (16)	0% (12)	-
	100 ~ 200	50% (2)	-6% (7)	25% (4)	-
	200 ~ 300	-	13% (5)	33% (4)	-
	300 ~ 400	0% (3)	0% (2)	17% (2)	-
	>400	0% (1)	0% (8)	17% (6)	0% (2)

Findings from these three tables are summarized below:

- Statistics shown in Table 19 indicated that under identical scenarios more drivers would likely stop when approaching an RLC intersection. For example, the percentage of drivers who stopped when encountering a yellow phase at a speed of 35-45mph and a distance of 100-200ft increased 13% from the upstream intersection to the RLC intersection. It indicated that the presence of red-light cameras had a significant influence on driving behavior.
- Statistics shown in Table 20 highlighted a similar pattern between the downstream and upstream intersections, providing further evidence of "spillover effects" on driver responses during a yellow phase. For example, the percentage of drivers who stopped when encountering the yellow phase at a speed of 45-55mph and a distance of 200-300ft increased 33% from the upstream intersection to the downstream intersection.

Tables 21 to 23 show the same statistics for the RLC-ineffective US 301 intersection, including observations from both its upstream and downstream intersections. Some interesting results are summarized below:

- Despite insignificant changes in the frequency of side-impact crashes after the RLC deployment, there was a significant increase in the percentage of drivers who decided to stop during the yellow phase at the RLC-intersection when compared to its upstream intersection.
- The “spillover effect” was not observed at this RLC-ineffective intersection cluster.
- The inconsistent “spillover effect” observation between the RLC-effective and RLC-ineffective cluster was likely due to localized driving behavioral differences: the RLC-ineffective cluster had a much higher percentage of aggressive drivers who may less likely be affected by the RLC deployment.

Table 21: Percentage of Drivers Who Decide to Stop at the Yellow Phase at US 301

US 301		**Vehicle Speed at the Onset of Yellow (MPH)**						
RLC Intersection (N = 470)		<35	35 ~ 45	45 ~ 55	55 ~ 65	65 ~ 75	75 ~ 85	>85
Vehicle’s distance-to-stop-line at the onset of yellow (feet)	<200	0% (2)	0% (1)	0% (3)	0% (10)	0% (14)	0% (2)	0% (1)
	200 ~ 300	-	100% (1)	0% (4)	33% (6)	0% (10)	-	0% (1)
	300 ~ 400	-	-	67% (3)	38% (13)	55% (11)	100% (1)	0% (1)
	400 ~ 500	-	-	89% (9)	79% (19)	63% (16)	100% (1)	-
	500 ~ 600	-	-	85% (13)	100% (9)	100% (7)	100% (3)	50% (2)
	600 ~ 700	-	-	100% (4)	94% (18)	100% (20)	100% (4)	100% (1)
	>700	-	-	-	100% (9)	100% (8)	100% (2)	-

* The number within the parenthesis is the sample size.

Table 22: Comparison of Drivers Who Decide to Stop at US 301 and its Upstream Intersections

US 301		**Vehicle Speed at the Onset of Yellow (MPH)**						
% (RLC – Upstream)		<35	35 ~ 45	45 ~ 55	55 ~ 65	65 ~ 75	75 ~ 85	>85
Vehicle’s distance-to-stop-line at the onset of yellow (feet)	<200	-	-	-	-	-	-	-
	200 ~ 300	-	-	-50%	33%	-	-	-
	300 ~ 400	-	-	21%	25%	55%	-	-
	400 ~ 500	-	-	17%	8%	34%	-	-
	500 ~ 600	-	-	-15%	0%	20%	-	-
	600 ~ 700	-	-	0%	-6%	0%	0%	-
	>700	-	-	-	0%	0%	0%	-

Table 23: Comparison of Drivers Who Decide to Stop at the Downstream and Upstream Intersections of the US 301 Intersection

US 301		Vehicle Speed at the Onset of Yellow (MPH)						
% (Downstream – Upstream)		<35	35 ~ 45	45 ~ 55	55 ~ 65	65 ~ 75	75 ~ 85	>85
Vehicle's distance-to-stop-line at the onset of yellow (feet)	<200	-	-	-	-	-	-	-
	200 ~ 300	-	-	-50%	0%	-	-	-
	300 ~ 400	-	-	-14%	37%	0%	-	-
	400 ~ 500	-	0%	29%	-5%	-29%	-	-
	500 ~ 600	-	0%	0%	-33%	20%	-	-
	600 ~ 700	-	-	0%	0%	0%	0%	-
	>700	-	-	-	-	-	-	-

Behavior of Aggressive Drivers during the All-Red and/or Red Phases

To better understand the effects of RLC on the behaviors of aggressive drivers, this study analyzed the following statistics at the two intersection clusters:

- Percentage of drivers entering the intersection during the all-red or red phase:
  - MD 650 cluster: *3.07%* upstream, *2.69%* at the RLC site, *2.74%* downstream
  - US 301 cluster: *9.21%* upstream, *3.80%* at the RLC site, *3.57%* downstream

- Percentage of drivers entering the intersection one second before the all-red phase:
  - MD 650 cluster: 17.18% upstream, 15.77% at the RLC site, 15.75% downstream
  - US 301 cluster: 3*1.58%* upstream, *15.19%* at the RLC site, *17.86%* downstream

From these statistics the following observations of RLC impacts can be made:

- The presence of a RLC indeed discouraged aggressive drivers from running a red light (e.g., from 9.21% at upstream to 3.8% at the US 301 intersection).
- The "spillover effect" on red-light-running behavior did not extend to the downstream intersection (the percentage remained steady there when compared to the RLC site). The same pattern was found at the RLC-effective MD 650 intersection cluster.
- The observations on red-light-running reduction effect was further supported by the percentage of drivers crossing over the stop line one second prior to the all-red phase at both study sites (e.g., from 31.58% to 15.19% and 17.86% at the US301 cluster).

The total number of observed drivers who decided to pass when encountering a yellow phase was 270 at the MD 650 cluster and 79 at the US 301 cluster.

Effects on the Dilemma Zone and Rear-End Collisions

According to both the literature and the before-and-after comparison of the 27 Maryland intersections (see Section 3), a RLC deployment is likely to cause an increase in the frequency of rear-end collisions. Researchers suspect that improper decisions made in the dilemma zones, when the drivers notice the presence of the RLC, are likely to be a main contributor. This study took the following steps to analyze this potential effect:

- Computed the changes in speeds and acceleration/deceleration rates of each vehicle approaching during the yellow phase the two RLC intersection clusters;

- Estimated the spatial distribution of the dilemma zones within each approaching speed category;
- Calculated the “must-go” and “must-stop” zones;
- Recorded the action of each observed driver and the vehicle’s distance from the stop line when encountering the yellow phase;
- Calculated the percentages of drivers who decided to stop when they were within the “must-go” zone and decided to pass when they were within the “must-stop” zone.

An illustration of the dilemma zone, the “must-go”, and the “must-stop” zones is shown in Figure 8. Tables 24 and 25 show these distributions. Some findings are summarized below:

- The percentage of drivers who decided to stop when in the “must-go” zone was 12% at the MD 650 intersection, 3.9% at the US 301 intersection, 10.1% at the MD 450 intersection, and 2.9% at the MD 97 intersection. Conceivably, this might cause rear-end collisions.
- Only a relatively small percentage of drivers were observed to pass when in “must-stop” zones. Such drivers, classified as aggressive driving populations, were at risk of causing side-impact crashes.
- The percentage of drivers trapped in the dilemma zone at the RLC-ineffective US 301 intersection was much higher (37%) than the one at the RLC-effective MD 650 intersection (6.7%). A similar pattern was observed at the downstream intersections and the two individual RLC intersections (13.5% at the RLC-effective MD 450 intersection and 29.4% at RLC-ineffective MD 97 intersection).
-

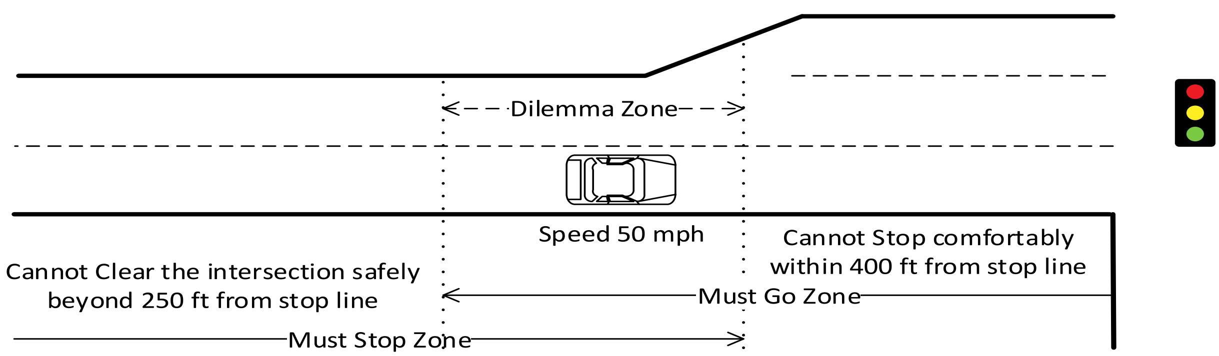


Figure 8: A Graphical Illustration of Dilemma Zone

Table 24: Comparison of Drivers who make Inappropriate Decisions during the Yellow Phase between the MD 650 and US 301 Study Sites

Site	Intersection	Choose to stop within their “must-go” zone (rear-end collision)	Choose to pass within their “must-stop” zone (side-impact crash)	No. of vehicles trapped in DZ	Total No. of vehicles encountering the yellow phase
MD 650 (Effective)	Upstream	0.4% (1)	5.9% (15)	23.7% (60)	253
	RLC	12% (32)	0.7% (2)	6.7% (18)	267
	Downstream	6.1% (12)	2.3% (5)	5.1% (10)	196
US 301 (Ineffective)	Upstream	0.5% (2)	0.9% (4)	30.1% (131)	435
	RLC	3.9% (21)	1.3% (7)	37.4% (202)	540
	Downstream	2.4% (7)	4.7% (14)	27.0% (80)	296

* The number within the parenthesis is the sample size.

Table 25: Comparison of Drivers who make Inappropriate Decisions during the Yellow Phase between the MD 450 and MD 97 Study Sites

Site	Choose to stop within their “must-go” zone (rear-end collision)	Choose to pass within their “must-stop” zone (side-impact crash)	No. of vehicles trapped in DZ	Total No. of vehicles encountering the yellow phase
MD 450 (Effective)	10.11% (9)	1.12% (1)	13.48% (12)	89
MD 97 (Ineffective)	2.94% (4)	0.74% (1)	29.41% (40)	136

4.3 Summary of Empirical Evidences

The empirical findings associated with the effectiveness of RLC deployment were classified into the following three categories:

Category-1: RLC Deployment’s Effectiveness and the Evidence of the Spillover Effect

In addition to RLC’s potential influence on crash frequency, the empirical studies revealed the following positive effects on traffic safety:

- Reduction of aggressive driving at the RLC and its downstream intersections;
- Drivers were more inclined to reduce speed when passing the RLC and its downstream intersections during the yellow phase;
- More drivers chose to stop when encountering the yellow phase at the RLC and its downstream intersections;
- A decrease in the percentage of red-light-running and aggressive passing actions (i.e., entering the intersection one second ahead of the all-red phase) at the RLC and its downstream intersections.

Category-2: Undesirable Effects of RLC Deployment

The following undesirable driver responses in the dilemma zones at the RLC intersections may shed some light on the cause of a potential increase in rear-end collisions:

- Some drivers made improper decisions such as stopping in the "must-go" zone, or passing in the "must-stop" zone;
- More drivers stop in the "must-go" zone at the RLC intersection when compared to the upstream and downstream intersections.

Category-3: Characteristics of RLC-effective and Ineffective Intersections

The RLC-effective intersections differed from the RLC-ineffective intersections in the following safety related statistics:

- A much lower percentage of aggressive driving populations (those who drove at 10 mph over the posted speed limit);
- More drivers reduced their speeds when passing the RLC-effective intersection;
- An increase in the percentage of drivers who chose to stop when encountering a yellow phase;
- A lower percentage of drivers trapped in their respective dilemma zones;
- A relatively lower percentage of drivers ran the light during the all-red and red phases.

These findings were based on observations of over 1,000 drivers at the eight intersections and a video image processing tool was developed to extract and analyze the behavior data.

5. Conclusions and Recommendations

5.1 Conclusion

This study conducted a two-phase evaluation. Part I evaluated the effectiveness of RLC deployments at 27 local intersections over the past decade, including a comparison with those findings in the literature with respect to reducing rear-end collisions and side-impact crashes. Based on the findings discussed in Part I, Part II investigated the impact that RLCs had on driver behaviors, especially their responses to the yellow phase, based on field observations of more than 1,000 drivers at two RLC intersection clusters (each includes an upstream, an RLC, and a downstream intersection) and two individual RLC intersections.

Behavioral observations included drivers' approaching speeds, acceleration/deceleration rates, and their responses to a yellow phase. Findings confirmed the RLC deployment's spillover effect at the immediate downstream intersection. Evaluation results are summarized below:

- The literature review and Part I before-and-after studies confirmed that proper implementation of the RLC program indeed reduced side-impact crashes, but not rear-end collisions.
- Depending mostly on the characteristics of the local driving populations, the presence of RLC may either increase or decrease the number of rear-end collisions.
- This program reduced the percentage of aggressive drivers at both the RLC and its downstream intersections.
- A properly implemented RLC program has significant influence on driver behaviors. For example, it was found that drivers were more likely to reduce their speed when passing the RLC and its downstream intersections when encountering a yellow phase. In addition, more drivers decided to stop when encountering a yellow phase.
- With an advanced warning sign placed at a proper distance ahead of the intersection, RLC deployment was found to decrease the percentage of red-light-running vehicles and drivers' aggressive passing behaviors (i.e., entering the intersection one second ahead of the all-red phase).
- RLCs were shown to have a spillover effect at the immediate downstream intersections.

When implementing the RLC program, great care should be exercised to prevent some potential negative effects on traffic safety. Failing to carefully follow the deployment guidelines such as the one published by FHWA and only use the RLC as a last resort, such implementation may cause some undesirable results. For example, the observed increase in stopping in a "must-go" zone could potentially cause an increase in rear-end collisions. Overall, based on these findings one can comfortably conclude that the positive effects from a properly implemented RLC program generally outweigh any negatives.

5.2 Recommendations

Much remains to be done to ensure the success of the RLC program in different jurisdictions. Some imperative tasks to be done first are listed below:

- Development of effective deployment guidelines that account for the behavioral discrepancies among driving populations and locality-specific constraints.
- Observations of vehicle approaching speeds at a candidate RLC-intersection, especially the percentage of aggressive drivers, should be analyzed along with the intersection crash data before the deployment.
- For intersections with a high percentage of aggressive drivers, the responsible transportation agency needs to implement certain safety strategies to reduce the percentage of such drivers, to increase the probability of a successful RLC deployment.
- Extensive field observations at both RLC and non-RLC intersections are essential for the development of guidelines and design of control strategies.

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