Safety Evaluation of Red Light Indicator Lights at Intersections

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FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS in 2005 to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program Report 500 guides as part of the implementation of the American Association of State Highway and Transportation Officials Strategic Highway Safety Plan. The ELCSI-PFS studies provide a crash modification factor and benefit–cost (B/C) economic analysis for each of the targeted safety strategies identified as priorities by the pooled fund member States.

This study evaluated red-light indicator lights (RLILs). RLILs are auxiliary lights mounted on signal heads, mast arms, or poles that were connected to a traffic-control signal. This strategy is to reduce the frequency of crashes resulting from drivers disobeying traffic signals by providing a safer means for police to enforce the red interval. The RLIL activates at the onset of the red phase and allows an enforcement officer to observe red-light running from downstream of the intersection. Results indicate statistically significant crash reductions for most crash types (i.e., total crashes, fatal and injury crashes, right-angle, and left-turn). The B/C ratio estimated with conservative cost and service life assumptions indicates this strategy was highly beneficial for four-legged signalized intersections. This report will benefit traffic engineers, enforcement personnel, and safety planners by providing insight for greater intersection safety.

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Director, Office of Safety
Research and Development

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16. Abstract The Development of Crash Modification Factors program conducted the safety evaluation of red-light indicator lights (RLILs) at intersections for the Evaluation of Low-Cost Safety Improvements Pooled Fund Study. This study evaluated safety effectiveness of RLILs. RLILs are auxiliary lights mounted on signal heads, mast arms, or poles that are directly connected to a traffic-control signal. The RLIL activates at the onset of the red phase and allows an enforcement officer to observe red-light running from downstream of the intersection. This strategy is intended to reduce the frequency of crashes resulting from drivers disobeying traffic signals by providing a safer and more efficient means for police to enforce the red interval. Geometric, traffic, and crash data were obtained at treated four-legged signalized intersections in Florida. To account for potential selection bias and regression-to-the-mean, an empirical Bayes before–after analysis was conducted using reference groups of untreated four-legged signalized intersections with characteristics similar to those of the treated sites. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment. Results indicate statistically significant crash reductions for most crash types. Disobeyed signal crashes had an estimated crash modification factor (CMF) of 0.71. Total crashes, fatal and injury crashes, right-angle, and left-turn crashes had estimated CMFs of 0.94, 0.86, 0.91, and 0.60, respectively. The benefit-cost ratio estimated with conservative cost and service life assumptions was 92:1 for four-legged signalized intersections. The results suggest that the treatment, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective. In addition to the crash-related benefits, RLILs can improve the efficiency and safety of red-light running enforcement efforts. While this study did not evaluate the efficiency and safety impacts with respect to enforcement, it should be noted that RLILs do allow police to observe violators from a downstream position, eliminating the need for a second observer (upstream) and the need to pursue a violator through the red light.			
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

AADT	average annual daily traffic
B/C	benefit–cost
CAR	Crash Analysis Reporting (system)
CMF	crash modification factor
DOT	Department of Transportation
EB	empirical Bayes
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
KABCO	Scale used to represent injury severity in crash reporting (K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, and O is property damage only)
LED	light-emitting diode
RLILs	red-light indicator lights
SE	standard error
SPF	safety performance function
USDOT	U.S. Department of Transportation

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes. The ultimate goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and promote those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit–cost (B/C) ratios through research. State transportation departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in broad applications of new strategies for safety improvements. Forty State transportation departments provide technical feedback on safety improvements to the DCMF program and implement new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS), which functions under the DCMF program.

This study investigated the safety effectiveness of red-light indicator lights (RLILs). RLILs are auxiliary lights mounted on signal heads, mast arms, or poles that are directly connected to a traffic-control signal. The RLIL activates at the onset of the red phase and allows an enforcement officer to observe red-light running from downstream of the intersection. This strategy is intended to reduce the frequency of crashes resulting from drivers disobeying traffic signals by providing a safer and more efficient means for police to enforce the red interval. Moreover, for the strategy to be effective, agencies should educate drivers of their existence and intent. Few studies have explored the safety effectiveness of RLILs; in particular, no studies have shown the crash-based safety effectiveness for four-legged intersections.

The research team obtained geometric, traffic, and crash data at treated four-legged rural and urban intersections in Florida. To account for potential selection bias and regression-to-the-mean (RTM), the research team conducted an empirical Bayes (EB) before–after analysis using reference groups of untreated four-legged signalized intersections with characteristics similar to those of the treated sites. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatment.

The results indicate reductions for all crash types analyzed except rear-end crashes. Reductions were statistically significant at the 95-percent confidence level for all crash types. The crash type with the smallest crash modification factor (CMF)—which translated to the greatest reduction—was left-turn crashes with a CMF of 0.60. For all crash types combined, the research team estimated a CMF of 0.94. The CMFs for disobeyed signal, fatal and injury, right-angle, and nighttime crashes were 0.71, 0.86, 0.91, and 0.89, respectively. The research team estimated an insignificant CMF of 1.016 for rear-end crashes.

A disaggregate analysis sought to identify those conditions under which the treatment was most effective. Because total, fatal and injury, right-angle, and disobeyed signal crashes were the focus of this treatment, these crash types were the focus of the disaggregate analysis. The disaggregate analysis showed that CMFs decreased over the first few years of treatment, indicating that they were more effective in reducing crashes as drivers became accustomed to them. The smallest

CMFs (i.e., the greatest reductions) found were for the only district with agencies that noted increased enforcement and public awareness campaigns. The research team found no significant difference in effects between white incandescent and blue light-emitting diode (LED) indicators.

For total, fatal and injury, and right-angle crashes, RLILs appeared to be more effective in rural areas and at intersections with lower total entering volume and a lower proportion of entering traffic from the minor road. The data indicated that the opposite was true for disobeyed signal crashes; the research team found RLILs were more effective in urban areas and at intersections with higher total entering volume and a higher proportion of entering traffic from the minor road. Owing to correlations among these factors, the disaggregate effects should not be combined for quantitative analysis; however, the indications can be considered when prioritizing intersections for treatment.

The B/C ratio estimated with conservative cost and service life assumptions and considering the benefits for total crashes was 92:1 for all signalized intersections. With the recommended U.S. Department of Transportation (USDOT) sensitivity analysis, this value could range from 53:1 to 130:1. These results suggest that the strategy—even with conservative assumptions on cost, service life, and the value of a statistical life—can be highly cost effective.

In addition to the crash-related benefits, RLILs can improve the efficiency and safety of red-light running enforcement efforts. While this study did not evaluate the efficiency and safety impacts with respect to enforcement, it is important to note that RLILs do allow police to observe violators from a downstream position, eliminating the need for a second observer (upstream) and the need to pursue a violator through the intersection during the red interval.

CHAPTER 1. INTRODUCTION

This chapter presents background information on the installation of RLILs at traffic signals. It also provides a brief overview of the ELCSI-PFS, of which the study reported here is a part, and the literature review conducted for this study.

BACKGROUND ON STRATEGY

This strategy involves installing RLILs—also known as signal indicator lights, enforcement lights, rat lights or boxes, or tattletale lights—at traffic signals. RLILs can be mounted on the signal head, as shown in Figure 1, or on the mast arm. The indicator activates simultaneously with the red interval, allowing an enforcement officer downstream to identify whether a vehicle has violated the red interval. While the lights should be visible for the enforcement officer to more safely conduct enforcement operations, the lights should be designed such that they do not confuse drivers (i.e., they should not be red, yellow, or green).

Figure 1. Photo. RLIL on signal head.

In its series of reports on innovative intersection safety treatments, FHWA presented a summary on enforcement lights.[1] The summary states that compared with other enforcement methods, enforcement lights can provide safety, efficiency, and/or cost benefits, including the following:

- Allows red-light running monitoring from downstream of any leg of an intersection.
- Eliminates the need for unsafe pursuit from an officer positioned upstream. The officer would normally need to cross the intersection during the red interval.
- Allows a single officer to conduct downstream enforcement (instead of requiring two officers), resulting in increased efficiency.
- Results in lower installation and maintenance costs than automated enforcement systems (e.g., red light photo enforcement).
- Does not use controversial automated photography.

The FHWA summary also includes several implementation considerations. Because RLILs are not traffic-control devices, there are no compliance issues with the *Manual on Uniform Traffic Control Devices for Streets and Highways*.[2] However, it is worthwhile to consider the following points regarding implementation:

- RLILs should be visible to downstream enforcement officers but should minimize confusion or distraction to drivers. Covering the indicator in one or more directions may help reduce confusion and distraction.
- RLILs should be high enough to be visible over large vehicles and should be out of reach of vandals.
- Wiring should connect to the controller output for the red interval to power the RLIL simultaneously.
- Warning and regulatory signs can be used to supplement RLILs to remind drivers of enforcement or fines.
- Attainment of judicial support for acceptance of the citations given based on the RLILs is critical.
- Public awareness campaigns and increased enforcement may amplify RLIL effectiveness.

BACKGROUND ON STUDY

In 1997, the American Association of State Highway and Transportation Officials Standing Committee on Highway Traffic Safety, with the assistance of FHWA, the National Highway Traffic Safety Administration, and the Transportation Research Board Committee on Transportation Safety Management, met with safety experts in the field of driver, vehicle, and highway issues from various organizations to develop a strategic plan for highway safety. These participants developed 22 key emphasis areas that affect highway safety.[3]

The National Cooperative Highway Research Program published a series of guides to advance the implementation of countermeasures targeted to reduce crashes and injuries. Each guide addresses one of the emphasis areas and includes an introduction to the problem, a list of objectives for improving safety, and strategies for each objective. The guides designate each strategy as proven, tried, or experimental. For many of the strategies discussed in these guides, no States or agencies have performed evaluations; the guides consider about 80 percent of the strategies tried or experimental.

In 2005, to support the implementation of the guides, FHWA organized a pooled fund study of States to evaluate low-cost safety strategies as part of this strategic highway safety effort. Over the years, the pooled fund has grown in size and now includes 40 States. The purpose of the ELCSI-PFS is to evaluate the safety effectiveness of high priority tried and experimental low-cost safety strategies selected by member States through scientifically rigorous crash-based studies. The use of RLILs was selected as a strategy to be evaluated as part of this effort.

The ELCSI-PFS conducts its research within the FHWA's DCMF program, which is a comprehensive, long-term safety research effort. FHWA established the DCMF program in November 2012 to support and complement the efforts of the ELCSI-PFS. The ultimate goal of the DCMF program is to save lives by identifying new safety countermeasures that effectively reduce crashes and promoting those countermeasures for nationwide installation by providing measures of their safety effectiveness, including B/C ratios, through research.

LITERATURE REVIEW

Reddy et al. conducted the leading study to date, examining the effectiveness of white enforcement lights in Hillsborough County, FL.[(4)] They noted that white enforcement lights allowed police officers to operate more effectively because the required manpower could be cut in half. Prior to installation, it took two officers to enforce red lights (one upstream to observe the red light and the other downstream to stop the offending driver). Reddy et al. evaluated 17 signalized intersections in Hillsborough County to determine the effectiveness of white lights in reducing red-light violations and associated crashes. They observed red-light violations in the a.m. and p.m. peak hours for 5 months prior to installation and 3 months after installation. In addition, they collected crash data from 2000 to 2005 from the Florida Department of Transportation (FDOT) Crash Analysis Reporting (CAR) system.[(4)]

A review of the crash data indicated an average of 828 crashes per year at the treatment sites before treatment and 860 crashes per year after treatment. Further analysis determined an average of 56 disregarded traffic signal crashes per year in the before period and 52 crashes per year in the after period. Considering only the approaches with white lights, red-light running crashes decreased from 40.17 crashes per year to 28 crashes per year after treatment. The authors noted an increase in all crashes countywide during the study period, while the trend in red-light running crashes stopped increasing in 2002, the year that white light installation began.[(4)]

The number of red-light running citations increased from 17,561 per year before treatment to 24,551 per year after treatment. The researchers documented that police officers found the white lights made the task of red-light enforcement simpler and safer. The red-light violation data collected at the study intersections showed a statistically significant reduction at the 90-percent confidence level in violations from 759 to 567 after white light installation. Owing to high variation, the results from the analyses of crash data were less conclusive than the results of the violation data.[4]

CHAPTER 2. OBJECTIVE

The research described in this report examined the safety impacts of the application of RLILs at signalized intersections. The objective was to estimate the safety effectiveness of this strategy as measured by crash frequency. The research team considered only intersection-related crashes, and further sub-target crash types included the following:

- Total crashes (all types and severities combined).
- Injury crashes (K, A, B, and C injuries on KABCO scale).[1]
- Right-angle crashes (all severities combined).
- Left-turn crashes (all severities combined).
- Rear-end crashes (all severities combined).
- Nighttime crashes (all severities combined).
- Crashes in which driver(s) disobeyed traffic signal (all severities combined).

A further objective was to address questions of interest, such as the following:

- Do effects vary by traffic volume?
- Do effects vary by intensity of treatment (e.g., number of enforcement lights per intersection)?
- Do effects vary depending on the exact type of indicator light (e.g., blue LED versus white bulb)?
- Do effects vary by posted speed limit on the major route?
- Are the effects short-lived?
- Are spillover effects evident?

The evaluation of overall effectiveness included the consideration of the installation costs and crash savings in terms of the B/C ratio.

Meeting these objectives placed some special requirements on the data collection and analysis tasks, including the need to do the following:

- Select a large enough sample size to detect with statistical significance what may be small changes in safety for some crash types.
- Identify appropriate untreated reference sites. This included reference sites both adjacent and not adjacent to treated sites in order to consider potential spillover and migration

[1]The KABCO scale is used to represent injury severity in crash reporting (K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, and O is property damage only).

effects. The term *spillover* is used to describe the effect of the treatment at nearby locations because motorists may be unsure of the exact locations of the treatment and may change their behavior at the nearby locations as well. Crash migration may occur if motorists change their behavior at the treatment sites and then compensate at other locations, or if motorists choose alternate routes to avoid the treatment.

- Properly account for changes in safety due to changes in traffic volume and other nontreatment factors.

CHAPTER 3. STUDY DESIGN

The study design involved a sample size analysis and prescription of needed data elements. The sample size analysis assessed the size of sample required to statistically detect an expected change in safety and also determined what changes in safety could be detected with likely available sample sizes.

SAMPLE SIZE ESTIMATION OVERVIEW

When planning a before–after safety evaluation study, it is vital to ensure that enough data are included such that it is statistically possible to detect the expected change in safety. While the expected change in safety is unknown in the planning stages, it is still possible to estimate the number of required sites (i.e., intersections) based on the best available information about the expected change in safety. Alternatively, one could estimate the change in safety that one could statistically detect for the number of available sites. Chapter 9 of Hauer provides a detailed explanation of sample size considerations and estimation methods.[5] The sample size analysis presented in this section addresses two cases: (1) how large a sample would be required to statistically detect an expected change in safety and (2) what changes in safety could be detected with available sample sizes.

For case 1, the research team assumed that a conventional before–after study with comparison group design would be used because available sample size estimation methods were based on this assumption. The sample size estimates from this method would be conservative in that the EB methodology would likely require fewer sites. To facilitate the analysis, it was also assumed that the number of comparison intersections was equal to the number of treatment intersections and the durations of the before and after periods were equal, which was again a conservative assumption.

Table 1 provides the crash rate assumptions. Initially, the research team assumed that the locations of interest for this treatment would be four-legged and three-legged signalized intersections. However, very few three-legged intersections were treated, and therefore, these intersections were dropped from the dataset. The research team used a central Florida study as the basis for assumptions on intersection crash rates.[6] Intersection crash rates differ substantially depending on a number of factors (e.g., traffic volume, geometric configuration, and area type). Therefore, the intersection crash rates assumed represent the general lower and upper end of the crash frequency spectrum in Florida. Rate C represents the intersection crash rate for before-period data for all intersections in Florida.

Table 1. Before-period crash rate assumptions for signalized intersections in Florida.

Crash Type	Rate A: Orange County (2x2 Lane Signalized Intersections)[1]	Rate B: Seminole County (6x4 Lane or 6x6 Lane Signalized Intersections)[1]	Rate C: Before-Period (All Treatment Sites)[2]
All	2.47	28.45	9.33
Injury	1.79	4.8	4.84
Right-angle	0.55	3.93	1.82
Left-turn	0.55	1.6	0.95
Rear-end	0.89	17.2	3.97
Nighttime	—	—	2.92
Disobeyed signal	—	—	0.81

[1]Data source: Kowdla.(6)
[2]Data source: project database.
Rate = Crashes/intersection/year.
— Indicates no available data.

Table 2 and table 3 provide estimates of the required number of before- and after-period intersection-years for crash rates A, B, and C to achieve statistical significance at 95- and 90-percent confidence levels, respectively. The minimum sample indicated the level for which a study seemed worthwhile (i.e., it was feasible to detect with the specified level of confidence the largest effect that one might reasonably expect based on current knowledge about the strategy). The research team based these sample size calculations on specific assumptions regarding the number of crashes per intersection and years of available data. Intersection-years is the number of intersections where the strategy was in effect multiplied by the number of years of data before or after implementation. For example, if a strategy was implemented at nine intersections and data were available for 3 years since implementation, then there was a total of 27 intersection-years of after-period data available for the study.

Table 2. Minimum required before-period intersection-years for treated intersections at the 95-percent confidence level.

Crash Type	Expected Percent Reduction in Crashes	Rate A	Rate B	Rate C
All	**10**	**751**	**65**	**199**
	20	113	10	30
	30	38	3	11
	40	17	1	5
Fatal and injury	**10**	**1,036**	**386**	**384**
	20	156	58	58
	30	53	20	20
	40	23	9	9
Right-angle	**10**	**3,373**	**472**	**1,020**
	20	507	71	153
	30	173	24	52
	40	75	10	23
Left-turn	10	3,373	1,159	1,955
	20	**507**	**174**	**293**
	30	173	59	100
	40	75	26	43
Rear-end	**10**	**2,084**	**108**	**468**
	20	313	16	71
	30	107	6	24
	40	46	2	11
Nighttime	**10**	**—**	**—**	**636**
	20	—	—	96
	30	—	—	33
	40	—	—	14
	10	—	—	2,290
Disobeyed	**20**	**—**	**—**	**344**
	30	—	—	117
	40	—	—	51

Note: Assumes equal number of intersection-years for treatment and comparison intersections and equal length of before and after periods.
Boldface indicates the sample size values recommended in this study.
— Indicates no data.

Table 3. Minimum required before-period intersection-years for treated intersections at the 90-percent confidence level.

Crash Type	Expected Percent Reduction in Crashes	Rate A	Rate B	Rate C
All	**10**	**467**	**41**	**124**
	20	78	7	21
	30	27	2	8
	40	12	1	4
Fatal and injury	**10**	**644**	**240**	**239**
	20	108	40	40
	30	37	14	14
	40	16	6	6
Right-angle	**10**	**2,096**	**293**	**635**
	20	351	49	106
	30	122	17	37
	40	53	7	16
Left-turn	10	2,096	721	1,215
	20	**351**	**121**	**203**
	30	122	42	70
	40	53	18	31
Rear-end	**10**	**1,296**	**67**	**291**
	20	217	11	49
	30	75	4	17
	40	33	2	8
Nighttime	**10**	—	—	**395**
	20	—	—	66
	30	—	—	23
	40	—	—	10
Disobeyed	10	—	—	1,425
	20	—	—	**238**
	30	—	—	82
	40	—	—	36

Note: Assumes equal number of intersection-years for treatment and comparison intersections and equal length of before and after periods.
Boldface indicates the sample size values recommended in this study.
— Indicates no data.

The sample size values recommended for this study are highlighted in bold in table 2 and table 3. These were recommended based on conservative estimates of the anticipated effects of the treatment. As noted, the sample size estimates provided were also conservative in that the state-of-the-art EB methodology proposed for the evaluations would require fewer intersections than the less robust conventional before–after study with a comparison group. Estimates could be predicted with greater confidence or a smaller reduction in crashes would be detectable if there were more intersection-years of data available in the after period. The same holds true if the actual data used for the analysis had a higher crash rate for the before period than was assumed.

Case 2 considered the data collected for both the before and after periods. RLILs were installed at 108 signalized intersections between 2004 and 2010. The before and after periods varied across intersections depending on the year of treatment installation. The total intersection-years of data available was 365 for the before period for two-lane major roadways and 599 for the after period. From this, one can estimate the minimum percent reduction detectable for the two confidence levels (i.e., 90 and 95 percent). The results of these calculations are shown in table 4. The calculations are based on the methodology in Hauer.(5)

Table 4. Sample analysis for crash effects.

Crash Type	Intersection-Years in Before Period	Intersection-Years in After Period	Minimum Percent Reduction Detectable for Crash Rate Assumption[1] *P* = 0.10	Minimum Percent Reduction Detectable for Crash Rate Assumption[1] *P* = 0.05
Total	365	599	5	10
Fatal and injury	365	599	10	10
Right-angle	365	599	10	15
Left-turn	365	599	15	15
Rear-end	365	599	10	10
Nighttime	365	599	10	10
Disobeyed	365	599	15	20

[1]Results were to nearest 5-percent interval, and the crash rate assumption was based on actual crash rate for the before period.

For the available data, the minimum percentage changes in crash frequency that could be statistically detected at the 95- and 90-percent significance levels were estimated using the before-period crash rates (Rate C) in table 1. The results indicate that the data should be sufficient for detecting the anticipated crash reduction effects highlighted in table 2 (i.e., 10-percent reductions for all crash types except left-turn and disobeyed signal crashes, if such an effect were present). Using these results, the project team decided to proceed with the evaluation using the data available at the time.

CHAPTER 4. METHODOLOGY

This study employed the EB methodology for observational before–after studies.[5] This methodology is considered rigorous in that it accounts for RTM using a reference group of similar but untreated sites. In the process, safety performance functions (SPFs) were used, which did the following:

- Overcame the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- Accounted for time trends.
- Reduced the level of uncertainty in the estimates of safety effect.
- Properly accounted for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.
- Provided a foundation for developing guidelines for estimating the likely safety consequences of a contemplated strategy.

Figure 2 shows the change in safety for a given crash type at a site in the EB approach.

$$\Delta\, Safety = \lambda - \pi$$

Figure 2. Equation. Estimated change in safety.

Where:

λ = Predicted number of crashes that would have occurred in the after period without the strategy.
π = Number of reported crashes in the after period.

In estimating λ, the effects of RTM and changes in traffic volume were explicitly accounted for using SPFs, relating crashes of different types to traffic flow and other relevant factors for each jurisdiction based on untreated sites (reference sites). The research team calibrated annual SPF multipliers to account for temporal effects on safety (e.g., variation in weather, demography, and crash reporting).

In the EB procedure, the SPF is used to first estimate the number of crashes that would be expected in each year of the before period at locations (i.e., reference sites) with traffic volumes and other characteristics similar to the one being analyzed. The sum of these annual SPF estimates (*P*) is then combined with the count of crashes (*x*) in the before period at a strategy site to obtain an estimate of the expected number of crashes (*m*) before strategy. Figure 3 shows this estimate of *m*:

$$m = w(P) + (1 - w)(x),$$

Figure 3. Equation. EB estimated of expected crashes.

Where *w*, the EB weight, is estimated from the mean and variance of the SPF estimate as seen in figure 4.

$$w = \frac{1}{1+kP},$$

Figure 4. Equation. EB weight.

Where:

k = Constant for a given model, which is estimated from the SPF calibration process with the use of a maximum likelihood procedure. In that process, a negative binomial distributed error structure is assumed with *k* being the overdispersion parameter of this distribution.

A factor is then applied to *m* to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period divided by *P*, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance of λ.

The estimate of λ is then summed over all sites in a strategy group of interest (to obtain λ_{sum}) and compared with the count of crashes observed during the after period in that group (π_{sum}). The variance of λ is also summed over all sites in the strategy group.

Figure 5 shows how to estimate the index of effectiveness (θ).

$$\theta = \frac{\pi_{sum}/\lambda_{sum}}{1+\left(Var(\lambda_{sum})/\lambda_{sum}^2\right)}$$

Figure 5. Equation. Index of effectiveness.

The standard deviation of θ is shown in figure 6.

$$StDev(\theta) = \sqrt{\frac{\theta^2\left(\frac{Var(\pi_{sum})}{\pi_{sum}^2}+\frac{Var(\lambda_{sum})}{\lambda_{sum}^2}\right)}{\left(1+\frac{Var(\lambda_{sum})}{\lambda_{sum}^2}\right)^2}}$$

Figure 6. Equation. Standard deviation of index of effectiveness.

The percent change in crashes is calculated as $100(1-\theta)$; thus, a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30-percent reduction in crashes with a standard deviation of 12 percent.

CHAPTER 5. DATA COLLECTION

FDOT provided the majority of the data for this strategy, including treatment sites, information regarding the enforcement lights (e.g., manufacturer specifications and law enforcement practices), screening for construction activity for many treatment sites, and access to its mainframe computer. This allowed the research team to query crash, roadway, and traffic data. Several city traffic engineering departments and police departments also provided information. Additional details about the design, installation, and maintenance of RLILs, as well as lessons learned, are provided in the appendix of this report.

INSTALLATION DATA

The FDOT central office undertook an initiative to deploy enforcement lights at signalized intersections. It provided the FDOT districts with enforcement light equipment (e.g., mounts and bulbs) and lists of intersections for potential installations. Districts 1, 2, and 5 were able to implement this treatment widely. The engineering departments of these districts provided the following data for this evaluation:

- Treatment locations.
- Installation dates.
- Movements monitored (e.g., northbound through, westbound left).
- Enforcement light type (i.e., white incandescent or blue LED).

After receiving lists of all the potential treatment sites from the districts, the research team selected treatment sites appropriate for this study. Initially, there were more than 300 potential treatment sites with installation dates varying from 2003 to 2010. Only those treatment sites with an installation date on or after 2004 allowed retrieval of before-period data from the available data in Florida's CAR system. This excluded a number of potential sites from the study. The CAR did not contain complete crash data for sites located on other route types, thus excluding sites not located on U.S., State, or county routes. The research team identified the number of approaches using aerial imagery of the potential treatment sites and observed that only a small proportion were three-legged intersections. Such a small sample size would not likely produce statistically robust results; consequently, the research team removed the three-legged treatment intersections from further consideration in this study. The final treatment group for this strategy was composed of 108 four-legged intersections located in three districts in Florida (districts 1, 2, and 5).

The study also solicited information on law enforcement practices and public awareness campaigns regarding the enforcement lights. A number of local agencies provided feedback regarding the enforcement practices and public awareness, particularly in district 1. The appendix of this report provides the responses by city and county agencies tasked with red-light enforcement.

REFERENCE SITES

As noted in the study design, the potential for spillover or crash migration effects existed for this strategy. To address this potential issue, the research team formed two reference groups. The first group, a potential spillover reference group, consisted of signalized four-legged intersections immediately adjacent to a treatment site. In other words, a selected spillover reference site would not have a signalized intersection between it and a treatment site. The second group, a non-spillover reference group, consisted of signalized four-legged intersections that had one or more untreated signalized intersections separating them from a treatment site. If the research team detected no crash migration or spillover effects, then it pooled the two reference groups to form the reference group for the EB method. If crashes increased or decreased significantly at the spillover sites, then these sites would not help to identify the safety effectiveness of the strategy at treated sites reliably. This would also indicate effects of the strategy on adjacent intersections. In all, the research team selected 30 reference sites. Sixteen were spillover reference sites, and the remaining 14 were non-spillover sites. For each reference site, the research team queried all available crash records between January 1, 2003, and December 31, 2012.

ROADWAY DATA

Using crash report data, FDOT provided roadway data for the installation and reference sites. Selected roadway data elements included the following:

- District.
- County.
- Shoulder type.
- Functional classification (which also defined area type).
- Surface width.
- Median width.
- On-curve presence.
- Posted speed limit.

CRASH DATA

FDOT's crash database, the CAR system, provided the crash data for the treatment and reference sites using a two-stage process. First, the project team determined the node number for each site. This number was a unique number that FDOT assigned to each intersection within a county for identification purposes. The crash database also used these node numbers for location identification. After compiling the node numbers, the second stage was to query crash records. The research team queried records using the "around a node" option within the CAR system and a defined influence area of a 250-ft radius around each intersection.

TRAFFIC DATA

The crash reports that the CAR system generated also contained traffic volume data. Most important was the average annual daily traffic (AADT) values for the mainline and cross-street roadway sections for the intersections. In addition, the 2012 *Florida Transportation Information (FTI) DVD* provided traffic volumes for State roadways where no crashes occurred.[7] Finally, the research team estimated traffic volumes for cross streets with missing data based on nearby traffic counts, surrounding land use, roadside development, and interconnectivity.

TREATMENT COST DATA

FDOT provided estimates of the costs and service lives of the treatments for use in conducting a B/C analysis of the treatment. Red-signal enforcement light sets (including housing) cost approximately $50 to $150 for traditional (rather than LED) bulbs. Generally, four to eight indicator sets were needed for a major intersection to cover all signals and intervals for a total intersection cost of $200 to $1,200. Cost depended substantially on whether LED or traditional bulbs were used; LED bulbs cost approximately three times as much initially but required much less power. The power cost was generally negligible in comparison with the power used by the signal, into which the indicator was directly wired. Therefore, the analysis ignored the power cost.

In addition, installation cost and service life data were explored through vendors,[2] State transportation departments, and newspaper articles. (See references 1 and 8–12.) The cost of lights was dependent on color and hardware required for installation. The research team found that the lights cost between $77 and $300 per light. In addition, the installation of the indicator lights required manpower and equipment, and the associated cost depended on where the lights were mounted (i.e., on the back of signal head or on a pole). The cost per intersection ranged from $1,000 to $3,000 for installation. The State transportation departments reported the life span of the indicator lights was between 5 and 10 years.

DATA CHARACTERISTICS AND SUMMARY

Table 5 defines the crash types used by Florida. Table 6 provides summary information for the data collected for the treatment and reference sites. Installations dates ranged from 2004 to 2010. The before and after periods varied by location with the installation year marking the change from before to after. Before periods started as early as 2003 and ended as late as 2009. After periods started as early as 2005 and ended in 2012. The information in table 6 should not be used to make simple before–after comparisons of crashes per site-year because it does not account for factors other than the strategy that might cause a change in safety between the before and after periods. Such comparisons require an EB analysis, as presented in chapter 7.

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[2]Melvin Barrios of Industrial Traffic Solutions, e-mail correspondence, December 3, 2014, and http://lanecontrols.com/tattle-tale/.

Table 5. Definitions of crash types.

Crash Types	Definition
Total	Identified as all crashes, without exclusion
Fatal and injury	Resulted in the following: 5—Fatal Injury 4—Incapacitating Injury 3—Non-incapacitating Evident Injury 2—Possible Injury
Right-angle	First Harmful Event coded as 03—Collision With MV in Transport (Angle)
Left-turn	First Harmful Event coded as 04—Collision With MV in Transport (Left Turn)
Rear-end	First Harmful Event coded as 01—Collision With MV in Transport (Rear-End)
Nighttime	Light Condition coded as anything other than 01-Daytime or 88-Unknown
Disobeyed signal	1st Contributing Cause coded as 11—Disregarded Traffic Signal

MV = Moving vehicle.

Table 6. Before and after data summary for treatment and reference sites.

Variable	Treatment	Reference		
		Spillover	Non-Spillover	Combined
Number of sites	108	19	11	30
Site-years before	365	190	110	300
Site-years after	599			
Before total crashes	10.085	3.989	5.355	4.490
After total crashes	8.367			
Before fatal and injury crashes	5.167	2.242	2.818	2.453
After fatal and injury crashes	4.025			
Before right-angle crashes	1.986	0.621	0.891	0.720
After right-angle crashes	1.548			
Before left-turn crashes	0.981	0.363	0.464	0.400
After left-turn crashes	0.509			
Before rear-end crashes	4.386	1.711	2.345	1.943
After rear-end crashes	3.888			
Before nighttime crashes	3.219	0.932	1.427	1.113
After nighttime crashes	2.496			
Before disobeyed crashes	0.819	0.237	0.391	0.293
After disobeyed crashes	0.586			
Before major AADT	Avg. 35,841 Min. 5,900 Max. 80,500	Avg. 35,341 Min. 10,900 Max. 80,500	Avg. 31,705 Min. 13,900 Max. 67,500	Avg. 34,008 Min. 10,900 Max. 80,500
After major AADT	Avg. 34,084 Min. 5,000 Max. 79,000			
Before minor AADT	Avg. 13,934 Min. 845 Max. 62,666	Avg. 6,938 Min. 910 Max. 40,850	Avg. 10,327 Min. 1,048 Max. 28,500	Avg. 8,180 Min. 910 Max. 40,850
After minor AADT	Avg. 12,146 Min. 867 Max. 59,000			

Note: Crash rates are presented as crashes/site/year.
Avg. = Average.
Min. = Minimum.
Max = Maximum.

CHAPTER 6. DEVELOPMENT OF SPFs

This section presents the SPFs developed for each crash type. The SPFs support the use of the EB methodology to estimate the safety effectiveness of the strategy.[5] The research team used generalized linear modeling to estimate model coefficients assuming a negative binomial error distribution, which was consistent with the state of research in developing these models. In specifying a negative binomial error structure, the dispersion parameter, *k*, was estimated iteratively from the model and the data. For a given dataset, smaller values of *k* indicate relatively better models (i.e., less dispersion).

SPFs FOR SPILLOVER AND MIGRATION EFFECTS

Before developing SPFs, the research team analyzed separate reference groups to identify potential crash migration and spillover effects. The project team used data from both reference groups to develop yearly multipliers for each group. Figure 7 provides the form of the SPF. Table 7 presents the estimated coefficients, as well as the value of *k*, the overdispersion parameter of the model.

$$\frac{crashes}{year} = e^{a} \times TotalEnter^{b} \times PropAADTMin^{c} \times e^{(ShldT1 \times d)}$$

Figure 7. Equation. SPF for spillover and migration.

Where:

TotalEnter = Total entering volume.
PropAADTMin = Proportion of entering volume from minor route.
ShldT1 = Indicator for paved shoulder.
a, *b*, *c*, *d* = Parameters estimated in the SPF calibration process.

Table 7. Parameter estimates for the reference group SPF for total crashes.

	Parameter Estimate				
Crash Type	***a***	***b***	***c***	***d***	***k***
Total	−5.019	0.598	1.534	−0.245	0.225

Table 8 presents the observed crashes versus predicted crashes for each of the two reference groups. In the table, group 1 is the non-spillover/migration reference group, and group 2 is the potential spillover/migration reference group. Yearly factors are the ratio of observed crashes to predicted crashes for the given group within the given year. Because the base model was independent of year, yearly fluctuations were not a consideration in predicted crashes. Crash spillover was evident when the ratio for the spillover group became smaller with increasing time (because treatments were in use from 2004 to 2010). Crash migration occurred when the ratio increased with time. However, table 8 and figure 8 illustrate that there was no noticeable trend for the potential spillover/migration group. The ratios for groups 1 and 2 follow a consistent trend, indicating that neither crash spillover nor crash migration was observable. However, there was a slight underprediction for the non-spillover/migration group and a slight overprediction for the potential spillover/migration group. In addition, there was no apparent increasing or decreasing trend for either group, indicating that there was no observed districtwide crash migration or spillover effects.

Table 8. Observed and predicted crashes for reference groups.

Year	Observed Crashes		Predicted Crashes		Yearly Factors	
	Group 1	Group 2	Group 1	Group 2	Group 1	Group 2
2003	55	60	52.945	82.127	1.039	0.731
2004	65	97	53.146	81.677	1.223	1.188
2005	62	78	55.166	84.369	1.124	0.925
2006	57	82	54.400	82.999	1.048	0.988
2007	48	62	54.387	82.548	0.883	0.751
2008	68	75	53.389	83.822	1.274	0.895
2009	64	77	52.874	79.854	1.210	0.964
2010	68	72	52.045	80.265	1.307	0.897
2011	47	72	51.791	78.853	0.907	0.913
2012	55	83	52.011	78.185	1.057	1.062

Note: Group 1 is non-spillover/migration, and group 2 is potential spillover/migration.

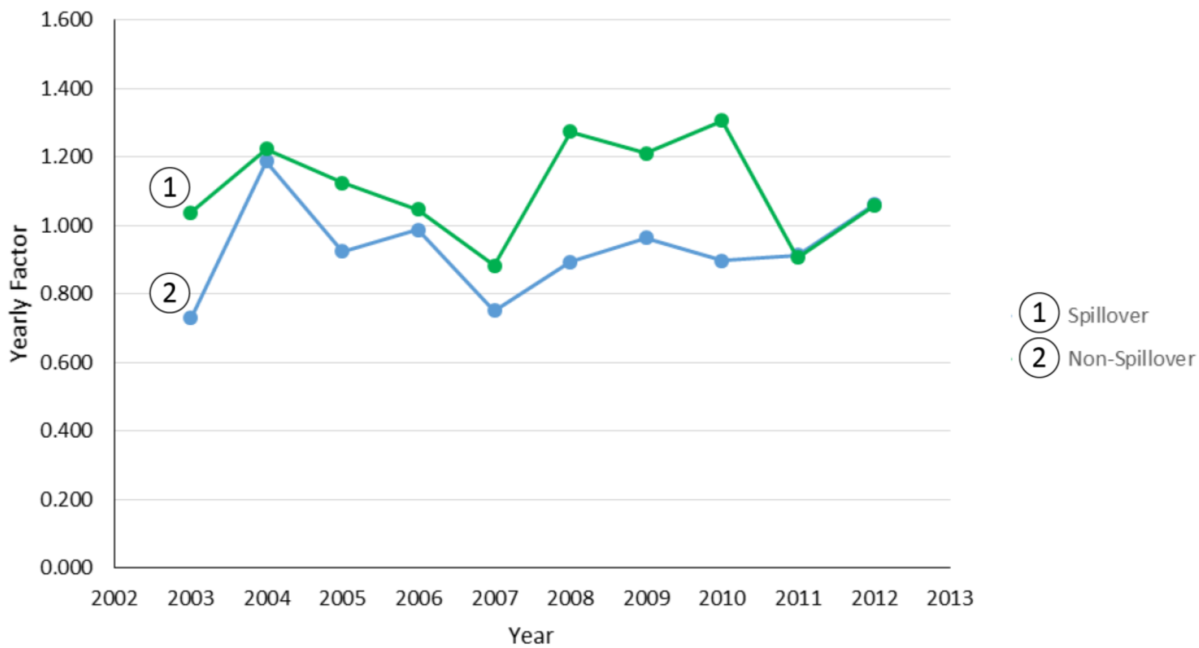

Figure 8. Graph. Yearly multiplier by year for reference groups.

While the results shown in table 8 and figure 8 provided evidence that crash migration and spillover were not of concern, they were insufficient to definitively conclude that the analysis could combine the two groups into a single reference group. Therefore, the research team conducted a supplementary analysis to estimate a second SPF, including an indicator for group 2 (the potential spillover/migration group) after the application of the nearby treatments. Table 9 presents the SPF results. The model includes yearly indicators to account for annual fluctuation that other predictor variables do not capture.

Table 9. SPF results with indicator variable for potential spillover/migration sites.

Variable	Coefficient	SE	*P*-Value
Log-total entering	0.643	0.098	< 0.001
Proportion AADT minor	1.045	0.463	0.024
Paved shoulder	−0.204	0.096	0.034
Year 2004 indicator	0.369	0.171	0.031
Year 2005 indicator	0.187	0.176	0.290
Year 2006 indicator	0.204	0.182	0.264
Year 2007 indicator	−0.020	0.198	0.919
Year 2008 indicator	0.231	0.192	0.230
Year 2009 indicator	0.242	0.193	0.210
Year 2010 indicator	0.242	0.193	0.210
Year 2011 indicator	0.105	0.197	0.595
Year 2012 indicator	0.231	0.194	0.233
Indicator for spillover/migration group	−0.218	0.137	0.111
Group 2 with treatment indicator	−0.001	0.145	0.994
Constant	−5.478	1.022	< 0.001
Overdispersion	0.201	N/A	N/A

SE = Standard error.
N/A = Not applicable.

The resulting SPF showed no statistical difference for group 2 compared with group 1. Post-treatment application in that the indicator variable was insignificant, with the direction of effect being negative. This indicates that no crash migration or spillover effects occurred in group 2 after the application of the treatment at nearby sites. In addition, the research team included an indicator to account for systematic differences between the potential spillover/migration group and non-spillover/migration group (see table 8). Because the potential spillover/migration group consistently overpredicted crashes, the indicator should have been negative (meaning that fewer crashes would be predicted at potential spillover/migration sites compared to non-spillover/migration sites). This was found to be the case; however, the indicator was not statistically significant even at the 90-percent confidence level ($P > 0.10$). This study found similar results for the other crash types considered.

Table 10 presents SPF model results (similar to the SPF results in table 9) for the nearby treatment indicator for all crash types without providing the estimates for other variables. This shows that spillover/migration did not occur for any crash types. Overall, the research team concluded that the two potential reference groups could be combined to estimate the SPFs for the EB analysis.

Table 10. SPF estimates for nearby treatment effect for group 2.

SPF Estimates	Crash Type						
	Total	**Fatal and Injury**	**Right-Angle**	**Left-Turn**	**Rear-End**	**Disobey Signal**	**Nighttime**
Coefficient	−0.001	−0.018	0.307	−0.346	0.014	−0.154	−0.327
SE	0.145	0.164	0.276	0.341	0.202	0.490	0.232
P-value	0.994	0.913	0.266	0.310	0.943	0.752	0.160

SPFs FOR COMBINED REFERENCE DATA

The form of the SPF for total crashes for combined reference groups is given by figure 9, and the results are presented in table 11, where *k* is also provided for each SPF.

$$\frac{crashes}{year} = e^{a} \times TotalEnter^{b} \times PropAADTMin^{c} \times e^{(ShldT1 \times d + Curve \times f)}$$

Figure 9. Equation. SPF for EB analysis.

Where:

Curve = Indicator for intersection being on a horizontal curve.

Table 11. Parameter estimates and SEs for Florida signalized intersection SPF for total crashes.

Crash Type	Parameter Estimate					
	a	***b***	***c***	***d***	***f***	***k***
Total	−4.217	0.513	1.757	−0.343	−0.365	0.195
SE	(1.047)	(0.098)	(0.422)	(0.098)	(0.109)	N/A

Note: The letters for parameters in table 11 correspond with those in figure 9.
N/A = Not applicable.

In addition, the research team considered crash sample size for reference sites in the development of SPFs. Because total crashes ranged from a minimum of 110 crashes in 2008 to a maximum of 162 in 2004, the research team developed an SPF for total crashes. For all other crash types, there were too few crashes per year to develop separate reliable SPFs. Therefore, the research team used the total crashes SPF for other crash types, along with a proportion factor relating the crash type in question with total crashes. The research team multiplied the prediction from the SPF by the proportion factor to determine the number of predicted crashes of each specific crash type. The following crash type proportions were used:

- Fatal and injury crashes = 0.570.
- Right-angle crashes = 0.152.
- Left-turn crashes = 0.132.
- Rear-end crashes = 0.391.
- Disobey signal crashes = 0.048.
- Nighttime crashes = 0.305.

Table 12 provides annual factors (i.e., multipliers) estimated from the total crashes SPF. For multipliers greater than 1.00, more crashes were predicted for that year than the base year. For multipliers less than 1.00, fewer crashes were predicted for that year than the base year. The base year for multipliers was 2003. All crash types used the annual factors from the total crashes SPF.

Table 12. SPF-generated yearly multipliers.

Crash Type	2004	2005	2006	2007	2008	2009	2010	2011	2012
Total	1.430	1.202	1.208	0.957	1.245	1.244	1.246	1.089	1.228

Based on the large difference in crash rates between the treatment and reference sites (see table 6), the team decided to calibrate the SPF to the treatment site data just before treatment. The difference in crash rates was too large to be explained by RTM bias. Therefore, the research team used the treatment sites to account for the underprediction, using only the final year of crash data before treatment installation to calibrate the SPF. This was consistent with the approach used by Srinivasan et al.(13)

In the study by Srinivasan et al., the authors calibrated SPFs to be more representative of the treatment group using before-period data.(13) The authors plotted 6 consecutive years of crash data for treatment sites to look for evidence of randomly high crashes during the before period. The plot showed that the counts for 2, 3, and 4 years before treatment were higher than for 1, 5, and 6 years before treatment. The authors selected 5 or more years before treatment to calibrate the SPF.

Figure 10 provides a plot of the before-period crashes at the treatment sites for the current study. Figure 10 is based on 40 of 108 sites for which 4 years of before data were available. (Crash data were not available for 4 years before treatment for the other 68 sites.) The plot indicates that the year before installation was the least prone to randomly high crash counts, as was also the case for the Srinivasan et al. data.(13) This result is intuitive for two reasons. First, the timeframe to identify and treat the intersections generally ranged from 6 months to 1 year. Second, there was a lag between the end of a calendar year and the availability of crash data for that year. As such, it was unlikely that crash data were available for inclusion in the site-selection process for the year prior to RLIL installation. The large difference between predicted and observed crashes at treatment sites was similar in magnitude to the difference found by Srinivasan et al.(13)

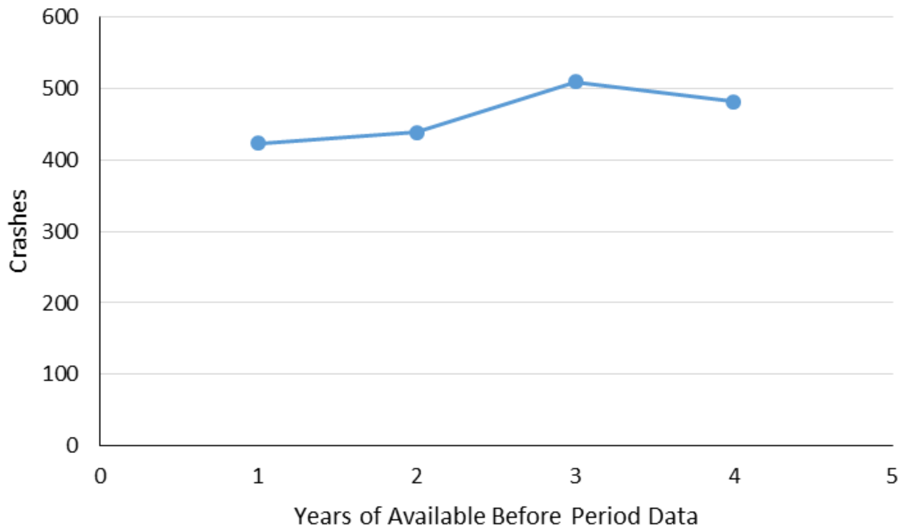

Figure 10. Graph. Crash totals by year before treatment.

The research team developed calibration factors by dividing the observed number of crashes for the year prior to treatment by the predicted number of crashes in the same year. This involved 2003 to 2009 data because installations occurred from 2004 to 2010. The research team developed calibration factors separately by crash type, which was consistent with Srinivasan et al.[(13)] The following calibration factors by crash type were used:

- Total crashes = 1.638.
- Fatal and injury crashes = 1.546.
- Right-angle crashes = 2.034.
- Left-turn crashes = 1.146.
- Rear-end crashes = 1.782.
- Disobey signal crashes = 3.083.
- Nighttime crashes = 1.639.

CHAPTER 7. BEFORE–AFTER EVALUATION RESULTS

This chapter presents the evaluation results, the aggregate results for all intersections, and the results disaggregated by treatment duration, district, indicator type, area type, entering volume, and proportion of volume from the minor road.

AGGREGATE ANALYSIS

Table 13 provides the estimates of expected number of crashes in the after period without treatment, the observed crashes in the after period, and the estimated CMFs, and their SEs for all crash types considered.

Table 13. Aggregate results.

	Crash Type						
Statistic	**Total**	**Fatal and Injury**	**Right-Angle**	**Left-Turn**	**Rear-End**	**Disobey Signal**	**Nighttime**
EB estimate of crashes expected in the after period without strategy	5,337.4	2,816.0	1,023.3	507.3	2,291.6	470.8	1,673.8
Count of crashes observed in the after period	5,012	2,411	927	305	2,329	336	1,495
Estimate of CMF	**0.939**	**0.856**	**0.905**	**0.600**	1.016	**0.713**	**0.892**
SE of estimate of CMF	0.022	0.027	0.042	0.041	0.033	0.048	0.034

Note: Boldface indicates CMF estimates that are statistically significant at the 95-percent confidence level.

The results in table 13 indicate statistically significant reductions at the 95-percent confidence level for all crash types analyzed except rear-end crashes, for which the negligible increase was statistically insignificant. The crash type with the smallest CMF (which translates to the greatest reduction) was left-turn crashes with a CMF of 0.600. For all crash types combined, a CMF of 0.94 was estimated. The CMFs for fatal and injury, right-angle, disobeyed signal, and nighttime crashes were 0.86, 0.91, 0.71, and 0.89, respectively. An insignificant CMF of 1.02 was estimated for rear-end crashes.

DISAGGREGATE ANALYSIS

The disaggregate analysis sought to identify those conditions under which the treatment was most effective. Because total, fatal and injury, right-angle, and disobeyed signal crashes were the focus of this treatment, these crash types were the focus of the disaggregate analysis. The research team identified several variables as being of interest, including treatment duration, indicator type, level of enforcement, number of indicators, area type, curve presence, major and minor approach traffic volumes, number of lanes, median width, surface width, and posted speed limit. The disaggregate CMFs may be used in prioritizing installation sites, but interpretations should be made with caution. While the research team conducted disaggregate analyses by variables of interest, these characteristics were likely not independent, and the research team does not advise combining disaggregate CMFs. However, based on the disaggregate analysis, one could consider several characteristics qualitatively when prioritizing sites for treatment.

For treatment duration, as shown in table 14, RLILs became more effective with time. This was evident because the CMFs for total, fatal and injury, and right-angle crashes became smaller as additional time passed after the treatment. The CMFs for total crashes and right-angle crashes were not statistically significant after 1 or 2 years of implementation but became significant after the second year of implementation. While CMFs became smaller over time for most crash types, the CMF for disobeyed signal crashes was significant and stable after the first year of installation.

Table 14. Results disaggregated by treatment duration and district.

Crash Type	Treatment Duration (years)	CMF (SE)	District	CMF (SE)
Total crashes	1	1.024 (0.037)	1	**0.736 (0.077)**
Total crashes	2	0.963 (0.027)	2	0.995 (0.033)
Total crashes	2+	**0.939 (0.022)**	5	**0.934 (0.031)**
Fatal and injury crashes	1	0.917 (0.047)	1	**0.676 (0.082)**
Fatal and injury crashes	2	**0.888 (0.035)**	2	**0.895 (0.044)**
Fatal and injury crashes	2+	**0.856 (0.027)**	5	**0.868 (0.037)**
Right-angle crashes	1	0.989 (0.079)	1	**0.756 (0.112)**
Right-angle crashes	2	0.944 (0.057)	2	1.036 (0.075)
Right-angle crashes	2+	**0.905 (0.042)**	5	**0.856 (0.054)**
Disobeyed signal crashes	1	**0.748 (0.099)**	1	**0.368 (0.086)**
Disobeyed signal crashes	2	**0.784 (0.074)**	2	**0.797 (0.088)**
Disobeyed signal crashes	2+	**0.713 (0.048)**	5	**0.750 (0.066)**

Note: Boldface indicates CMF estimates that are statistically significant at the 95-percent confidence level.

To assess enforcement and education practices, the research team disaggregated the results by district, as the last two columns of Table 14 show. Across all crash types, the CMFs were smallest for district 1. Local agencies in district 1 responded to the research team regarding the enforcement of the indicator lights. Several counties and cities reported initial advertisements in local newspapers and participation in awareness campaigns. In addition, a few agencies in this district noted that they used the lights and had increased enforcement after their application. No agencies in districts 2 or 5 reported awareness campaigns or increased enforcement. The CMF estimates for districts appear to support these implementation practices (i.e., having publicity and awareness campaigns in combination with some increased enforcements result in smaller CMFs).

For indicator type, as table 15 shows, there was no difference between use of white incandescent indicator lights and blue LED indicator lights for all crash types. For total, fatal and injury, and right-angle crashes, the CMF for white incandescent lights was slightly smaller than the CMF for blue LED lights; however, the difference was not significant at the 95-percent confidence level.

Table 15 also presents the disaggregate results by area type. The results show that RLILs were more effective at rural intersections than urban intersections for total, fatal and injury, and right-angle crashes. These differences were all significant at the 95-percent confidence level. However, although the strategy appeared to be more effective at urban intersections for disobeyed signal crashes, the difference was not statistically significant at the 95-percent confidence level. District 1 did not include any rural sites; all rural sites were located in districts 2 and 5. This implies that the differential effects are likely the result of higher enforcement or awareness campaigns for rural sites.

Table 15. Results disaggregated by indicator type and area type.

Crash Type	Indicator Type	CMF (SE)	Area Type	CMF (SE)
Total crashes	White incandescent	**0.921 (0.027)**	Rural	**0.701 (0.051)**
Total crashes	Blue LED	0.975 (0.038)	Urban	0.963 (0.024)
Fatal and injury crashes	White incandescent	**0.842 (0.034)**	Rural	**0.580 (0.061)**
Fatal and injury crashes	Blue LED	**0.880 (0.045)**	Urban	**0.883 (0.030)**
Right-angle crashes	White incandescent	0.900 (0.053)	Rural	**0.477 (0.078)**
Right-angle crashes	Blue LED	0.911 (0.068)	Urban	0.953 (0.046)
Disobeyed signal crashes	White incandescent	**0.729 (0.060)**	Rural	0.928 (0.150)
Disobeyed signal crashes	Blue LED	0.678 (0.077)	Urban	**0.681 (0.050)**

Note: Boldface indicates CMF estimates that are statistically significant at the 95-percent confidence level.

As shown in table 16, CMFs were significantly smaller for intersections with a total entering volume of less than 40,000 vehicles per day for total, fatal and injury, and right-angle crashes compared with intersections with a higher total entering volume. The strategy was more effective for disobeyed signal crashes at intersections with a higher total entering volume. In all cases, the differences were significant at the 95-percent confidence level. The same trend appears to be true for the proportion of the total entering volume on the minor approach. For intersections with less than 20 percent of the entering volume from the minor road approaches, the CMFs for total, fatal and injury, and right-angle crashes were smaller. However, the difference was not statistically significant at the 95-percent confidence level. For disobeyed signal crashes, the CMF was smaller when more than 20 percent of the entering volume was from the minor road; however, the difference was not significant at the 95-percent confidence level.

Table 16. Results disaggregated by entering volume and proportion entering on minor road approaches.

Crash Type	Entering Volume	CMF (SE)	Proportion from Minor Roads	CMF (SE)
Total crashes	< 40,000	**0.749 (0.033)**	< 0.2	**0.858 (0.041)**
Total crashes	40,000+	1.018 (0.029)	0.2+	0.969 (0.026)
Fatal and injury crashes	< 40,000	**0.716 (0.041)**	< 0.2	**0.813 (0.049)**
Fatal and injury crashes	40,000+	**0.916 (0.035)**	0.2+	**0.873 (0.033)**
Right-angle crashes	< 40,000	**0.749 (0.061)**	< 0.2	0.882 (0.074)
Right-angle crashes	40,000+	0.978 (0.055)	0.2+	0.913 (0.050)
Disobeyed signal crashes	< 40,000	0.911 (0.091)	< 0.2	0.899 (0.092)
Disobeyed signal crashes	40,000+	**0.608 (0.054)**	0.2+	**0.614 (0.054)**

Note: Boldface indicates CMF estimates that are statistically significant at the 95-percent confidence level.

Further analysis considered the total number of RLILs present at intersections. There was a positive correlation between total entering volume and number of RLILs, indicating that there were more RLILs at intersections with a higher total entering volume. There was also a positive correlation with the number of RLILs and urban area type and proportion of entering volume from the minor route. In combination, this led to findings that showed fewer RLILs were more effective for total, fatal and injury, and right-angle crashes than most indicators. In addition, there was likely substantial positive correlation between area type and total entering volume, as well as between total entering volume and proportion entering from the minor road. Correlation between area type and entering volume prohibited combining these CMFs for the purpose of crash prediction.

In summary, the disaggregate analysis showed that RLILs were almost immediately effective in reducing disobeyed signal crashes and became more effective over time for all other crash types. In addition, RLILs appeared to be more effective for total, fatal and injury, and right-angle crashes in rural areas at signalized intersections with lower total entering volume and a lower proportion of entering traffic from the minor road. On the other hand, RLILs appeared to be more effective in urban areas at signalized intersections with higher total entering volume and a higher proportion of entering traffic from the minor road. The analysis showed that one should not combine these factors for quantitative analysis, but they could be considered when prioritizing intersections for treatment. The research team found no significant difference in the results between use of white incandescent bulbs and blue LED bulbs; however, the level of enforcement and the level of awareness campaigns conducted appeared to affect the effectiveness.

CHAPTER 8. ECONOMIC ANALYSIS

The research team conducted an economic analysis to estimate the B/C ratio for this strategy at signalized intersections. The team used the statistically significant reduction in total crashes as the benefit for this treatment strategy. On the cost side and in the absence of details of each installation, the analysis conservatively assumed that the installation of RLILs cost $3,000 per intersection. In total, 108 intersections received RLIL treatments at an estimated cost of $324,000. As summarized in the appendix of this report, the cost of bulbs ranged from $50 to $300. The local agencies involved with the installation of RLILs noted that there was negligible cost for operation because the bulbs were directly wired into the existing traffic signals. The minimal operational cost was offset by the reduced enforcement cost and thus was not factored into this analysis in order to be more conservative.

The analysis assumed the useful service life for safety benefits was 5 years. This was based on information provided by vendors. This service life is likely conservative because 5 years is the minimum service life reported by several vendors, with some potential service lives estimated at up to 10 years.

The FHWA Office of Safety Research and Development suggested that, based on the Office of Management and Budget *Circular A-4*, a real discount rate of 7 percent should be applied to calculate the annual cost of the treatment for the 5-year service life.(14) With this information, the capital recovery factor was 4.1 for all intersections.

For the benefit calculations, the most recent FHWA mean comprehensive crash costs disaggregated by crash severity and crash geometry type were used as a base.(16) Council et al. developed these costs based on 2001 crash costs and found the values in table 17 by crash type and severity.(16) Table 17 also provides the proportion of fatal and injury crashes and the proportion of property damage only (PDO) crashes for each crash geometry type. Considering the proportion of crashes by type and severity, the unit cost (in 2001 dollars) for crashes at signalized intersections in this study was $51,395.

Table 17. Crash costs and distributions by crash type and severity.

Crash Geometry Type	Frequency	K/A/B/C Cost[1]	PDO Cost	K/A/B/C Percent[1]	PDO Percent
Multi-vehicle rear-end	2,362	$48,236	$9,919	49.1	50.9
Multi-vehicle head-on	137	$131,356	$4,980	59.1	40.9
Multi-vehicle crossing path	1,593	$108,401	$8,598	50.6	49.4
Multi-vehicle sideswipe	222	$138,339	$5,905	18.5	81.5
Multi-vehicle backing	32	$53,966	$4,579	9.4	90.6
Single-vehicle struck parked vehicle	21	$108,300	$4,587	47.6	52.4
Single-vehicle struck pedestrian	84	$173,191	$5,432	82.1	17.9
Single-vehicle struck bicycle	64	$173,191	$5,432	87.5	12.5
Single-vehicle struck object	145	$237,600	$5,618	49.7	50.3
Single-vehicle rolled over	12	$324,366	$13,331	91.7	8.3
Other/undefined	340	$316,501	$4,463	30.3	69.7

[1]K/A/B/C refers to the KABCO scale.

Because the analysis was performed in 2014, the unit cost in 2001 dollars was updated to 2014 dollars by applying the ratio of USDOT 2014 value of a statistical life of $9.2 million to the 2001 value of $3.8 million.(15,16) Applying this ratio of 2.42 to the unit cost resulted in an aggregate 2014 unit cost for total crashes of $124,377 for signalized intersections.

The research team calculated the total crash reduction by subtracting the actual crashes in the after period from the expected crashes in the after period had the treatment not been implemented. The research team then divided the total crash reduction by the average number of after-period years per site to compute the total crashes saved per year. The number of total crashes saved per year was 58.7 for all intersections. Considering the number of treated intersections, this resulted in an average savings of 0.54 crashes per intersection per year.

The research team obtained the annual benefits (i.e., crash savings) by multiplying the crash reduction per site-year by the cost of a crash, all severities combined. The research team calculated the B/C ratio as the ratio of the annual benefit to the annual cost. The B/C ratio was 92:1 for all signalized intersections. USDOT recommended a sensitivity analysis be conducted by assuming values of a statistical life of 0.57 and 1.41 times the recommended 2014 value.(17) These factors were applied directly to the estimated B/C ratios to obtain a range of 53:1 to 130:1 for all signalized intersections. These results suggest that the strategy, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective for reducing total crashes at signalized intersections. While the resulting B/C ratio was very high, users should keep in mind the low-cost nature of this strategy and that implementing other strategies with lower B/C ratios might result in larger reductions in crashes.

CHAPTER 9. SUMMARY AND CONCLUSIONS

The objective of this study was to undertake a rigorous before–after evaluation of the safety effectiveness of RLILs as measured by crash frequency. The study used data from Florida to examine the effects on specific crash types, including total, fatal and injury, right-angle, left-turn, rear-end, nighttime, and disobeyed signal crashes. Based on the combined results, the research team recommends the CMFs shown in table 18 for the various crash types.

Table 18. Results of Florida

Statistic	Crash Type						
	Total	**Fatal and Injury**	**Right-Angle**	**Left-Turn**	**Rear-End**	**Disobey Signal**	**Nighttime**
Estimate of CMF	**0.939**	**0.856**	**0.905**	**0.600**	1.016	**0.713**	**0.892**
SE of estimate of CMF	0.022	0.027	0.042	0.041	0.033	0.048	0.034

Note: Boldface indicates CMF estimates that are statistically significant at the 95-percent confidence level.

A disaggregate analysis of the results indicated that RLILs were almost immediately effective, and the effect was sustained for disobeyed signal crashes. For other crash types, CMFs decreased over the first few years of treatment, indicating that they were more effective for reducing crashes as drivers became accustomed to them. The smallest CMFs were for the only district with agencies that noted enforcement and public awareness campaigns. There was no indication of a notable increase in the level of enforcement. There were consistent reports that enforcement was based on intersections with high crash counts and that it was not focused on intersections with red-light indicators only. Some agencies focused awareness campaigns on the indicator lights, while others focused on red-light running in general. The research team found no significant difference between indicator types used.

In addition, RLILs appeared to be more effective for total, fatal and injury, and right-angle crashes in rural areas at signalized intersections with lower total entering volume and a lower proportion of entering traffic from the minor road. The research team found the opposite was true for disobeyed signal crashes, where RLILs appeared to be more effective in urban areas at signalized intersections with higher total entering volume and a higher proportion of entering traffic from the minor road. The analysis showed that one should not combine these factors for quantitative analysis but can consider them when prioritizing intersections for treatment.

The B/C ratio estimated with conservative cost and service life assumptions and considering the benefits for total crashes was 92:1 for all signalized intersections. With the USDOT recommended sensitivity analysis, this value could range from 53:1 to 130:1. These results suggest that the strategy—even with conservative assumptions on cost, service life, and the value of a statistical life—can be cost effective.

APPENDIX. ADDITIONAL INSTALLATION DETAILS

This appendix presents additional details provided by FDOT and local agencies about the use of this strategy. The information presented here may be of use to other agencies interested in using this strategy. Participants were asked to provide responses to six questions. The following section provides the questions and responses.

1. Were there any notable variations in level of enforcement from location to location by district or any variations in driver awareness campaigns? Was the driving public made aware of what the indicator lights are and how they are used (e.g., supplemental warning and regulatory signs)?

District 1 provided the most feedback to this question, indicating that some level of awareness campaign was used. The Bartow Police Department noted that it participated in some awareness programs in conjunction with the Polk County Community Traffic Safety Team during the initial installation. However, after installation, the department did not participate in any awareness programs other than enforcement of the lights. Since installation, the Bartow Police Department noted that it has used the lights for the purposes of red-light violators, and they have been beneficial to the department's enforcement efforts. The department began using the lights immediately after installation and has continued using them.

The Charlotte County Sheriff's Office (CCSO) noted that the white strobe lights were a very useful tool that helped with enforcement efforts, but since installation, CCSO has not increased its time of duration at those specific intersections. The CCSO increases its red-light enforcement or duration at intersections based on traffic crash statistics. The Collier County Sheriff's Office noted that it used press releases when the indicators were first installed, using some minor coverage in print media. The Collier County Sheriff's Office did not change levels of red-light enforcement or conduct special operations because of the indicator lights.

Highlands County indicated that it completed public awareness programs dealing with all topics involving traffic enforcement/education. However, the county did not single out red-light running. Most awareness programs focused on local news media or meetings held at different homeowners' associations. The Lake Wales Police Department noted that a press release was issued when the lights were initially installed.

The Manatee County Sheriff's Office indicated that it conducted red-light enforcement details three times per month, targeting 1 of the 10 most dangerous intersections based on crash statistics. The Sheriff's Office also noted that the strobe installation made enforcement less manpower dependent. The Sheriff's Office did not conduct any public awareness programs strictly targeting strobe enforcement; however, the office frequently had newspaper articles concerning red-light enforcement. The Naples Police Department distributed press releases on the indicator lights (e.g., an article printed in the local newspaper) and also talked about the lights on several talk radio shows on an AM station.

Districts 2 and 5 did not comment on any awareness campaigns or utilization of the indicators.

2. The installation dates for the treatment sites on our list range from 2004 to 2010. What types of indicator lights (e.g., white incandescent) were installed at these treatment sites? Were the indicator lights located on the signal heads, mast arms, or other locations? If you have standard drawings or specifications that addresses these questions, please pass them along.

Orange County noted that the first bulbs were incandescent, 69-watt pedestrian bulbs; later they were “corncob” style 360-degree blue LED bulbs. Additionally, Orange County noted that some nearby agencies have mounted them to the mast arm, some have mounted them directly to the bottom of the green, and others have mounted the lights on top of the signal head.

Orange County has mounted them above the signal in every case. If a mast arm was used, a slip fit-threaded 1.5-inch PVC coupler was used to place the fixture on top of the signal brackets to secure it with a tapped screw. The globe would face up and be visible 360 degrees. If mounted on a span wire, agencies used typical pedestrian-style feet and tubes with the 90-degree elbows to turn them down. If the direction had an exclusive left and some standard ball indications, the confirmation lights were installed as far as possible from each other, left-most left-turn signal and right-most ball signal. In the area, conduit 90-degree elbows or a horizontal mounting installation to the pedestrian foot have been used. The pedestrian hardware increased the cost.

Figure 11 provides an assembly sheet for the confirmation light with globe.

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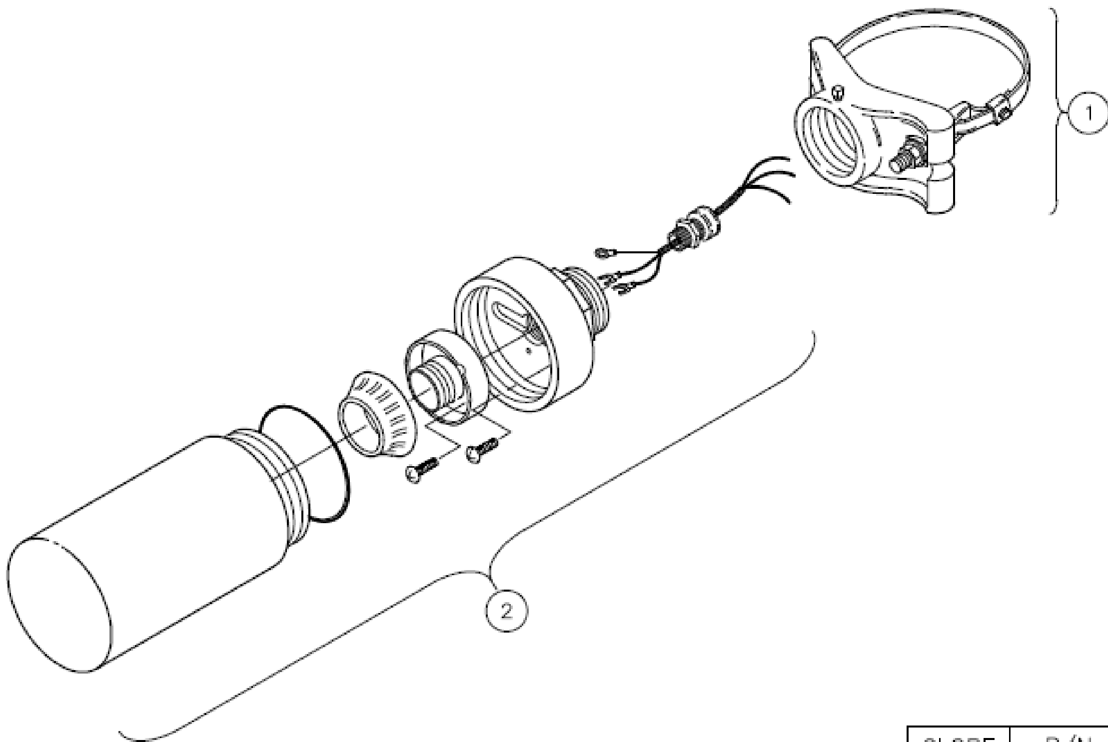
ASSEMBLY SHEET

REF:	TITLE:	PELCO NO.:
	Confirmation Light w/ Globe, Alum	SM-0286

PART NO
SM-0286-CL-PNC
SM-0286-RD-42-SS-PNC

Globe
Band Length
Stainless Upgrade
Process No Color=PNC
Paint=PXX



GLOBE	P/N
Clear	SM-0281
Blue	SM-0280
Red	SM-0295

OPTIONS
Globe: Clear (CL), Blue (BL), Red (RD), None
Band Length: 29" Fits 4"-8" Pole Dia. 42" Fits 4"-12" Pole Dia.
Stainless Upgrade (AB-0303-SS)
Paint

Recommended:
67 or 69 Watt 8000 Hr Traffic Signal Lamp (Not to Exceed 75 Watt)

ITEM	PART NO.	DESCRIPTION	QTY
1	AB-0121-L	Astro Mini-Brac, 1-1/2" NPS, Band Mount, Alum	1
2	SM-0284-XX	Confirmation Light w/ Globe, Alum	1

DRAWN: L ACORD DATE: 10/1/98 | CHK'D: R WOODS DATE: 2/20/06 | REV. M-04/28/10 CM | REV CHK'D: KAK-04/30/10 | SHT. 1 OF 1

Figure 11. Diagram. Assembly sheet for confirmation light with globe.

3. Were there any other requirements (e.g., minimum or maximum traffic volume, presence of turn lanes, etc.) for the installation of indicator lights?

Red-light indicator lights were installed on both State highways and municipal streets. Locations were requested by city agencies, police, or pedestrian safety committees. FDOT provided the bulb holder/socket with the local signal agency providing cable and additional necessary hardware for mounting. FDOT approved the locations and provided the hardware as part of a safety initiative.

4. Please describe any notable challenges related to the indicator light installation and how you overcame them.

A potential challenge is the presence of the indicator if the intersection goes to flash. The indicators are wired directly to the red bulb of the signal that they represent to simplify the wiring required. They flash with the signal indication, which means the intersection has red, yellow, white, and blue lights potentially if it goes to flash.

5. Please describe any notable challenges related to the indicator light maintenance and how you overcame them.

No agencies reported maintaining the indicators; several noted that the operations costs were negligible.

6. What lessons learned or recommendations would you share with another State interested in the widespread application of red-light indicator lights?

During the daytime, both the white and blue bulbs can be hard to see. At night, there was no visibility problem, the blue being distinctly noticeable. Agencies reported that RLILs mounted globe down/socket up seemed to make them slightly more visible because the sunlight might be more obscured (depending on the time of day), and the plastic globe lens seemed to last slightly longer. In addition, a broken lens would not allow the socket to get very wet, but a poor installation could allow it to fill with water.

The Florida two-point span wire gave agencies an attachment that typically made the light slightly obstructed from the front (drivers' view), so all were mounted toward the back for the officer's viewing. A box span wire design was very easy to plan, but a diagonal span intersection created problems due to use of two-way or greater assemblies and the ability to define the back of a signal. In addition, if the globe was mounted underneath the signal, the two-way (or greater) bracket might become impossible to install in a conventional fashion. Neighboring agencies installed additional hanger brackets adjacent to a two-way signal to indicate which signal they represented by associated physical location (i.e., left of the left signal and right of the right signal.) If the two-point style hanger were not used, as is common in Florida, one might be limited to use of the bottom of the signal. Being connected to the red means that the "special" indication on the bottom would operate in conjunction with the signal indication on the top.

One agency reported avoiding any five-section left-turns (unless part of a sequential side street movement) because of enforcement concerns; in addition, that agency avoided a two-way or greater signal combo because it was not clearly obvious what direction the supplement light indicated. The light has also been used on a blank-out no-turn-on-red symbol.

The public may inquire about what the lights mean. Even some police officers may not be aware of the purpose. (These officers are usually from an agency that has not been involved in the enforcement use in their jurisdiction.) Public awareness notification does not yet seem to exist in a user-friendly fashion.

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