Safety Evaluation of Flashing Yellow Arrow at Signalized Intersections

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FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA's) 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's Report 500 Series as part of the implementation of the American Association of State Highway and Transportation Officials Strategic Highway Safety Plan.[(1)] 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 the safety effectiveness of the flashing yellow arrow (FYA) treatment at signalized intersections in reducing the frequency of left-turn crashes. The study divided the treatments into seven categories depending on the phasing system in the before period. The first five categories had permissive or protected-permissive phasing in the before period and experienced a reduction in left-turn crashes and left-turn-with-opposing-through crashes at the intersection level. Intersections in categories 6 and 7 had at least one protected left-turn phase in the before period, and after phasing had an FYA protected-permissive left-turn phase without time-of-day operation (category 6) and with time-of-day operation (category 7). These categories experienced an increase in left-turn and left-turn-with-opposing-through crashes. Economic analysis for categories 1–5 showed the treatment is cost effective in improving safety. B/C analyses were not conducted for categories 6 and 7 because these treatments are typically used for capacity improvements rather than safety. This report will benefit safety and traffic engineers and safety planners by providing greater insight into intersection safety.

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Director, Office of Safety and Operations
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16. Abstract

This study evaluated the safety effect of the flashing yellow arrow (FYA) treatment at signalized intersections. The major objective of this strategy is to reduce the frequency of left-turn (LT) crashes, especially those that involve a collision between left turns and vehicles traveling straight through from the opposite direction. The project team conducted an empirical Bayes before–after analysis of installations in Nevada, North Carolina, Oklahoma, and Oregon. The treatments were divided into seven categories depending on the phasing system in the before and after periods, number of roads where FYAs were implemented, and number of legs at each intersection. The first five categories involved permissive or protected-permissive phasing in the before period. Intersections in these five treatment categories experienced a reduction in the primary target crashes under consideration: LT crashes and left-turn-with-opposing-through (LTOT) crashes at the intersection level. The reduction ranged from 15 to 50 percent depending on the treatment category. Intersections in categories 6 and 7 had at least one protected LT phase in the before period, and after phasing had an FYA protected-permissive LT phase without time-of-day operation (category 6) and with time-of-day operation (category 7). Consistent with results from previous studies, these intersections experienced an increase in LT and LTOT crashes. The B/C ratios for categories 1–5 ranged from 56:1 to 144:1.

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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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for 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 AND SYMBOLS

Abbreviations

AADT	annual average daily traffic
ANG	angle
B/C	benefit–cost
CMF	crash modification factor
CMFunction	crash modification function
DCMF	Development of Crash Modification Factors
EB	empirical Bayes
ELCSI	Evaluation of Low-Cost Safety Improvements
FHWA	Federal Highway Administration
FYA	flashing yellow arrow
GIS	geographic information system
HSIP	Highway Safety Improvement Program
KABC	injury and fatal
KABCO	scale used to represent injury severity in crash reporting, where K is fatal injury, A is incapacitating injury, B is nonincapacitating injury, C is possible injury, and O is property damage only
LT	left-turn
LTOT	left-turn-opposing-through
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NDOT	Nevada Department of Transportation
PDO	property-damage-only
PFS	Pooled Fund Study
PPLT	protected-permissive left-turn
RE	rear-end
SE	standard error
SPF	safety performance function
TOD	time-of-day
USD	United States dollars
USDOT	United States Department of Transportation

Symbols

a_0	intercept
a_1 through a_n	coefficients for independent variables
Annual Cost	annualized cost of the treatment
C	treatment cost
CMF	crash modification factor
CMF_i^*	crash modification factor for site *i*
EB_exp_before	empirical Bayes expected left-turn-opposing-through crashes per year at the intersection level in the before period
f	generic function
i	numbered item in equation
k	overdispersion parameter of a negative binomial regression model

m	predicted number of crashes before the strategy is implemented
N	expected service life
P	sum of annual safety performance function estimates
R	discount rate
sum	summation of factor over all sites in the strategy group
Var	variance
w	weight applied to the predicted number of crashes
x	count of crashes
X_1 through X_n	independent variables
γ	predicted crashes
$\Delta Safety$	change in safety
θ	index of effectiveness
λ	expected number of crashes that would have occurred in the after period without the treatment
π	actual number of reported crashes in the after period

EXECUTIVE SUMMARY

The Federal Highway Administration 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 promoting 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 evaluating safety effectiveness and B/C ratios before investing in broad applications of new strategies for safety improvements. Forty State transportation departments provided technical feedback on safety improvements to the DCMF Program and implemented new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study, which functions under the DCMF Program.

This study investigated the safety effectiveness of the flashing yellow arrow (FYA) treatment at signalized intersections. One objective of this strategy is to reduce the frequency of left-turn (LT) crashes, especially those that involve a collision between left turns and vehicles traveling straight through from the opposite direction (also called left-turn-opposing-through (LTOT) crashes).

The project team obtained geometric, traffic, and crash data at treated and untreated signalized intersections in Nevada, North Carolina, Oklahoma, and Oregon and conducted an empirical Bayes before–after analysis using reference groups of untreated signalized intersections with similar characteristics to the treated sites. “Before” refers to pretreatment data obtained prior to installing the FYA phase, and “after” refers to posttreatment data obtained after installing the FYA phase. The evaluation included 307 treated sites and 438 reference sites from these 4 States. The evaluation considered six crash types: total, injury and fatal, rear-end, angle, LT, and LTOT.

Based on before and after LT phasing and the number of legs at the intersection, the sites were divided into seven treatment groups, as shown in table 1.

Table 1. Treatment categories.

Category	Before Phasing	After Phasing	Number of Legs
1	Traditional PPLT	FYA PPLT on one road	3
2	Traditional PPLT	FYA PPLT on one road	4
3	Traditional PPLT	FYA PPLT on both roads	4
4	Permissive or traditional PPLT	FYA permissive on one road	4
5	Permissive	FYA permissive on one road	4
6	At least one protected phase	FYA PPLT without TOD operation	4
7	At least one protected phase	FYA PPLT with TOD operation	4

PPLT = protected-permissive left-turn; TOD = time-of-day.

The first five treatment categories involved permissive or PPLT phasing in the before period. Intersections in these five treatment categories experienced a reduction in the primary target crashes under consideration: LT crashes at the intersection level and LTOT crashes at the intersection level. The reduction ranged from 15 to 50 percent depending on the treatment category, with B/C ratios ranging from 56:1 to 144:1. Intersections in categories 6 and 7 had at least one protected LT phase in the before period. Consistent with results from previous studies, these intersections experienced an increase in LT and LTOT crashes. Agencies typically use categories 6 and 7 for capacity improvements rather than safety, but the implications for safety are important.

CHAPTER 1. INTRODUCTION

PURPOSE OF STUDY

A flashing yellow arrow (FYA) for permissive left-turn (LT) movements at signalized intersections helps drivers turning left on a permissive circular green signal avoid confusion. Confusion may arise from left-turning drivers who see a permissive circular green signal and mistakenly believe that the left turn has the right-of-way over opposing traffic, especially under some geometric conditions.

BACKGROUND ON STUDY

In 1997, the American Association of State Highway and Transportation Officials' Standing Committee on Highway Traffic Safety—with the assistance of the Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration, and the Transportation Research Board Committee on Transportation Safety Management—met with experts in the fields of driver, vehicle, and highway safety to develop a strategic plan for highway safety. These participants developed 22 key areas that affect highway safety.

The National Cooperative Highway Research Program (NCHRP) published a series of guides to advance the implementation of countermeasures targeted at reducing crashes and injuries.[(1)] Each guide addresses 1 of the 22 emphasis areas and includes an introduction to the problem, a list of objectives for improving safety in that emphasis area, and strategies for each objective. The guides designate each strategy as proven, tried, or experimental. Many of the strategies discussed in these guides have not been rigorously evaluated; approximately 80 percent of the strategies are considered tried or experimental.

FHWA organized a pooled fund study of 40 States to evaluate low-cost safety strategies as part of this strategic highway safety effort. The purpose of the FHWA Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS) is to evaluate the safety effectiveness of several tried and experimental low-cost safety strategies through scientifically rigorous crash-based studies. The ELCSI-PFS selected the use of FYAs at signalized intersections as a strategy to evaluate as part of this effort.

The ELCSI-PFS conducts its research under FHWA's Development of Crash Modification Factors (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. FHWA intends to use the research conducted under the DCMF Program to save lives by identifying new countermeasures that effectively reduce crashes and promoting those countermeasures for nationwide installation by providing measures of their safety effectiveness, including benefit–cost ratios (B/C), through research.

LITERATURE REVIEW

Through the years, researchers have conducted different types of studies, including driver comprehension, driver simulator, operational, and crash-based, to evaluate FYAs. A recent review by Schattler and Lund and a recent simulator study by Hurwitz et al. provide further information about driver comprehension, driver simulator, and operational studies.[2,3] This literature review focuses on results from crash-based studies.

Perez conducted a simple/naive before–after evaluation to compare the safety impacts of PPLT FYA phase installation at seven intersections in Federal Way, WA.[4] The phasing in the before period included protected LT phasing in some cases and traditional PPLT in other cases. The study report noted that the introduction of FYAs also included other changes at these intersections. Intersections that were converted from a protected LT phase to a PPLT FYA phase experienced an approximately 15-percent increase in crashes with a 41-percent increase in severity rates. Conversely, intersections that converted from a traditional PPLT phase to a PPLT FYA phase experienced a 39-percent reduction in crashes and a 62-percent reduction in severity rates.

Srinivasan et al. investigated the safety impact of FYA installation using data from 51 signalized intersections in 3 States: North Carolina, Oregon, and Washington.[5] The researchers applied the empirical Bayes (EB) method to the North Carolina sites. Similar to Perez's evaluation, some intersection approaches had a permissive LT phase or traditional PPLT phase in the before period, while a majority of the converted approaches had a protected LT phase in the before period.[4] The Srinivasan report provided results for the following three categories:[5]

- At least one treated leg had permissive LT phasing in the before period (9 sites) (20 legs treated).
- All treated legs had traditional PPLT phasing in the before period (13 sites) (27 legs treated).
- All converted legs had protected phasing in the before period (29 sites) (56 legs treated).

Table 2 shows a summary of the results from Srinivasan et al.[5]

Table 2. Results from FYA implementation.[5]

LT Phasing Before	Number of Sites	Number of Legs Treated	Crash Type	CMF	SE of CMF	Significant*
At least one treated leg had permissive only	9	20	Total intersection crashes	0.753	0.094	Yes
At least one treated leg had permissive only	9	20	Total intersection LT crashes	0.635	0.126	Yes
All treated legs had PPLT	13	27	Total intersection crashes	0.922	0.104	No
All treated legs had PPLT	13	27	Total intersection LT crashes	0.806	0.146	No
All converted legs had protected	29	56	Total intersection crashes	1.338	0.097	Yes
All converted legs had protected	29	56	Total intersection LT crashes	2.242	0.276	Yes

*Significance was measured at the 95-percent confidence level.
SE = standard error.

The intersections in the first category experienced the largest reduction in crashes statistically significant at the 95-percent confidence level: a 36-percent reduction in intersection LT crashes and a 25-percent reduction in total intersection crashes. The intersections in the second category experienced smaller reductions not statistically significant at the 95-percent confidence level: a 19-percent reduction in intersection LT crashes and an 8-percent reduction in total intersection crashes. The intersections in the third category experienced a significant increase in crashes: a 124-percent increase in intersection LT crashes and a 34-percent increase in total intersection crashes.

Pulugurtha and Khader evaluated the impact of FYA installations at 18 signalized intersections in Charlotte, NC.[6] Not all legs underwent conversion to FYA phasing. Similar to the Srinivasan et al. study, the before condition varied between permissive, traditional PPLT, and protected phasing.[5] Pulugurtha and Khader also reported that a few intersections were unsignalized in the before period.[6] The study included data from 18 control intersections in Charlotte, NC, with similar characteristics to the treated intersections. The researchers used data from control intersections to estimate safety performance functions (SPFs) for an EB before–after evaluation. Data on LT volume were available and included in the evaluation. Results indicated that LT crashes involving left-turning vehicles decreased in 14 of the 18 intersections following FYA installation. The findings for total crashes were similar—total crashes decreased in 16 of the 18 intersections following FYA installation. Benefits of FYA installations were lower in higher volume sites that had higher crash frequencies before installation.

Simpson and Troy evaluated the impact of FYAs using data from 222 signalized intersections in North Carolina.[7] This study used the SPFs from chapter 12 of the *Highway Safety Manual* (urban and suburban arterials) to account for the changes in traffic volume from the before to after periods.[8]

The study did not use the EB method for the following reasons:

- The average number of target crashes per year (1.08) was small for urban areas.
- North Carolina has implemented FYAs on a large scale and may not be prioritizing high-crash locations. Consequently, it was a challenge to find untreated reference sites similar to the treatment sites in the same area.

The authors estimated crash modification factors (CMFs) for total crashes, injury and fatal (KABC) crashes, left-turn-opposing-through (LTOT) crashes (considered by the authors to be the target crash type), and KABC target crashes on a treated approach. The authors conducted a manual review of crash reports to identify target crashes. The before phasing included permissive LT, traditional PPLT, and protected LT. The authors examined the following five categories of phasing changes:

- **Category 1:** Permissive only to FYA PPLT.
- **Category 2:** Protected only to FYA PPLT.
- **Category 2A:** Protected only to FYA PPLT with time-of-day (TOD) operation.
- **Category 3:** Five-section PPLT to FYA PPLT.
- **Category 4:** Permissive only to FYA permissive only.

While some intersections were exclusive to a particular category, for others, the changes in one or more legs belonged to one category while changes in one or more other legs belonged to another category. Two sets of results were reported for each category—the first set only included intersections exclusive to that category and the second set included all legs that belonged to that category.

Table 3 shows the results for target crashes and KABC target crashes for the second set for each category.

Table 3. Results from FYA implementation in North Carolina.[7]

Category	Number of Legs Converted to FYA PPLT Phase	Crash Type	Actual After Period Crashes	Expected After Period Crashes	CMF	SE of CMF
1	41	Target	84.2	51	*0.598	0.105
1	41	KABC target	41.2	25	*0.592	0.146
2	49	Target	28.1	107	*3.684	0.748
2	49	KABC target	11.8	61	*4.778	1.397
2A	34	Target	6.4	20	2.372	1.053
2A	34	KABC target	4.6	13	2.371	1.043
3	254	Target	528.8	444	*0.838	0.053
3	254	KABC target	282.9	212	*0.747	0.067
4	64	Target	33.1	17	*0.498	0.145
4	64	KABC target	21.9	8	*0.349	0.139

*CMFs that were statistically significant at the 95-percent confidence level.
SE = standard error.

Simpson and Troy found results consistent with Srinivasan et al. for categories 1, 2, and 2A, which had protected LT phasing in the before period.(5) The sample in category 2A was limited because only those time periods during FYA operation were included.

Schattler et al. used the EB before–after method to evaluate the safety impacts of FYA installation in Peoria, IL.(9) The evaluation included 86 intersections where the State had installed FYAs at 164 approaches. The before condition at these intersections was a traditional PPLT phase with a five-section head, and the after condition was an FYA PPLT phase with a four-section head. The authors based their analysis on 3 yr of before and after data. The authors used 100 untreated comparison intersections to develop SPFs as part of the before–after EB evaluation, which focused on LT and LTOT crashes. The study reported the following significant reductions for LT and LTOT crashes:

- **LT crashes at an FYA approach:** Average CMF of 0.617 (ranging from 0.605 to 0.629 with a 95-percent confidence level).
- **LT crashes at an FYA approach with a supplemental sign:** Average CMF of 0.589 (ranging from 0.573 to 0.605 with a 95-percent confidence level).
- **LTOT crashes at an FYA approach:** Average CMF of 0.714 (ranging from 0.698 to 0.730 with a 95-percent confidence level).
- **LTOT crashes at an FYA approach with a supplemental sign:** Average CMF of 0.711 (ranging from 0.687 to 0.735 with a 95-percent confidence level).

The study reported a B/C ratio of 19.8:1 for the FYA treatment.

Summary of Literature Review

Previous studies have generally shown that FYA treatment is associated with a reduction in LT crashes as long as the before-period phasing is not a protected LT. The specific CMF values varied for many reasons, including (1) the methodology used for the evaluation, (2) the definition of target crashes, (3) the phasing in the before period, and (4) the States used in the evaluation. Most of the evaluations used data from only one State. Srinivasan et al. used data from 3 States, but the sample was limited to 51 sites with the majority (29 sites) having protected LT phasing in the before period.(5) It is clear that an evaluation with a large sample of sites from multiple States would provide useful information on the effectiveness of FYA phasing under different circumstances.

CHAPTER 2. STUDY OBJECTIVE

This research examined the safety impacts of FYAs using data from sites in Nevada, North Carolina, Oklahoma, and Oregon. The objective was to estimate the safety effectiveness of FYAs as measured by crash frequency using before and after data, where “before” refers to pretreatment data obtained prior to installing the FYA phase and “after” refers to posttreatment data obtained after installing the FYA phase. The primary target crash types were LT and LTOT. However, changes in signal phasing are sometimes accompanied by changes in signal timing, altering the green time allocated for through movements. This change in time can affect the propensity for rear-end (RE) and angle (ANG) crashes. Because of this, the evaluation included the following intersection crash types:

- Total.
- KABC.
- RE.
- ANG.
- LT.
- LTOT.

When performing the evaluation, the project team recognized that States do not define these crash types the same way. In some cases, States assign a crash type after conducting a manual examination of each crash report, which could include a review of the collision diagram and crash narratives. For example, Simpson and Troy conducted a manual review of each crash report to determine whether a particular LT crash involved a collision with opposing through vehicles and if the LT crash occurred at the treated approaches of an intersection.(7) They went to such lengths because of issues with crash report coding. For example, when a subset of treatment sites was tested, 45 percent of target LTOT crashes consisted of crashes miscoded as LT different roadway, ANG, or head-on. However, such a manual review of individual crash reports was beyond the scope of this effort. Therefore, this evaluation relied on the best judgment of each State agency in determining the appropriate crash type based on the coded crash reports, and the focus was on intersection-level crashes rather than approach-level crashes.

The objectives of this study were to determine the overall safety effect of the treatment(s) and answer the following questions:

- Do safety effects vary with traffic volume?
- Do safety effects vary with the frequency of crashes before treatment?
- Are safety effects different in different States?

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

CHAPTER 3. STUDY DESIGN

When planning a before–after safety evaluation study, it is vital to ensure enough data are included to statistically detect the expected change in safety. Even though those designing the study do not know the expected change in safety in the planning stage, it is still possible to make a rough determination of how many sites the study will require based on the best available information about the expected change in safety. Alternatively, one could estimate the statistically detectable change in safety for the number of available sites. For a detailed explanation of sample-size considerations, as well as estimation methods, see chapter 9 in *Observational Before-After Studies in Road Safety*.(10)

The two case analyses presented in this chapter address the sample size required to detect an expected change in safety using statistics and the change in safety that can be detected with available sample sizes.

CASE 1: SAMPLE SIZE REQUIRED TO DETECT AN EXPECTED CHANGE IN SAFETY

For this first case, the project team assumed a conventional before–after analysis with a comparison group design in keeping with available sample-size estimation methods. The sample-size estimates from this method are often conservative as using the EB method requires fewer sites. To facilitate the analysis, the project team assumed that the number of comparison sites was equal to the number of treatment sites, which is a conservative assumption.

Many States now introduce FYAs as a system-wide treatment, so the possibility of bias due to regression to the mean is minimal. Therefore, the before-period crash data from treated sites were used for sample-size calculations. When the study was designed, the treatment categories were not yet available. As a result, the project team based the study design computations on a generic FYA treatment. Table 4 provides the crash-rate assumptions used.

Table 4. Before-period crash-rate assumptions.

Crash Type	Nevada	North Carolina	Oklahoma	Oregon
Total	8.79	7.99	5.62	2.31
KABC	3.64	2.88	1.98	1.06
RE	3.21	3.04	2.58	1.13
ANG	4.10	1.63	0.47	0.13
LT	2.65	1.50	1.54	0.31
LTOT	N/A	1.10	1.47	0.19

N/A = not available.
Note: All crash rates are per site (intersection) per year.

Table 5 provides estimates of the required number of before- and after-period intersection years for statistical significance at both the 90- and 95-percent confidence levels. Intersection years are 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 is in effect at 10 intersections, and data are available for 4 yr since implementation, then there is a total of 40 intersection years of after-period data available for the study. The minimum sample of required before-period intersection years indicates the level for which a study seems worthwhile based on current knowledge about the strategy, that is, when it is feasible to detect with the stated level of confidence the largest effect that one may reasonably expect. The project team based these sample-size calculations on the methodology in *Observational Before-After Studies in Road Safety* and on specific assumptions regarding the number of crashes per mile and years of available data.[(10)]

Table 5. Minimum required before-period intersection years for various confidence levels.

Crash Type	Expected Reduction in Crashes (Percent)	95-Percent Confidence				90-Percent Confidence			
		NV	NC	OK	OR	NV	NC	OK	OR
All	10	*143	*158	*224	*545	*101	*111	*158	*385
All	20	30	33	46	113	21	23	33	80
All	30	11	12	17	40	8	8	12	29
All	40	5	5	7	18	3	4	5	13
KABC	10	346	438	636	1,189	245	309	449	840
KABC	20	*71	*90	*131	*245	*51	*64	*93	*175
KABC	30	26	32	47	88	18	23	33	62
KABC	40	11	14	21	39	8	10	15	27
RE	10	393	414	488	1,115	277	293	345	788
RE	20	*81	*86	*101	*230	*58	*61	*72	*164
RE	30	29	31	36	82	21	22	26	58
RE	40	13	13	16	36	9	10	11	26
ANG	10	307	773	2,681	9,692	217	546	1,894	6,846
ANG	20	*63	*160	*553	*2,000	*45	*113	*394	*1,423
ANG	30	23	57	198	715	16	40	140	508
ANG	40	10	25	87	315	7	18	62	223
LT	10	475	840	818	4,065	336	593	578	2,871
LT	20	*98	*173	*169	*839	*70	*123	*120	*597
LT	30	35	62	60	300	25	44	43	213
LT	40	15	27	27	132	11	19	19	94
LTOT	10	N/A	1,145	857	6,632	N/A	809	605	4,684
LTOT	20	N/A	236	177	1,368	N/A	168	126	974
LTOT	30	N/A	*85	*63	*489	N/A	*60	*45	*347
LTOT	40	N/A	37	28	216	N/A	26	20	153

*Recommended sample-size values.
N/A = not available.
Note: These data assume an equal number of site years for treatment and comparison sites and an equal length of before and after periods.

Table 5 highlights the sample-size values for the intersection years recommended in this study. The project team recommends these values based on the likelihood of obtaining the estimated sample size and the anticipated effects of the treatment. As noted, the sample-size estimates provided are conservative. The state-of-the-art EB method proposed for the evaluations requires fewer sites than a less robust, conventional before–after study with a comparison group that was used for the calculations. One may predict estimates with greater confidence, or detect a smaller reduction in crashes, if more site years of data are available in the after period.

CASE 2: CHANGE IN SAFETY THAT CAN BE DETECTED WITH AVAILABLE SAMPLE SIZES

The statistical accuracy attainable for a given sample size is measured by the standard deviations in the CMF value (i.e., the estimated change in safety performance). From this, based on the method in *Observational Before-After Studies in Road Safety*, one can estimate *p*-values for various sample sizes and expected CMF values for a given crash history.[10]

Using the available data from the four States in this evaluation, the project team estimated the minimum percentage changes in crash frequency that could be statistically detectable at the 90- and 95-percent confidence levels, as presented in table 6. The data in table 6 does not account for the treatment categories but instead accounts for a generic FYA treatment. The results indicate that the data should be sufficient for the project team to detect the recommended crash reduction values from table 5 if installation of a FYA indeed results in a decrease in crashes. Using these results, the project team proceeded with the evaluation using the data available at that time.

Table 6. Sample analysis for crash effects.

Crash Type	Intersection Years in Before Period	Intersection Years in After Period	Minimum Percent Reduction Detectable* ($p = 0.10$)	Minimum Percent Reduction Detectable* ($p = 0.05$)
Total	2,083	727	4	5
KABC	2,083	727	6	7
RE	2,083	727	6	7
ANG	2,083	727	7	8
LT	2,083	727	7	9
LTOT	1,582	504	14	16

*Crash rate assumption is based on crash rates in table 5.
Note: Results are to nearest 1 percent.

CHAPTER 4. METHODOLOGY

This evaluation used the EB method for observational before–after studies.[10] This methodology is considered rigorous because it accounts for regression to the mean using a reference group of similar but untreated sites. In the process, the project team used SPFs to address the following:

- Overcome the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- Account for time trends.
- Reduce the level of uncertainty in the resulting CMF(s).
- Properly account for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

The methodology also provides a foundation for estimating the likely safety consequences of a contemplated strategy.

Figure 1 illustrates the change in safety ($\Delta Safety$) for a given crash type at a site using the EB method.

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

Figure 1. Equation. Estimated Δ*Safety*.

Where:

λ = expected number of crashes that would have occurred in the after period without implementing a given safety strategy.
π = number of reported crashes in the after period.

When estimating λ, researchers typically use SPFs and the EB method to account for the effects of regression to the mean and changes in traffic volume explicitly, relating crashes of different types to traffic flow and other relevant factors for each jurisdiction based on untreated or reference sites. Regression to the mean is unlikely with the FYA treatment, so to estimate SPFs, the project team used data from the before period of the treated sites along with data from the complete study period of the reference sites. They calibrated annual SPF multipliers to account for temporal effects on safety, such as variation in weather, demography, and crash reporting.

For the EB method, the first step is to use the SPF to predict the estimated number of crashes each year of the before period. 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 predicted number of crashes before the strategy is implemented (m). Figure 2 shows this estimate of m.

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

Figure 2. Equation. EB estimate of expected crashes.

Where w is the weight applied to the predicted number of crashes. As illustrated in figure 3, w is estimated from the mean and variance of the SPF estimate.

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

Figure 3. Equation. EB weight.

Where k is the overdispersion parameter of a negative binomial regression model, which is estimated from the SPF calibration process by using a maximum likelihood procedure.

A factor was 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 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 to 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.

The index of effectiveness (θ) is estimated as shown in figure 4.

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

Figure 4. Equation. θ.

Figure 5 shows how the standard deviation of θ is calculated.

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

Figure 5. Equation. Standard deviation of θ.

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

Nevada, North Carolina, Oklahoma, and Oregon provided data for this study.[1] These States supplied details about the intersections, traffic volumes on the major and minor roads, and crashes for both installation and reference sites. They also provided crash injury severities relative to the KABCO scale, in which K represents fatal injury, A represents incapacitating injury, B represents nonincapacitating injury, C represents possible injury, and O represents property damage only. This chapter summarizes the data assembled for the analysis.

NEVADA

This section details the data collection process for Nevada, including installation data, reference sites, roadway data, traffic data, crash data, and treatment cost data.

Installation Data

Nevada Department of Transportation (NDOT) staff furnished an initial list of 454 intersections across the State where they had installed FYAs. All installations were conversions from a five-section protected-permissive signal head to a four-section FYA head. The Highway Safety Improvement Program (HSIP) selected and funded the FYA installations as part of Nevada's systemic improvements. HSIP did not select most FYA installations based on individual site analyses or high-crash locations; rather, they based their selection on corridor priorities or as part of a whole-system improvement. The exception to this was that high-crash locations were likely the earliest FYA installations. After early installations and signs of public acceptance of FYAs, NDOT conducted installations on a more widespread, systemic basis. They performed all installations on mast-arm signals (i.e., no span wire).

Reference Sites

The project team identified reference sites from an initial list of 38 signals provided by NDOT, where the State planned to install FYAs. The project team identified an additional 73 reference sites where NDOT had recently installed FYAs. This analysis excluded the after period of these sites.

Roadway Data

NDOT provided a basic roadway file in a spatial format. The project team used this to verify the locations of study sites and identify route names. The project team collected roadway and intersection physical characteristics by manual inspection of aerial and street-level imagery.

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[1]All data were unpublished and obtained directly from respective agency staff.

Traffic Data

NDOT supplied traffic volume data in a spatial format. The data were available from two sources. One was a road line–based file that Nevada created as part of its Highway Performance Monitoring System data delivery. The other was a set of point traffic counts. The project team used these files to collect volume counts for major and minor roads from 2006 to 2013. LT phasing data for both treated and references sites were collected using Google Street View™.(14)

Crash Data

NDOT provided the project team with crash data for each intersection. NDOT staff ran individual queries for each treatment and reference site and delivered the crashes in individual files, which the project team compiled into one crash database for the study. NDOT staff conducted their crash query using their standard procedure and parameter, such as a distance of 200 ft to associate crashes to the intersections, as well as other standard internal steps in their crash query process (e.g., checking for alternate route names).

The project team was able to compile crashes for all crash types of interest except LTOT crashes. The crash and vehicle information did not include sufficient detail to identify with confidence which LT crashes would have occurred between opposing-direction vehicles.

Treatment Cost Data

NDOT did not provide cost data for FYA installations.

NORTH CAROLINA

This section details the data collection process for North Carolina, including installation data, reference sites, roadway data, traffic data, crash data, and treatment cost data.

Installation Data

Data on FYA installations in North Carolina were readily available because the North Carolina Department of Transportation (NCDOT) had previously compiled a database of treated intersections to conduct their own analysis on the effect of FYAs.(7) NCDOT staff provided a copy of this database containing locations, signal timing, traffic volume, and crash data for 222 intersections where they had installed FYAs. They indicated that the initial group consisted of more than 1,600 intersections with FYAs, but it was reduced to 222 by considering whether additional changes occurred after installing FYAs and examining the availability of crash, signal plan, and completion date data.

Reference Sites

NCDOT did not assemble a reference group for its analysis, so the project team identified a suitable reference group. After discussions with NCDOT staff, the project team decided to use a separate list of 191 intersections; these were sites the State identified for future FYA installation and sites where FYAs were recently installed (the after periods were excluded from the analysis).

Roadway Data

The treatment site database provided by NCDOT contained some information on the characteristics of the road and intersection geometry. The list of reference sites had less detail, including only location and route name information. The project team used spatial roadway inventory data obtained from the NCDOT Geographic Information System (GIS) Unit and visual inspection of aerial and street-level imagery to obtain the remaining necessary information on intersection characteristics.

Traffic Data

Traffic volume data for the treatment sites were supplied in the database previously compiled by NCDOT. The project team collected traffic volumes for the reference sites manually using an NCDOT online map-based database of historical traffic volume counts. LT phasing data for both treated and references sites were collected using Google Street View.

Crash Data

NCDOT supplied the crash data for treatment and reference sites. The initial database had crash data for the treatment sites but not in the annual format necessary for the EB method. The project team gave NCDOT the list of treatment and reference sites with all required county and route name or number combinations to enable them to develop a database query of crash data for the sites.

Treatment Cost Data

NCDOT did not provide cost data for FYA installations.

OKLAHOMA

This section details the data collection process for Oklahoma, including installation data, reference sites, roadway data, traffic data, crash data, and treatment cost data.

Installation Data

The city of Norman, OK, conducted a citywide installation of FYAs at all signalized intersections that had exclusive LT lanes. Most installations involved converting five-section protected-permissive signal heads to four-section FYA heads. City staff provided a list of 67 treated intersections and their locations and installation dates.

Reference Sites

Because Norman installed FYAs at every eligible site, it was not possible to identify a comparable reference group within the city. After discussing with Norman and Oklahoma DOT staff, the project team decided to use signalized intersections in a nearby city, Edmond, OK, as a reference group. Edmond is of similar size to Norman, and both are located outside Oklahoma City, OK. The project team began with a list of intersections in Edmond where traffic volume data were available and conducted visual inspections of the signals to select those with protected-permissive phasing (comparable to the before condition of the treated Norman sites). The project team identified 55 intersections in Edmond for the reference group.

Roadway Data

The project team inspected aerial images and street-level images for each site to collect data on intersection characteristics, such as number of turn lanes and median presence.

Traffic Data

The city staff in Norman and Edmond provided data on traffic volumes for the sites in their jurisdictions. The traffic volume data were in several formats, including spatial files, spreadsheets, and PDFs. The project team used this information to assemble traffic volume counts by major and minor roads for all study sites.

Crash Data

The project team obtained crash data for both State and local roads from the Oklahoma crash data website.(15) The project team queried crashes for Norman and Edmond from 2004 to 2014. The project team used the spatial coordinates to map the crashes using a GIS and associate the crashes with the study sites. The project team considered crashes within 250 ft of a study site to be associated with that site. Because crashes on local roads were spatially placed at the nearest intersections (even midblock crashes), only crashes identified as intersection-related were selected. The project team also removed all crashes within the 250-foot distance that were associated with another (nonstudy) intersection. This occurred in cases where the distance between the study site and another intersection was less than 250 ft.

Treatment Cost Data

Oklahoma DOT indicated that they spent approximately $6,500 per intersection to install FYAs on all legs of a four-leg intersection.

OREGON

This section details the data collection process for Oregon, including installation data, reference sites, roadway data, traffic data, crash data, and treatment cost data.

Installation Data

Oregon DOT staff provided a list of signals on which they installed FYAs. The list included the city, location, installation date, and the number of roads treated with FYAs. This initial list included 190 signals geographically dispersed across the State. Oregon DOT staff noted that most FYA installations consisted of only changing the signal head; they performed no other changes in conjunction with the FYA installation. The preconversion phasing of the treated sites was a mix of protected-permissive, permissive, and protected phasing, though most conversions began as protected-permissive phasing. Almost all FYA installations in Oregon were on four-section heads.

Reference Sites

The project team identified reference sites by starting with the list of all State-owned signals provided in spatial data format by Oregon DOT. The project team selected and inspected signals near the identified treatment sites as potential reference sites. In particular, they used online street-level views to identify the type of LT phasing used at each potential reference site. The project team noted whether the signal was protected, permissive-protected, or permissive. The project team conducted the final selection of 87 reference sites in a way that matched the distribution of before phasing in the treatment group.

Roadway Data

The project team initially obtained roadway data from Oregon DOT in spatial format. This spatial roadway network served to verify the locations of intersections and route names or numbers. However, the project team obtained most roadway characteristics, including signal-specific details, through a manual inspection of the site from aerial images and street-level imagery.

Traffic Data

The project team obtained traffic volume data from Oregon DOT. The most recent years (beginning in 2014) of volume were available via spatial data. For past years (2006–2013), the project team obtained individual PDFs containing records of yearly volume counts conducted on Oregon State highways. Through a manual matching process, the project team recorded past years of traffic volumes for major and minor roads of the treatment and reference sites. Minor-road traffic volume was often sparsely available or not available at all.

Crash Data

Crash data were obtained from Oregon DOT. The project team initially requested data from 2002 to 2013. Oregon provided the crash data in geospatial format; however, there was a difference in the presentation and availability of crash data before and after 2007. Before 2007, Oregon DOT geocoded crashes using the route and milepost of the road, meaning that only crashes that occurred on State roads are available in the pre-2007 period. After 2007, all crashes were geocoded individually, meaning that Oregon DOT assigned every crash (on either State or local roads) a spatial coordinate. Many of the treatment sites were intersections of State and local roads, which limited the number of sites the study could include. The project team made the decision to use only those sites that received FYA treatments during or after 2008. This approach eliminated many potential treatment sites, since many of them received FYA treatments before 2008.

The project team associated crashes to specific intersections via spatial proximity. They used a 250-foot radius for the spatial query (i.e., they considered only crashes within 250 ft of an intersection). This distance was used for associating crash data with intersections because, when the project team filtered the Oregon crash data to only see the crashes labeled as intersection-related, the maximum distance from an intersection appeared to be 250 ft. The project team also removed all crashes within the 250-foot distance that were associated with intersections that were not involved in this study. This removal occurred in cases where the distance between the study site and another intersection was less than 250 ft.

Treatment Cost Data

Oregon DOT did not provide cost data for FYA installations.

DATA SUMMARY BY STATE

Table 7 through table 14 provide a summary of site characteristics for the reference group in each of the four States. Table 15 through table 22 present the summary statistics for the treatment group.

Table 7. Nevada three-leg reference group summary statistics (15 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Years per site	2.00	8.00	6.53	1.77
AADT on major road	4,752.00	34,357.00	22,154.00	8,662.00
AADT on minor road	544.00	25,935.00	11,737.00	6,422.00
Total crashes per site year	0.86	13.43	5.64	4.07
KABC crashes per site year	0.50	6.71	2.74	2.07
RE crashes per site year	0.14	5.71	2.11	1.68
ANG crashes per site year	0.43	9.00	2.90	2.48
LT crashes per site year	0.00	5.00	1.75	1.46

AADT = annual average daily traffic.

Table 8. Nevada four-leg reference group summary statistics (223 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Years per site	2.00	8.00	6.93	1.36
AADT on major road	1,300.00	57,679.00	24,022.00	24,060.00
AADT on minor road	384.00	41,592.00	9,546.00	7,217.00
Total crashes per site year	0.20	43.14	10.82	8.90
KABC crashes per site year	0.00	19.71	4.96	4.06
RE crashes per site year	0.00	21.14	4.15	4.22
ANG crashes per site year	0.00	27.71	5.44	4.41
LT crashes per site year	0.00	16.43	3.14	2.68

AADT = annual average daily traffic.

Table 9. North Carolina three-leg reference group summary statistics (19 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Years per site	11.00	11.00	11.00	0.00
AADT on major road	8,126.00	35,030.00	18,033.00	8,407.00
AADT on minor road	2,252.00	13,857.00	6,546.00	3,677.00
Total crashes per site year	1.18	14.27	4.95	3.48
KABC crashes per site year	0.18	3.82	1.48	1.03
RE crashes per site year	0.27	5.91	2.05	1.75
ANG crashes per site year	0.00	3.45	0.89	1.00
LT crashes per site year	0.00	2.82	0.90	0.66
LTOT crashes per site year	0.00	2.36	0.50	0.56

AADT = annual average daily traffic.

Table 10. North Carolina four-leg reference group summary statistics (42 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Years per site	11.00	11.00	11.00	0.00
AADT on major road	5,893.00	41,304.00	17,797.00	8,170.00
AADT on minor road	381.00	30,677.00	7,830.00	5,879.00
Total crashes per site year	1.36	33.36	7.90	6.61
KABC crashes per site year	0.45	8.36	2.34	1.65
RE crashes per site year	0.36	11.82	3.07	2.71
ANG crashes per site year	0.00	9.64	1.89	1.77
LT crashes per site year	0.09	4.91	1.09	1.17
LTOT crashes per site year	0.00	4.73	0.73	0.90

AADT = annual average daily traffic.

Table 11. Oklahoma three-leg reference group summary statistics (7 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Years per site	2.00	10.00	7.29.00	3.25
AADT on major road	8,600.00	19,794.00	16,040.00	5,147.00
AADT on minor road	399.00	5,829.00	3,432.00	2,121.00
Total crashes per site year	0.80	6.20	2.67	2.02
KABC crashes per site year	0.20	1.70	0.89	0.61
RE crashes per site year	0.20	2.10	0.99	0.88
ANG crashes per site year	0.00	1.00	0.24	0.36
LT crashes per site year	0.40	2.30	0.95	0.64
LTOT crashes per site year	0.20	2.30	0.85	0.69

AADT = annual average daily traffic.

Table 12. Oklahoma four-leg reference group summary statistics (46 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Years per site	2.00	10.00	9.04	2.08
AADT on major road	6,012.00	44,209.00	18,896.00	8,284.00
AADT on minor road	882.00	22,274.00	9,607.00	7,363.00
Total crashes per site year	0.20	21.20	5.80	5.10
KABC crashes per site year	0.00	6.20	2.01	1.82
RE crashes per site year	0.00	11.70	2.04	2.13
ANG crashes per site year	0.00	2.60	0.78	0.72
LT crashes per site year	0.00	8.50	2.13	2.28
LTOT crashes per site year	0.00	8.40	2.06	2.23

AADT = annual average daily traffic.

Table 13. Oregon three-leg reference group summary statistics (7 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Years per site	5.00	7.00	6.57	0.79
AADT on major road	16,352.00	23,105.00	20,931.00	2,533.00
AADT on minor road	1,315.00	9,423.00	5,898.00	3,413.00
Total crashes per site year	0.43	5.43	3.07	1.92
KABC crashes per site year	0.14	3.00	1.63	0.91
RE crashes per site year	0.14	4.00	1.53	1.26
ANG crashes per site year	0.00	0.29	0.06	0.11
LT crashes per site year	0.29	1.86	1.06	0.66
LTOT crashes per site year	0.00	1.57	0.60	0.63

AADT = annual average daily traffic.

Table 14. Oregon four-leg reference group summary statistics (79 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Years per site	1.00	7.00	6.25	1.64
AADT on major road	4,983.00	41,000.00	16,876.00	8,283.00
AADT on minor road	1,110.00	25,457.00	8,212.00	6,265.00
Total crashes per site year	0.29	40.14	6.38	7.09
KABC crashes per site year	0.00	18.71	3.13	3.45
RE crashes per site year	0.00	23.00	3.31	4.41
ANG crashes per site year	0.00	2.14	0.54	0.56
LT crashes per site year	0.00	8.14	1.56	1.65
LTOT crashes per site year	0.00	4.00	0.82	0.92

AADT = annual average daily traffic.

Table 15. Nevada three-leg treatment group summary statistics (3 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	1.00	6.00	4.33	2.89
AADT on major road	9,400.00	33,708.00	18,983.00	12,944.00
AADT on minor road	1,040.00	12,984.00	6,069.00	6,191.00
Total crashes per site year	0.00	2.67	1.61	1.42
KABC crashes per site year	0.00	0.67	0.44	0.38
RE crashes per site year	0.00	1.33	0.67	0.67
ANG crashes per site year	0.00	1.50	0.78	0.75
LT crashes per site year	0.00	1.33	0.72	0.67

AADT = annual average daily traffic.

Table 16. Nevada four-leg treatment group summary statistics (82 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	1.00	6.00	5.37	1.02
AADT on major road	4,627.00	48,083.00	21,717.00	9,418.00
AADT on minor road	773.00	19,758.00	8,646.00	4,526.00
Total crashes per site year	0.80	40.50	8.34	6.81
KABC crashes per site year	0.00	17.67	3.39	3.17
RE crashes per site year	0.00	16.67	3.07	3.05
ANG crashes per site year	0.20	19.83	3.74	3.66
LT crashes per site year	0.00	11.17	2.65	2.43

AADT = annual average daily traffic.

Table 17. North Carolina three-leg treatment group summary statistics (27 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	5.00	8.00	6.89	0.70
AADT on major road	7,469.00	33,854.00	18,585.00	7,137.00
AADT on minor road	464.00	12,888.00	5,440.00	3,339.00
Total crashes per site year	0.14	17.13	4.69	3.85
KABC crashes per site year	0.14	4.88	1.72	1.28
RE crashes per site year	0.14	7.00	1.80	1.59
ANG crashes per site year	0.00	3.29	0.76	1.00
LT crashes per site year	0.00	3.40	0.89	0.77
LTOT crashes per site year	0.00	2.60	0.58	0.63

AADT = annual average daily traffic.

Table 18. North Carolina four-leg treatment group summary statistics (151 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	3.00	8.00	6.91	1.02
AADT on major road	5,678.00	56,097.00	20,327.00	9,199.00
AADT on minor road	404.00	28,222.00	6,967.00	5,779.00
Total crashes per site year	0.63	44.00	8.58	6.52
KABC crashes per site year	0.00	13.88	3.08	2.43
RE crashes per site year	0.00	24.38	3.26	3.19
ANG crashes per site year	0.00	8.67	1.79	1.66
LT crashes per site year	0.00	7.33	1.60	1.56
LTOT crashes per site year	0.00	6.57	1.19	1.31

AADT = annual average daily traffic.

Table 19. Oklahoma three-leg treatment group summary statistics (8 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	6.00	8.00	6.88	0.64
AADT on major road	7,055.00	26,457.00	15,824.00	7,011.00
AADT on minor road	1,561.00	8,752.00	4,242.00	2,415.00
Total crashes per site year	1.14	6.67	2.50	1.78
KABC crashes per site year	0.17	2.83	0.97	0.81
RE crashes per site year	0.14	3.33	0.99	1.11
ANG crashes per site year	0.00	0.25	0.07	0.10
LT crashes per site year	0.14	1.57	0.73	0.53
LTOT crashes per site year	0.14	1.43	0.68	0.47

AADT = annual average daily traffic.

Table 20. Oklahoma four-leg treatment group summary statistics (51 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	2.00	8.00	7.04	1.30
AADT on major road	7,146.00	30,107.00	17,347.00	6,681.00
AADT on minor road	2,297.00	18,356.00	7,136.00	4,057.00
Total crashes per site year	0.86	20.14	6.11	4.89
KABC crashes per site year	0.14	7.83	2.13	1.85
RE crashes per site year	0.00	13.86	2.84	2.87
ANG crashes per site year	0.00	2.13	0.54	0.51
LT crashes per site year	0.00	9.00	1.66	1.78
LTOT crashes per site year	0.00	8.83	1.59	1.77

AADT = annual average daily traffic.

Table 21. Oregon three-leg treatment group summary statistics (5 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	1.00	2.00	1.40	0.55
AADT on major road	4,000.00	14,098.00	9,595.00	4,223.00
AADT on minor road	1,922.00	3,173.00	2,432.00	657.00
Total crashes per site year	0.00	2.00	1.00	0.79
KABC crashes per site year	0.00	1.00	0.40	0.55
RE crashes per site year	0.00	2.00	0.70	0.84
ANG crashes per site year	0.00	0.50	0.10	0.22
LT crashes per site year	0.00	0.00	0.00	0.00
LTOT crashes per site year	0.00	0.00	0.00	0.00

AADT = annual average daily traffic.

Table 22. Oregon four-leg treatment group summary statistics (26 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	1.00	2.00	1.42	0.50
AADT on major road	7,250.00	26,125.00	15,960.00	5,679.00
AADT on minor road	2,647.00	8,140.00	5,548.00	1,994.00
Total crashes per site year	0.00	9.00	3.48	2.52
KABC crashes per site year	0.00	5.00	1.27	1.28
RE crashes per site year	0.00	6.00	1.42	1.40
ANG crashes per site year	0.00	2.00	0.35	0.61
LT crashes per site year	0.00	4.00	1.02	1.13
LTOT crashes per site year	0.00	3.00	0.63	0.95

AADT = annual average daily traffic.

DATA SUMMARY BY TREATMENT CATEGORY

This evaluation investigated seven treatment categories. The literature review revealed that the before condition could make a significant difference on the impact of FYA installation. For example, if a State introduces an FYA as a replacement for protected LT phasing, it could lead to an increase in LT crashes. For this reason, based on the phasing system before and after implementing the FYA, the project team identified seven treatment categories. Table 23 details the seven treatment categories.

Table 23. Seven treatment categories.

Category	Before Phasing	After Phasing	Number of Legs	Number of Sites
1	Traditional PPLT	FYA PPLT on one road	3	40
2	Traditional PPLT	FYA PPLT on one road	4	136
3	Traditional PPLT	FYA PPLT on both roads	4	64
4	Permissive or traditional PPLT	FYA permissive on one road	4	25
5	Permissive	FYA permissive on one road	4	12
6	At least one protected phase	FYA PPLT without TOD operation	4	18
7	At least one protected phase	FYA PPLT with TOD operation	4	12

Table 24 through table 30 provide summary statistics for each treatment category across all four States. The title of each table also indicates the number of intersections in each category. The note below each table provides the specific treatment that was installed (i.e., before and after LT phasing) and number of intersections from each State. The information in these tables should not be used to make simple before–after comparisons of crashes per intersection year since they do not account for factors (other than the FYA installation) that may cause a change in crashes between the before and after periods. Table 31 and table 32 provide the summary statistics for the reference groups.

Table 24. Summary statistics for treatment category 1 (46 sites; three-leg intersections).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	1.00	8.00	6.20	1.94
After years per site	1.00	5.00	2.85	1.00
AADT on major road (before)	4,000.00	33,854.00	17,079.00	7,865.00
AADT on major road (after)	4,010.00	32,000.00	16,115.00	7,402.00
AADT on minor road (before)	464.00	12,984.00	5,035.00	3,407.00
AADT on minor road (after)	336.00	16,015.00	5,014.00	3,665.00
Total crashes (before) per site year	0.00	17.13	3.70	3.58
Total crashes (after) per site year	0.00	9.00	3.01	2.45
KABC crashes (before) per site year	0.00	4.88	1.36	1.24
KABC crashes (after) per site year	0.00	3.50	1.09	1.08
RE crashes (before) per site year	0.00	7.00	1.44	1.49
RE crashes (after) per site year	0.00	4.67	1.25	1.16
ANG crashes (before) per site year	0.00	3.29	0.59	0.89
ANG crashes (after) per site year	0.00	2.33	0.41	0.63
LT crashes (before) per site year	0.00	3.40	0.76	0.72
LT crashes (after) per site year	0.00	2.67	0.64	0.76
LTOT crashes (before) per site year	0.00	2.60	0.57	0.59
LTOT crashes (after) per site year	0.00	2.33	0.52	0.64

AADT = annual average daily traffic.
Note: The change for this category was traditional PPLT phase to FYA PPLT phase on one road. For LTOT crashes, the analysis used 37 intersections instead of 40 intersections because LTOT crash data from Nevada were not available. Among the 40 sites, 25 were from North Carolina, 3 were from Nevada, 8 were from Oklahoma, and 4 were from Oregon.

Table 25. Summary statistics for treatment category 2 (136 sites; four-leg intersections).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	1.00	8.00	5.54	2.06
After years per site	1.00	6.00	2.61	1.33
AADT on major road (before)	4,627.00	56,097.00	19,487.00	8,983.00
AADT on major road (after)	4,378.00	50,866.00	18,473.00	8,828.00
AADT on minor road (before)	404.00	28,222.00	6,322.00	4,481.00
AADT on minor road (after)	398.00	23,815.00	5,897.00	4,082.00
Total crashes (before) per site year	0.00	22.83	6.31	4.66
Total crashes (after) per site year	0.00	23.00	5.47	4.47
KABC crashes (before) per site year	0.00	8.83	2.40	2.05
KABC crashes (after) per site year	0.00	10.00	2.09	1.93
RE crashes (before) per site year	0.00	14.00	2.39	2.24
RE crashes (after) per site year	0.00	13.00	2.15	2.17
ANG crashes (before) per site year	0.00	10.17	1.69	1.93
ANG crashes (after) per site year	0.00	8.00	1.51	1.73
LT crashes (before) per site year	0.00	7.67	1.60	1.53
LT crashes (after) per site year	0.00	6.00	1.28	1.34
LTOT crashes (before) per site year	0.00	5.50	1.06	1.23
LTOT crashes (after) per site year	0.00	3.67	0.72	0.81

AADT = annual average daily traffic.
Note: The change for this category was traditional PPLT phase to FYA PPLT phase on one road. For LTOT crashes, the analysis used 88 intersections instead of 136 intersections because LTOT crash data from Nevada were not available. Among the 136 sites, 55 were from North Carolina, 48 were from Nevada, 14 were from Oklahoma, and 19 were from Oregon.

Table 26. Summary statistics for treatment category 3 (64 sites; four-leg intersections).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	1.00	8.00	5.97	1.64
After years per site	1.00	5.00	1.59	0.87
AADT on major road (before)	7,146.00	47,375.00	20,551.00	8,523.00
AADT on major road (after)	7,517.00	47,250.00	19,942.00	8,069.00
AADT on minor road (before)	3,135.00	19,100.00	8,831.00	3,755.00
AADT on minor road (after)	3,115.00	18,100.00	8,529.00	3,489.00
Total crashes (before) per site year	0.86	40.50	9.07	7.17
Total crashes (after) per site year	0.00	39.00	7.14	6.56
KABC crashes (before) per site year	0.00	17.67	3.55	3.29
KABC crashes (after) per site year	0.00	24.00	2.88	3.30
RE crashes (before) per site year	0.00	16.67	3.19	3.00
RE crashes (after) per site year	0.00	17.00	2.90	3.13
ANG crashes (before) per site year	0.00	19.83	3.07	4.02
ANG crashes (after) per site year	0.00	21.00	2.24	3.23
LT crashes (before) per site year	0.00	11.17	3.15	2.64
LT crashes (after) per site year	0.00	9.00	1.85	1.90
LTOT crashes (before) per site year	0.00	8.83	2.35	2.08
LTOT crashes (after) per site year	0.00	5.00	1.32	1.35

AADT = annual average daily traffic.
Note: The change for this category was traditional PPLT phase to FYA PPLT phase on both roads. For LTOT crashes, the analysis used 31 intersections (instead of 64 intersections) because LTOT crash data from Nevada were not available. Among the 64 sites, 6 were from North Carolina, 33 were from Nevada, 23 were from Oklahoma, and 2 were from Oregon.

Table 27. Summary statistics for treatment category 4 (25 sites; four-leg intersections).

Variable	Minimum	Maximum	Mean	Standard Deviation
Years before/site	6.00	8.00	7.20	0.50
Years after/site	2.00	4.00	2.80	0.50
AADT on major road (before)	5,678.00	42,906.00	19,599.00	9,451.00
AADT on major road (after)	6,975.00	37,319.00	18,641.00	9,255.00
AADT on minor road (before)	599.00	12,687.00	5,344.00	3,743.00
AADT on minor road (after)	515.00	10,300.00	4,817.00	3,103.00
Total crashes (before) per site year	1.13	12.71	5.86	3.39
Total crashes (after) per site year	0.50	19.00	5.62	4.56
KABC crashes (before) per site year	0.25	5.57	2.14	1.50
KABC crashes (after) per site year	0.00	6.00	1.74	1.52
RE crashes (before) per site year	0.13	6.14	2.22	1.56
RE crashes (after) per site year	0.00	9.00	2.14	2.26
ANG crashes (before) per site year	0.00	4.14	1.32	1.20
ANG crashes (after) per site year	0.00	6.00	1.31	1.44
LT crashes (before) per site year	0.29	2.86	1.07	0.70
LT crashes (after) per site year	0.00	3.00	0.75	0.76
LTOT crashes (before) per site year	0.00	2.63	0.75	0.60
LTOT crashes (after) per site year	0.00	2.67	0.53	0.59

AADT = annual average daily traffic.
Note: The change for this category was permissive or traditional PPLT phase to FYA PPLT phase on one road. All sites were from North Carolina.

Table 28. Summary statistics for treatment category 5 (12 sites; four-leg intersections).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	7.00	8.00	7.58	0.51
After years per site	2.00	3.00	2.42	0.51
AADT on major road (before)	7,467.00	25,842.00	14,614.00	5,863.00
AADT on major road (after)	6,868.00	33,451.00	15,950.00	7,397.00
AADT on minor road (before)	856.00	9,977.00	4,841.00	2,638.00
AADT on minor road (after)	847.00	12,355.00	5,470.00	3,424.00
Total crashes (before) per site year	1.86	15.29	5.49	3.95
Total crashes (after) per site year	0.00	18.00	6.19	4.99
KABC crashes (before) per site year	0.86	7.29	2.54	2.07
KABC crashes (after) per site year	0.00	7.00	2.35	2.10
RE crashes (before) per site year	0.25	5.00	1.67	1.52
RE crashes (after) per site year	0.00	9.67	2.68	2.77
ANG crashes (before) per site year	0.00	2.50	1.00	0.86
ANG crashes (after) per site year	0.00	2.50	0.86	0.86
LT crashes (before) per site year	0.25	7.29	1.77	2.35
LT crashes (after) per site year	0.00	3.33	1.29	1.27
LTOT crashes (before) per site year	0.00	6.57	1.31	2.09
LTOT crashes (after) per site year	0.00	2.67	0.92	0.98

AADT = annual average daily traffic.
Note: The change for this category was permissive to FYA permissive on one road. All sites were from North Carolina.

Table 29. Summary statistics for treatment category 6 (18 sites; four-leg intersections).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	1.00	8.00	6.20	1.94
After years per site	1.00	5.00	2.85	1.00
AADT on major road (before)	4,000.00	33,854.00	17,079.00	7,865.00
AADT on major road (after)	4,010.00	32,000.00	16,115.00	7,402.00
AADT on minor road (before)	464.00	12,984.00	5,035.00	3,407.00
AADT on minor road (after)	336.00	16,015.00	5,014.00	3,665.00
Total crashes (before) per site year	0.00	17.13	3.70	3.58
Total crashes (after) per site year	0.00	9.00	3.01	2.45
KABC crashes (before) per site year	0.00	4.88	1.36	1.24
KABC crashes (after) per site year	0.00	3.50	1.09	1.08
RE crashes (before) per site year	0.00	7.00	1.44	1.49
RE crashes (after) per site year	0.00	4.67	1.25	1.16
ANG crashes (before) per site year	0.00	3.29	0.59	0.89
ANG crashes (after) per site year	0.00	2.33	0.41	0.63
LT crashes (before) per site year	0.00	3.40	0.76	0.72
LT crashes (after) per site year	0.00	2.67	0.64	0.76
LTOT crashes (before) per site year	0.00	2.60	0.57	0.59
LTOT crashes (after) per site year	0.00	2.33	0.52	0.64

AADT = annual average daily traffic.
Note: The change for this category was from at least one protected LT phase to FYA PPLT phase without TOD operation. Eleven sites were from North Carolina, six were from Oklahoma, and one was from Oregon.

Table 30. Summary statistics for treatment category 7 (12 sites; four-leg intersections).

Variable	Minimum	Maximum	Mean	Standard Deviation
Before years per site	6.00	8.00	7.33	0.78
After years per site	2.00	4.00	2.67	0.78
AADT on major road (before)	15,711.00	39,666.00	28,303.00	7,549.00
AADT on major road (after)	13,905.00	39,381.00	26,150.00	6,735.00
AADT on minor road (before)	3,154.00	27,870.00	18,381.00	8,120.00
AADT on minor road (after)	3,044.00	26,468.00	16,670.00	7,274.00
Total crashes (before) per site year	1.43	44.00	18.10	11.02
Total crashes (after) per site year	1.33	37.50	17.13	10.54
KABC crashes (before) per site year	0.43	13.88	5.52	3.67
KABC crashes (after) per site year	0.00	14.00	6.01	4.20
RE crashes (before) per site year	0.57	24.38	9.40	6.60
RE crashes (after) per site year	1.33	17.50	7.30	5.49
ANG crashes (before) per site year	0.00	5.00	2.78	1.51
ANG crashes (after) per site year	0.00	6.00	3.05	1.83
LT crashes (before) per site year	0.00	2.13	1.05	0.73
LT crashes (after) per site year	0.00	4.00	1.60	1.27
LTOT crashes (before) per site year	0.00	2.13	0.83	0.62
LTOT crashes (after) per site year	0.00	3.00	1.08	0.96

AADT = annual average daily traffic.
Note: The change for this category was from at least one protected LT phase to FYA PPLT phase with TOD operation. All sites were from North Carolina.

Table 31. Summary statistics for three-leg reference sites (48 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Number of years per site	2.00	11.00	8.42	2.62
AADT on major road	4,752.00	35,030.00	19,525.00	7,699.00
AADT on minor road	399.00	25,935.00	7,997.00	5,602.00
Total crashes per site year	0.43	14.27	4.56	3.44
KABC crashes per site year	0.14	6.71	1.81	1.51
RE crashes per site year	0.14	5.91	1.84	1.57
ANG crashes per site year	0.00	9.00	1.30	1.87
LT crashes per site year	0.00	5.00	1.20	1.03
LTOT crashes per site year	0.00	2.36	0.60	0.60

AADT = annual average daily traffic.
Note: For LTOT crashes, 33 sites were used.

Table 32. Summary statistics for four-leg reference sites (390 sites).

Variable	Minimum	Maximum	Mean	Standard Deviation
Number of years per site	1.00	11.00	7.48	2.05
AADT on major road	1,300.00	57,679.00	21,331.00	19,317.00
AADT on minor road	381.00	41,592.00	9,231.00	7,010.00
Total crashes per site year	0.20	43.14	9.01	8.22
KABC crashes per site year	0.00	19.71	3.96	3.73
RE crashes per site year	0.00	23.00	3.62	3.99
ANG crashes per site year	0.00	27.71	3.52	4.08
LT crashes per site year	0.00	16.43	2.48	2.46
LTOT crashes per site year	0.00	8.40	1.14	1.51

AADT = annual average daily traffic.
Note: For LTOT crashes, 167 sites were used.

CHAPTER 6. DEVELOPMENT OF SPFS

This chapter presents the SPFs the project team estimated. The EB method used SPFs to estimate the safety effectiveness of FYAs.[10] The project team used generalized linear modeling to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the research in developing these models. The independent variables included the following:

- Major road annual average daily traffic (AADT).
- Minor road AADT.
- Number of legs (three or four legs; this is a categorical variable).
- LT phasing. The coding for this categorical variable was based on the maximum LT protection at an intersection (i.e., protected, protected-permissive, or permissive).
- Number of through lanes on the major road.
- Presence/absence of a median on the major road.
- Number of approaches with LT lanes.

The variables are included in a log-linear form as follows in figure 6.

$$\gamma = exp\ (a_0 + a_1X_1 + \ldots a_nX_n)$$

Figure 6. Equation. Functional form for SPF.

Where:
γ = predicted crashes.
a_0 = intercept.
a_1 through a_n = coefficients for independent variables X_1 through X_n.

The project team estimated separate SPFs for each crash type, then they estimated annual SPF multipliers, as discussed in chapter 4. Table 33 through table 36 show the SPFs and k.

Table 33. SPFs for North Carolina.

Parameter	Total	Total SE	KABC	KABC SE	RE	RE SE	ANG	ANG SE	LT	LT SE	LTOT	LTOT SE
Intercept	−9.3892	0.7389	−9.4022	0.8479	−8.8501	0.8562	−5.0539	0.6443	−8.6495	1.2812	−11.6494	1.4903
ln(major road AADT)	0.7480	0.0727	0.6918	0.0831	0.9240	0.0874	0.0344	0.0066	0.5622	0.1236	0.7233	0.1430
ln(minor road AADT)	0.4188	0.0393	0.3632	0.046	ns	—	0.4695	0.0728	0.4170	0.0665	0.5094	0.0765
Minor road AADT/1,000	ns	—	ns	—	0.0632	0.0074	ns	—	ns	—	ns	—
Four-leg intersection	0.4706	0.0883	0.4728	0.102	0.3153	0.1038	0.8347	0.1561	ns	—	0.3367	0.1730
Three-leg intersection	*	—	*	—	*	—	*	—	ns	—	*	—
Protected**	ns	—	ns	—	ns	—	ns	—	−0.5983	0.2011	−0.7178	0.2388
Protected-permissive**	ns	—	ns	—	ns	—	ns	—	ns	—	ns	—
Permissive**	ns	—	ns	—	ns	—	ns	—	*	—	*	—
k	0.2348	0.0234	0.2707	0.0302	0.2883	0.0327	0.6556	0.0724	0.5558	0.0608	0.6927	0.0805

*Reference level for categorical variables.
**This parameter is the maximum LT protection.
—No data.
SE = standard error; ns = not significant at the 95-percent confidence level.

Table 34. SPFs for Nevada.

Parameter	Total	Total SE	KABC	KABC SE	RE	RE SE	ANG	ANG SE	LT	LT SE
Intercept	−5.3115	0.5018	−6.1513	0.6002	−9.9082	0.6318	−5.0429	0.5956	−4.8807	0.6370
ln(major road AADT)	0.6269	0.0502	0.6156	0.0587	0.9098	0.0620	0.4904	0.0586	0.4644	0.0637
Major road AADT/1,000	ns	—	ns	—	ns	—	0.0475	0.0059	ns	—
ln(minor road AADT)	ns	—	ns	—	ns	—	0.6236	0.1582	ns	—
Minor road AADT/1,000	0.0480	0.0053	0.0496	0.0059	0.0509	0.0062	—	—	0.0462	0.0066
Four-leg intersection	0.6878	0.1420	0.6154	0.1632	0.6816	0.1727	0.2089	0.0882	0.6195	0.1784
Three-leg intersection	*	—	*	—	*	—	*	—	*	—
Protected**	ns	—	ns	—	1.2900	0.2514	ns	—	ns	—
Protected-permissive**	ns	—	ns	—	0.8371	0.2356	ns	—	ns	—
Permissive**	ns	—	ns	—	*	—	ns	—	ns	—
2 to 3 major through lanes	ns	—	*	—	ns	—	*	—	ns	—
4 to 5 major through lanes	ns	—	ns	—	ns	—	0.3849	0.1748	ns	—
6 to 8 major through lanes	ns	—	0.4690	0.1801	ns	—	0.5645	0.1815	ns	—
Median on major road	0.2158	0.0766	ns	—	ns	—	0.2089	0.0882	0.3296	0.0942
No median on major road	*	—	ns	—	ns	—	*	—	*	—
k	0.2987	0.0248	0.3638	0.0325	0.3944	0.0357	0.3437	0.0301	0.4238	0.0388

*Reference level for categorical variables.
**This parameter is the maximum LT protection.
—No data.
SE = standard error; ns = not significant at the 95-percent confidence level.
Note: LTOT crash data from Nevada were not available.

Table 35. SPFs for Oklahoma.

Parameter	Total	Total SE	KABC	KABC SE	RE	RE SE	LT	LT SE	LTOT	LTOT SE
Intercept	−10.2224	1.6357	−11.7369	1.8897	−17.8424	1.9333	−8.6650	2.0715	−9.1959	2.1088
ln(major road AADT)	0.8544	0.1486	0.9437	0.1783	1.5973	0.1825	0.5676	0.1954	0.6219	0.1990
ln(minor road AADT)	0.3615	0.0924	0.3289	0.1036	0.3648	0.1071	0.3946	0.1165	0.3879	0.1188
Protected**	ns	—	−0.7335	0.3114	ns	—	−1.0676	0.3445	−1.1240	0.3519
Protected-permissive**	ns	—	ns	—	ns	—	ns	—	ns	—
Permissive**	ns	—	*	—	ns	—	*	—	*	—
2 to 3 major through lanes	ns	—	ns	—	*	—	ns		ns	—
4, 5, 6, or 8 major through lanes	ns	—	ns	—	−0.6830	0.2548	ns	—	ns	—
Four-leg intersection; 3–4 legs with LT lanes	0.5737	0.2059	0.7150	0.2502	0.5582	0.2465	0.6731	0.2842	0.7447	0.2921
Four-leg intersection; 1–2 legs with LT lanes	ns	—	ns	—	ns	—	ns	—	ns	—
Three-leg intersection	*	—	*	—	*	—	*	—	*	—
k	0.3450	0.0498	0.3766	0.0642	0.3978	0.0652	0.4897	0.0826	0.5083	0.0856

*Reference level for categorical variables.
**This parameter is the maximum LT protection.
—No data.
SE = standard error; ns = not significant at the 95-percent confidence level.
Note: Reliable SPFs could not be estimated for ANG crashes. Therefore, the SPF for KABC crashes was used with an adjustment factor to estimate ANG crashes.

Table 36. SPFs for Oregon.

Parameter	Total	Total SE	KABC	KABC SE	RE	RE SE	ANG	ANG SE	LT	LT SE	LTOT	LTOT SE
Intercept	−10.4421	1.4462	−11.7273	1.6767	−16.2910	2.0043	−9.4320	2.2539	−12.188	1.9374	−8.8092	2.4495
ln(major road AADT)	1.1382	0.1516	1.2070	0.1741	1.6910	0.2168	0.6969	0.2205	1.2146	0.1946	0.8783	0.2531
Four-leg intersection	ns	—	ns	—	ns	—	2.0337	0.5905	0.7536	0.3130	ns	—
Three-leg intersection	ns	—	ns	—	ns	—	*	—	*	—	—	—
Protected**	0.4866	0.1996	0.4416	0.2198	0.8799	0.2268	ns	—	ns	—	ns	—
Protected-permissive**	ns	—	ns	—	0.2600	0.1218	ns	—	ns	—	ns	—
Permissive**	*	—	*	—	*	—	ns	—	ns	—	ns	—
2 to 3 major through lanes	ns	—	ns	—	*		ns	—	ns	—	ns	—
4, 5, 6, or 8 major through lanes	ns	—	ns	—	−0.5626	—	ns	—	ns	0.2109	ns	—
Four-leg intersection; 3–4 legs with LT lanes	0.9897	0.2236	0.9000	0.2535	0.8172	0.2673	ns	—	ns	—	ns	—
Four-leg intersection; 1–2 legs with LT lanes	0.5479	0.2296	ns	—	ns	—	ns	—	ns	—	ns	—
Three-leg intersection	*	—	*	—	*	—	ns	—	ns	—	ns	—
k	0.3185	0.0494	0.3484	0.0639	0.3455	0.0632	0.6724	0.1659	0.6264	0.1116	0.9958	0.1932

*Reference level for categorical variables.

**This parameter is the maximum LT protection.

—No data.

SE = standard error; ns = not significant at the 95-percent confidence level.

Note: Minor road AADT was not available in Oregon for a significant number of intersections and hence were not included in the SPFs.

CHAPTER 7. BEFORE–AFTER EVALUATION RESULTS

AGGREGATE ANALYSIS

Table 37 through table 43 provide the treatment category, number of intersection legs, number of sites (intersections), crash type, observed crashes in the after period, estimate of expected crashes in the after period without treatment, and estimated CMF and its SE for all crash types considered. CMFs that are statistically different from 1.0 at the 95-percent confidence level are indicated with an asterisk.

Table 37. CMFs for category 1 (40 sites; three-leg intersections).

Crash Type	Actual After-Period Crashes	Expected After-Period Crashes	CMF	SE of CMF
Total	363	427.2	*0.849	0.053
KABC	129	162.7	*0.791	0.080
RE	148	169.4	0.871	0.084
ANG	49	63.5	0.768	0.122
LT	80	99.0	0.804	0.106
LTOT	60	70.4	0.846	0.131

*CMFs statistically different from 1.0 at the 95-percent confidence level.
SE = standard error.
Note: LTOT crash counts for Nevada were not available. For LTOT crashes, 37 sites were used.

Table 38. CMFs for category 2 (136 sites; four-leg intersections).

Crash Type	Actual After-Period Crashes	Expected After-Period Crashes	CMF	SE of CMF
Total	1,951	2,194.8	*0.889	0.027
KABC	722	900.3	*0.801	0.038
RE	753	851.4	*0.884	0.042
ANG	486	505.4	0.960	0.054
LT	413	552.9	*0.746	0.047
LTOT	200	324.1	*0.615	0.055

*CMFs statistically different from 1.0 at the 95-percent confidence level.
SE = standard error.
Note: LTOT crash counts for Nevada were not available. For LTOT crashes, 88 sites were used.

Table 39. CMFs for category 3 (64 sites; four-leg intersections).

Crash Type	Actual After-Period Crashes	Expected After-Period Crashes	CMF	SE of CMF
Total	750	916.4	*0.818	0.036
KABC	286	365.3	*0.782	0.055
RE	306	338.6	0.902	0.066
ANG	207	233.7	0.885	0.068
LT	185	296.2	*0.624	0.053
LTOT	75	147.6	*0.507	0.064

*CMFs statistically different from 1.0 at the 95-percent confidence level.
SE = standard error.
Note: LTOT crash counts for Nevada were not available. For LTOT crashes, 31 sites were used.

Table 40. CMFs for category 4 (25 sites; four-leg intersections).

Crash Type	Actual After-Period Crashes	Expected After-Period Crashes	CMF	SE of CMF
Total	409	410.0	0.997	0.058
KABC	124	153.1	*0.808	0.082
RE	159	157.9	1.005	0.093
ANG	94	90.9	1.030	0.123
LT	55	75.1	*0.729	0.109
LTOT	39	52.9	*0.733	0.130

*CMFs statistically different from 1.0 at the 95-percent confidence level.
SE = standard error.

Table 41. CMFs for category 5 (12 sites; four-leg intersections).

Crash Type	Actual After-Period Crashes	Expected After-Period Crashes	CMF	SE of CMF
Total	192	209.3	0.915	0.078
KABC	74	93.6	*0.787	0.104
RE	84	68.0	1.227	0.165
ANG	23	30.2	0.753	0.173
LT	42	68.2	*0.612	0.105
LTOT	30	54.3	*0.548	0.111

*CMFs statistically different from 1.0 at the 95-percent confidence level.
SE = standard error.

Table 42. CMFs for category 6 (18 sites; four-leg intersections).

Crash Type	Actual After-Period Crashes	Expected After-Period Crashes	CMF	SE of CMF
Total	378	359.1	1.051	0.065
KABC	120	118.3	1.011	0.110
RE	152	164.0	0.925	0.087
ANG	57	55.8	1.014	0.159
LT	82	52.5	*1.551	0.219
LTOT	71	36.8	*1.910	0.299

*CMFs statistically different from 1.0 at the 95-percent confidence level.
SE = standard error.

Table 43. CMFs for category 7 (12 sites; four-leg intersections).

Crash Type	Actual After-Period Crashes	Expected After-Period Crashes	CMF	SE of CMF
Total	518	531.6	0.974	0.050
KABC	178	163.1	1.089	0.095
RE	227	250.9	0.903	0.068
ANG	96	81.8	1.169	0.141
LT	44	34.4	1.267	0.226
LTOT	30	25.7	1.151	0.242

SE = standard error.

In categories 2 and 3, the after period was an FYA PPLT phase on one or more roads. For these two treatment categories, LT and LTOT crashes decreased between 25 and 50 percent, KABC crashes decreased about 20 percent, and total crashes decreased between 10 and 20 percent. The after period for category 1 also had an FYA PPLT phase but consisted of three-leg intersections. In this category, the reduction of LT crashes was not statistically significant, but the reductions of total and KABC crashes were statistically significant.

In categories 4 and 5, the after period was an FYA permissive phase. The results for these two categories were quite similar with statistically significant reductions in KABC, LT, and LTOT crashes.

Not surprisingly, LT crashes increased in categories 6 and 7 where FYA PPLT phases replaced protected phases in at least one of the approaches with or without TOD operation. Agencies typically make this change to improve capacity (not safety) to allow more time for through movements, but the implications on safety are important to recognize.

Since categories 2 and 3 are two common treatments, table 44 and table 45 provide further results from these categories by State. In category 2, sites in Oregon and North Carolina experienced a statistically significant reduction in LT crashes following FYA installation. In category 3, sites in all States experienced a statistically significant reduction in LT crashes following the treatment; however, the magnitude of the reduction was not consistent across the States. The results from Oklahoma are surprising, especially the increase in ANG and RE crashes following FYA installation. The reasons for the differences in the results across the States are not known at this time.

Table 44. CMFs by State for treatment category 2.

State	Number of Sites	Crash Type	Actual After-Period Crashes	Expected After-Period Crashes	CMF	SE of CMF
Oklahoma	14	Total	88	77.6	1.131	0.135
Oklahoma	14	KABC	26	28.0	0.921	0.195
Oklahoma	14	RE	55	33.3	*1.641	0.255
Oklahoma	14	ANG	11	8.6	1.253	0.402
Oklahoma	14	LT	17	21.0	0.804	0.207
Oklahoma	14	LTOT	14	19.1	0.725	0.204
Oregon	19	Total	246	339.7	*0.719	0.075
Oregon	19	KABC	125	173.8	*0.711	0.099
Oregon	19	RE	97	167.5	*0.572	0.086
Oregon	19	ANG	32	44.9	0.694	0.164
Oregon	19	LT	71	120.8	*0.577	0.103
Oregon	19	LTOT	45	75.0	*0.584	0.127
Nevada	48	Total	430	447.4	0.960	0.052
Nevada	48	KABC	188	199.4	0.941	0.077
Nevada	48	RE	159	181.8	0.873	0.077
Nevada	48	ANG	167	164.6	1.013	0.087
Nevada	48	LT	142	120.5	1.176	0.112
Nevada	0	LTOT	—	—	—	—
North Carolina	55	Total	1,187	1,330.1	*0.892	0.033
North Carolina	55	KABC	383	499.0	*0.767	0.047
North Carolina	55	RE	442	468.8	0.942	0.056
North Carolina	55	ANG	276	287.3	0.959	0.074
North Carolina	55	LT	183	290.6	*0.628	0.055
North Carolina	55	LTOT	141	229.9	*0.611	0.061

*CMFs statistically different from 1.0 at the 95-percent confidence level.
—Crash data not provided by State.
SE = standard error.

Table 45. CMFs by State for treatment category 3.

State	Number of Sites	Crash Type	Actual After-Period Crashes	Expected After-Period Crashes	CMF	SE of CMF
Oklahoma	23	Total	299	286.9	1.041	0.069
Oklahoma	23	KABC	102	105.9	0.961	0.107
Oklahoma	23	RE	127	111.1	1.140	0.115
Oklahoma	23	ANG	50	25.8	*1.921	0.319
Oklahoma	23	LT	68	103.2	*0.657	0.087
Oklahoma	23	LTOT	60	99.4	*0.602	0.084
Oregon	2	Total	38	64.7	*0.552	0.156
Oregon	2	KABC	18	30.5	*0.525	0.198
Oregon	2	RE	15	37.8	*0.357	0.135
Oregon	2	ANG	9	8.5	0.897	0.412
Oregon	2	LT	6	20.0	*0.247	0.126
Oregon	2	LTOT	2	5.6	*0.226	0.149
Nevada	2	Total	268	353.3	*0.758	0.050
Nevada	33	KABC	138	162.8	0.846	0.078
Nevada	33	RE	90	115.3	*0.779	0.088
Nevada	33	ANG	127	162.7	*0.780	0.074
Nevada	33	LT	95	117.3	*0.809	0.089
Nevada	0	LTOT	—	—	—	—
North Carolina	6	Total	145	211.5	*0.684	0.065
North Carolina	6	KABC	28	66.0	*0.421	0.086
North Carolina	6	RE	74	74.4	0.989	0.137
North Carolina	6	ANG	21	36.8	*0.565	0.136
North Carolina	6	LT	16	55.7	*0.285	0.074
North Carolina	6	LTOT	13	42.6	*0.303	0.088

*CMFs statistically different from 1.0 at the 95-percent confidence level.
—Crash data not provided by State.
SE = standard error.

Overall, the results of the aggregate analysis are similar to the results from previous research.(2–9) FYA installation generally leads to a reduction in LT crashes as long as the change is not from a fully protected LT phase. Some previous studies investigated crashes at the approach level, which was not possible in this effort.(7,9)

CRASH MODIFICATION FUNCTION

The project team estimated CMFunctions to investigate the effect of site characteristics on the effectiveness of a particular treatment. CMFunctions were only estimated for categories 2 and 3, as these were the two most common categories and had sufficient sample sizes to provide useful results. CMFunctions were estimated for the two target crash types: LT and LTOT crashes.

Methodology for Estimating CMFunction

The traditional approach for estimating CMFunctions includes using the CMF value as the dependent variable and site/treatment characteristics as independent variables. One way to express this is shown in figure 7.

$$CMF = f(site\ characteristics)$$

Figure 7. Equation. General form for CMFunction.

Where f is the generic function.

This CMFunction could then be estimated as a regression equation. Elvik recommended considering the variance of the CMF in this estimation.(16) The inverse of the variance is typically introduced as a weight in a weighted regression model. For example, for an observation (or site) named i whose CMF is CMF_i with a variance of $Var(CMF_i)$, the weight would be $1/Var(CMF_i)$. For linear regression, this would be appropriate.

It is also possible to use a different model form, such as a lognormal model, to ensure that a predicted CMF from a CMFunction is always greater than zero. For the lognormal model, Bonneson showed that the appropriate weight for a weighted lognormal regression model would instead be $CMF_i/Var(CMF_i)$.(17) Based on figure 5, $Var(CMF_i)$ is not independent of CMF_i (i.e., lower CMF values tend to have lower variances as well).

For either the normal regression or lognormal regression models with weights, reliable estimates of CMFs and their variances are needed. To have reliable estimates of these parameters, sites with similar characteristics are often combined. However, this aggregation can lead to a loss of useful information. In this study, a different approach was proposed to overcome the disadvantage of losing information due to aggregation. This approach involved rewriting the equation for the CMFunction, as shown in figure 8.

$$CMF_i^* = \frac{\pi_i}{\lambda_i} = f\ (site\ characteristics)$$

Figure 8. Equation. Rewritten form of CMFunction.

Where CMF_i^* is the crash modification factor for site i. Figure 8 can again be rewritten, as shown in figure 9.

$$\pi_i = \lambda_i \times f(site\ characteristics)$$

Figure 9. Equation. Another rewritten form of CMFunction.

As written in figure 9, it is possible to estimate this equation as a count data model (such as the Poisson or negative binomial models) with π as the dependent variable and λ as the offset. This approach is similar to estimating an SPF for predicting the number of crashes per mile, where crash frequency is included as the dependent variable and section length is included as the offset. One limitation of this approach is that the offset is an estimated value from the EB evaluation with a variance. There has been limited research in traffic safety on the implications of errors/variance in the independent variables, but further research is needed, possibly using simulation. Nevertheless, researchers of a recent study investigated and compared this new approach for estimating CMFunctions with traditional approaches and found the new approach to be quite useful, especially when used with disaggregate data with less-frequent crash types.(18)

The independent variables in the CMFunction included the following:

- Expected crashes per site per year in the before period.
- Indicator variables for the State.

The project team estimated negative binomial regression models. Figure 10 illustrates the functional form for the CMFunction.

$$CMF = exp(a_0 + a_1X_1 + a_2X_2 + \cdots a_nX_n)$$

Figure 10. Equation. Functional form for CMFunction.

Table 46 shows the parameter estimates and corresponding standard errors (SEs) for the CMFunction for category 2.

For category 3, only the State variable was significant for both LT and LTOT crashes, indicating that the CMFunction does not provide any additional information compared to table 45. So, CMFunctions for category 3 are not presented in table 46.

For category 2, only the State variable was significant for LT crashes, indicating that the CMFunction did not provide any additional information compared to table 44. As a result, table 46 does not show the CMFunctions for LT crashes.

For LTOT crashes in category 2, the natural log of the EB expected crashes per year in the before period and the State variable for LTOT crashes were statistically significant. Two CMFunctions were estimated, one with the State variables (model 2) and the other without the State variables (model 1). In table 46, the State with coefficient 0.0000 (i.e., Oregon) was the reference State. The coefficient for the natural log of the EB expected crashes per year before FYA installation (i.e., ln(*EB_exp_before/year*)) was negative, implying that the treatment was more effective in locations with a greater expected number of LTOT crashes without the treatment.

Table 46. CMFunctions for treatment category 2.

Variable	LTOT Crashes Model 1	Model 1 SE	LTOT Crashes Model 2	Model 2 SE
Intercept	−0.3656	0.0994	−0.5193	0.2077
ln(*EB_exp_before/year*)	−0.2626	0.1069	−0.2892	0.1119
North Carolina	ns	—	0.1887	0.2467
Oklahoma	ns	—	0.3023	0.3734
Oregon	ns	—	0.0000	0.0000
k	0.2963	—	0.2872	—

—No data.
ns = not statistically significant.
Note: LTOT crash data for Nevada were not available.

The CMFunctions based on model 1 for LTOT crashes for treatment category 2 are shown in figure 11, in which 0.694 was calculated by raising *e* to the power of −0.3656.

$$CMF = 0.694 \times (EB\_exp\_before)^{-0.2626}$$

Figure 11. Equation. CMFunction for LTOT crashes.

Where *EB_exp_before* is the EB expected LTOT crashes per year at the intersection level in the before period.

CHAPTER 8. ECONOMIC ANALYSIS

The project team undertook the economic analysis for treatment categories 1–5. Treatment categories 6 and 7 (changed from protected phases to FYA PPLT phases) were implemented for reasons other than safety (typically operational efficiency), and as a result, the project team did not include them in the economic analysis. To conduct the economic analysis, the following steps were taken:

1. The project team estimated the EB expected property-damage-only (PDO) crashes in the after period and actual PDO crashes in the after period using the EB expected and actual crashes in the after period for total and KABC crashes.

2. Using the number of intersection years in the after period, the project team determined the changes in PDO and KABC crashes per intersection year.

3. For benefit calculations, the project team disaggregated the most recent FHWA mean comprehensive crash costs by crash severity and used location type as a base.[19] They developed these costs based on 2001 crash costs; the unit costs for KABC and PDO crashes in urban areas were (in 2001 U.S. dollars (USD)) \$91,917 and \$7,068, respectively.[19] This was updated to 2015 USD by applying the ratio of the U.S. Department of Transportation (USDOT) 2015 value of a statistical life of \$9.4 million to the 2001 value of \$3.8 million.[20] Applying this ratio of 2.47 to the unit costs resulted in an aggregate 2015 unit cost of \$227,744 for KABC crashes and \$17,513 for PDO crashes. A sensitivity analysis was conducted based on the USDOT 2015 document, which led to a minimum and maximum for the benefit values and B/C ratio.

4. The project team estimated the annualized cost of the treatment (*Annual Cost*), as shown in figure 12.

$$Annual\ Cost = \frac{C \times R}{1 - (1 + R)^{-N}}$$

Figure 12. Equation. Annual cost.

Where:
C = treatment cost.
R = discount rate (as a decimal) and assumed to be 0.07.
N = expected service life of 10 yr.

Oklahoma indicated that the installation cost is about \$6,500 for a four-leg intersection (i.e., about \$1,625 per approach leg). In a recent study in Illinois, Schattler et al. assumed that the installation cost was \$6,000 per approach leg.[9] The higher installation cost from Illinois was used to obtain a conservative estimate for the B/C ratio. In using this cost, the project team assumed that the signal pole was structurally adequate to accommodate the retrofit. The team also assumed that there would be no additional maintenance costs for the FYA treatment compared to traditional phasing systems.

5. The project team calculated the B/C ratio as the ratio of the annual crash savings to the annualized treatment cost. Table 47 provides the results.

Table 47. Results of economic analysis.

Treatment Category	KABC Crash Reduction*	PDO Crash Reduction*	Economic Benefits From Crash Reduction*	Annualized Treatment Cost*	B/C Ratio Mean	B/C Ratio Min	B/C Ratio Max
1	0.30	0.27	$72,010	$854	84:1	46:1	116:1
2	0.50	0.18	$117,626	$1,709	69:1	38:1	95:1
3	0.78	0.85	$191,990	$3,417	56:1	31:1	78:1
4	1.16	−1.12	$245,410	$1,709	144:1	79:1	198:1
5	0.68	−0.08	$152,535	$1,709	89:1	49:1	123:1

*Data are per intersection per year.
Min = minimum; Max = maximum.

CHAPTER 9. SUMMARY AND CONCLUSIONS

The project team obtained geometric, traffic, and crash data at treated signalized intersections in Nevada, North Carolina, Oklahoma, and Oregon and conducted an EB before–after evaluation using reference groups of untreated signalized intersections with similar characteristics to the treated sites. The evaluation included 307 treated sites and 438 reference sites from these four States. The project team considered six crash types: total, KABC, RE, ANG, LT, and LTOT.

TREATMENT CATEGORIES

Based on the before and after LT phasing and the number of legs at the intersection, the sites were divided into seven treatment groups, as shown in table 48.

Table 48. Treatment categories.

Category	Before Phasing	After Phasing	Number of Legs	Number of Sites
1	Traditional PPLT	FYA PPLT on one road	3	40
2	Traditional PPLT	FYA PPLT on one road	4	136
3	Traditional PPLT	FYA PPLT on both roads	4	64
4	Permissive or traditional PPLT	FYA permissive on one road	4	25
5	Permissive	FYA permissive on one road	4	12
6	At least one protected phase	FYA PPLT without TOD operation	4	18
7	At least one protected phase	FYA PPLT with TOD operation	4	12

Note: LTOT crash data for Nevada were not available, so fewer sites were used.

CMFS

Table 37 through table 43 show the CMFs for the seven treatment categories for the six crash types. The first five categories involved permissive or protected-permissive phasing in the before period. Intersections in these five categories experienced a reduction in the primary target crashes under consideration (i.e., LT and LTOT crashes at the intersection level). The reduction ranged from 15 to 50 percent depending on the treatment category. Intersections in categories 6 and 7 had at least one protected LT phase in the before period. These intersections experienced an increase in LT and LTOT crashes after the introduction of FYAs. Overall, the results were similar to those from previous research.[2–9] FYA installation generally led to a reduction in LT crashes as long as the change was not from a fully protected LT phase. Some previous studies investigated crashes at the approach level, which was not possible in this effort.[7,9]

The project team estimated CMFunctions using data from treatment category 2 to determine if the CMF was a function of site characteristics, such as expected crashes in the before period and the State in which it was installed. The CMFunctions for LTOT crashes for treatment category 2 are given in figure 11.

Table 49 shows the B/C ratios for treatment categories 1–5. The B/C ratios ranged from 56:1 to 144:1.

Table 49. B/C ratios for treatment categories 1–5.

Treatment Category	B/C Ratio Mean	B/C Ratio Min	B/C Ratio Max
1	84:1	46:1	116:1
2	69:1	38:1	95:1
3	56:1	31:1	78:1
4	144:1	79:1	198:1
5	89:1	49:1	123:1

Min = minimum; Max = maximum.

There were some limitations in this study. LT volumes were not available and hence could not be included in the evaluation. The project team could not reliably obtain approach-level crashes from the coded crash reports. As a result, the evaluation focused on intersection-level crashes instead. In addition to these limitations, it is important to note that many of these signals were part of signal systems, and changes in signal timings of other intersections in the same corridor could have affected the safety of the intersections that were evaluated in this study.

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