Safety Evaluation of Intersection Conflict Warning Systems

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FOREWORD

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

Intersection conflict warning systems (ICWSs), evaluated for their safety effectiveness under this study, are intended to reduce the frequency of crashes by alerting drivers to conflicting vehicle paths on adjacent approaches at unsignalized intersections. For two-lane at two-lane intersections, results showed significant reductions for total, fatal and injury, right-angle, and rear-end crashes. For four-lane at two-lane intersections, results showed significant reductions for total, fatal and injury, right-angle, and nighttime crashes. The results suggest that the ICWSs can be cost-effective safety improvements. This report will benefit roadway designers and safety planners to provide greater intersection safety.

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Director, Office of Safety
Research and Development

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16. Abstract

FHWA organized a pooled fund study of 40 States to evaluate low-cost safety strategies as part of its strategic highway safety effort. One of the strategies selected for evaluation was intersection conflict warning systems (ICWSs). This strategy is intended to reduce the frequency of crashes by alerting drivers to conflicting vehicles on adjacent approaches at unsignalized intersections. Geometric, traffic, and crash data were obtained for four-legged, rural, two-way stop-controlled intersections with ICWS installations in Minnesota, Missouri, and North Carolina. To account for potential selection bias and regression-to-the-mean, an empirical Bayes before–after analysis was conducted, using reference groups of similar four-legged, rural, two-way stop-controlled intersections without ICWS installation. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the strategy. The combined results for all States indicated statistically significant crash reductions for most crash types for two-lane at two-lane intersections and for four-lane at two-lane intersections. For two-lane at two-lane intersections, the statistically significant crash modification factors (CMFs) for total, fatal and injury, right-angle, and rear-end crashes were 0.73, 0.70, 0.80, and 0.43, respectively. For four-lane at two-lane intersections, the statistically significant CMFs for total, fatal and injury, right-angle, and nighttime crashes were 0.83, 0.80, 0.85, and 0.61, respectively. The benefit-cost ratio estimated with conservative cost and service life assumptions was 27:1 for all two-lane at two-lane intersections and 10:1 for four-lane at two-lane intersections. The results suggest that the ICWS strategy, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective. Because this is an evolving strategy, the results of this study reflect installation practices to date.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

AADT	average annual daily traffic
B/C	benefit-cost
CAS	collision avoidance system
CICAS	Cooperative Intersection Collision Avoidance System
CMF	crash modification factor
EB	empirical Bayes
FHWA	Federal Highway Administration
ICAS	intersection collision avoidance system
ICWS	intersection conflict warning system
KABCO	Scale used to represent injury severity in crash reporting (K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, O is property damage only)
LED	light-emitting diode
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
NCDOT	North Carolina Department of Transportation
NHTSA	National Highway Traffic Safety Administration
PDO	property damage only
PRT	perception-response time
RICWS	rural intersection conflict warning system
RTM	regression-to-the-mean
SPF	safety performance function
USDOT	U.S. Department of Transportation
VEWF	vehicle entering when flashing

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) organized a pooled fund study of 40 States to evaluate low-cost safety strategies as part of its strategic highway safety effort. The purpose of the FHWA Evaluation of Low-Cost Safety Improvements Pooled Fund Study is to evaluate the safety effectiveness of high-priority, low-cost safety strategies selected by member States through scientifically rigorous crash-based studies. One of the strategies selected by member States for evaluation was the application of intersection conflict warning systems (ICWSs). This strategy is intended to reduce the frequency of crashes by alerting drivers to conflicting vehicles on adjacent approaches at unsignalized intersections, particularly those with one-way or two-way stop control. Few studies have explored the safety effectiveness of an ICWS; no studies have evaluated their effectiveness at four-legged intersections using a statistically rigorous methodology, such as the empirical Bayes (EB) before–after method.

Geometric, traffic, and crash data were obtained for four-legged, rural, two-way stop-controlled intersections with ICWS installations in Minnesota, Missouri, and North Carolina. To account for potential selection bias and regression-to-the-mean (RTM), an EB before–after analysis was conducted using reference groups of similar four-legged, rural, two-way stop-controlled intersections without ICWS installation. Separate analyses were conducted for intersections with two lanes or four lanes on the major approaches. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the strategy.

The combined results for all States indicated reductions for all crash types analyzed (i.e., total, fatal and injury, right-angle, rear-end, and nighttime) for both two-lane at two-lane intersections and four-lane at two-lane intersections. The reductions were statistically significant at the 95-percent confidence level for all crash types except nighttime crashes for two-lane at two-lane intersections. The reductions were statistically significant at the 95-percent confidence level for all crash types except rear-end crashes for four-lane at two-lane intersections.

For two-lane at two-lane intersections, the statistically significant crash modification factors (CMFs) for total, fatal and injury, right-angle, and rear-end crashes were 0.733, 0.701, 0.803, and 0.425, respectively. Nighttime crashes had an estimated CMF of 0.898, which was not statistically significant at the 95-percent confidence level. It is important to consider the sample size used to develop the CMF when interpreting the results because some of the CMFs were based on relatively small samples.

For four-lane at two-lane intersections, the statistically significant CMFs for total, fatal and injury, right-angle, and nighttime crashes were 0.827, 0.802, 0.850, and 0.612, respectively. Rear-end crashes had an estimated CMF of 0.973, which was not statistically significant at the 95-percent confidence level.

The disaggregate analysis sought to identify those conditions under which the ICWS strategy was most effective. Because total, fatal and injury, and right-angle crashes were the focus of this strategy, these crash types were also the focus of the disaggregate analysis. Because installation category was the main factor for the disaggregate analysis, the categories developed by the North Carolina Department of Transportation (NCDOT) were expanded for use in this study.[1]

Categories for further analysis included the following:

- Category 1—Overhead signs and flashers at the intersection on major; loop on minor.
- Category 2—Overhead signs and flashers at the intersection on minor; loop on major.
- Category 3a—Post-mounted signs and flashers in advance of the intersection on major; loop on minor.
- Category 3b—Post-mounted signs and flashers at the intersection on minor; loop on major.
- Category 4—Locations with a combination of category 1 through category 3.

The disaggregate analysis for two-lane at two-lane intersections indicated larger percentage crash reductions for sites with an ICWS installed on the major route, particularly for a post-mounted ICWS in advance of the intersection. Additional benefit may have been provided by including the "WHEN FLASHING" message as part of the system. The CMFs from the disaggregate analysis can be used in prioritizing installation sites, but interpretations should be made with caution. One should pay particular attention to the sample size used to develop the CMFs.

The disaggregate analysis for four-lane at two-lane intersections indicated larger percentage crash reductions for sites with intersection lighting and for sites with a higher expected average crash frequency in the before period. There was no substantive difference for sites with warning on the major route versus warning on the minor route. The CMFs from the disaggregate analysis can be used in prioritizing installation sites, but interpretations should again be made with caution.

The benefit-cost (B/C) ratio estimated with conservative cost and service life assumptions and, only considering the benefits for total crashes, was 27:1 for all two-lane at two-lane intersections and 10:1 for four-lane at two-lane intersections. The benefits were calculated from the significant reduction found for combined States for all two-lane at two-lane intersections and based on the statistically significant reduction found for four-lane at two-lane. With the U.S. Department of Transportation (USDOT)-recommended sensitivity analysis, these values could range from 16:1 to 39:1 for two-lane at two-lane intersections and 6:1 to 14:1 for four-lane at two-lane intersections. These results suggest that the ICWS strategy—even with conservative assumptions on cost, service life, and the value of a statistical life—can be cost effective.

Because ICWS is an evolving strategy, this study reflected installation practices to date. Future studies may show different results as installation practices change. In particular, the use of overhead ICWSs on the major route was limited to installations at the intersection (i.e., no advance warning), while post-mounted ICWSs on the major route were installed in advance of the intersection. Future research should compare these installation practices, considering placement of warning signs. Specifically, section 2C.05 of the *Manual on Uniform Traffic Control Devices* (MUTCD) provides guidance for the placement of warning signs so that they provide adequate perception-response time (PRT).[2]

CHAPTER 1. INTRODUCTION

BACKGROUND ON THE ICWS STRATEGY

The ICWS strategy involves installing ICWSs on the approaches of rural, four-legged, unsignalized intersections. ICWSs may be installed on the major and/or minor approaches. These systems employ vehicle detectors to alert motorists of conflicting vehicles on an adjacent approach. Installation practices current at the time of this study used warning signs on the major approaches alerting motorists with the message "VEHICLE ENTERING WHEN FLASHING" (VEWF), "CROSSING TRAFFIC WHEN FLASHING," or "WATCH FOR ENTERING TRAFFIC." Signs on the minor approaches alerted entering motorists with "TRAFFIC APPROACHING WHEN FLASHING," "LOOK FOR TRAFFIC" (with yellow light-emitting diode (LED) arrow-shaped flashers), or visual graphic displays. Figure 1 presents a Google Street View™ image of an ICWS application in Missouri. Refer to appendix A for further examples of ICWS applications observed in this study.

Figure 1. Photo. ICWS visual display from Google Street View™.[3]

Use of ICWSs is one strategy employed at intersections with limited sight distance and/or intersections with a history of crashes involving gap acceptance problems. As Crowson and Jackels noted, there has been no specific guidance for the design, placement, and message of these systems, resulting in a broad range of approaches for States that are implementing these systems.[4] For this reason, the ENTERPRISE transportation pooled fund sponsored the research by Crowson and Jackels to develop a consistent approach for uniform deployment, provide further evaluation, and to recommend preliminary standards for the MUTCD.[2,4] Their research presented typical system components and developed recommended layouts for four scenarios based on which road the alert was directed and the number of lanes of the intersection. This research served as an evaluation of the safety effectiveness of ICWS applications to date through a crash-based analysis.[(4)]

BACKGROUND ON STUDY

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

The National Cooperative Highway Research Program published a series of guides to advance the implementation of countermeasures targeted to reduce crashes and injuries. Each guide addresses one of the emphasis areas and includes an introduction to the problem, a list of objectives for improving safety, and strategies for each objective. Each strategy is designated as proven, tried, or experimental. Many of the strategies discussed in these guides have not been rigorously evaluated; about 80 percent of the strategies are considered tried or experimental.

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

LITERATURE REVIEW

Literature on ICWSs was limited. This section summarizes the salient research related to specific strategies. Very few studies were identified that investigated the effects of ICWSs.

Lyle evaluated a series of progressively more informative (and emphatic) signs used to warn drivers of a hazardous intersection at two locations in Maine.[(5)] The most informative (and emphatic) device was a warning sign stating “Vehicles Entering When Flashing” with corresponding flashing beacons. The measures of effectiveness for this study were observed speed reductions and driver sign recall. The active sign was found to produce the greatest decrease in speed, but the decrease was not significantly different from that produced by the next most progressive sign (“Vehicles Entering” with continuous flashing beacons). Surveys showed that motorists who saw the active warning sign had better recall, not only of the sign but also of the presence of a vehicle in the intersection.

Bretherton and Miao developed guidelines for traffic-actuated warning signs at intersections with limited sight distance based on data from 18 intersections in Gwinnett County, GA.[(6)] The 85th percentile speed, existing sight distance, required minimum sight distance, and crash history were presented. The authors selected sites with at least three preventable crashes in 1 year, or at least one preventable crash for 3 consecutive years. A post-mounted “Vehicle Approaching” sign was used on the minor street approach for several intersections, and a post-mounted “Vehicle Entering Highway” sign was used on the major street approach for several intersections. The authors noted that "…the results show that the signs did effectively reduce the number of [preventable] accidents."[(6)](p. 12) Preventable crashes were defined as those related to limited sight distance. It should be noted that, because of the method of site selection, the results suffered from RTM bias.

Hanscom conducted a test of a collision countermeasure system in Prince William County, VA, using data from 1993 to 2000.[(7)] The primary measures of effectiveness were sign response speed, intersection arrival speed, first speed reduction, second speed reduction, and projected time to collision. Novelty speed effects were observed, but increased projected time to collision was sustained in the after period. A simple before–after crash analysis was conducted for side-impact crashes, and 2.6 crashes were observed per year for the 5-year before period, and no crashes were observed in the 2-year after installation period.

Peabody et al. also examined the effectiveness of a vehicle-activated warning system for stop-controlled intersections in Norridgewock, ME.[(8)] A conflict analysis showed a 35- to 40-percent reduction in intersection conflicts. A survey of drivers found that 67 percent said that the signs would prevent crashes, and 64 percent recommended the system for other intersections. Limited crash data were collected, and no crash effectiveness of the strategy was estimated.

The Pennsylvania Department of Transportation conducted a before–after analysis of a post-mounted collision avoidance system (CAS) at two locations from 1999 to 2005.[(9)] A speed study showed that operating speeds initially declined but increased after 3 years. A gap acceptance study found that typical gaps did not change from the before to the after period. Users were surveyed, and 97 percent said that the CAS was beneficial, and 93 percent said that the system should be installed at other locations. Summary statistics were presented for crash data. At one site, two crashes were observed in the 2-year before period, and no crashes occurred in the 2-year after period. At the second site, two crashes were observed in the before period, and three crashes were observed in the after period. (One occurred while the system was malfunctioning.) The authors of the Pennsylvania study noted that the sample size was too small to conduct a safety analysis.[(9)]

The Missouri Department of Transportation (MoDOT) studied the safety effectiveness of post-mounted warning systems at 9 stop-controlled intersection major street approaches and 10 stop-controlled intersection minor street approaches.[(10)] A simple before–after study found 28-, 72-, 37-, and 75-percent reductions in total, severe, angle, and severe-angle crashes, respectively, at the locations with the installation on the major street approach. They also found 32-, 33-, 44-, and 38-percent reductions in total, severe, angle, and severe-angle crashes at the locations, respectively, with the installations on the minor street approaches. MoDOT noted that one-third of the individual locations showed little or no improvement.

Simpson and Troy evaluated VEWF signs at 56 two-lane at two-lane intersections in North Carolina.[(1)] Installation dates ranged from 1996 to 2010. A before–after analysis assessed the crash reduction factor for multiple crash types. The following definitions were provided for the four categories of signs used in North Carolina:[(1)]

- Category 1—Overhead signs and flashers on major; loop on minor.
- Category 2—Overhead signs and flashers on minor; loop on major.

- Category 3—Post-mounted signs and flashers on major; loop on minor.
- Category 4—Locations with a combination of category 1 through category 3.

Table 1 presents the results of the analyses for two-lane at two-lane intersections. The authors found that deployments with alerts on the major road in advance of the intersection and locations with a combination of both major and minor road alerts were the most effective for two-lane at two-lane stop-controlled intersections, with CMFs for total crashes of 0.68 and 0.75, respectively.[1]

In addition, intersections with four lanes on the major route were considered; however, no apparent reductions in crashes were found for these sites. The authors suggested that VEWF systems may not be an appropriate strategy for most intersections with four lanes on the major route experiencing a strong frontal impact crash pattern.

Table 1. CMFs for VEWF signs.[1]

VEWF Category	CMF	Standard Error
Total Crashes		
All sites	**0.897**	0.047
1	**1.059**	0.098
2	**0.953**	0.084
3	**0.675**	0.076
4	0.749	0.115
Target Crashes		
All sites	**0.929**	0.055
1	**1.074**	0.112
2	**1.001**	0.096
3	**0.679**	0.088
4	0.797	0.144
Injury Crashes		
All sites	**0.878**	0.059
1	**0.917**	0.108
2	**0.934**	0.106
3	**0.732**	0.102
4	0.870	0.187
Severe Injury Crashes		
All sites	0.697	0.159
1	**0.613**	0.236
2	0.761	0.268
3	0.699	0.301
4	0.242	0.212

Statistically significant results at the 95-percent confidence level are indicated in boldface.

Pierowicz et al. developed a prototype intersection collision avoidance system (ICAS) for use within vehicles.[11] The system was derived through the review of national databases such as the National Automotive Sampling System, General Estimates System, and Fatality Analysis Reporting System.[12] Four intersection crash scenarios were identified, as were three potential countermeasures. Two of the countermeasures, the Driver Advisory System and the Defensive

System, were developed in a full-scale study for performance. Several recommendations were made from this research including the following:

- Integrate left turn across path sensor algorithms developed on the ICAS into the NHTSA Intelligent Vehicle Initiative.
- Continue development of map-based unsignalized intersection system.
- Fund development of forward-viewing, wide-field sensor.
- Investigate use of signal-to-vehicle communication to improve ICAS effectiveness.
- Continue investigation of driver-vehicle interface effectiveness and driver acceptance.

LIMITATIONS OF PREVIOUS RESEARCH

Most previous research studies focused on surrogate measures for intersection safety performance because typically only one or two applications were implemented. Some research studies were able to consider a simple before–after approach in an attempt to quantify a reduction in targeted crash types. However, these studies did not quantify a margin of error for the associated reductions, and they did not account for RTM bias. Only one of the studies reported in this chapter attempted to account for RTM, but details of how this was done were not provided. In addition, a linear assumption was used to account for changes in traffic volume experienced at the installation sites rather than safety performance functions (SPFs) typically used for EB evaluations. The study did find statistically significant crash reductions at the 95-percent confidence level for certain crash types for two-lane at two-lane intersections when all installation categories were combined. Not enough intersections and reference sites were available to study four-lane at two-lane intersections, and CMFs for several crash types for individual installation categories were statistically insignificant. Further, there was no attempt to quantify the impact of system placement on the major road (i.e., in advance of or at the intersection).

CHAPTER 2. OBJECTIVE

This research examined the safety impacts of the application of ICWSs in Minnesota, Missouri, and North Carolina. The objective was to estimate the safety effectiveness of this strategy as measured by crash frequency. Target crash types included the following:

- Total crashes (all types and severities combined).
- Injury crashes (K (fatal injury), A (incapacitating injury), B (non-incapacitating injury), and C (possible injury) on KABCO scale).
- Right-angle crashes (all severities combined).
- Rear-end crashes (all severities combined).
- Nighttime crashes (all severities combined).

While the ICWS strategy specifically targets right-angle crashes, other crash types were considered to determine whether there were supplemental benefits or drawbacks. Rear-end crashes were the only additional crash type determined to occur commonly enough to be reasonably considered independently in the analysis. The research team surmised that there was potential for other drivers to be alerted in addition to the conflicting vehicles for which the systems were designed. This could lead to reductions in rear-end crashes on both the major and minor routes, owing to increased awareness. This would differentiate the outcome from the effects of traffic signals, which typically produce an increase in rear-end crashes while reducing right-angle crashes.

A further objective was to address questions of interest, such as whether effects varied depending on the following characteristics:

- Type of installation (i.e., specific type or combination of ICWS).
- Location of installation (i.e., post mounted, overhead, or in advance or at the intersection).
- Intensity (i.e., number of approaches).
- Level of traffic volume.
- Posted speed limit on the major route or minor routes.
- Presence of turn lanes.
- Presence of intersection lighting.
- Before period expected crash frequency.

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

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

- Select a large enough sample size to detect, with statistical significance, what may be small changes in safety for some crash types.
- Identify appropriate reference sites without ICWS installation.
- Properly account for changes in safety due to changes in traffic volume and other factors unrelated to ICWS installation.
- Pool data from multiple jurisdictions to improve reliability of the results and facilitate broader applicability of the products of the research.

CHAPTER 3. STUDY DESIGN

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

SAMPLE SIZE ESTIMATION OVERVIEW

When planning a before–after safety evaluation study, it is vital to ensure that enough data are included such that the expected change in safety can be statistically detected. Even though in the planning stage, the expected change in safety is unknown, it is still possible to make a rough estimate of how many sites would be required based on the best available information about the expected change in safety. Alternatively, one could estimate, for the number of available sites, the change in safety that could be statistically detected. For a detailed explanation of sample size considerations, as well as estimation methods, see chapter 9 of Hauer.[13] The sample size analysis presented here is limited to two cases: (1) how large a sample would be required to statistically detect an expected change in safety, and (2) what changes in safety could be detected with available sample sizes.

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

Table 2 provides the crash rate assumptions. The locations of interest for the ICWS strategy were four-legged, stop-controlled intersections. Intersection crash rates differ substantially depending on a number of factors (e.g., traffic control, traffic volume, geometric configuration, and area type). Therefore, the intersection crash rates assumed for these computations represented the before data for installation sites in North Carolina, Missouri, and Minnesota. Rates A and B were calculated as the weighted average crash rate for two-lane and multilane major routes, respectively.

Table 2. Before period crash rate assumptions for four-legged, stop-controlled intersections.

	Crash Rate (crashes/intersection/yr)							
	North Carolina		Missouri		Minnesota		Rate A	Rate B
Crash Type	Two-Lane	Multilane	Two-Lane	Multilane	Two-Lane	Multilane	Two-Lane	Multilane
Total	3.817	4.317	1.932	3.712	1.535	5.929	3.300	4.246
Fatal and injury	2.228	2.867	0.886	1.962	0.744	3.786	1.877	2.596
Right-angle	2.430	3.150	1.091	2.077	0.698	3.571	2.049	2.754
Rear-end	0.304	0.217	0.159	0.519	0.209	0.500	0.274	0.373
Nighttime	0.494	0.583	0.295	0.885	0.209	1.071	0.434	0.762

Table 3 provides estimates of the required number of before and after period intersection-years for statistical significance at both a 90- and 95-percent confidence level for crash rates A and B. The minimum sample indicates the level for which a study seemed worthwhile; that is, it was feasible to detect with the level of confidence the largest effect that could reasonably be expected based on what was currently known about the ICWS strategy. These sample size calculations were based on specific assumptions regarding the number of crashes per intersection and years of available data. Rate A (from table 2) was used for two-lane at two-lane intersections, and rate B (from table 2) was used for four-lane at two-lane intersections. Site-years are the number of sites where the strategy was implemented multiplied by the number of years of data before or after implementation. For example, if a strategy was implemented at nine sites and data were available for 3 years since implementation, then there would be a total of 27 site-years of after period data available for the study.

Table 3. Minimum required before period site-years for ICWS installation sites.

Expected Percent Reduction in Crashes		Minimum Before Period Site-Years[1] 95-Percent Confidence Rate A	95-Percent Confidence Rate B	90-Percent Confidence Rate A	90-Percent Confidence Rate B
Total	10	564	439	351	273
	20	**85**	**66**	**59**	**46**
	30	29	23	21	16
	40	13	10	9	7
Fatal and injury	10	991	717	616	446
	20	**149**	**108**	**103**	**75**
	30	51	37	36	26
	40	22	16	16	12
Right-angle	10	908	676	564	420
	20	**136**	**102**	**94**	**70**
	30	47	35	33	25
	40	20	15	14	11
Rear-end	10	6,788	4,987	4,218	3,098
	20	1,017	747	703	516
	30	**346**	**254**	**242**	**178**
	40	149	110	105	77
Nighttime	10	4,286	2,441	2,663	1,517
	20	642	366	444	253
	30	**219**	**125**	**153**	**87**
	40	94	54	66	38

[1]Assumes equal number of site-years for ICWS installation and comparison sites and equal length of before and after periods.
Boldface indicates the sample size values recommended in this study.

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

Case 2 considers the data collected for both the before and after periods. The total site-years of data available for two-lane major roadways was 360 for the before period and 255 for the after period. The total site-years of data available for multilane major roadways was 126 for the before period and 100 for the after period. The statistical accuracy attainable for a given sample size is described by the standard deviations of the estimated percent change in safety. From this, *P*-values were estimated for various sample sizes and expected changes in safety for a given crash history. A set of such calculations is shown in table 4 and table 5. The calculations are based on the methodology in Hauer.[13]

For the available data, the minimum percentage change in crash frequency that could be statistically detected at 90- and 95-percent significance levels were estimated using the same crash rates in table 2. The results indicate that the data should be able to detect the anticipated crash reduction effects highlighted in table 3 (i.e., 20-percent reductions for all crash types except for rear-end and nighttime crashes for both two-lane and multilane roadways), if such an effect were present. Using these results, a decision was made to proceed with the evaluation using the data available at the time.

Table 4. Sample analysis for crash effects (two-lane intersections).

Crash Type	Intersection-Years in Before Period	Intersection-Years in After Period	Minimum Percent Reduction Detectable for Crash Rate Assumption[1]	
			***P* = 0.10**	***P* = 0.05**
Total	360	255	10	15
Fatal and injury			15	15
Right-angle			15	15
Rear-end			30	30
Nighttime			25	25

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

Table 5. Sample analysis for crash effects (multilane intersections).

Crash Type	Intersection-Years in Before Period	Intersection-Years in After Period	Minimum Percent Reduction Detectable for Crash Rate Assumption[1]	
			***P* = 0.10**	***P* = 0.05**
Total	126	100	15	15
Fatal and injury			20	20
Right-angle			15	20
Rear-end			35	40
Nighttime			30	30

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

CHAPTER 4. METHODOLOGY

The EB methodology for observational before–after studies was used for the evaluation. This methodology was considered rigorous in that it accounted for RTM using a reference group of similar sites without ICWS installation. In the process, SPFs were used for the following reasons:

- They overcome the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- They account for time trends.
- They reduce the level of uncertainty in the estimates of safety effect.
- They 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 developing guidelines for estimating the likely safety consequences of a contemplated strategy.

In the EB approach, the change in safety (Δ) for a given crash type at a site is given by figure 2.

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

Figure 2. Equation. Estimated change in safety.

Where:

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

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

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

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

Figure 3. Equation. Empirical Bayes estimate of expected crashes.

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

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

Figure 4. Equation. Empirical Bayes weight.

Where:

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

A factor 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 was the sum of the annual SPF predictions for the after period divided by *P*, the sum of these predictions for the before period. The result, after applying this factor, was an estimate of λ. The procedure also produced an estimate of the variance of λ.

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

The index of effectiveness (θ) is estimated in figure 5.

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

Figure 5. Equation. Index of effectiveness.

The standard deviation of θ is given in figure 6.

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

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

The percent change in crashes was 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

Minnesota, Missouri, and North Carolina provided data containing locations and dates of ICWS installations. Each State also identified approximately 30 reference sites for four-legged intersections with two lanes on the major route and 30 reference sites for four-legged intersections with four lanes on the major route. These States also provided roadway geometry, traffic volumes, and crash data for both installation and reference sites. Additional details about the design, installation, and maintenance of ICWSs, as well as lessons learned, can be found in appendix B.

MINNESOTA

Installation Data

The Minnesota Department of Transportation (MnDOT) provided a list of intersections where ICWSs had been installed, along with information about whether the installations were on the major and/or minor routes. In addition, the list provided by MnDOT included information about the specific messages shown on each of the signs or whether the ICWS consisted of a visual display. The final list of installation sites comprised 10 two-lane at two-lane intersections and 3 four-lane at two-lane intersections (13 total installation sites). All Minnesota installation sites were post mounted, and all sites had a warning sign on the minor roadway approach. Six of the two-lane at two-lane intersections also had an installation on the major approaches of the intersections. The four-lane at two-lane intersections had visual displays for minor route approaches. All two-lane at two-lane installations specified "WHEN FLASHING" on the messages provided on the warning signs. Twenty more installation sites were identified by MnDOT, but these were still in the process of being installed and thus could not be used in this study.

Reference Sites

Reference sites were provided by MnDOT separately for two-lane at two-lane intersections and for four-lane at two-lane intersections. Data were provided for 28 two-lane at two-lane intersections and 35 four-lane at two-lane intersections. Intersections were identified that were in close proximity to the installation sites, preferably along the same major route as installation sites. Sites were selected if they had similar traffic and geometric characteristics to installation sites. Selecting sites in close proximity reduced the effects of differences in driver population and spatial factors, such as weather or terrain.

Roadway Data

MnDOT provided roadway data for the installation and reference sites. Various roadway characteristics were coded by the project team from the records provided, and from Google Earth™, including the following:

- Number of lanes on the major route approaches.
- Presence of right- and left-turn lanes on the major and minor approaches.
- Intersection angle.

- Median presence.
- Median width.
- Presence of channelization on the minor approaches.
- Presence of intersection lighting.
- Presence of overhead flashers.
- Posted speed limit.
- Presence of multiple STOP signs.
- Presence of advance intersection warning sign.
- Presence of STOP AHEAD warning sign.

Traffic Data

MnDOT also provided traffic volume data for the installation and reference sites. Traffic data were typically available for State highways every 2 to 3 years. County highway data were provided for every 4 to 5 years. The years of average annual daily traffic (AADT) counts were provided for each value of AADT. The counts covered both the before and after periods for installation and reference sites. For years with missing data, linear interpolation of AADT counts were used, or an extrapolation was used if the after period counts did not cover the latest year. If no apparent trend was observed in the AADT data, the extrapolated value was defined as the same as the previous year's AADT value.

Crash Data

MnDOT provided crash data for installation and reference intersections from 2006 to 2012. Because crash data were provided separately for each intersection, no linking was necessary, but the data had to be manually coded for each intersection.

ICWS Cost Data

MnDOT provided cost estimates of the installations for use in conducting a B/C analysis of the ICWS strategy. Table 6 provides itemized cost data for post-mounted signs for two-lane at two lane intersections and four-lane at two-lane intersections. The project team noted that intersection warning systems included static signs on the major road, blank-out signs on the minor road, micro-loops on the major road, loops or micro-loops on the minor road, controller cabinets, and onsite contractor warranty, which included a 72-h response to address any system malfunction. Maintenance and operations costs were not provided, nor was an estimate of lifespan.

Table 6. Minnesota installation cost data.

Countermeasure	Mobilization	Engineering	Construction	Design Build Oversight
Post-mounted on all approaches for two-lane major approach	~ $5,000	$11,807	$75,650	$17,000
Post-mounted on all approaches for four-lane major approach	~ $5,000	$13,130	$103,833	$17,000

MISSOURI

Installation Data

MoDOT provided a list of projects where ICWSs had been installed, along with information about whether the installations were on the major and/or minor routes. In addition, MoDOT provided details on how the ICWS signs were activated, the mounting type, the specific message on each sign, any additional signs/countermeasures, and any additional improvements made at the site during the analysis years. The final list of sites consisted of 6 two-lane at two-lane intersections and 8 four-lane at two-lane intersections (14 total installation sites). All Missouri installation sites were post mounted. Five of the six two-lane at two-lane intersections had ICWSs on the minor approaches. Two of the six had ICWSs on the major approaches. Five of eight four-lane at two-lane intersections had an ICWS on the minor approaches, and four had an ICWS on the major approaches. Two-lane at two-lane sites with an ICWS on the minor approaches had "WHEN FLASHING" plaques, while only one four-lane at two-lane site had the plaque.

Reference Sites

Reference sites were provided by MoDOT separately for two-lane at two-lane intersections and for four-lane at two-lane intersections. Data were provided for 35 two-lane at two-lane intersections and 28 four-lane at two-lane intersections. Intersections were identified that were in close proximity to the installation sites, preferably along the same major route. Sites were selected if they had similar traffic and geometric characteristics to installation sites. Selecting sites in close proximity reduced the effects of differences in driver population and spatial factors, such as weather or terrain.

Roadway Data

MoDOT provided roadway data for the installation and reference sites. Various roadway characteristics were coded by the project team from the records provided, and from Google Earth™, including the following:

- Number of lanes on the major route approaches.
- Presence of right- and left-turn lanes on the major and minor approaches.
- Intersection angle.
- Median presence.
- Median width.
- Presence of channelization on the minor approaches.
- Presence of intersection lighting.
- Presence of overhead flashers.
- Posted speed limit.
- Presence of multiple STOP signs.
- Presence of advance intersection warning sign.
- Presence of STOP AHEAD warning sign.

Traffic Data

MoDOT also provided traffic volume data for the installation and reference sites. Traffic data were typically available for State highways every 2 to 3 years. County highway data were provided for every 4 to 5 years. The years of AADT counts were provided for each value of AADT. The counts covered both the before and after periods for installation and reference sites. For years with missing data, linear interpolation of AADT counts were used, or an extrapolation was used if the after period counts did not cover the latest year. If no apparent trend was observed in the AADT data, the extrapolated value was defined as the same as the previous year's AADT value.

Crash Data

MoDOT provided crash data for the installation and reference intersections from 2000 to 2012. The crash data were linked to each intersection using the intersection identifier.

ICWS Cost Data

MoDOT provided estimates of the costs and services lives of the installations for use in conducting a B/C analysis of the ICWS strategy. Table 7 provides the approximate cost and lifespan for a post-mounted ICWS on the major approaches as reported by MoDOT. In addition, maintenance costs were noted to vary substantially. Annual maintenance costs for mainline warning systems with loops on the minor routes were estimated to be $800 per year. For intersections with mainline detection using probes or microwave and wireless communication, the estimated annual maintenance was $3,000 per intersection. Ignoring the cost of intersection lighting, utility costs were estimated to average $275 for mainline flashers and $400 for side-street flashers.

Table 7. Missouri installation cost and service life data.

Intersection Type	Installation Type	Cost	Lifespan
Two-lane at two-lane intersection	Post-mounted ICWS on major approach	$25,000 to $33,500	10 years minimum
Four-lane at two-lane intersection	Post-mounted ICWS on minor approaches	~ $75,000	10 years minimum

NORTH CAROLINA

Installation Data

NCDOT provided a list of intersections where an ICWS had been installed, along with information about whether the installations were on the major and/or minor routes. In addition, the list provided by NCDOT included information about the specific messages shown on each of the signs, the project improvement description, statement of existing physical conditions, statement of problem, additional countermeasures, sign size details, detector types, detector locations, and detector timings. The final list of installation sites consisted of 53 two-lane at two-lane intersections and 13 four-lane at two-lane intersections (66 total installation sites). All four-lane at two-lane installations were on major approaches, and nine had post-mounted ICWS signs. Four of the sites had overhead ICWS signs, and nine sites specifically stated "WHEN FLASHING." Thirty-eight two-lane at two-lane sites had ICWS signs on the major approaches, and 23 had ICWS signs on the minor approaches. Post-mounted ICWS signs were present at 16 two-lane at two-lane sites, and 40 had overhead ICWS signs.

Reference Sites

Reference sites were provided by NCDOT separately for two-lane at two-lane intersections and for four-lane at two-lane intersections. Data were provided for 35 two-lane at two-lane intersections and 35 four-lane at two-lane intersections. These intersections were provided based on reference sites NCDOT had obtained for other projects, and all were used in this study.

Roadway Data

NCDOT provided roadway data for the installation and reference sites. Various roadway characteristics were coded by the project team from the records provided, and from Google Earth™, including the following:

- Number of lanes on the major route approaches.
- Presence of right- and left-turn lanes on the major and minor approaches.
- Intersection angle.
- Median presence.
- Median width.
- Presence of channelization on the minor approaches.
- Presence of intersection lighting.
- Presence of overhead flashers.
- Posted speed limit.
- Presence of multiple STOP signs.
- Presence of advance intersection warning sign.
- Presence of STOP AHEAD warning sign.

Traffic Data

NCDOT also provided traffic volume data for the installation and reference sites. Traffic data were available for State highways every 2 years. Because NCDOT is responsible for State and county roads, all roads are considered to be State maintained. The years of AADT counts were provided for each value of AADT. The counts covered both the before and after periods for installation and reference sites. For years with missing data, linear interpolation of AADT counts was used, or an extrapolation was used if the after period counts did not cover the latest year. If no apparent trend was observed in the AADT data, the extrapolated value was defined as the same as the previous year's AADT value.

Crash Data

NCDOT provided crash data for the installation and reference intersections from 1992 to 2012. The crash data were linked to each intersection using the intersection ID. All data were used for SPF development; however, a maximum of 5 years before and after were used for the analysis of installation sites.

ICWS Cost Data

NCDOT provided estimates of the costs and services lives of the installation for use in conducting a B/C analysis of the ICWS strategy. Total cost estimates were provided for each of the installations from 1996 to 2011. Owing to the difference in time for cost estimates, the cost estimates were normalized by consumer price index to develop an average cost based on 2014. Table 8 provides installation cost data for sites based on the type of ICWS and based on which approaches were installed. In addition, Table 8 contains information for annual maintenance cost, annual operations cost, and estimated lifespan for installations used by NCDOT for economic analysis.

North Carolina assumed an annual maintenance cost of $500 per year, an operations cost of $125 per year, and a lifespan of 10 years for installations. These values did not differ by installation type. The average installation cost of an overhead sign on a single approach was approximately $30,000, with a maximum value of approximately $50,000. The average installation cost of a post-mounted installation on the major approach only was approximately $20,000 for two-lane at two-lane intersections, with a maximum value of approximately $50,000. For four-lane at two-lane intersections, the average cost was $117,000, and the maximum cost was $142,500. For two-lane at two-lane intersections with overhead signs on all approaches, the average cost was approximately $50,000, and the maximum cost was $78,000.

Table 8. North Carolina installation cost and service life data.

Condition	Installation Cost			Annual Costs		Lifespan (years)
	Minimum	Mean	Maximum	Maintenance Cost	Operations Cost	
Overhead on minor only	$20,000	$29,500	$46,000	$500	$125	10
Overhead on major and minor	$20,000	$49,000	$78,000	$500	$125	10
Overhead on major only	$13,500	$28,000	$49,000	$500	$125	10
Post-mounted only two lane	$9,000	$21,600	$49,000	$500	$125	10
Post-mounted only four lane	$49,000	$117,000	$142,500	$500	$125	10

DATA CHARACTERISTICS AND SUMMARY

Table 9 defines the crash types used by each State. The project team attempted to make the crash type definitions consistent.

Table 9. Definitions of crash types.

Crash Type	State		
	Minnesota	**Missouri**	**North Carolina**
Total	Identified as all crashes, without exclusion	Identified as all crashes, without exclusion	Identified as all crashes, without exclusion
Fatal and injury	Resulted in a fatality, or A, B, or C injury	Resulted in fatal, disabling injury, or minor injury	Resulted in K, A, B, or C severity
Right-angle	Diagram is coded as 5—Right-angle	Accident class name is coded as right-angle	First harmful event is angle
Rear-end	Diagram is coded as 1—Rear-end	Accident class name is coded as rear-end	First harmful event is rear-end
Nighttime	Lighting condition is coded as sunrise, sunset, or any value of dark	Lighting condition is coded as any value of dark	Lighting condition is coded as dusk, dawn, or any value of dark

Table 10 summarizes information for the data collected for the installation sites. The information in table 10 should not be used to make simple before–after comparisons of crashes per site-year because it does not account for factors, other than the ICWS strategy, that may cause a change in safety between the before and after periods. Such comparisons are properly done with the EB analysis as presented later. Table 11 summarizes information for the reference site data.

Table 10. Data summary for installation sites.

Variable	Two-Lane Sites			Four-Lane Sites		
	Minnesota	Missouri	North Carolina	Minnesota	Missouri	North Carolina
Number of sites	10	6	53	3	8	13
Site-years before	43	44	263	14	52	60
Site-years after	16	28	211	4	41	55
Total crashes before[1]	1.54	1.93	3.82	5.93	3.71	4.32
Total crashes after[1]	1.25	1.32	2.91	4.00	2.90	4.55
Fatal and injury crashes before[1]	0.74	0.89	2.23	3.79	1.96	2.87
Fatal and injury crashes after[1]	0.38	0.64	1.60	2.25	1.15	2.84
Right-angle crashes before[1]	0.70	1.09	2.43	3.57	2.08	3.15
Right-angle crashes after[1]	0.81	0.71	1.83	2.25	1.49	3.31
Rear-end crashes before[1]	0.21	0.16	0.30	0.50	0.52	0.22
Rear-end crashes after[1]	0.00	0.14	0.18	0.25	0.39	0.29
Nighttime crashes before[1]	0.21	0.30	0.49	1.07	0.89	0.58
Nighttime crashes after[1]	0.19	0.11	0.52	0.50	0.68	0.42
Major AADT before	Avg 2,374 Min 810 Max 6,300	Avg 2,547 Min 1,420 Max 4,846	Avg 4,076 Min 299 Max 11,450	Avg 11,293 Min 6,400 Max 17,800	Avg 14,773 Min 9,104 Max 37,504	Avg 9,193 Min 1,323 Max 27,635
Major AADT after	Avg 2,345 Min 900 Max 6,500	Avg 2,334 Min 973 Max 5,123	Avg 4,041 Min 830 Max 10,000	Avg 13,225 Min 7,300 Max 18,600	Avg 16,530 Min 9,285 Max 33,685	Avg 10,868 Min 1,934 Max 30,500
Minor AADT before	Avg 1,257 Min 600 Max 3,250	Avg 618 Min 196 Max 1,846	Avg 1,776 Min 420 Max 4,100	Avg 1,934 Min 1,200 Max 3,350	Avg 957 Min 269 Max 3,000	Avg 2,044 Min 568 Max 5,500
Minor AADT after	Avg 1,512 Min 550 Max 3,700	Avg 723 Min 243 Max 1,431	Avg 1,906 Min 370 Max 4,300	Avg 1,700 Min 1,250 Max 2,950	Avg 965 Min 404 Max 2,742	Avg 2,268 Min 890 Max 5,700

[1]Crash rates are presented as crashes/site/year.
Avg = Average.
Min = Minimum.
Max = Maximum.

Table 11. Data summary for reference sites.

Variable	Two-Lane Sites			Multilane Sites		
	Minnesota	Missouri	North Carolina	Minnesota	Missouri	North Carolina
Number of sites	28	35	35	35	28	35
Site-years	196	455	672	245	364	630
Total crashes[1]	1.34	0.90	1.36	1.49	2.35	1.91
Fatal and injury crashes[1]	0.67	0.33	0.71	0.70	0.96	1.02
Right-angle crashes[1]	0.62	0.35	0.53	0.76	1.02	0.88
Rear-end crashes[1]	0.26	0.20	0.31	0.18	0.31	0.32
Nighttime crashes[1]	0.41	0.17	0.26	0.35	0.54	0.42
Major AADT	Avg 6,286 Min 2,033 Max 12,200	Avg 2,432 Min 79 Max 6,895	Avg 5,462 Min 720 Max 17,000	Avg 10,119 Min 3,250 Max 21,000	Avg 6,687 Min 3,169 Max 12,770	Avg 12,111 Min 3,541 Max 28,000
Minor AADT	Avg 1,462 Min 390 Max 4,400	Avg 330 Min 18 Max 1,176	Avg 1,095 Min 235 Max 5,300	Avg 1,337 Min 310 Max 4,400	Avg 493 Min 106 Max 1,455	Avg 1,049 Min 100 Max 5,600

[1]Crash rates are presented as crashes/site/year.
Avg = Average.
Min = Minimum.
Max = Maximum.

CHAPTER 6. DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

This chapter presents the SPFs developed for each State, which are subsequently used in the EB methodology.(13) Generalized linear modeling was used to estimate model coefficients assuming a negative binomial error distribution, which was consistent with the state of research in developing these models. In specifying a negative binomial error structure, the overdispersion parameter, k, was estimated iteratively from the model and the data. For a given dataset, smaller values of k indicated relatively better models.

SPFs were calibrated separately for intersections with two-lane and multilane major routes for Minnesota, Missouri, and North Carolina using the corresponding reference sites from each State. The SPFs developed are presented by State in the following sections.

The form of the SPFs for all States is given in figure 7.

$$\frac{crashes}{year} = exp^{a} \times TotalEntering^{b} \times exp^{(characteristic \times c + \ldots + characteristic \times t)}$$

Figure 7. Equation. SPF model form for all States.

Where:

TotalEntering = Total entering volume (major route AADT + minor route AADT).
characteristic = Intersection characteristics included in SPF, defined by associated estimated parameters c through s.

The following definitions were used for all States for parameters with intersection characteristics:

c = Proportion of total entering volume from minor approach.
d = Presence of flashers on the minor route approaches.
e = Presence of flashers on the major route approaches.
f = Number of major route left-turn lanes.
g = Number of minor route left-turn lanes.
h = Number of major route right-turn lanes.
i = Number of minor route right-turn lanes.
j = Advance intersection warning sign on major route approaches.
l = Posted speed limit on major route.
m = Presence of lighting at intersection.
n = Advance STOP AHEAD warning sign on minor route approaches.
o = Intersection angle.
p = Presence of channelization on minor route approaches.
q = Presence of dual stop signs on the minor route approaches.
r = Median width on major route.
s = Posted speed limit on minor route.
t = Presence of a median on major route.

In addition, the following parameter was provided for each SPF:

k = Overdispersion parameter of the model.

MINNESOTA SAFETY PERFORMANCE FUNCTIONS

The SPFs for two-lane at two-lane intersections are provided in table 12, and the SPFs for four-lane at two-lane intersections are provided in table 13.

Table 12. Minnesota two-lane at two-lane intersection SPFs.

Crash Type	Parameter Estimates (Standard Error)													
	a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*l*	*m*	*n*	*k*
Total	-7.913 (1.314)	0.866 (0.143)	2.976 (0.569)	-0.527 (0.195)	—	—	—	—	—	—	—	—	—	0.258
Fatal and injury	-5.791 (1.786)	0.557 (0.195)	2.611 (0.779)	-0.841 (0.337)	—	—	0.473 (0.266)	—	—	—	—	—	—	0.424
Right-angle	-14.557 (4.266)	0.825 (0.272)	2.010 (1.129)	-0.856 (0.412)	—	-0.364 (0.174)	0.620 (0.313)	—	—	0.742 (0.420)	0.115 (0.053)	0.551 (0.328)	—	0.433
Rear-end	-20.508 (4.817)	2.259 (0.583)	3.350 (1.709)	-0.932 (0.495)	1.024 (0.511)	—	—	-0.833 (0.391)	0.379 (0.215)	—	—	-0.837 (0.456)	—	0.562
Nighttime	-12.177 (3.036)	1.251 (0.335)	2.588 (1.361)	—	—	—	—	—	—	—	—	-0.769 (0.346)	—	0.254

— Indicates not applicable.

Table 13. Minnesota four-lane at two-lane intersection SPFs.

Crash Type	Parameter Estimates (Standard Error)									
	a	*b*	*c*	*e*	*j*	*n*	*o*	*p*	*q*	*k*
Total	-8.481 (1.581)	1.198 (0.151)	4.121 (0.839)	0.966 (0.237)	-0.337 (0.190)	-0.394 (0.144)	-0.032 (0.005)	-0.417 (0.191)	0.712 (0.192)	0.056
Fatal and injury	-5.123 (1.808)	0.772 (0.180)	2.391 (0.985)	1.144 (0.260)	-1.038 (0.300)	—	-0.034 (0.007)	—	0.787 (0.228)	0.012
Right-angle	-9.030 (2.105)	1.227 (0.203)	2.914 (1.160)	1.051 (0.276)	-0.763 (0.258)	—	-0.039 (0.007)	-0.505 (0.261)	0.605 (0.255)	0.070
Rear-end	-7.843 (3.385)	0.730 (0.363)	—	—	—	-0.717 (0.386)	—	—	—	1.611
Nighttime	-10.665 (2.672)	1.202 (0.262)	5.010 (1.458)	1.357 (0.408)	—	-0.816 (0.261)	-0.021 (0.009)	—	—	4e-7

— Indicates not applicable.

MISSOURI SAFETY PERFORMANCE FUNCTIONS

The SPFs for two-lane at two-lane intersections are provided in table 14, and the SPFs for four-lane at two-lane intersections are provided in table 15.

Table 14. Missouri two-lane at two-lane intersection SPFs.

Crash Type	Parameter Estimates (Standard Error)													
	a	***b***	***c***	***e***	***f***	***h***	***i***	***j***	***m***	***n***	***o***	***p***	***q***	***s***	***k***
Total	-8.314 (1.252)	0.700 (0.130)	2.912 (0.593)	—	—	0.788 (0.298)	0.187 (0.091)	0.298 (0.141)	0.601 (0.157)	—	0.023 (0.009)	—	-0.683 (0.409)	—	0.294
Fatal and injury	-14.938 (2.243)	1.166 (0.193)	5.192 (0.726)	—	—	—	—	—	0.701 (0.207)	—	0.044 (0.013)	—	—	—	0.368
Right-angle	-19.026 (2.821)	1.454 (0.241)	6.575 (0.921)	-1.531 (0.556)	0.518 (0.205)	--	0.986 (0.315)	0.372 (0.218)	0.812 (0.235)	—	0.045 (0.016)	-2.147 (0.655)	-1.007 (0.429)	0.032 (0.012)	0.363
Rear-end	-12.296 (2.431)	1.258 (0.300)	—	—	—	1.928 (0.356)	—	0.824 (0.324)	—	-0.931 (0.313)	—	0.916 (0.257)	—	—	0.650
Nighttime	-11.085 (2.625)	0.639 (0.246)	2.786 (1.022)	—	-0.321 (0.192)	1.064 (0.504)	—	—	0.841 (0.280)	—	0.043 (0.021)	—	—	—	2e-7

— Indicates not applicable.

Table 15. Missouri four-lane at two-lane intersection SPFs.

Crash Type	Parameter Estimates (Standard Error)													
	a	***b***	***c***	***d***	***e***	***f***	***h***	***j***	***l***	***n***	***o***	***p***	***r***	***s***	***k***
Total	-2.179 (1.355)	0.871 (0.118)	10.185 (1.824)	—	-0.462 (0.199)	0.455 (0.117)	0.246 (0.077)	0.925 (0.163)	-0.057 (0.011)	0.286 (0.138)	-0.034 (0.007)	0.319 (0.098)	-0.005 (0.003)	—	0.268
Fatal and injury	-1.058 (1.675)	0.729 (0.124)	5.733 (2.031)	—	—	0.361 (0.151)	—	0.890 (0.156)	-0.037 (0.010)	—	-0.056 (0.008)	0.288 (0.121)	-0.007 (0.003)	0.017 (0.007)	0.123
Right-angle	-3.586 (1.427)	0.502 (0.146)	13.626 (2.097)	0.804 (0.207)	—	—	—	1.319 (0.211)	—	0.429 (0.164)	-0.037 (0.008)	0.581 (0.136)	—	0.016 (0.006)	0.368
Rear-end	-9.471 (2.289)	1.738 (0.294)	8.643 (3.508)	—	-1.607 (0.428)	—	0.419 (0.166)	1.181 (0.321)	-0.155 (0.023)	1.064 (0.297)	—	—	—	0.027 (0.014)	0.549
Nighttime	-12.962 (1.738)	1.381 (0.188)	5.658 (2.807)	—	-0.532 (0.254)	—	—	0.727 (0.212)	—	—	—	—	-0.009 (0.004)	—	0.360

— Indicates not applicable.

NORTH CAROLINA SAFETY PERFORMANCE FUNCTIONS

The SPFs for two-lane at two-lane intersections are provided in table 16, and the SPFs for four-lane at two-lane intersections are provided in table 17.

Table 16. North Carolina two-lane at two-lane intersection SPFs.

Crash Type	Parameter Estimates (Standard Error)										
	a	***b***	***c***	***g***	***h***	***i***	***l***	***o***	***q***	***s***	***k***
Total	-5.148 (0.578)	0.683 (0.054)	1.977 (0.223)	0.131 (0.074)	—	—	-0.012 (0.005)	-0.008 (0.002)	—	—	0.213
Fatal and injury	-6.098 (0.676)	0.656 (0.067)	1.725 (0.284)	—	—	0.139 (0.080)	—	—	0.211 (0.061)	-0.009 (0.005)	0.262
Right-angle	-5.567 (0.675)	0.577 (0.071)	2.233 (0.302)	—	—	0.201 (0.084)	—	-0.009 (0.003)	0.290 (0.066)	—	0.350
Rear-end	-10.130 (1.527)	1.331 (0.151)	—	—	—	-0.861 (0.269)	-0.039 (0.012)	-0.010 (0.005)	—	—	0.741
Nighttime	-8.312 (1.219)	0.669 (0.116)	2.379 (0.437)	—	-0.296 (0.112)	—	—	-0.007 (0.004)	—	0.028 (0.008)	0.214

— Indicates not applicable.

Table 17. North Carolina four-lane at two-lane intersection SPFs.

Crash Type	Parameter Estimates (Standard Error)												
	a	***b***	***c***	***f***	***h***	***i***	***l***	***o***	***p***	***q***	***r***	***t***	***k***
Total	-4.414 (1.083)	0.642 (0.093)	3.742 (0.451)	—	—	—	-0.037 (0.012)	—	0.306 (0.142)	0.301 (0.124)	—	—	0.258
Fatal and injury	-5.128 (1.072)	0.472 (0.109)	3.838 (0.537)	-0.254 (0.132)	-0.158 (0.071)	0.114 (0.056)	—	—	0.345 (0.189)	0.760 (0.187)	—	—	0.291
Right-angle	-2.584 (1.232)	0.217 (0.123)	3.791 (0.625)	—	—	0.319 (0.058)	—	—	—	0.642 (0.168)	—	-0.697 (0.286)	0.495
Rear-end	-12.819 (2.966)	0.562 (0.228)	2.553 (0.946)	—	—	0.417 (0.098)	0.074 (0.040)	0.032 (0.008)	—	—	-0.014 (0.005)	—	1.005
Nighttime	-8.531 (1.727)	0.803 (0.173)	2.315 (0.750)	—	—	—	—	—	—	0.314 (0.209)	-0.009 (0.005)	—	0.399

— Indicates not applicable.

CHAPTER 7. BEFORE–AFTER EVALUATION RESULTS

AGGREGATE ANALYSIS

Table 18 through table 21 provide the estimates of expected crashes in the after period without installation, the observed crashes in the after period, and the estimated CMF and its standard error for all crash types considered. Results are provided separately for each State as well as for all States combined. Results are provided separately for individual States because the application practices varied for all three. Minnesota used a variety of post-mounted signs, including static signs with flashers, blank-out signs with flashers, visual displays, and signs with LED arrows indicating the direction of conflicting vehicles. Missouri used post-mounted static signs with flashers exclusively. North Carolina used static signs that were a mix of post mounted and overhead where the overhead signs were installed at the intersection. The results were combined to further draw inferences on the overall effect of ICWSs.

The results for Minnesota in table 18 were inconsistent across crash types and by number of through lanes on the major route. Statistically significant reductions at the 95-percent confidence level were found for fatal and injury crashes for two-lane at two-lane intersections only. However, the sample sizes were quite small, so readers should use caution when attempting to draw meaningful conclusions from the results.

Table 18. Aggregate analysis results for Minnesota.

Statistic	Total	Fatal and Injury	Right-Angle	Rear-End	Nighttime
Two-Lane at Two-Lane					
EB estimate of crashes expected in the after period without strategy	23.00	11.13	6.49	7.62	2.89
Count of crashes observed in the after period	20	6	13	0	3
Estimate of CMF	0.856	**0.525**	1.945	0.000	1.003
Standard error of estimate of CMF	0.216	0.225	0.618	N/A	0.588
Four-Lane at Two-Lane					
EB estimate of crashes expected in the after period without strategy	21.50	8.27	13.80	1.09	1.99
Count of crashes observed in the after period	16	9	9	1	2
Estimate of CMF	0.737	1.052	0.642	0.811	1.003
Standard error of estimate of CMF	0.196	0.388	0.225	0.764	0.710

Statistically significant results at the 95-percent confidence level are indicated in boldface.

The results for Missouri in table 19 indicate reductions for nearly all crash types for both two-lane at two-lane intersections and four-lane at two-lane intersections. No statistically significant results were found for two-lane at two-lane intersections because of small sample sizes; however, significant reductions were found for four-lane at two-lane intersections. Reductions were found for total crashes, fatal and injury crashes, and nighttime crashes that were significant at the 95-percent confidence level.

Table 19. Aggregate analysis results for Missouri.

Statistic	Total	Fatal and Injury	Right-Angle	Rear-End	Nighttime
Two-Lane at Two-Lane					
EB estimate of crashes expected in the after period without strategy	47.08	16.18	25.42	5.74	3.71
Count of crashes observed in the after period	37	18	20	4	3
Estimate of CMF	0.777	1.088	0.771	0.642	0.810
Standard error of estimate of CMF	0.151	0.298	0.200	0.343	0.467
Four-Lane at Two-Lane					
EB estimate of crashes expected in the after period without strategy	164.26	84.06	75.42	19.51	46.00
Count of crashes observed in the after period	119	47	61	16	28
Estimate of CMF	**0.719**	**0.554**	0.799	0.778	**0.594**
Standard error of estimate of CMF	0.089	0.096	0.134	0.252	0.143

Statistically significant results at the 95 percent confidence level are indicated in boldface.

The results for North Carolina in table 20 indicate statistically significant reductions at the 95-percent confidence level for all crash types except nighttime crashes for two-lane at two-lane intersections. A statistically significant reduction at the 95-percent confidence level was found for nighttime crashes for four-lane at two-lane intersections; however, insignificant decreases were found for total crashes, fatal and injury crashes, and right-angle crashes. These findings are explored further in the Disaggregate Analysis section of this chapter.

Table 20. Aggregate analysis results for North Carolina.

Statistic	Total	Fatal and Injury	Right-Angle	Rear-End	Nighttime
Two-Lane at Two-Lane					
EB estimate of crashes expected in the after period without strategy	842.71	488.25	490.26	87.10	122.25
Count of crashes observed in the after period	613	338	387	39	110
Estimate of CMF	**0.727**	**0.691**	**0.788**	**0.444**	0.897
Standard error of estimate of CMF	0.037	0.046	0.050	0.081	0.099
Four-Lane at Two-Lane					
EB estimate of crashes expected in the after period without strategy	278.74	163.86	206.25	12.47	37.52
Count of crashes observed in the after period	250	156	182	16	23
Estimate of CMF	0.893	0.947	0.877	1.224	**0.595**
Standard error of estimate of CMF	0.081	0.104	0.094	0.388	0.157

Statistically significant results at the 95-percent confidence level are indicated in boldface.

The combined results in table 21 indicate reductions for all crash types analyzed for both two-lane at two-lane and four-lane at two-lane intersections. The reductions were statistically significant at the 95-percent confidence level for all crash types except nighttime crashes for two-lane at two-lane intersections. The reductions were statistically significant at the 95-percent confidence level for all crash types except for rear-end crashes for four-lane at two-lane intersections.

Table 21. Aggregate analysis results for combined States.

Statistic	Total	Fatal and Injury	Right-Angle	Rear-End	Nighttime
Two-Lane at Two-Lane					
EB estimate of crashes expected in the after period without strategy	912.79	515.56	522.17	100.46	128.84
Count of crashes observed in the after period	670	362	420	43	116
Estimate of CMF	**0.733**	**0.701**	**0.803**	**0.425**	0.898
Standard error of estimate of CMF	0.035	0.045	0.049	0.073	0.096
Four-Lane at Two-Lane					
EB estimate of crashes expected in the after period without strategy	464.50	263.56	295.47	33.07	85.52
Count of crashes observed in the after period	385	212	252	33	53
Estimate of CMF	**0.827**	**0.802**	**0.850**	0.973	**0.612**
Standard error of estimate of CMF	0.059	0.072	0.075	0.224	0.108

Statistically significant results at the 95-percent confidence level are indicated in boldface.

For two-lane at two-lane intersections, the crash type with the smallest CMF (which translates to the greatest reduction) was rear-end with a CMF of 0.425, which was statistically significant at the 95-percent confidence level. Total, fatal and injury, and right-angle crashes had estimated CMFs of 0.733, 0.701, and 0.803, respectively, which were also statistically significant at the 95-percent confidence level. Nighttime crashes had an estimated CMF of 0.898, which was not statistically significant at the 95-percent confidence level. It is important to consider the sample size used to develop each CMF when interpreting the results. For example, the sample sizes used to develop CMFs for rear-end and nighttime crashes were relatively low, resulting in larger standard errors and confidence intervals compared with the CMFs for total, fatal and injury, and right-angle crashes.

For four-lane at two-lane intersections, the crash type with the smallest CMF (which was statistically significant at the 95-percent confidence level) was nighttime crashes, with a CMF of 0.612. Total, fatal and injury, and right-angle crashes had estimated CMFs of 0.827, 0.802, and 0.850, respectively, which were also statistically significant at the 95-percent confidence level.

Rear-end crashes had an estimated CMF of 0.973, which was not statistically significant at the 95-percent confidence level.

As discussed in the literature review, the most comprehensive study to date of ICWS applications was conducted by Simpson and Troy using data from North Carolina.[1] This report includes recommended CMFs for two-lane at two-lane intersection but does not provide recommended CMFs for four-lane at two-lane intersections because the small sample size precluded a rigorous analysis. Simpson and Troy recommended a CMF of 0.897 for total crashes and 0.878 for injury crashes at two-lane at two-lane intersections.[1] Greater crash benefits were indicated in the present study, which were attributed to the following characteristics of the present study:

- Included only four-legged intersections.
- Limited the number of study years to no more than 5 years before and 5 years after installation.
- Used SPFs to account for changes in traffic volumes.
- Used annual multipliers to account for trends at reference sites.
- Used a multistate database.

DISAGGREGATE ANALYSIS

The disaggregate analysis sought to identify those conditions under which the ICWS strategy was most effective. Because total, fatal and injury, and right-angle crashes were the focus of this strategy, these crash types were the focus of the disaggregate analysis. Several variables were identified as being of interest and available for all three States, including installation category, message, presence of turn lanes, presence of lighting, presence of additional countermeasures, major and minor route AADT, major and minor route posted speed limit, and expected crash frequency in the before period.

For installation category, the categories developed by NCDOT were expanded for use in this study. Categories for further analysis were as follows:

- Category 1—Overhead signs and flashers at the intersection on major; loop on minor.
- Category 2—Overhead signs and flashers at the intersection on minor; loop on major.
- Category 3a—Post-mounted signs and flashers in advance of the intersection on major; loop on minor.
- Category 3b—Post-mounted signs and flashers at the intersection on minor; loop on major.
- Category 4—Locations with a combination of category 1 through category 3.

For two-lane at two-lane intersections, all categories were considered in the disaggregate analysis. For four-lane at two-lane intersections, categories 3a and 3b were included in the disaggregate analysis. Category 1 and category 2 systems were found only in North Carolina, and these systems were installed at the intersection on both the major and minor road. Category 3a signs were found only in Missouri and North Carolina and were installed in advance of the intersection. Category 3b systems were found only in Minnesota and Missouri and were installed at the intersection.

Table 22 provides the disaggregate results by category for two-lane at two-lane intersections and four-lane at two-lane intersections. The number of intersections is indicated for each installation category. For each crash type, the estimated CMF, standard error (in parentheses), and sample size in terms of observed crashes in the after period is provided. It is important to consider the sample size used to develop the CMFs when applying the CMFs.

For two-lane at two-lane intersections, results indicate statistically significant reductions at the 95-percent confidence level for all crash types for category 1, 3a, and 4 systems. Considering the standard errors of the CMFs, it was difficult to draw a conclusion about the relative effectiveness of categories 1, 3a, and 4; with the exception of the CMFs for right-angle crashes, the results were not statistically different at the 95-percent confidence level. The majority of the category 4 sites consisted of a combination of categories 1 and 2 or a combination of categories 3a and 3b.

For four-lane at two-lane intersections, the results indicate statistically significant reductions at the 95-percent confidence level for all crash types for category 3a and for total crashes only for category 3b systems. The CMFs for categories 3a and 3b were not significantly different for any crash type.

Table 22. CMFs by installation category.

Crash Type	Installation Category				
	1	2	3a	3b	4
Two-Lane at Two-Lane					
No. of sites (N)	16	15	14	8	16
Total	**0.740** (0.070) 173	0.892 (0.075) 241	**0.519** (0.056) 120	0.886 (0.162) 42	**0.704** (0.087) 94
Fatal and injury	**0.600** (0.075) 91	0.944 (0.101) 144	**0.450** (0.069) 58	1.064 (0.287) 18	**0.742** (0.122) 51
Right-angle	**0.807** (0.096) 111	1.084 (0.110) 169	0.**454** (0.067) 61	1.247 (0.299) 25	**0.697** (0.113) 54
Four-Lane at Two-Lane					
No. of sites (N)	N/A	N/A	12	7	N/A
Total	N/A	N/A	**0.745** (0.068) 243	**0.690** (0.127) 35	N/A
Fatal and injury	N/A	N/A	**0.734** (0.083) 138	0.896 (0.210) 22	N/A
Right-angle	N/A	N/A	**0.769** (0.082) 174	0.763 (0.173) 23	N/A

Statistically significant results at the 95-percent confidence level are indicated in boldface.
In each cell containing results is the estimated CMF, standard error (in parentheses), and the sample size in terms of observed crashes in the after period.
N/A = Not applicable.

It was not appropriate to compare the effectiveness of overhead versus post-mounted applications on the major route from the study results because the placement of treatment differed for the two groups. Post-mounted ICWSs were installed in advance of the intersection, whereas all overhead signs were installed at the intersection. Ideally, to address the difference between post-mounted and overhead signs, the placement should be taken into consideration. The MUTCD states that warning signs should be placed to provide an adequate PRT. This suggests that the findings in table 22 may have been influenced by system placement, which could not be addressed in this research.[2]

Table 23 presents the disaggregate results for intersections by sign message. For two-lane at two-lane intersections, the ICWS strategy appeared to be slightly more effective when the message specifically stated "WHEN FLASHING," compared with signs that did not have the message. Considering the standard errors of the CMFs, there was no statistical difference between the two conditions. All systems in Minnesota located at two-lane at two-lane intersections had a "WHEN FLASHING" message and were therefore considered in this category. There was no apparent difference by message for four-lane at two-lane intersections.

Table 23. CMFs by message ("WHEN FLASHING" versus not present).

Lanes	Crash Type	Message	Expected	Observed	CMF	Standard Error
2	Total crashes	Present	656.20	458	**0.697**	0.040
		Not present	256.59	212	**0.824**	0.070
	Fatal and injury crashes	Present	373.70	242	**0.646**	0.050
		Not present	141.85	120	0.842	0.095
	Right-angle crashes	Present	364.80	275	**0.752**	0.056
		Not present	157.38	145	0.918	0.095

Statistically significant results at the 95-percent confidence level are indicated in boldface.

Table 24 presents the disaggregate results by the presence of intersection lighting. There was no apparent difference by lighting presence for two-lane at two-lane intersections. For four-lane at two-lane intersections, the strategy appeared to be more effective at sites with intersection lighting. The difference was statistically significant at the 95-percent confidence level for fatal and injury crashes.

Table 24. CMFs by lighting presence.

Lanes	Crash Type	Lighting	Expected	Observed	CMF	Standard Error
4	Total crashes	Present	169.49	119	**0.697**	0.085
		None	295.01	266	0.898	0.079
	Fatal and injury crashes	Present	87.27	48	**0.545**	0.093
		None	176.29	164	0.925	0.099
	Right-angle crashes	Present	78.89	62	0.777	0.127
		None	216.57	190	0.872	0.090

Statistically significant results at the 95-percent confidence level are indicated in boldface.

Table 25 presents the disaggregate results by expected crash frequency in the before period. There was no apparent difference by expected crash frequency for two-lane at two-lane intersections. For four-lane at two-lane intersections, the ICWS strategy was more effective when the expected crash frequency was higher in the before period. This is logical because the strategy was often used at intersections with unusually high crashes or issues related to limited sight distance. For total crashes, there did not appear to be a benefit if the expected crash frequency was less than or equal to three crashes per year before installation; however, there was a significant reduction for sites with more than three expected crashes per year in the before period. The results for right-angle crashes were significantly different from each other for sites with less than or equal to 2.5 expected crashes per year versus sites with more than 2.5 expected crashes per year before installation. There did not appear to be a benefit if the expected fatal and injury crash frequency was less than or equal to two crashes per year before installation; however, there was a significant reduction for sites with more than two expected fatal and injury crashes per year in the before period.

Table 25. CMFs by before period expected crash frequency.

Lanes	Crash Type	Crashes Per Year	Expected	Observed	CMF	Standard Error
4	Total crashes	≤ 3	114.23	121	1.047	0.147
		> 3	350.27	264	**0.751**	0.062
	Fatal and injury crashes	≤ 2	66.28	74	1.101	0.179
		> 2	197.28	138	**0.696**	0.075
	Right-angle crashes	≤ 2.5	93.32	116	1.228	0.176
		> 2.5	202.15	136	**0.669**	0.075

Statistically significant results at the 95-percent confidence level are indicated in boldface.

CHAPTER 8. ECONOMIC ANALYSIS

An economic analysis was conducted to estimate the B/C ratio for using the ICWS strategy for two-lane at two-lane intersections and four-lane at two-lane intersections. The statistically significant reduction in total crashes for combined States was used as the benefit for two-lane at two-lane intersections and for four-lane at two-lane intersections.

Based on details provided by NCDOT, the analysis used the average cost estimate for each installation type (e.g., overhead signs on both approaches) by major route number of approach lanes. Approximate costs provided by MoDOT were used for installations in Missouri. For sites in Minnesota, the cost estimates provided by MnDOT were used. The average installation cost for all two-lane at two-lane intersections was $41,590. The average installation cost was $106,150 for four-lane at two-lane intersections. In addition, an annual maintenance and operations cost of $1,075 was assumed for two-lane at two-lane intersections based on information provided by MoDOT. A value of $1,200 for maintenance and utility costs was assumed for four-lane at two-lane sites based on information provided by MoDOT for sites with loop detectors. A value of $3,400 was used for four-lane at two-lane sites with wireless communication. These values were more conservative than the estimated value of $625 used by NCDOT. In total, 69 two-lane at two-lane intersections and 24 four-lane at two-lane intersections were installed.

The analysis assumed that the useful service life for safety benefits was 10 years. This was based on information provided from Minnesota, Missouri, and North Carolina. This was likely conservative in that this was the minimum service life reported from the three States. MoDOT noted that loop detectors might need to be replaced every 5 years, and this cost was considered in the annual maintenance cost.

The FHWA Office of Safety Research and Development suggested using the Office of Management and Budget *Circular A-4: Regulatory Analysis* to determine the conservative real discount rate of 7 percent that was applied to calculate the annual cost of the treatment for the 10-year service life.(14) With this information, the capital recovery factor was computed to be 7.024 for all intersection types.

For the benefit calculations, the most recent FHWA mean comprehensive crash costs disaggregated by crash severity and location type were used as a base.(15) These costs were developed based on 2001 crash costs, and the unit cost (in 2001 dollars) for fatal and injury crashes was $158,177 and $7,428 for property damage only (PDO) crashes. This was updated to 2014 dollars by applying the ratio of the USDOT 2014 value of a statistical life of $9.2 million to the 2001 value of $3.8 million.(16,17) Applying this ratio of 2.42 to the unit costs for PDO and fatal and injury crashes and then weighting by the frequencies of these two crash types in the after period resulted in an aggregate 2014 unit cost for total crashes of $202,060 for two-lane at two-lane intersections and $219,876 for four-lane at two-lane intersections.

The total crash reduction was calculated by subtracting the actual crashes in the after period from the expected crashes in the after period if the ICWS strategy had not been implemented. The total crash reduction was then divided by the average number of after period years per site to compute the total crashes saved per year. The number of total crashes avoided per year was 65.69 for all two-lane at two-lane intersections and 19.08 for four-lane at two-lane intersections. Considering the number of intersections installed, this resulted in an average "savings" (avoidance) of 0.95 crashes per intersection per year for two-lane at two-lane intersections and 0.79 crashes per intersection per year for four-lane at two-lane intersections.

The annual benefits (i.e., dollar value of crash avoidance) were obtained by multiplying the crash reduction per site per year by the cost of a crash, with all severities combined. The B/C ratio was calculated as the ratio of the annual benefit to the annual cost. The B/C ratio was estimated to be 27:1 for two-lane at two-lane intersections and 10:1 for four-lane at two-lane intersections. USDOT recommended that sensitivity analysis be conducted by assuming values of a statistical life of 0.57 and 1.41 times the recommended 2014 value.(16) These factors can be applied directly to the estimated B/C ratios to obtain a range of 16:1 to 39:1 for two-lane at two-lane intersections and 6:1 to 14:1 for four-lane at two-lane intersections. These results suggest that the ICWS strategy, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective in reducing total crashes at four-legged intersections with stop-control on the minor approaches.

CHAPTER 9. SUMMARY AND CONCLUSIONS

The objective of this study was to undertake a rigorous before–after evaluation of the safety effectiveness of ICWS as measured by crash frequency. The study used data from three States, Minnesota, Missouri, and North Carolina, to examine the effects for the following specific crash types: total, fatal and injury, right-angle, rear-end, and nighttime crashes. Based on the combined results, the CMFs shown in table 26 are recommended for the various crash types.

Table 26. Recommended CMFs (based on combined States).

Statistic	Total	Fatal and Injury	Right-Angle	Rear-End	Nighttime
Two-Lane at Two-Lane					
Estimate of CMF	**0.733**	**0.701**	**0.803**	**0.425**	0.898
Standard error of estimate of CMF	0.035	0.045	0.049	0.073	0.096
Four-Lane at Two-Lane					
Estimate of CMF	**0.827**	**0.802**	**0.850**	0.973	**0.612**
Standard error of estimate of CMF	0.059	0.072	0.075	0.224	0.108

Statistically significant results at the 95-percent confidence level are indicated in boldface.

The aggregate results indicated statistically significant crash reductions at the 95-percent confidence level for all crash types except nighttime crashes for two-lane at two-lane intersections. The results also indicated statistically significant crash reductions in all crash types except rear-end crashes for four-lane at two-lane intersections.

The disaggregate analysis sought to identify those conditions under which the ICWS strategy was most effective. Because total, fatal and injury, and right-angle crashes were the focus of this strategy, these crash types were the focus of the disaggregate analysis. The disaggregate analysis of the results for two-lane at two-lane intersections indicated larger percentage crash reductions for sites with ICWSs installed on the major route, particularly for post-mounted ICWSs in advance of the intersection. An additional benefit may be provided by including the "WHEN FLASHING" message as part of the system. The disaggregate CMFs can be used in prioritizing installation sites, but interpretations should be made with caution. One should pay particular attention to the sample size used to develop the CMFs.

The disaggregate analysis for four-lane at two-lane intersections indicated larger percentage crash reductions for sites with intersection lighting and for sites with a higher expected average crash frequency in the before period. There was no substantive difference for sites with warning on the major route versus warning on the minor route. The disaggregate CMFs can be used in prioritizing installation sites, but again, interpretations should be made with caution.

The B/C ratio estimated with conservative cost and service life assumptions and only considering the benefits for total crashes was 27:1 for all two-lane at two-lane intersections and 10:1 for four-lane at two-lane intersections. The benefits were calculated from the significant reduction found for combined States for all two-lane at two-lane intersections and based on the statistically significant reduction found for four-lane at two-lane intersections. With the USDOT-recommended sensitivity analysis, these values could range from 16:1 to 39:1 for two-lane at two-lane intersections and 6:1 to 14:1 for four-lane at two-lane intersections. These results suggest that the ICWS strategy—even with conservative assumptions on cost, service life, and the value of a statistical life—can be cost effective.

Because this is an evolving strategy, this study reflects installation practices to date. Future studies may show different results as installation practices change. In particular, the use of an overhead ICWS on the major route was limited to the installations at the intersection (i.e., no advance warning), while post-mounted ICWSs on the major route were installed in advance of the intersection. Future research should compare these installation practices, considering placement of warning signs. Specifically, section 2C.05 of the MUTCD provides guidance for the placement of warning signs so that they provide adequate PRT.(2)

APPENDIX A: EXAMPLE INSTALLATIONS BY STATE

The following appendix presents Google Street View™ images of ICWS installations used in each State.

MINNESOTA

All sites in Minnesota were post mounted. Figure 8 through figure 10 present examples of signs used in Minnesota.

Figure 8. Photo. Major route blank-out sign with flashing beacon from Google Street View™.[(18)]

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Figure 9. Photo. Minor route sign with LED arrow-shaped flashers from Google Street View™.(19)

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Figure 10. Photo. Minor route visual display from Google Street View™.(20)

MISSOURI

All sites in Missouri were post mounted. Figure 11 through figure 13 present examples of signs used in Missouri.

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Figure 11. Photo. Major route static sign with flashing beacons from Google Street View™.(21)

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Figure 12. Photo. Minor route static sign with flashing beacons from Google Street View™.(22)

©Google® 2016

Figure 13. Photo. Dual major route static sign with flashing beacons from Google Street View™.(23)

NORTH CAROLINA

Sites in North Carolina were post mounted and/or mounted overhead. Figure 14 through figure 16 present examples of signs used in North Carolina.

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Figure 14. Photo. Major and minor route overhead static signs with flashing beacons from Google Street View™.(24)

Figure 15. Photo. Minor route overhead static sign with flashing beacons from Google Street View™.[25]

Figure 16. Photo. Major route static sign with flashing beacons from Google Street View™.[26]

APPENDIX B: ADDITIONAL INSTALLATION DETAILS

The following appendix presents additional details provided by Minnesota, Missouri, and North Carolina. States were asked to provide responses to the following questions:

1. How were treatment signs, messages, and approaches selected for treatment? For example, how were sites selected to have treatment on the major or minor approaches only, or how were sites selected to be treated on BOTH the major and minor routes?

2. How were signs and messages selected (e.g., visual display versus message, “When Flashing” versus no message, or overhead versus post-mounted)?

3. Do you know if other geometric changes or countermeasures (e.g., addition of turn lanes) were implemented concurrently with the ICWS?

4. We would like to provide a summary of the ICWS characteristics below. Do you have any standard drawings that applied to the treatment sites considered by the study?

    a. Location of sign on major approach and/or minor approaches.
    b. Location/type of detection on major and/or minor approaches.
    c. Messages on the signs.
    d. Sign size.
    e. Detector timing parameters.

5. Was crash history the major criteria for site selection? Were any specific crash types targeted? Please specify any criteria.

6. Were there any requirements for ICWS implementation (e.g., minimum major/minor route volumes, minimum/maximum speed limits)?

7. Please describe any notable challenges related to ICWS installation and how you overcame them.

8. Please describe any notable challenges related to ICWS maintenance and how you overcame them.

9. What lessons learned or recommendations would you share with another State interested in the application of ICWS?

10. Can you provide any estimates on cost of ICWS operation and maintenance for intersections with installations only on minor approaches, only on major approaches, or on both the major and minor approaches? Are there any noted differences for overhead versus post-mounted installations?

RESPONSES FROM MINNESOTA

Minnesota responded to all 10 questions. Their responses are listed in numeric order. The responses are listed separately for cooperative intersection collision avoidance system (CICAS) sites and for ICWS sites.

The following responses were received regarding CICAS installations:

1. The locations for the CICAS system were selected based on their crash history. These were locations with a documented crash history of angle crashes at expressway intersections. Only the minor approach received treatment via the CMS that was installed at the intersection. A report describing the location selection and the preliminary candidate message types can be found at http://www.dot.state.mn.us/guidestar/2001_2005/ids/2007_33.pdf.

2. Details on the various signs and messages where researched over a several year period. Details on these studies can be found at http://www.dot.state.mn.us/guidestar/2006_2010/cicas.html. Ultimately, the design that was implemented was informed by this research as well as feasibility aspects brought forward by the University.

3. No additional geometric changes were incorporated into the deployment of the CICAS system.

4. Additional details are discoverable but would require some effort (detector parameters, etc.) or may be included in reports published at the hyperlink in A2. See page 13/27 of the report found at http://www.dot.state.mn.us/guidestar/2001_2005/ids/2007_33.pdf.

5. The TH 52/CSAH 9 intersection had a known crash history of high speed right-angle crashes and that brought the project to its location. While there was no specific site criteria that was used to identify site selection factors used for other locations the following factors were used to identify the other deployment sites: number and severity of right-angle crashes (looking for high frequency and high severity in terms of fatal and serious injury crashes) and expressway intersections with stop control. A report describing the location selection can be found at http://www.dot.state.mn.us/guidestar/2001_2005/ids/2007_33.pdf.

6. No. There was concern about higher volume roads where the system would be frequently showing a no movement recommendation due to smaller gaps based on the traffic composition. This pushed the system out of "super" high volume expressways in urban areas to more rural environments where the demand was not as consistent throughout the day.

7. The installation was fairly straight forward but there were some challenges with post design and guardrail requirements for the system. Engineering judgment was used to move forward with an acceptable layout.

8. Since this system was a prototype keeping the system operational 24/7 was a challenge. This was confounded by having remote locations not near the university staff office

facilities. Diagnostics could be done remotely to check system status but diagnosing repairs required a site visit and potentially ordering replacement parts. It should also be noted that the vendor for the signs at one of the locations went out of business, making it difficult to repair the signs and get parts. Also, electricity for the large DMS signs was very expensive.

9. A plethora of information was used to develop and design this new elaborate system. Substantial information was gathered at the locations that provided details on drivers and their gap acceptance. In the end, drivers still made bad choices at intersections and crashes occurred even after the system was installed. Every crash that occurred after the system was installed had the correct message displayed, indicating that no movement was advised. A system with lower installation and maintenance cost would be more likely to be built.

10. Due to the prototype nature of this project we are not able to provide any meaningful costs on the installation and operation of this system. The project costs were high due to the research and development that went into the system, the goal was that someone would commercialize the product with standard detection and logic in the future based on the results of this research.

The following responses were received regarding the ICWS installations:

1. The locations for the [rural intersection conflict warning system] RICWS system were selected based on their crash history and local input into intersections to test this new technology—these locations in general were not considered black spots. The default system design was to employ warning signs for all approaches to the intersection

2. The goal was to provide a system that leveraged off the shelf technology so the project looked to leverage existing signs (MUTCD compliant) and compliment them with technology to flash when conditions warranted.

3. No additional geometric changes were incorporated into the deployment of the RICWS system.

4. Attached are files that contain some of the information requested in the above bullets.

5. The locations selected were based on a variety of factors including the perception of a crash problem (i.e., lots of near misses, less than standard site distance, limited crash history). Angle crashes were the focus of this intersection treatment.

6. No.

7. The installation was fairly straight forward but there were some challenges keeping the system operational 100% of the time.

8. Since this system was a prototype keeping the system operational 24/7 was a challenge. This was confounded by not having an easy way to diagnose whether the system was operational or not.

9. While this system is relatively simple to design and install substantial effort was focused on keeping the system operational throughout the deployment. A system with lower installation and maintenance cost would be more desirable in the future.

10. Due to the prototype nature of this project we are not able to provide any meaningful costs on the installation and operation of this system. The project costs were high due to the research and development that went into the system, the goal was that someone would commercialize the product with standard detection and logic in the future based on the results of this research. A new system has been designed and deployed based on the lessons learned from this system, however the costs are well in excess of $50k per intersection.

RESPONSES FROM MISSOURI

Missouri provided responses to four of the questions.

Response to question 2: For the message, we have a couple that have been used, but it seems like the "traffic approaching when flashing" is being taken out of service due to litigation concerns (may not always flash).

Response to question 5. These locations were driven by crash issues.

Response to question 9. If we see a continued trend in angle collisions after installation, we may decide to modify the access and potentially install a j-turn design (RCUT).

Response to question 10. I am confident we are hoping to get a 10 year plus lifespan out of the locations we have installed this countermeasure.

RESPONSES FROM NORTH CAROLINA

North Carolina responded to all 10 questions. Its responses are listed in numeric order. Figure 17 and Figure 18 provide the pre- and post-2012 crash reduction factors used by NCDOT. Figure 19 through figure 21 present example diagrams of ICWS applications in North Carolina.

1. Treatment sites were selected by the local traffic engineering staff, for the most part based on an observed crash experience. The decision of where to place signs (overhead in the intersection or in advance of the intersection, an on which approaches) likely depended upon:

    a. Whether there was an existing standard overall flasher in the intersection.

        i. At some of the locations, a standard overhead flasher was already in place (likely as a safety treatment that hadn't worked well). If there was an existing overhead flasher, the ICWS likely replaced the standard flasher in the same spot.

    b. Whether there were site distance issues at the intersection.
        i. In some cases, if the intersection was located in a curve, the flashers may be placed in advance of the intersection on the major road so that drivers could better see the warning.
    c. The personal preference of the local Division/Regional traffic engineers in the area where it was placed (this may be the biggest reasoning behind the design at each site).

2. The decision on which messages to use also depended upon the preference of the local traffic engineering staff. Some feel more comfortable adding the "When Flashing" to the message than others due to potential/perceived liability issues.

3. The ICWS should be the only change made to the sites during the study periods.

4. See the attached drawings of the countermeasures for examples (Examples 1–3).[See figure 19 through figure 21.]

5. Yes, most of the sites were selected based on an existing crash pattern. The number of total crashes in the before period at each site varies from 0 crashes to 9.5 crashes per year, with an average of 3.7 crashes per year at 74 sites. Note, there was only 1 site with 0 crashes in the before period. Target crashes were frontal impact, specifically angle crash types where a vehicle pulled out from the stop-controlled leg. The number of target crashes in the before period at each site varied from 0 crashes per year to 8.5 crashes per year, with an average of 3.0 crashes per year at 74 sites. Many of the sites were funded through the Spot Safety program, where they competed with other safety projects based on the B/C ratio, among other items. A site with a strong pattern of crashes, including some high severity crashes, may be more likely to be funded depending upon the total cost of the project.

6. There were not volume or speed thresholds. Intersection AADTs ranged from approximately 3,000 to 30,000, with an average of 7,300 at 74 sites. Major road speed limits ranged from 35 to 55 mph, although a majority of sites were located on high-speed facilities.

7. We have no notable challenges related to ICWS installation to report. We have been installing these countermeasures since 1997, so there may have been some installation issues to overcome initially, but we do not have a record of those items.

8. We also do not have any notable challenges related to ICWS maintenance. We have been installing these countermeasures since 1997, so there may have been some maintenance issues to overcome initially, but we do not have a record of those items.

9. In our experience, ICWS may work best when signs are posted on the major road in advance of the intersection. A combination of signs (i.e., minor road signs with major road signs in advance of the intersection) may be most effective. Also, ICWS appears to be more effective when the major road is a two-lane cross-section as opposed to a four-lane divided cross-section. Probably the biggest thing we learned was the crash reduction factor estimates we used for this type of project pre-2012 to post-2012 in our B/C process

within our Spot Safety program. Since there was no good crash reduction factor research available prior to 2012, we decided to use a 25 percent reduction in total crashes for these types of countermeasures. After our evaluation of the sites we shared, we adjusted our crash reduction factor estimates to match the data results our analysis provided. Based on the new information, I believe there were a lot of sites we would have never installed this countermeasure; those with a low opportunity for same improvements (see values for Post-2012 below).

Countermeasure	Crash Pattern Affected -- Site Specification	Percent Reduction
2.2 Upgrade Overhead Warning Flasher Actuated Vehicles Entering	Total Crashes	25*

Figure 17. Graphic. North Carolina pre-2012 crash reduction factor.

Countermeasure	Crash Pattern Affected -- Site Specification	Percent Reduction
2.2 Actuated Vehicle Entering When Flashing (2-Lane at 2-Lane Intersections)	Overhead Signs and Flashers on Major, Loop on Minor Total Crashes	-6
	Overhead Signs and Flashers on Minor, Loop on Major Total Crashes	5
	Post Mounted Signs and Flashers on Major, Loop on Minor Total Crashes	32
(Combination of countermeasure scenarios above)	Combination of Signs and Flashers on Major/Minor, Loops on Major/Minor Total Crashes	25
(4-Lane at 2-Lane Intersections)	All Potential Countermeasure Scenarios Total Crashes	-7

Figure 18. Graphic. North Carolina post-2012 crash reduction factor.

10. We are currently using $500 for the annual maintenance costs and $125 for the annual utility costs in our B/C process within our Spot Safety program. We do not differentiate the costs between the following four categories:

- Overhead signs and flashers on major, loop in minor.
- Overhead signs and flashers on minor, loop on major.
- Post mounted signs and flashers on major, loop on minor.
- Combination of signs and flashers on major/minor, loops on major/minor.

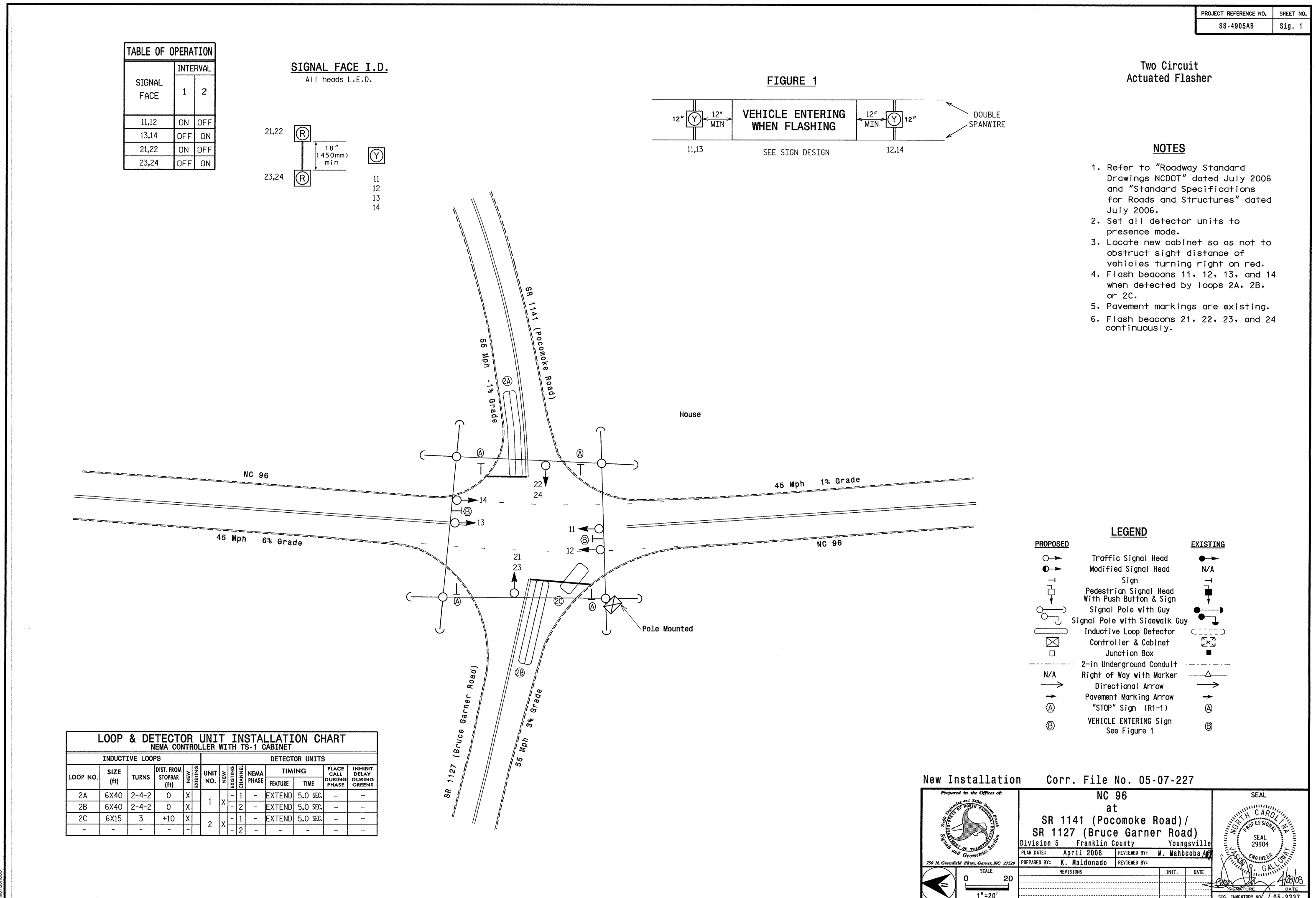

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Figure 19. Diagram. Example 1—overhead sign on major route.

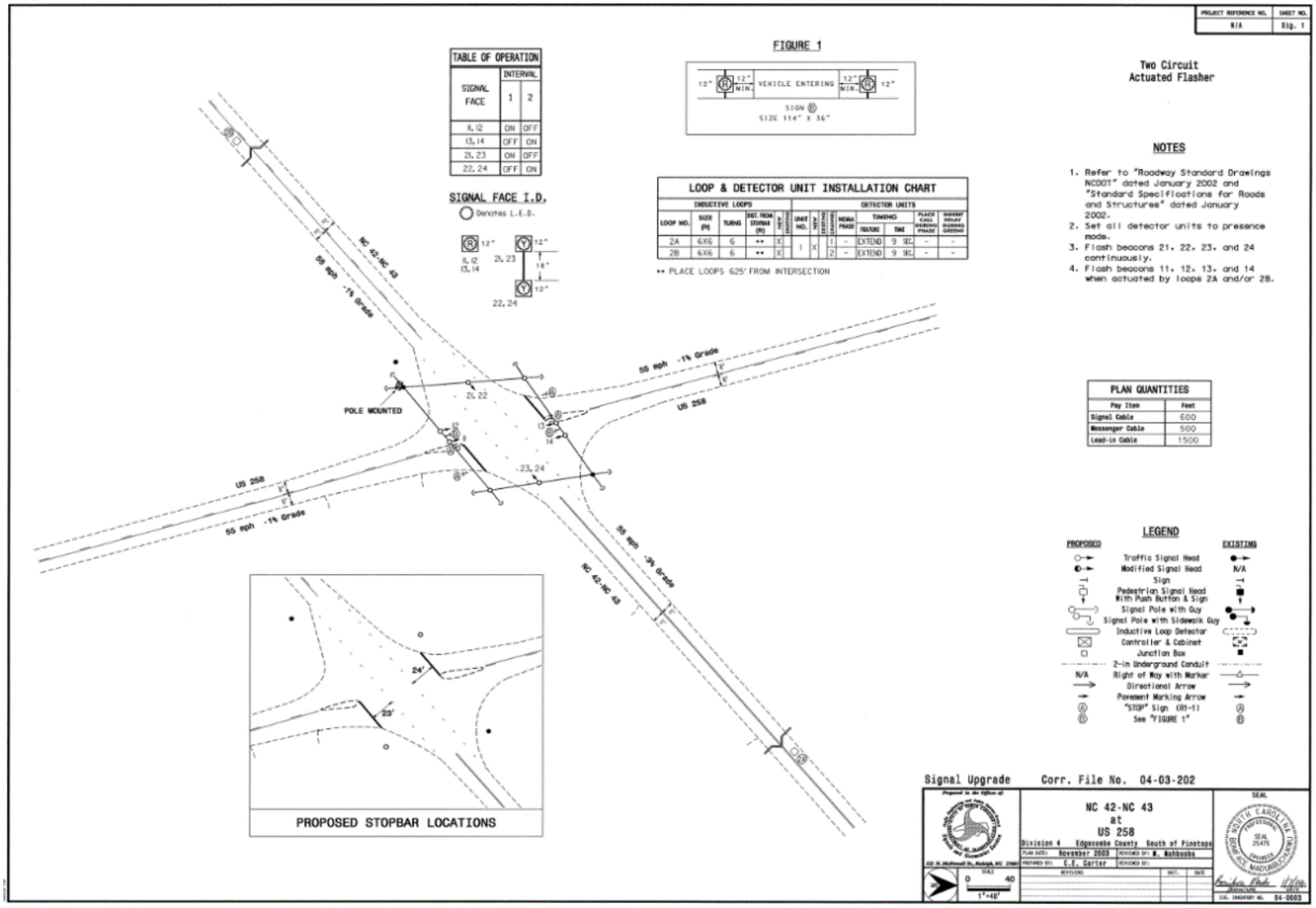

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Figure 20. Diagram. Example 2—overhead sign on minor route.

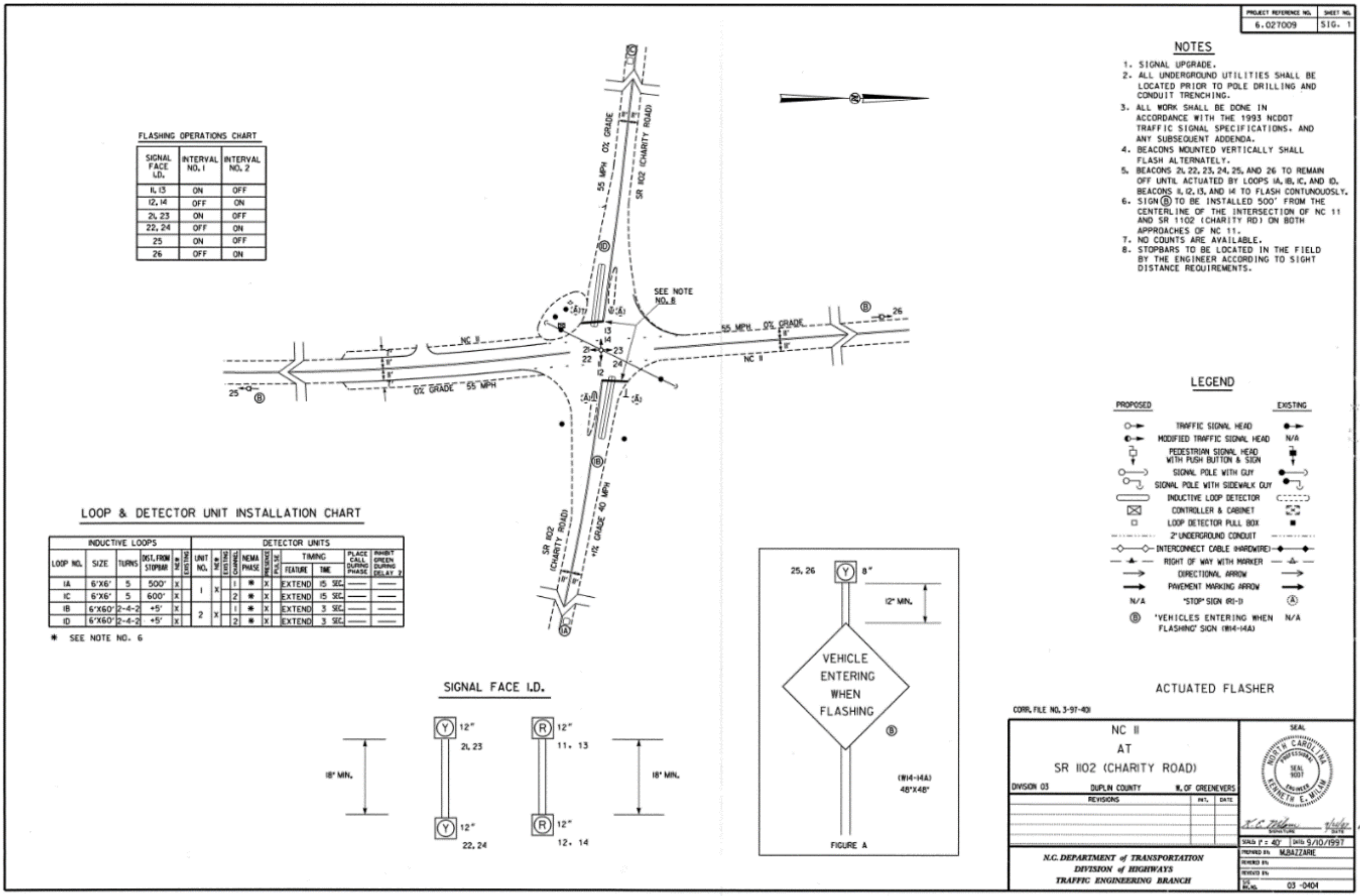

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Figure 21. Diagram. Example 3—post-mounted sign on major approach.

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