Safety Evaluation of Multiple Strategies at Signalized Intersections

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Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS in 2005 to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program *Report 500 Guides* as part of the implementation of the American Association of State Highway and Transportation Officials (AASHTO) 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.

This study evaluated multiple low-cost safety improvements at signalized intersections for basic signing, pavement marking, and signal enhancements. This strategy was intended to reduce the frequency and severity of crashes at signalized intersections by alerting drivers to the presence, type, and configuration of the approaching intersection. The results indicate reductions for all crash types analyzed (i.e., total, fatal and injury, rear-end, right-angle, and nighttime crashes). The economic analysis results suggest that implementation of multiple low-cost treatments at signalized intersections, even with conservative assumptions for cost, service life, and the value of a statistical life, can be cost effective. This report is intended for safety engineers, highway designers, planners, and practitioners at State and local agencies involved with AASHTO Strategic Highway Safety Plan implementation.

Monique R. Evans, P.E., CPM
Director, Office of Safety
Research and Development

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16. Abstract
The Development of Crash Modification Factors program conducted safety evaluations of multiple strategies at signalized intersections for the Evaluation of Low Cost Safety Improvements Pooled Fund Study. This study evaluated multiple low-cost treatments at signalized intersections. Improvements included basic signing, pavement marking, and signal enhancements. This strategy was intended to reduce the frequency and severity of crashes at signalized intersections by alerting drivers to the presence, type, and configuration of the approaching intersection. Geometric, traffic, and crash data were obtained at three- and four-legged, two- and four-lane major road, urban, and rural signalized intersections in South Carolina. To account for potential selection bias and regression-to-the-mean, an empirical Bayes before–after analysis was conducted using reference groups of untreated intersections with characteristics similar to the treated sites to develop safety performance functions for the intersection configurations included in this study. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatments. The aggregate results indicate reductions for all crash types analyzed (i.e., total, fatal and injury, rear-end, right-angle, and nighttime). The crash modification factors (CMFs) for fatal and injury and right-angle crashes were 0.893 and 0.883, respectively, which were statistically significant at the 95-percent confidence level. The CMFs for total, rear-end, and nighttime crashes were 0.955, 0.974, and 0.969, respectively, which were not statistically significant at the 95-percent confidence level. Note that the CMF for total crashes was statistically significant at the 90-percent confidence level. The benefit–cost ratio estimated with conservative cost and service life assumptions was 4.1:1 for total crashes at signalized intersections. The results suggest that the implementation of multiple low-cost treatments, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective.

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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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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	annual average daily traffic
B/C	benefit–cost
CMF	crash modification factor
DCMF	Development of Crash Modification Factors (program)
EB	empirical Bayes
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FHWA	Federal Highway Administration
KABCO	Scale used to represent injury severity in crash reporting (K is fatal injury, A is incapacitating injury, B is non-incapacitating injury, C is possible injury, and O is property damage only)
LED	light-emitting diode
MUTCD	*Manual on Uniform Traffic Control Devices*
NCHRP	National Cooperative Highway Research Program
PDO	property damage only
PE	preliminary engineering
RTM	regression to the mean
SCDOT	South Carolina Department of Transportation
SPF	safety performance function
TWLTL	two-way left-turn lane
USD	U.S. dollars
USDOT	U.S. Department of Transportation

EXECUTIVE SUMMARY

The Federal Highway Administration established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes. The ultimate goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and to promote those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit–cost (B/C) ratios through research. State transportation departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in broad applications of new strategies for safety improvements. Forty State transportation departments have provided technical feedback on safety improvements to the DCMF program and have implemented new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study, which functions under the DCMF program. This study evaluated multiple low-cost treatments at signalized intersections. Improvements included basic signing, pavement marking, and signal enhancements. This strategy was intended to reduce the frequency and severity of crashes at signalized intersections by alerting drivers to the presence, type, and configuration of the approaching intersection. Both urban and rural signalized intersections on divided and undivided State-maintained roads (non-freeways) were selected as locations for treatments. Study results have shown that by making improvements such as those described here, the South Carolina Department of Transportation was able to achieve a small but statistically significant crash reduction. Although the expected crash savings per location were not as large as for some higher cost treatments (e.g., converting conventional intersections to roundabouts), the low cost of these treatments has allowed many more locations to be treated.

Geometric, traffic, and crash data were obtained at three- and four-legged, two- and four-lane major road, urban and rural signalized intersections in South Carolina. To account for potential selection bias and regression-to-the-mean, an empirical Bayes before–after analysis was conducted. Safety performance functions were developed using reference groups of untreated intersections with characteristics similar to the treated sites. The analysis also controlled for changes in traffic volumes over time and time trends in crash counts unrelated to the treatments.

The aggregate results indicate reductions for all crash types analyzed (i.e., total, fatal and injury, rear-end, right-angle, and nighttime). The crash modification factors (CMFs) for fatal and injury and right-angle crashes were 0.893 and 0.883, respectively, which were statistically significant at the 95-percent confidence level. The CMFs for total, rear-end, and nighttime crashes were 0.955, 0.974, and 0.969, respectively, which were not statistically significant at the 95-percent confidence level. Note that the CMF for total crashes was statistically significant at the 90-percent confidence level.

The disaggregate analysis identified specific CMFs by crash type and different conditions. The analysis revealed those conditions under which the combination of treatments may be more effective. Variables of interest for this analysis included area type (urban or rural), number of legs (three or four), lane configuration of the mainline and the cross street, traffic volumes, and expected crashes without treatment. For area type, the results showed larger crash reductions at

urban intersections for total, fatal and injury, and rear-end crashes. The results disaggregated by number of legs indicated the treatments were more effective for total, fatal and injury, and rear-end crashes at three-legged intersections. The disaggregate analysis by lane configuration showed larger reductions for all crash types at intersections with two-lane major roads. For total entering volume, the disaggregate analysis indicated the combination of treatments was slightly more effective on average for intersections with lower traffic volumes. While the disaggregate analysis indicated conditions under which the treatments may be more effective, the variables are likely correlated, and caution should be exercised in interpreting and applying the disaggregate analysis results. The disaggregate analysis also showed the multitreatment strategy could yield similar crash reductions across the range of expected crashes without the treatments. This confirms the need for caution when interpreting the disaggregate results because the net effect of multiple correlations is a negligible effect on the expected number of crashes, which collectively captures the effects of other variables.

Assuming a 7-year service life, conservative costs, and the benefits for total crashes, the B/C ratio was 4.1:1. With the U.S. Department of Transportation recommended sensitivity analysis, these values could range from 2.3:1 up to 5.8:1. The B/C ratio when excluding the cost of pedestrian improvements was 11.7:1. These results suggest that implementation of multiple low-cost treatments, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective in reducing crashes at signalized intersections.

CHAPTER 1. INTRODUCTION

This chapter presents background information on the low-cost strategies implemented by South Carolina at signalized intersections. It also provides a brief overview of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS), of which the study reported here is a part.

BACKGROUND ON MULTIPLE STRATEGIES AT SIGNALIZED INTERSECTIONS

In recent years, there has been an increased interest in systemic installations of low-cost safety treatments throughout an entire jurisdiction. South Carolina Department of Transportation (SCDOT) embraced this approach in its intersection safety improvement plan and identified a number of low-cost strategies for implementation at stop-controlled and signalized intersections statewide. Typical low-cost treatments at signalized intersections in South Carolina included improvements to basic signing, pavement markings, and traffic signals. Figure 1 shows an example of the systemic, low-cost improvements at a four-legged signalized intersection with four through lanes on both the major and minor roads.

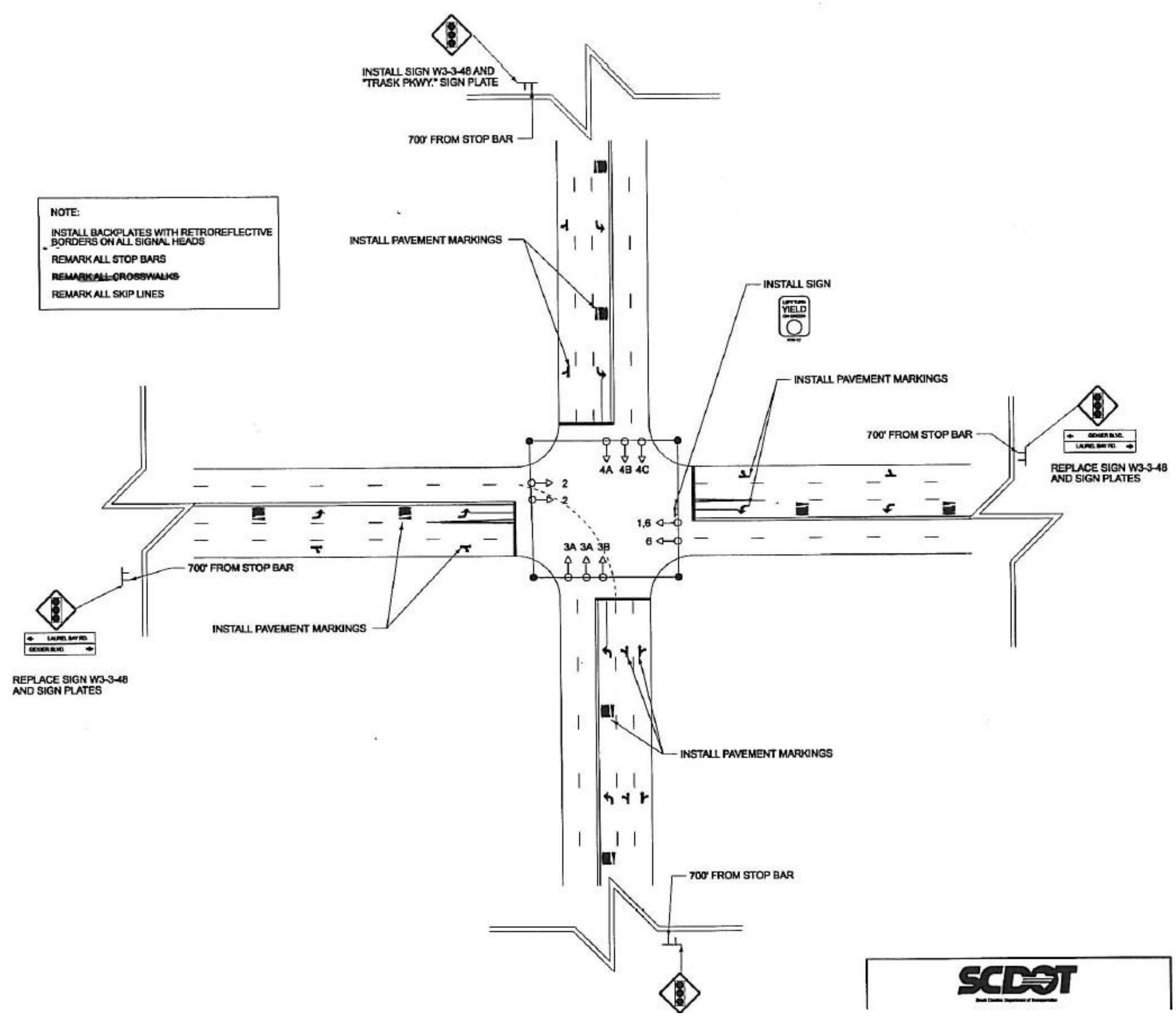


Figure 1. Illustration. Example of signalized intersection improvements.

The following list presents the types of traffic signal improvements used in South Carolina:

- Replace all signal heads.
- Replace pedestrian signal heads, pushbuttons, and signs.
- Install backplates with retroreflective borders on all signal heads.
- Re-stripe stop lines.
- Re-stripe crosswalks.
- Install warning signs.
- Install overhead signs (e.g., R10-12, R3-5L, R3-5R).
- Install curb ramps.

The appendix of this report provides further details and considerations. Each treatment was installed when appropriate but not at all intersections. Each intersection received a unique package of improvements suited for implementation at that site.

BACKGROUND ON STUDY

The goal of the ELCSI-PFS is to develop reliable estimates of the effectiveness of the safety improvements that are identified as strategies in the National Cooperative Highway Research Program (NCHRP) *Report 500 Guides*.[(1)] These estimates are determined by conducting scientifically rigorous evaluations at sites in the United States where these strategies are being implemented. The study has spanned multiple phases. In March 2005, the first Technical Advisory Committee Meeting of the ELCSI-PFS was held at the Turner-Fairbank Highway Research Center. The purpose of the meeting was to discuss the study and applicable strategies from the NCHRP *Report 500 Guides* and to develop a prioritization of those strategies for potential evaluation in the study.[(1)] Since this initial meeting, several phases have been undertaken to evaluate strategies.

Phase V of the ELCSI-PFS has been a "build-to-evaluate" effort in which States volunteered to install a variety of promising low-cost safety countermeasures and contribute the appropriate data to allow a rigorous crash-based evaluation of their safety effectiveness. This phase has had two parts—implementation and evaluation. The implementation portion (part 1) defined the before period, including installation data (location and date), roadway data, traffic data, and crash data. The evaluative portion (part 2) began within 3 years of the conclusion of the installation phase. Four safety strategies were identified for implementation and evaluation in phase V. Five States volunteered and provided data for the phase V evaluations. Table 1 shows these safety improvement strategies and the volunteering States for each.

Table 1. Phase V safety strategies and participating States.

Safety Strategy/ Participating State	Combination of Cable Median Barrier and Rumble Strips	Combination of Center-Line Rumble Strips and Edge-Line Rumble Strips	Multistrategy Improvements at Signalized Intersections	Multistrategy Improvements at Stop-Controlled Intersections
Illinois	X	—	—	—
Kentucky	X	X	—	—
Missouri	X	X	—	—
Pennsylvania	—	X	—	—
South Carolina	—	—	X	X

—Not used.

As the implementing agency in a volunteering State, SCDOT initiated a project to improve safety at more than 2,200 intersections statewide through low-cost engineering techniques focused primarily on signing and markings in 2009. These intersections—600 of which were classified as rural—comprise only 2 percent of all State-maintained intersections but account for nearly half of all intersection crashes and fatalities. It was envisioned that the project would span 3 years and implement improvements at approximately 700–800 intersections each year.

This report documents the safety effectiveness evaluations of multiple strategies at signalized intersections implemented in South Carolina. The evaluation of multiple strategies at stop-controlled intersections can be found in the companion report entitled *Safety Evaluation of Multiple Strategies at Stop-Controlled Intersections*.[2]

CHAPTER 2. LITERATURE REVIEW

The research team identified literature on the signalized intersection strategies of interest. Although previous research had been conducted for several of the individual treatments, literature on some of the related strategies was limited. There were also very few studies that investigated the effects of multiple strategies. The following is a summary of the salient research related to specific strategies.

WARNING SIGNS

Polanis conducted an evaluation of installing advance warning signs (i.e., providing positive guidance) for signalized intersections.(3) The results of the evaluation indicated that right-angle crashes decreased by 35 percent with a standard error of 1 percent. The reduction was highly statistically significant, but the study relied on a simple before–after study design and a limited dataset with a small sample size (11 sites) from one city.

A number of studies have examined the use of fluorescent yellow sheeting on warning signs. Using fluorescent yellow sheeting is an inexpensive method of increasing the conspicuity of signs without violating the provisions contained in the *Manual on Uniform Traffic Control Devices* (MUTCD).(4) Multiple studies confirm the superiority of fluorescent signs in terms of conspicuity. Jenssen et al. conducted a comparative evaluation of fluorescent and nonfluorescent signs on a closed track in Norway.(5) Subjects seated in moving railcars were asked to indicate when they could detect and recognize the size, shape, and content of fluorescent and nonfluorescent signs. The performance of the fluorescent signs proved to be superior; the subjects were able to detect and recognize the fluorescent signs well before they could detect and recognize the nonfluorescent signs. Burns and Johnson studied fluorescent and nonfluorescent materials and found that the photometric properties of fluorescent materials explained their superior visibility and conspicuity.(6)

RETROREFLECTIVE SIGN POSTS

A recent study by the Virginia Department of Transportation directly relates to the retroreflective sign post strategy. This study examined the effectiveness of retroreflective material on stop sign posts with respect to visibility and driver compliance.(7) The authors measured performance with respect to visibility using a video survey in which participants were asked to pinpoint when a stop sign with retroreflective material and another without retroreflective material could be detected. The results indicated that, during daytime conditions, the vast majority of participants could detect the stop sign without retroreflective material sooner than the stop sign with retroreflective material. In contrast, during nighttime conditions, the vast majority of participants could detect the stop sign with retroreflective material sooner than the stop sign without retroreflective material. In terms of compliance, the behavior of drivers approaching a stop sign with retroreflective material was not observed to be different from that of a driver approaching a stop sign without retroreflective material.(7)

REFRESHING EXISTING PAVEMENT MARKINGS

The research team did not identify any studies analyzing the safety effects of refreshing existing pavement markings at signalized intersections.

INSTALLING ONE SIGNAL FACE PER LANE

Agent studied several low-cost strategies aimed at reducing crashes related to red-light running.[8] Among the strategies examined in the study was the installation of one signal face per lane. In the study, high-crash intersection locations were identified in Kentucky using the critical rate method with an emphasis on red-light running crashes. The low-cost strategies were then employed and evaluated at the identified intersection locations. A simple before–after study design was used in the evaluation. The evaluation of installing one signal face per lane was encouraging. The results of the evaluation indicated that this strategy reduced total crash frequency by 24 percent, angle crash frequency by 63 percent, and rear-end crash frequency by 10 percent.[8]

Sayed et al. analyzed the safety effects of various combinations of signal visibility-related treatments at signalized intersections in British Columbia, Canada.[9] The addition of signal heads was included in some of these treatment combinations. The results from all the combinations of intersection treatments indicated declines of 7.3 percent for total crashes, 6.6 percent for nighttime crashes, 5.9 percent for daytime crashes, 2.6 percent for severe crashes, and 8.5 percent for property damage only (PDO) crashes. All of the reductions were statistically significant at the 5-percent level except the reduction in severe crashes. Based on the aggregate results, it appears that the addition of signal heads, at least when coupled with other signal visibility-related countermeasures, produced meaningful declines in crash frequency.[9]

Felipe et al. conducted an evaluation of the effects of adding a primary head to signalized intersections.[10] The treatment locations were four-legged, urban intersections. The evaluation revealed that the treatment reduced total crashes by 28 percent, severe crashes by 17 percent, and PDO crashes by 31 percent. The evaluation also indicated that this countermeasure decreased right-angle crashes by 35 percent and rear-end crashes by 28 percent.[10]

RETROREFLECTIVE BORDERS ON BACKPLATES

Agent studied several low-cost strategies aimed at reducing crashes related to red-light running.[8] Among the strategies examined in the study was the installation of retroreflective borders on backplates. In the study, high-crash intersection locations were identified in Kentucky using the critical rate method with an emphasis on red-light running crashes. The low-cost strategies were then employed and evaluated at the identified intersection locations. A simple before–after study design was used in the evaluation. The evaluation of the retroreflective borders on backplates revealed that the total crash frequency decreased from 5.1 crashes per year in the before period to 4.1 crashes per year in the after period. This change represents a 20-percent reduction in total crash frequency. The study also revealed that angle crashes decreased by 44 percent and rear-end crashes decreased by 10 percent.[8]

Another instance of this treatment was documented in a Federal Highway Administration (FHWA) case study in South Carolina.[11] Three traffic signals that had backplates were retrofitted with retroreflective borders. These three signalized intersections had a history of red-light running, and the addition of retroreflective borders was intended to increase the visibility of the traffic signals. A simple before–after evaluation was then conducted. The results indicated that total crash frequency decreased by 29 percent, injury crash frequency decreased by 37 percent, and late-night/early-morning crash frequency decreased by 50 percent. In addition to its apparent effectiveness, application of the treatment specific to this effort had a low cost of $1,500 per intersection.(11)

Sayed et al. performed an evaluation of different combinations of signal visibility-related countermeasures using an empirical Bayes (EB) technique.(9) One of these combinations of treatments was the installation of new backplates with reflective tape along with the upgrading of signal lenses. The treatment sites for this combination of countermeasures were all located in the North Vancouver district of British Columbia. The study estimated that this combination of countermeasures caused reductions of approximately 9 percent in total crashes, 14 percent in nighttime crashes, 8 percent in daytime crashes, 10 percent in PDO crashes, and 10 percent in severe crashes. Another combination of treatments evaluated in this study was the upgrading of signal lenses and the addition of reflective tape to existing backplates. The treatment sites for this combination of treatments were all in the New Westminster district of British Columbia. The results indicated reductions of about 12 percent in total crashes, 17 percent in nighttime crashes, 10 percent in daytime crashes, 14 percent in PDO crashes, and 10 percent in severe crashes.(9)

Sayed et al. evaluated the effects of adding 3-inch yellow retroreflective sheeting to signal backplates.(12) Their evaluation used an EB before–after study design. The treatment sites were all located in urban areas. The results of the evaluation were that total crashes decreased by 15 percent with a standard error of 0.5 percent. Therefore, the results of this study were statistically significant at the 95-percent confidence level.(12)

TWELVE-INCH LIGHT-EMITTING DIODE (LED) LENSES

Sayed et al. assessed the performance of signal heads with 300 mm (equivalent to approximately 12 inches) lenses relative to signals with 200 mm (equivalent to approximately 8 inches) lenses in terms of crash frequency.(13) The assessment was based on 10 treatment sites in British Columbia, Canada, and used the EB method described by Pendleton, Higle, and Witkowski.(14,15) The results of the EB analysis indicated that total crash frequency decreased by 24 percent and injury crash frequency decreased by 16 percent.

A study of 12-inch lenses was also conducted in Michigan by FHWA.(16) Two improvements were made to 33 signalized intersections with a history of angle crashes: replacement of 8-inch lenses with 12-inch lenses and the implementation of an all-red clearance interval. The combination of treatments proved to be effective with a 33-percent reduction in total crashes, a 46-percent reduction in injury crashes, and a 76-percent reduction in angle crashes.(16)

Sayed et al. performed an evaluation of combinations of intersection treatments that included upgrading signal lenses using an EB technique.(9) The treatment group consisted of 139 intersections in 6 municipalities in British Columbia, Canada. The results for total, nighttime, daytime, severe, and PDO crashes were reductions of 7.3, 6.6, 5.9, 2.6, and 8.5 percent, respectively. The reductions in all but the severe crashes were statistically significant.(9)

Sayed et al. evaluated the safety effects of installing larger 12-inch signal lenses.[(13)] The dataset for this study included 10 urban intersections in British Columbia, Canada, and an EB before–after analysis was used. The effect on total crashes was estimated to be a 24-percent reduction, and the effect on severe crashes was estimated to be a 16-percent reduction.[(13)]

As part of the study reported in NCHRP Report 617, *Accident Modification Factors for Traffic Engineering and ITS Improvements*, an evaluation of installing larger signal lenses was conducted.[(17)] The treatment group consisted of 26 intersections where the existing 8-inch lenses were replaced by 12-inch lenses. The EB method was employed in this evaluation. The evaluation indicated that right-angle crashes were reduced by 42 percent (statistically significant at the 5-percent level), while total crashes remained unchanged. In order for the total crashes to have remained unchanged while right-angle crashes decreased, there must have been an increase in other crash types. The authors hypothesized that the increase occurred in rear-end crashes. An economic evaluation was also performed to assess the impact of this treatment. The results of the economic evaluation indicated that the treatment produced an estimated $11,800 reduction in total harm per intersection per year.[(17)]

LIMITATIONS OF PREVIOUS RESEARCH

Literature on the signalized intersection strategies of interest was scarce in some cases and nonexistent in others. Further, many of the existing studies did not provide a rigorous evaluation of the safety effects (i.e., several potential confounding factors were not considered). The simple before–after methodology, which was used in many of the evaluations, does not properly account for factors such as traffic volume changes, changes in crash reporting practices, and regression to the mean (RTM). The EB before–after methodology is the preferred method to account for the identified potential confounding factors. While a few of the evaluations employed the EB method, they generally lacked a robust treatment group (i.e., they were based on a limited sample or were limited to one jurisdiction). Finally, there were few studies that considered the implementation of the combination of the treatments of interest. Thus, additional research was warranted based on a more rigorous analysis of these treatments, especially research that would consider the effects of multiple low-cost strategies implemented in combination.

CHAPTER 3. OBJECTIVE

This research examined the safety impacts of multiple strategies implemented at signalized intersections throughout South 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, including K (fatal injury), A (incapacitating injury), B (non-incapacitating injury), and C (possible injury) as rated using the KABCO scale.
- Rear-end crashes (all severities combined).
- Right-angle crashes (all severities combined).
- Nighttime crashes (all severities combined).

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

- Do effects vary by area type (i.e., urban versus rural)?
- Do effects vary by approach configuration of intersection (i.e., three-legged versus four-legged)?
- Do effects vary by lane configuration of intersection (e.g., four mainline lanes and two cross-street lanes versus two mainline lanes and two cross-street lanes)?
- Do effects vary by traffic volume?
- Do effects vary by expected crashes?

The evaluation of overall effectiveness included the consideration of the installation costs and crash savings in terms of the benefit–cost (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 might be small changes in safety for some crash types.
- Identify appropriate untreated reference sites.
- Properly account for changes in safety due to changes in traffic volume and other factors unrelated to the strategy.

CHAPTER 4. 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.[18] The sample size analysis presented in this report 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 that the durations of the before and after periods were equal, which again, was were conservative assumptions.

Table 2 provides the crash rate assumptions. The locations of interest for this strategy were three- and four-legged, signalized intersections with two- and four-lane major roads. 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 a general estimate based on the reference sites identified for this study. Rates A and B represent rural and urban, four-legged, signalized intersections with two-lane major roads, respectively. Rates C and D represent rural and urban, signalized intersections with four-lane major roads, respectively.

Table 2. Before-period crash rate assumptions for four-legged signalized intersections in South Carolina.

Crash Type	Rate A Rural Signalized Intersections With Two-Lane Major Road	Rate B Urban Signalized Intersections With Two-Lane Major Road	Rate C Rural Signalized Intersections With Four-Lane Major Road	Rate D Urban Signalized Intersections With Four-Lane Major Road
Total	2.685	2.628	3.136	3.787
Injury	0.856	0.747	1.143	1.221
Rear-end	0.949	0.928	0.912	1.229
Right-angle	1.019	1.014	1.447	1.617

Crash Rate = crashes/intersection/year.

Table 3 and table 4 provide estimates of the minimum number of before and after period intersection-years for four-legged signalized intersections assuming that would be required for the four site types described above at both the 90- and 95-percent confidence levels. The minimum sample indicates the amount of data necessary to detect the safety effects with a desirable level of statistical significance. Larger safety effects require less data to achieve the same confidence level. These sample size calculations were based on specific assumptions regarding the number of crashes per intersection and years of available data. Intersection-years were the number of intersections where the strategy was implemented multiplied by the number of years of data before or after implementation. For example, if a strategy were implemented at nine intersections and data were available for 3 years since implementation, then there would be a total of 27 intersection-years of after period data available for the study. Note that the number of intersection-years was estimated by first estimating the required number of intersection-related crashes and then dividing by the appropriate intersection crash rate.

Table 3. Minimum required before-period intersection-years for treated sites at 95-percent confidence.

Crash Type	Expected Percent Reduction in Crashes	Number of Intersection-Years Type A	Type B	Type C	Type D
Total	10	691	706	592	490
Total	20	104	106	89	74
Total	30	35	36	30	25
Total	40	15	16	13	11
Fatal and injury	10	2,167	2,483	1,623	1,519
Fatal and injury	20	326	373	244	229
Fatal and injury	30	111	127	83	78
Fatal and injury	40	48	55	36	34
Rear-end	10	1,955	1,999	2,034	1,509
Rear-end	20	294	301	306	227
Rear-end	30	100	102	104	77
Rear-end	40	43	44	45	33
Right-angle	10	1,820	1,829	1,282	1,147
Right-angle	20	274	275	193	173
Right-angle	30	93	94	66	59
Right-angle	40	40	40	28	25

Note: Assumes equal number of site-years for treatment and comparison sites and equal length of before and after periods. Types A, B, C, and D represent four-legged intersection types. A represents rural, signalized intersections with two-lane major roads. B represents urban, signalized intersections with two-lane major roads. C represents rural, signalized intersections with four-lane major roads. D represents urban, signalized intersections with four-lane major roads.

Table 4. Minimum required before period intersection-years for treated sites at 90-percent confidence.

Crash Type	Number of Intersection-Years				
	Expected Percent Reduction in Crashes	Type A	Type B	Type C	Type D
Total	10	429	439	368	304
Total	20	72	73	62	51
Total	30	25	25	21	18
Total	40	11	11	9	8
Fatal and injury	10	1,347	1,544	1,009	944
Fatal and injury	20	225	258	169	158
Fatal and injury	30	78	90	59	55
Fatal and injury	40	34	39	25	24
Rear-end	10	1,215	1,242	1,264	938
Rear-end	20	203	208	212	157
Rear-end	30	71	72	73	55
Rear-end	40	31	31	32	24
Right-angle	10	1,132	1,137	797	713
Right-angle	20	189	190	133	119
Right-angle	30	66	66	46	41
Right-angle	40	28	29	20	18

Note: Assumes equal number of site-years for treatment and comparison sites and equal length of before and after periods. Types A, B, C, and D represent four-legged intersection types. A represents rural, signalized intersections with two-lane major roads. B represents urban, signalized intersections with two-lane major roads. C represents rural, signalized intersections with four-lane major roads. D represents urban, signalized intersections with four-lane major roads.

Case 2 considered the data collected for both the before and after periods. The statistical accuracy attainable for a given sample size was 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 5 through table 8. The calculations were based on the methodology in Hauer.[18] The tables indicate the total intersection-years of data available in the before and after period.

Table 5. Sample analysis for crash effects at rural two-lane intersections.

Crash Type	Intersection-Years in Before Period	Intersection-Years in After Period (Assumes 2-Year After Period for Each Site)	Minimum Percent Reduction Detectable for Crash Rate Assumption, *p* = 0.10*	Minimum Percent Reduction Detectable for Crash Rate Assumption, *p* = 0.05*
Total	705	282	10	15
Fatal and injury	705	282	15	20
Rear-end	705	282	15	20
Right-angle	705	282	15	20

Note: Results are to nearest 5-percent interval.
*Crash rate assumption is based on actual crash rate for the before period from table 2.

Table 6. Sample analysis for crash effects at urban two-lane intersections.

Crash Type	Intersection-Years in Before Period	Intersection-Years in After Period (Assumes 2-Year After Period for Each Site)	Minimum Percent Reduction Detectable for Crash Rate Assumption, *p* = 0.10*	Minimum Percent Reduction Detectable for Crash Rate Assumption, *p* = 0.05*
Total	705	282	10	15
Fatal and injury	705	282	15	20
Rear-end	705	282	15	20
Right-angle	705	282	15	20

Note: Results are to nearest 5-percent interval.
*Crash rate assumption is based on actual crash rate for the before period from table 2.

Table 7. Sample analysis for crash effects at rural four-lane intersections.

Crash Type	Intersection-Years in Before Period	Intersection-Years in After Period (Assumes 2-Year After Period for Each Site)	Minimum Percent Reduction Detectable for Crash Rate Assumption, *p* = 0.10*	Minimum Percent Reduction Detectable for Crash Rate Assumption, *p* = 0.05*
Total	705	282	10	10
Fatal and injury	705	282	15	15
Rear-end	705	282	15	20
Right-angle	705	282	15	15

Note: Results are to nearest 5-percent interval.
*Crash rate assumption is based on actual crash rate for the before period from table 2.

Table 8. Sample analysis for crash effects at urban four-lane intersections.

Crash Type	Intersection-Years in Before Period	Intersection-Years in After Period (Assumes 2-Year After Period for Each Site)	Minimum Percent Reduction Detectable for Crash Rate Assumption, *p* = 0.10*	Minimum Percent Reduction Detectable for Crash Rate Assumption, *p* = 0.05*
Total	705	282	10	10
Fatal and injury	705	282	15	15
Rear-end	705	282	15	15
Right-angle	705	282	15	15

Note: Results are to nearest 5-percent interval
*Crash rate assumption is based on actual crash rate for the before period from table 2.

Another strategy would be to estimate the level of significance (i.e., the *p*-value) for which a minimum desired effect can be detected. For instance, assume the minimum desired level of effect is 10 percent for total and target crashes. Based on the current knowledge of available data, table 9 indicates the *p*-value associated with a 10-percent change in crashes based on the before period data. These calculations used the crash rates from table 2. Given the existing sample size, it is likely this study can detect moderate treatment effects (e.g., a 10-percent change in total crashes) at the 10-percent level of significance.

Table 9. *p*-value for 10 percent change in crashes.

Crash Type	*p*-Value Rural Two-Lane	*p*-Value Urban Two-Lane	*p*-Value Rural Four-Lane	*p*-Value Urban Four-Lane
Total	0.11	0.11	0.09	0.07
Fatal and injury	0.33	0.36	0.27	0.25
Rear-end	0.31	0.31	0.32	0.25
Right-angle	0.29	0.29	0.22	0.20

REFERENCE SITE OVERVIEW

A reference group was required for the various intersection groups, including rural and urban, three- and four-legged, signalized intersections with two- and four-lane major roads. Each reference group should consist of untreated sites adjacent to or in the vicinity of the treated sites. The untreated sites in each reference group should have geometric, traffic, and crash data for the same years as treated sites. Each reference group should be similar to its corresponding treatment group—particularly in terms of area type (e.g., urban or rural), geometric configuration (e.g., number of legs and number of through lanes), and annual average daily traffic (AADT)—except that these intersections were not treated during the study period. Based on previous experience in similar analyses, the research team determined that at least 30 intersections for each intersection type in the reference group would be desirable, as shown in table 10. Where it is impractical or infeasible to obtain the required sample size for one or more intersection groups, it was possible to combine groups and account for the differences in the process of statistical model development.

Table 10. Reference groups and desirable sample sizes.

Number of Legs	Number of Through Lanes on Major Road	Rural	Urban	Total
3	Two-lane	30	30	60
3	Four-lane	30	30	60
4	Two-lane	30	30	60
4	Four-lane	30	30	60

Note: Sample included 120 urban sites and 120 rural sites for a total sample size of 240 sites.

CHAPTER 5. METHODOLOGY

This study employed the EB methodology for observational before–after studies. The EB method is considered rigorous in that it accounts for RTM bias using a reference group of similar but untreated sites. As a result, safety performance functions (SPFs) were developed and used in this study for the following reasons:

- They overcome the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- They can account for time trends. (The final SPFs did not use yearly indicator variables to account for time trend; more detailed discussions are provided in the section Before–After Adjustment Factors in chapter 7.)
- They reduce the level of uncertainty in the estimates of countermeasure effectiveness.
- They properly account for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.
- They provide 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, which relate 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 application of the EB procedure, a 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 a treatment 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. EB estimate of expected crashes.

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

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

Figure 4. Equation. EB weight.

Where *k* is the 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 treatment sites in each 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 treatment 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 6. DATA COLLECTION

SCDOT provided the majority of data for this study. The dataset included the following data elements:

- **Installation data**: SCDOT provided information related to treatment sites and start and completion dates for each improvement. SCDOT also provided the research team with work orders, drawings, and sketches for these locations. The research team used some of these additional data to verify the intersection configurations.

- **Reference site data**: SCDOT provided a list of intersections that had not been treated. The research team used these intersections as potential reference sites.

- **Traffic data**: SCDOT provided a statewide AADT data file for 2014. This file had information for almost all mainline routes and cross streets. The research team obtained additional AADT files for 2006 to 2014 from SCDOT's website. These publicly available files did not have all the details necessary. Many AADT for minor routes were missing. The research team used these files to calculate traffic growth factors and estimated AADTs for other years.

- **Crash data**: SCDOT provided the research team with crash data files for 2005 to 2014.

The research team collected additional data using Google® Earth™ and Google® Maps™.

INSTALLATION DATA

SCDOT administered the low-cost intersection improvements through the following two centralized contracts:

- All ground-level improvements, including all signing and pavement marking installations.
- All traffic signal improvements.

SCDOT provided the data in two separate files. The first included all installation data for the ground-level contract (918 locations). The other provided information on the work from the signal contract (158 locations). The improvements at signalized intersections included both ground-level and signal work. For this reason, the installation period often spanned 3 calendar years (e.g., the ground-level work began and was completed in 2010, and the signal work began later and was completed in 2012).

SCDOT assigned each intersection a unique identification number, where the location is determined by the following:

- County.
- Mainline route designation and number (e.g., US 25).
- Crossing route designation and number (e.g., SC 12).

The data files also included the following other related information:

- Work order number.

- Start and completion dates for each task (e.g., sign installation and signal installation) showing proposed signs and general intersection layout.

In addition to these two data files for ground-level and signal contracts, SCDOT also provided the research team with work orders and work plans from both ground-level and signal contracts. Each work plan provided a sketch of the intersection (including number of legs, lane configuration, and general geometric layout), as well as notes on proposed signs, markings, and other improvements.

Because the ground-level contract covered both the improvements at signalized and stop-controlled intersections, the first step was to separate signalized intersections from the file. Key pieces of information from this data file included county, route designations and numbers for both mainline and cross street (e.g., US 25, SC 12), start and completion dates of installation, number of lanes (e.g., two or four lanes on the mainlines, two lanes on the cross street), and area type (i.e., urban, rural).

The list with confirmed installation dates for signal improvements included 158 intersections. The research team merged the list from the ground-level contract with the signal contract to create a list of candidate treatment sites for signalized intersections.

The first step of processing the data was to convert route designation and number for both mainline and cross street into the following three identification codes:

- Route type code (i.e., US = 2, SC = 4, and S = 7).
- Route number.
- Route auxiliary (i.e., Mainline = 0, Alternate = 2, Business = 7).

These three identifiers would later be used to link the crash and traffic data files to each intersection. Once crash and traffic data were linked to each intersection, the research team summarized the number of crashes per year by type for each location.

The start and completion dates allowed the team to identify the before and after periods. Before- and after-periods included complete calendar years during which there was no installation activity. For example, if the work at a given intersection started at the ground level in December 2009 and the signal work was not completed until January 2011, 3 full calendar years (2009, 2010, and 2011) were considered installation years and removed from the dataset. The before period in this research was from 2005 (the first year of available data) to 2008 (the last full year of no construction activity). Similarly, the after period was from 2012 to 2014 (the last year of available data).

The result of this process was a list of signalized intersections with location identifiers in a uniform format across different data files. This list included the before and after periods. These intersections were candidates for the treatment group used in the EB evaluation. The team checked all work orders and work plans to collect the number of legs and verify the number of lanes for each intersection. Figure 7 shows an example of this process with the four-legged intersection between S-2 and S-65 in Spartanburg County, collected from the work plan for Work

Order #4. The research team performed a manual process of verifying candidate intersections in Google® Earth™ (i.e., visual verification) to select the final treatment group.

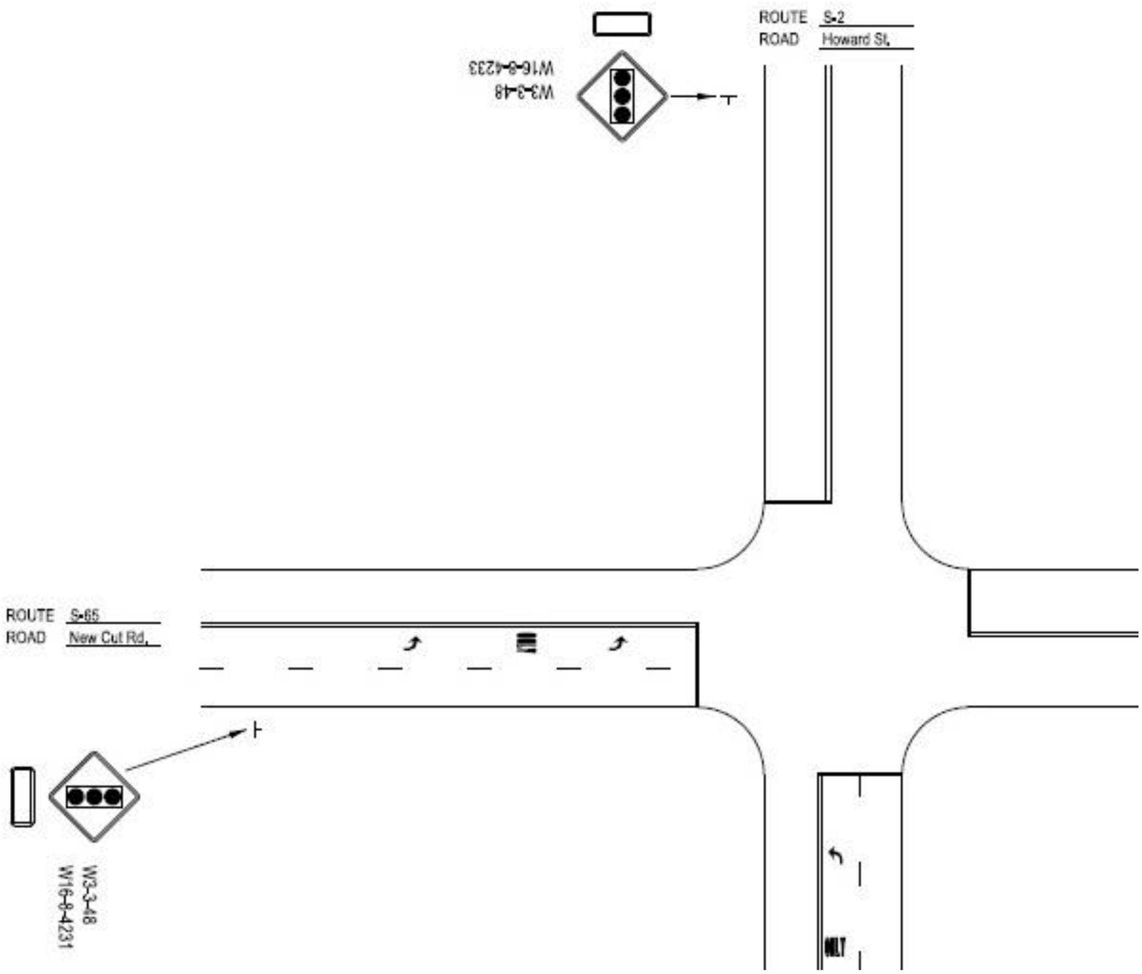


Figure 7. Illustration. Collecting the number of legs and verifying the number of lanes from the work plan.

Following SCDOT's advice, the research team decided to exclude all intersections in Beaufort County because there were some changes in route names and numbers in this county that could have led to inaccurate matching of traffic and crash data.

REFERENCE SITES

SCDOT provided the research team with a list of more than 3,000 intersections—both stop-controlled and signalized—for reference sites. Similar to the installation data, this list of intersections included key location identifiers (e.g., county, route designations, and numbers) and intersection characteristics (e.g., number of lanes on the mainline and cross street, area type, and type of traffic control). Therefore, the research team followed similar steps to process the raw data. The route identifiers were converted to a common format to link crash and traffic data for each intersection from different files. However, this data file did not provide the number of legs, a key variable for these potential reference sites.

The research team decided to collect the number of legs using Google® Earth™ and Google® Maps™. It was infeasible to locate and collect the number of legs from Google® Earth™ for every intersection because of resource constraints. Instead, the team randomly sampled at least 30 intersections for each group from the pool of candidate reference sites and took the following steps:

- **Step 1**: Separate the pool of signalized intersections into different categories using the available information (e.g., rural intersections with two lanes on the mainline and two lanes on the cross street, urban intersections with four lanes on the mainline).

- **Step 2**: Randomize the order in each intersection category using a random number generator.

- **Step 3**: Start from the top of the list for each category, locate the intersection in Google® Maps™ and Google® Earth™, determine the number of legs, and verify the number of lanes.

The research team repeated these steps until there were at least 30 sites for each group (e.g., three-legged, rural intersections with two mainline lanes and two cross-street lanes). In two cases, the total number of intersections in the candidate pools was approximately 30 sites. (The rural 2 x 2 category had 28 candidate locations, and the rural 4 x 2 category had 33 candidate locations.) In these two cases, the research team reviewed all sites and retained as many as possible.

TRAFFIC DATA

SCDOT provided the research team with a statewide traffic volume data file for 2014. The research team merged data in this file with both candidate treatment and reference sites. This data file had more details with AADT information for both mainline and cross streets for most intersections. The research team made a request, but SCDOT was not able to provide similar data for other years. With SCDOT's advice, the research team downloaded AADT files for 2006 to 2014 publicly available on SCDOT's website. However, these data files were much less detailed than the 2014 file the team received from SCDOT staff. AADT information from these files was not available for many mainline streets at the studied intersections and at a majority of intersection cross streets. The research team used these data files to create growth factors by county. The research team used the growth factors and the detailed 2014 data file to estimate AADT information for 2006 to 2013. AADT for 2005 was not available from SCDOT's website, so the team extrapolated 2005 AADT based on data for 2006 to 2008. If AADT for either the mainline or cross street was still missing after the data processing, the team dropped that intersection from the pools of treatment or reference sites.

CRASH DATA

SCDOT provided 10 years of crash data (2005 to 2014). A unique accident number (i.e., an "ano") identifies each crash in the data files. A combination of the following variables was used to identify the location of each crash:

- County number (e.g., 1 = Abbeville, 2 = Aiken, 3 = Allendale).
- Route type code (e.g., 2 = US, 4 = SC, and 7 = S).
- Route number.
- Route auxiliary (e.g., 0 = Mainline, 2 = Alternate, 7 = Business).
- Crossing route type code (2 = US, 4 = SC, and 7 = S).
- Crossing route number.
- Crossing route auxiliary (e.g., 0 = Mainline, 2 = Alternate, 7 = Business).
- Base distance offset from the intersection (e.g., 1 = 0.01 mi, 5 = 0.05 mi, 10 = 0.1 mi).

Note that the team used crossing route, in this context, as a reference point, and the offset determined the distance from that reference point to the crash location. Route and crossing route, in crash data files, did not necessarily mean the mainline and minor routes in the same context of an intersection. The route indicated the roadway on which the crash occurred, and the crossing route indicated the crossing street at the nearest intersection (reference point). Both could be the mainline or the minor roads of the intersection used as the reference point.

The research team screened crash location information to identify and count crashes at each intersection. The crash data files did not provide a specific code to determine intersection-related crashes. Therefore, the process of locating and counting crashes at each intersection relied solely on crash location. As recommended by SCDOT staff, the research team considered a crash intersection-related and counted it toward the number of crashes at an intersection if the location information indicated the crash along a particular mainline or cross street occurred within 0.05 mi (264 ft) of the intersection.

The research team used the number of fatalities and injuries coded for each crash to determine crash severity. The manner of collision determined rear-end and right-angle crashes. Light condition information was also available and identified nighttime crashes.

Table 11 presents the crash type definitions for South Carolina crash data.

Table 11. Definitions of crash types.

Total	Fatal and Injury	Rear-End	Right-Angle	Nighttime
Crashes of all types and severity levels	One of the following conditions: • At least one fatality (fat ≥ 1) • At least one injury (inj ≥ 1)	Manner of collision coded as "rear-end" (rims_mac = 10)	Manner of collision coded as "Angle 1" (rims_mac = 41), "Angle 2" (rims_mac = 42), or "Angle 3" (rims_mac = 43)	Light condition coded as anything other than "Daylight" (alc = 1)

TREATMENT COST DATA

SCDOT provided actual construction cost data for improvements at signalized intersections. Intersection construction costs were separated into subtotal pavement marking, signing, signal, and pedestrian-related treatment costs. Each intersection received a package of those treatments appropriate for implementation at the site from the list of potential treatments. The treatment costs varied at each intersection based on the unique package of treatments it received. Table 12 summarizes the marking and signing costs.

Table 12. Treatment cost summary.

Statistic	Pavement Marking	Signing	Total
Minimum	$384.34	$382.58	$552.45
Average	$4,696.33	$2,753.60	$6,958.70
Maximum	$19,042.12	$19,498.44	$29,740.51

Note that some intersections only received pavement marking or signing improvements, but all intersections had at least some treatments installed.

The signal improvements included upgrades such as installing retroreflective backplates, adding signal heads, and replacing signal heads. Some intersections also had pedestrian signals installed. These improvements were in addition to the marking and signing countermeasures. Costs for signal upgrades were provided as a typical cost quote. A typical signal head replacement, which included replacing eight signal heads, adding retroreflective borders on backplates, installing new electric service hardware, and installing overhead signs on the span wires, was quoted at $13,300. Pedestrian signal heads and poles with push-button assemblies were estimated at $18,300 per intersection with a $1,680 present value maintenance cost to change lamps every 3.5 years. *Americans with Disabilities Act*–compliant curb ramps were estimated at $2,500 each.

Maintenance costs were dependent on the countermeasures installed at a given intersection. Without a record of the countermeasures installed at each intersection, it was difficult to estimate maintenance costs and service life. In addition, preliminary engineering (PE) costs were not supplied by SCDOT. PE costs often represent 10 to 30 percent of the total project costs for systemic projects.

DATA CHARACTERISTICS AND SUMMARY

Table 13 and table 14 provide summary information for the data collected for the treatment and reference sites, respectively. The information in table 13 should not be used to make simple before–after comparisons of crashes per site-year because it does not account for factors, other than the strategy, that 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 13. Summary of treatment sites.

Data Element	Before Period	After Period
Number of sites	84	84
Three-legged, two lanes on the mainline and two lanes on the cross street	5	5
Four-legged, two lanes on the mainline and two lanes on the cross street	15	15
Three-legged, four lanes on the mainline and two lanes on the cross street	9	9
Four-legged, four lanes on the mainline and two lanes on the cross street	55	55
Number of site-years	411	209
Total crashes	5,132	2,675
Fatal and injury crashes	1,278	551
Right-angle crashes	2,061	921
Rear-end crashes	2,136	1,349
Nighttime crashes	1,263	581
Maximum mainline AADT	39,037	41,100
Average mainline AADT	20,668	20,447
Minimum mainline AADT	4,272	4,270
Maximum minor road AADT	18,970	20,000
Average minor road AADT	5,972	5,864
Minimum minor road AADT	115	111

Table 14. Summary of reference sites.

Data Element	Value
Number of sites	368
Number of site-years	3,680
Total crashes	11,365
Fatal and injury crashes	3,457
Right-angle crashes	4,538
Rear-end crashes	4,102
Nighttime crashes	2,473
Maximum mainline AADT	48,308
Average mainline AADT	12,146
Minimum mainline AADT	1,563
Maximum minor road AADT	18,893
Average minor road AADT	3,393
Minimum minor road AADT	113

CHAPTER 7. DEVELOPMENT OF SPFs

This section presents the SPFs developed for each crash type. The SPFs support the use of the EB methodology to estimate the safety effectiveness of a strategy.(18) The research team estimated negative binomial regression models to predict the number of crashes. In specifying a negative binomial error structure, the dispersion parameter, *k*, was estimated iteratively from the model and the data. For a given dataset, smaller values of *k* indicate relatively better models. The research team developed one SPF for each of the following intersection configurations:

- **3 x 22**: Three-legged intersections with two lanes on the mainline and two lanes on the cross street.
- **4 x 22**: Four-legged intersections with two lanes on the mainline and two lanes on the cross street.
- **3 x 42**: Three-legged intersections with four lanes on the mainline and two lanes on the cross street.
- **4 x 42**: Four-legged intersections with four lanes on the mainline and two lanes on the cross street.

The research team developed correlation matrices for variables and used them as a guide for the SPF development process, which helped avoid highly correlated variables in the models. The model development followed a process of forward selection for selecting variables with the best fit. The team started with mainline and cross-street traffic volumes and their variants (e.g., natural logarithm and ratio of cross-street AADT to mainline AADT). Other candidate explanatory variables were then added, one by one, to the model. The model was reestimated, and the goodness of fit was reevaluated with each variable addition.

The research team initially included annual adjustment variables (i.e., indicators for years 2005 to 2014) in the SPFs during the first iteration of model development. However, most of these variables did not result in statistically significant parameters or help improve the fit of the SPFs. The inclusion of annual adjustment variables also led to heavily underpredicted crashes for some years (i.e., small coefficients on the negative side and far from being well fit), especially for the later years that covered the after period. The team eventually decided to drop these annual adjustment variables from the models and considered another approach to account for the annual trend (discussed later in this chapter).

In some cases, the research team could not develop an adequate model for a specific crash type. In these cases, the team used the SPF for total crashes and adjusted by the proportion of the number of crashes for the given crash type in total crashes.

The definition of variables included in the final SPFs are as follows:

- $\boldsymbol{Total_{axbc}}$: The predicted number of total crashes (all types and severity levels) for an intersection with *a* legs, *b* lanes on the mainline, and *c* lanes on the cross street (e.g., 3 x

42 for three-legged intersections with four lanes on the mainline and two lanes on the cross street).

- ***FI_{axbc}***: The predicted number of fatal and injury crashes for an intersection with *a* legs, *b* lanes on the mainline, and *c* lanes on the cross street.

- ***$Rear\text{-}End_{axbc}$***: The predicted number of rear-end crashes for an intersection with *a* legs, *b* lanes on the mainline, and *c* lanes on the cross street.

- ***$Right\text{-}Angle_{axbc}$***: The predicted number of right-angle crashes for an intersection with *a* legs, *b* lanes on the mainline, and *c* lanes on the cross street.

- ***$Night_{axbc}$***: The predicted number of nighttime crashes for an intersection with *a* legs, *b* lanes on the mainline, and *c* lanes on the cross street.

- ***aadt***: *ml_aadt* + *xst_aadt*, total traffic of intersection (vehicles/day).

- ***ml_aadt***: AADT on the mainline (vehicles/day).

- ***xst_aadt***: AADT on the cross street (vehicles/day).

- ***ratio1***: *ln*(*xst_aadt*)/*ln*(*ml_aadt*), with *ln*(*xst_aadt*) being the natural logarithm of AADT on the cross street and *ln*(*ml_aadt*) being the natural logarithm of AADT on the mainline.

- ***ratio2***: *xst_aadt*/*ml_aadt*, with *xst_aadt* and *ml_aadt* being the AADT on cross street and mainline, respectively.

- ***ratio3***: *xst_aadt*/(*xst_aadt* + *ml_aadt*), with *xst_aadt* and *ml_aadt* being the AADT on the cross street and mainline, respectively.

- ***ratio4***: *ln*(*xst_aadt*)/*ln*(*xst_aadt* + *ml_aadt*), with ln(*xst_aadt*) being the natural logarithm of AADT on the cross street and ln(*xst_aadt* + *ml_aadt*) being the natural logarithm of total traffic at the intersection.

- ***Urban***: Urban/rural indicator for the intersection (1 for urban, 0 otherwise).

- $\boldsymbol{\beta_1, \beta_2, \beta_3, \beta_4}$: Parameters estimated in the SPF development process using maximum likelihood method.

- ***k***: Overdispersion parameter.

SPFs FOR 3 X 22 INTERSECTIONS

The SPF for total crashes at three-legged intersections with two lanes on the mainline and two lanes on the cross street has the form shown in figure 8.

$$Total_{3\times22} = ml\_aadt^{\beta_1} \times xst\_aadt^{\beta_2} \times e^{(\beta_3\times urban\ +\beta_4)}$$

Figure 8. Equation. Total crash SPF for 3 x 22 intersections.

Table 15 presents the total crash SPF parameters for three-legged intersections with two lanes on the mainline and two lanes on the cross street.

Table 15. SPF parameters for total crashes at 3 x 22 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for mainline AADT	0.372	0.111
β_2	Coefficient for cross-street AADT	0.141	0.053
β_3	Coefficient for urban/rural indicator	0.304	0.149
β_4	Intercept term	−3.887	0.986
k	Overdispersion parameter	0.166	0.042

The research team could not develop a statistically significant model for fatal and injury crashes. The SPF for total crashes was used with an adjustment factor to predict fatal and injury crashes for three-legged intersections with two lanes on the mainline and two lanes on cross street.

The SPF for rear-end crashes at three-legged intersections with two lanes on the mainline and two lanes on the cross street has the form shown in figure 9.

$$Rear\ End_{3\times22} = ml\_aadt^{\beta_1} \times e^{(\beta_3\times urban\ +\beta_4)}$$

Figure 9. Equation. Rear-end crash SPF for 3 x 22 intersections.

Table 16 presents the rear-end crash SPF parameters for three-legged intersections with two lanes on the mainline and two lanes on the cross street.

Table 16. SPF parameters for rear-end crashes at 3 x 22 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for mainline AADT	0.687	0.157
β_3	Coefficient for urban/rural indicator	0.265	0.208
β_4	Intercept term	−6.403	1.409
k	Overdispersion parameter	0.367	0.096

The SPF for right-angle crashes at three-legged intersections with two lanes on the mainline and two lanes on the cross street has the form shown in figure 10.

$$Right\ Angle_{3\times22} = ml\_aadt^{\beta_1} \times e^{(\beta_2\times ratio\ 4+\beta_3\times urban\ +\beta_4)}$$

Figure 10. Equation. Right-angle crash SPF for 3 x 22 intersections.

Table 17 presents the right-angle crash SPF parameters for three-legged intersections with two lanes on the mainline and two lanes on the cross street.

Table 17. SPF parameters for right-angle crashes at 3 x 22 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for mainline AADT	0.512	0.197
β_2	Coefficient for *ratio4* = *ln*(*xst_aadt*)/*ln*(*xst_aadt* + *ml_aadt*)	3.898	1.249
β_3	Coefficient for urban/rural indicator	0.476	0.291
β_4	Intercept term	−8.863	2.198
k	Overdispersion parameter	0.198	0.123

The SPF for nighttime crashes at three-legged intersections with two lanes on the mainline and two lanes on the cross street has the form shown in figure 11.

$$Night_{3\times22} = ml\_aadt^{\beta_1} \times e^{(\beta_2 \times ratio\,4 + \beta_4)}$$

Figure 11. Equation. Nighttime crash SPF for 3 x 22 intersections.

Table 18 presents the nighttime crash SPF parameters for three-legged intersections with two lanes on the mainline and two lanes on the cross street.

Table 18. SPF parameters for nighttime crashes at 3 x 22 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for mainline AADT	0.675	0.194
β_2	Coefficient for *ratio4* = *ln*(*xst_aadt*)/*ln*(*xst_aadt* + *ml_aadt*)	4.355	1.340
β_4	Intercept term	−10.501	2.272
k	Overdispersion parameter	0.215	0.157

SPFs FOR 4 X 22 INTERSECTIONS

The SPF for total crashes at four-legged intersections with two lanes on the mainline and two lanes on the cross street has the form shown in figure 12.

$$Total_{4\times22} = ml\_aadt^{\beta_1} \times xst\_aadt^{\beta_2} \times e^{(\beta_3 \times urban + \beta_4)}$$

Figure 12. Equation. Total crash SPF for 4 x 22 intersections.

Table 19 presents the total crash SPF parameters for four-legged intersections with two lanes on the mainline and two lanes on the cross street.

Table 19. SPF parameters for total crashes at 4 x 22 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for mainline AADT	0.556	0.049
β_2	Coefficient for cross-street AADT	0.168	0.032
β_3	Coefficient for urban/rural indicator	−0.154	0.068
β_4	Intercept term	−5.301	0.497
k	Overdispersion parameter	0.234	0.029

The SPF for fatal and injury crashes at four-legged intersections with two lanes on the mainline and two lanes on the cross street has the form shown in figure 13.

$$FI_{4\times22} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\ 4 + \beta_4)}$$

Figure 13. Equation. Fatal and injury crash SPF for 4 x 22 intersections.

Table 20 presents the fatal and injury crash SPF parameters for four-legged intersections with two lanes on the mainline and two lanes on the cross street.

Table 20. SPF parameters for fatal and injury crashes at 4 x 22 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT	0.242	0.091
β_2	Coefficient for *ratio4* = *ln*(*xst_aadt*)/*ln*(*xst_aadt* + *ml_aadt*)	1.197	0.584
β_4	Intercept term	−3.683	1.015
k	Overdispersion parameter	0.242	0.081

The SPF for rear-end crashes at four-legged intersections with two lanes on the mainline and two lanes on the cross street has the form shown in figure 14.

$$Rear\ End_{4\times22} = ml\_aadt^{\beta_1} \times xst\_aadt^{\beta_2} \times e^{(\beta_3 \times urban\ + \beta_4)}$$

Figure 14. Equation. Rear-end crash SPF for 4 x 22 intersections.

Table 21 presents the rear-end crash SPF parameters for four-legged intersections with two lanes on the mainline and two lanes on the cross street.

Table 21. SPF parameters for rear-end crashes at 4 x 22 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for mainline AADT	0.855	0.085
β_2	Coefficient for cross-street AADT	0.242	0.054
β_3	Coefficient for urban/rural indicator	−0.157	0.116
β_4	Intercept term	−9.583	0.846
k	Overdispersion parameter	0.629	0.089

The SPF for right-angle crashes at four-legged intersections with two lanes on the mainline and two lanes on the cross street has the form shown in figure 15.

$$Right\ Angle_{4\times 22} = ml\_aadt^{\beta_1} \times xst\_aadt^{\beta_2} \times e^{(\beta_3 \times urban\ + \beta_4)}$$

Figure 15. Equation. Right-angle crash SPF for 4 x 22 intersections.

Table 22 presents the right-angle crash SPF parameters for four-legged intersections with two lanes on the mainline and two lanes on the cross street.

Table 22. SPF parameters for right-angle crashes at 4 x 22 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for mainline AADT	0.385	0.071
β_2	Coefficient for cross-street AADT	0.153	0.048
β_3	Coefficient for urban/rural indicator	−0.154	0.097
β_4	Intercept term	−4.547	0.719
k	Overdispersion parameter	0.357	0.064

The SPF for nighttime crashes at four-legged intersections with two lanes on the mainline and two lanes on the cross street has the form shown in figure 16.

$$Night_{4\times 22} = ml\_aadt^{\beta_1} \times xst\_aadt^{\beta_2} \times e^{\beta_4}$$

Figure 16. Equation. Nighttime crash SPF for 4 x 22 intersections.

Table 23 presents the nighttime crash SPF parameters for four-legged intersections with two lanes on the mainline and two lanes on the cross street.

Table 23. SPF parameters for nighttime crashes at 4 x 22 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for mainline AADT	0.541	0.091
β_2	Coefficient for cross-street AADT	0.117	0.060
β_4	Intercept term	−6.417	0.925
k	Overdispersion parameter	0.364	0.109

SPFs FOR 3 X 42 INTERSECTIONS

The SPF for total crashes at three-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 17.

$$Total_{3\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\,3 + \beta_3 \times urban + \beta_4)}$$

Figure 17. Equation. Total crash SPF for 3 x 42 intersections.

Table 24 presents the total crash SPF parameters for three-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 24. SPF parameters for total crashes at 3 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross-street AADT)	0.463	0.123
β_2	Coefficient for *ratio3* = *xst_aadt*/(*xst_aadt* + *ml_aadt*)	1.550	0.287
β_3	Coefficient for urban/rural indicator	−0.243	0.116
β_4	Intercept	−3.491	1.215
k	Overdispersion parameter	0.202	0.035

The SPF for fatal & injury crashes at three-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 18.

$$FI_{3\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\,3 + \beta_3 \times urban + \beta_4)}$$

Figure 18. Equation. Fatal & injury crash SPF for 3 x 42 intersections.

Table 25 presents the fatal and injury crash SPF parameters for three-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 25. SPF parameters for fatal and injury crashes at 3 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross-street AADT)	0.350	0.195
β_2	Coefficient for *ratio3* = *xst_aadt*/(*xst_aadt* + *ml_aadt*)	1.364	0.461
β_3	Coefficient for urban/rural indicator	−0.293	0.180
β_4	Intercept term	−3.534	1.929
k	Overdispersion parameter	0.247	0.093

The SPF for rear-end crashes at three-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 19.

$$Rear\ End_{3\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\ 4 + \beta_3 \times urban\ + \beta_4)}$$

Figure 19. Equation. Rear-end crash SPF for 3 x 42 intersections.

Table 26 presents the rear-end crash SPF parameters for three-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 26. SPF parameters for rear-end crashes at 3 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross-street AADT)	0.563	0.164
β_2	Coefficient for *ratio4* = *ln*(*xst_aadt*)/*ln*(*xst_aadt* + *ml_aadt*)	1.538	0.557
β_3	Coefficient for urban/rural indicator	−0.453	0.154
β_4	Intercept term	−6.156	1.770
k	Overdispersion parameter	0.230	0.075

The SPF for right-angle crashes at three-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 20.

$$Right\ Angle_{3\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\ 2 + \beta_4)}$$

Figure 20. Equation. Right-angle crash SPF for 3 x 42 intersections.

Table 27 presents the right-angle crash SPF parameters for three-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 27. SPF parameters for right-angle crashes at 3 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross-street AADT)	0.283	0.201
β_2	Coefficient for *ratio2 = xst_aadt/ml_aadt*	1.049	0.254
β_4	Intercept term	−2.970	1.998
k	Overdispersion parameter	0.487	0.099

The SPF for nighttime crashes at three-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 21.

$$Night_{3\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\,3 + \beta_3 \times urban\, + \beta_4)}$$

Figure 21. Equation. Nighttime crash SPF for 3 x 42 intersections.

Table 28 presents the nighttime crash SPF parameters for three-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 28. SPF parameters for nighttime crashes at 3 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross-street AADT)	0.277	0.231
β_2	Coefficient for *ratio3 = ln*(*xst_aadt*)/*ln*(*xst_aadt + ml_aadt*)	1.467	0.549
β_3	Coefficient for urban/rural indicator	−0.340	0.209
β_4	Intercept term	−3.080	2.293
k	Overdispersion parameter	0.445	0.140

SPFs FOR 4 X 42 INTERSECTIONS

The SPF for total crashes at four-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 22.

$$Total_{4\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\,2 + \beta_3 \times urban\, + \beta_4)}$$

Figure 22. Equation. Total crash SPF for 4 x 42 intersections.

Table 29 presents the total crash SPF parameters for four-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 29. SPF parameters for total crashes at 4 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross street-AADT)	0.932	0.043
β_2	Coefficient for *ratio2 = xst_aadt/ml_aadt*	0.822	0.089
β_3	Coefficient for urban/rural indicator	−0.169	0.067
β_4	Intercept term	−7.880	0.409
k	Overdispersion parameter	0.345	0.022

The SPF for fatal and injury crashes at four-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 23.

$$FI_{4\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\,2 + \beta_3 \times urban\, + \beta_4)}$$

Figure 23. Equation. Fatal and injury crash SPF for 4 x 42 intersections.

Table 30 presents the fatal and injury crash SPF parameters for four-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 30. SPF parameters for fatal and injury crashes at 4 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross-street AADT)	0.892	0.063
β_2	Coefficient for *ratio2 = xst_aadt/ml_aadt*	1.112	0.128
β_3	Coefficient for urban/rural indicator	−0.235	0.099
β_4	Intercept term	−8.641	0.599
k	Overdispersion parameter	0.471	0.049

The SPF for rear-end crashes at four-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 24.

$$Rear\ End_{4\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\,2 + \beta_4)}$$

Figure 24. Equation. Rear-end crash SPF for 4 x 42 intersections.

Table 31 presents the rear-end crash SPF parameters for four-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 31. SPF parameters for rear-end crashes at 4 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross-street AADT)	1.287	0.065
β_2	Coefficient for *ratio2 = xst_aadt/ml_aadt*	0.447	0.136
β_4	Intercept term	−12.538	0.642
k	Overdispersion parameter	0.578	0.054

The SPF for right-angle crashes at four-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 25.

$$Right\ Angle_{4\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\ 2 + \beta_3 \times urban\ + \beta_4)}$$

Figure 25. Equation. Right-angle crash SPF for 4 x 42 intersections.

Table 32 presents the right-angle crash SPF parameters for four-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 32. SPF parameters for right-angle crashes at 4 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross-street AADT)	0.747	0.056
β_2	Coefficient for *ratio2 = xst_aadt/ml_aadt*	1.096	0.116
β_3	Coefficient for urban/rural indicator	−0.242	0.088
β_4	Intercept term	−6.933	0.535
k	Overdispersion parameter	0.439	0.040

The SPF for nighttime crashes at four-legged intersections with four lanes on the mainline and two lanes on the cross street has the form shown in figure 26.

$$Night_{4\times42} = aadt^{\beta_1} \times e^{(\beta_2 \times ratio\ 2 + \beta_3 \times urban\ + \beta_4)}$$

Figure 26. Equation. Nighttime crash SPF for 4 x 42 intersections.

Table 33 presents the nighttime crash SPF parameters for four-legged intersections with four lanes on the mainline and two lanes on the cross street.

Table 33. SPF parameters for nighttime crashes at 4 x 42 intersections.

Parameter	Description	Estimated Value	Standard Error
β_1	Coefficient for total intersection AADT (= mainline AADT + cross-street AADT)	1.123	0.074
β_2	Coefficient for *ratio3* = *xst_aadt*/(*xst_aadt* + *ml_aadt*)	1.106	0.151
β_3	Coefficient for urban/rural indicator	−0.211	0.123
β_4	Intercept term	−11.341	0.712
k	Overdispersion parameter	0.560	0.071

BEFORE–AFTER ADJUSTMENT FACTORS

SPFs often account for time trend, as discussed in the first section of chapter 5. In this study, however, the SPFs did not include yearly indicator variables because, after numerous attempts, the research team could not achieve a reasonable level of statistical significance for these individual variables. The research team decided to account for the time trend by using a before–after adjustment factor. Instead of using one annual adjustment factor for each year, the research team made the decision to use adjustment factors to account for the difference (i.e., crash trend) between the before and after periods. These factors were calculated based on the observed and predicted crashes at the reference sites. Because SCDOT did not install the treatment at all sites in the same year, the installation periods varied. For this reason, the team calculated one adjustment factor for each installation period. The before–after adjustment factor was calculated as shown in figure 27.

$$Adj\_Factor = \frac{\frac{Obs_{after}}{Pred_{after}}}{\frac{Obs_{before}}{Pred_{before}}}$$

Figure 27. Equation. Before–after adjustment factor calculation.

Where:

Adj_Factor = factor for adjusting the difference between the before and after period.
$Obs_{\_before}$ = observed number of crashes at reference sites during before period.
$Pred_{before}$ = predicted number of crashes at reference sites during before period (calculated by SPF).
$Obs_{\_after}$ = observed number of crashes at reference sites during after period.
$Pred_{after}$ = predicted number of crashes at reference sites during after period (calculated by SPF).

Table 34 through table 38 present the before–after adjustment factors for each installation time frame and crash type.

Table 34. Before–after adjustment factor for total crashes.

Installation Year(s)	Observed Crashes—Before	Observed Crashes—After	Predicted Crashes —Before	Predicted Crashes—After	Adjustment Factor
2009–2011	4,542	3,619	4,560	3,389	1.072
2010–2011	5,672	3,619	5,679	3,389	1.069
2010–2012	5,672	2,519	5,679	2,251	1.120
2011	6,774	3,619	6,801	3,389	1.072

Table 35. Before–after adjustment factor for fatal and injury crashes.

Installation Year(s)	Observed Crashes—Before	Observed Crashes—After	Predicted Crashes—Before	Predicted Crashes—After	Adjustment Factor
2009–2011	1,448	1,035	1,388	1,032	0.962
2010–2011	1,794	1,035	1,730	1,032	0.967
2010–2012	1,794	701	1,730	686	0.986
2011	2,149	1,035	2,072	1,032	0.967

Table 36. Before–after adjustment factor for rear-end crashes.

Installation Year(s)	Observed Crashes—Before	Observed Crashes—After	Predicted Crashes—Before	Predicted Crashes—After	Adjustment Factor
2009–2011	1,534	1,431	1,652	1,225	1.259
2010–2011	1,895	1,431	2,055	1,225	1.267
2010–2012	1,895	1,000	2,055	812	1.335
2011	2,260	1,431	2,459	1,225	1.271

Table 37. Before–after adjustment factor for right-angle crashes.

Installation Year(s)	Observed Crashes—Before	Observed Crashes—After	Predicted Crashes—Before	Predicted Crashes—After	Adjustment Factor
2009–2011	1,928	1,397	1,819	1,354	0.973
2010–2011	2,355	1,397	2,267	1,354	0.993
2010–2012	2,355	979	2,267	900	1.047
2011	2,787	1,397	2,717	1,354	1.006

Table 38. Before–after adjustment factor for nighttime crashes.

Installation Year(s)	Observed Crashes—Before	Observed Crashes—After	Predicted Crashes—Before	Predicted Crashes—After	Adjustment Factor
2009–2011	1,034	741	992	736	0.966
2010–2011	1,313	741	1,235	736	0.947
2010–2012	1,313	507	1,235	489	0.976
2011	1,535	741	1,479	736	0.970

CHAPTER 8. BEFORE–AFTER EVALUATION RESULTS

This chapter presents the evaluation results, both the aggregate results for all intersections and the results disaggregated by area type, intersection configuration, level of traffic, and the expected number of crashes in the before period.

AGGREGATE ANALYSIS

Table 39 provides the estimates of expected crashes in the after period without treatment, the observed crashes in the after period, and the estimated crash modification factor (CMF) and its standard error for each crash type considered in this study. The results in table 39 indicate reductions for all crash types analyzed in this study. The CMFs for fatal and injury and right-angle crashes were 0.893 and 0.883, respectively, which were statistically significant at the 95-percent confidence level. The CMFs for total, rear-end, and nighttime crashes were 0.955, 0.974, and 0.969, respectively. The CMFs for total, rear-end, and nighttime crashes were not statistically significant at the 95-percent confidence level, but the CMF for total crashes was statistically significant at the 90-percent confidence level.

Table 39. Aggregate results for EB before-after study.

Statistic	Total	Fatal and Injury	Rear-End	Right-Angle	Nighttime
EB estimate of crashes expected in the after period without the systemic improvement	2,801	617	1,385	1,042	599
Count of crashes observed in the after period	2,675	551	1,349	921	581
Estimated CMF	0.955	**0.893**	0.974	**0.883**	0.969
Standard error of the estimated CMF	0.023	0.045	0.034	0.035	0.048

Note: Boldface indicates statistically significant results at the 95-percent confidence level.

DISAGGREGATE ANALYSIS

The objective of disaggregate analyses was to identify specific CMFs by crash type and different conditions. The analysis also revealed those conditions under which the studied combination of multiple low-cost treatments were more effective. The research team identified several variables of interest, including area type (urban or rural), number of legs (three or four), lane configuration of the mainline and the cross street, and traffic volumes. All of these variables are likely correlated, and caution should be exercised in interpreting and applying the disaggregate analysis results.

Table 40 presents the disaggregate results by area type (urban or rural), indicating the sample size (number of sites), CMF, and standard error of the CMF (in parentheses) by group for each crash type considered in this study. For the 58 urban intersections, the results in table 40 indicate reductions in all crash types analyzed in this study. Specifically, the CMFs for total, fatal and injury, and right-angle crashes were 0.949, 0.854, and 0.884, respectively, and statistically significant at the 95-percent confidence level. The CMFs for rear-end and nighttime crashes were 0.960 and 0.974, respectively, and were not statistically significant at the 95-percent confidence level. For the 26 rural intersections, the results in table 40 indicate reductions for total, right-angle, and nighttime crashes. The results indicate increases in fatal and injury and rear-end crashes. Note the results for rural intersections were not statistically significant at the 95-percent confidence level. Based on the disaggregate analysis by area type, it appears the combination of these multiple treatments was more effective at urban intersections than rural intersections. However, as noted above, this effect may be due to other correlated variables.

Table 40. Disaggregate results by area type.

Statistic	Urban	Rural
Number of intersections	58	26
Total crash CMF (standard error)	**0.949** (0.025)	0.983 (0.058)
Fatal and injury crash CMF (standard error)	**0.854** (0.048)	1.054 (0.113)
Rear-end CMF (standard error)	0.960 (0.036)	1.060 (0.097)
Right-angle CMF (standard error)	**0.884** (0.038)	0.878 (0.082)
Nighttime CMF (standard error)	0.974 (0.053)	0.938 (0.112)

Note: Boldface indicates statistically significant results at the 95-percent confidence level.

Table 41 presents the disaggregate results by number of legs, indicating the sample size (number of sites), CMF, and standard error of the CMF (in parentheses) by group for each crash type considered in this study. For the 14 three-legged intersections, the results in table 41 indicate reductions in total, fatal and injury, rear-end, and right-angle crashes. The CMFs for total and rear-end crashes were 0.860 and 0.822, respectively, and statistically significant at the 95-percent confidence level. The CMF for fatal and injury crashes was 0.810 and statistically significant at the 90-percent confidence level. The CMFs for right-angle and nighttime crashes were not statistically significant at the 95-percent confidence level. For the 70 four-legged intersections, the results in table 41 indicate reductions in total, fatal and injury, right angle, and nighttime crashes. The CMF for right-angle crashes was 0.881 and statistically significant at the 95-percent confidence level. The CMF for fatal and injury crashes was 0.908 and statistically significant at the 90-percent confidence level. The CMFs for total, rear-end, and nighttime crashes were not statistically significant at the 95-percent confidence level. Based on the disaggregate analysis by number of legs, it appears this strategy was slightly more effective at three-legged intersections than four-legged intersections for total, fatal and injury, and rear-end crashes. However, as noted above, this effect may be due to other correlated variables.

Table 41. Disaggregate results by number of legs.

Statistic	Three-Legged	Four-Legged
Number of intersections	14	70
Total crash CMF (standard error)	**0.860** (0.053)	0.972 (0.025)
Fatal and injury crash CMF (standard error)	0.810 (0.103)	0.908 (0.049)
Rear-end CMF (standard error)	**0.822** (0.075)	1.000 (0.037)
Right-angle CMF (standard error)	0.895 (0.091)	**0.881** (0.037)
Nighttime CMF (standard error)	1.044 (0.126)	0.955 (0.052)

Note: Boldface indicates statistically significant results at the 95-percent confidence level.

Table 42 presents the disaggregate results by number of lanes, indicating the sample size (number of sites), CMF, and standard error of the CMF (in parentheses) by group for each crash type considered in this study. For the 20 intersections with two-lane major roads, the results in table 42 indicate reductions in all crash types analyzed in this study. The CMFs for total, fatal and injury, and right-angle crashes were 0.784, 0.756, and 0.654, respectively, and statistically significant at the 95-percent confidence level. For the 64 intersections with four-lane major roads, the results in table 42 indicate reductions in all crash types analyzed in this study. The CMF for right-angle crashes was 0.917 and statistically significant at the 95-percent confidence level. The CMF for fatal and injury crashes was 0.911 and statistically significant at the 90-percent confidence level. The CMFs for total, rear-end, and nighttime crashes were not statistically significant at the 95-percent confidence level. Based on the disaggregate analysis by number of lanes, it appears this strategy was more effective at two-lane major road intersections than four-lane major road intersections. However, as noted above, this effect may be due to other correlated variables.

Table 42. Disaggregate results by number of lanes.

Statistic	Two Mainline Lanes and Two Cross-Street Lanes	Four Mainline Lanes and Two Cross-Street Lanes
Number of intersections	20	64
Total crash CMF (standard error)	**0.784** (0.057)	0.978 (0.025)
Fatal and injury crash CMF (standard error)	**0.756** (0.112)	0.911 (0.049)
Rear-end CMF (standard error)	0.866 (0.091)	0.988 (0.036)
Right-angle CMF (standard error)	**0.654** (0.079)	**0.917** (0.038)
Nighttime CMF (standard error)	0.884 (0.124)	0.980 (0.052)

Note: Boldface indicates statistically significant results at the 95-percent confidence level.

Table 43 presents the disaggregate results by number of legs and number of lanes, indicating the sample size (number of sites), CMF, and standard error of the CMF (in parentheses) by group for each crash type considered in this study. For the five three-legged intersections with two-lane major roads, none of the CMFs were statistically significant at the 95-percent confidence level. For the nine three-legged intersections with four-lane major roads, the results in table 43 indicate reductions in total, fatal and injury, rear-end, and right-angle crashes. The CMFs for total and rear-end crashes were 0.846 and 0.829, respectively, and statistically significant at the 95-percent confidence level. The CMF for right-angle crashes was 0.833 and statistically significant at the

90-percent confidence level. The CMFs for fatal and injury and nighttime crashes were not statistically significant at the 95-percent confidence level.

For the 15 four-legged intersections with two-lane major roads, the results in table 43 indicate reductions in all crash types analyzed in this study. The CMFs for total, fatal and injury, and right-angle crashes were 0.732, 0.746, and 0.509, respectively, and statistically significant at the 95-percent confidence level. The CMFs for rear-end and nighttime crashes were not statistically significant at the 95-percent confidence level.

For the 55 four-legged intersections with four-lane major roads, the results in table 43 indicate reductions in total, fatal and injury, right-angle, and nighttime crashes. The CMF for right-angle crashes was 0.928 and statistically significant at the 90-percent confidence level. The CMFs for total, fatal and injury, rear-end, and nighttime crashes were not statistically significant at the 95-percent confidence level.

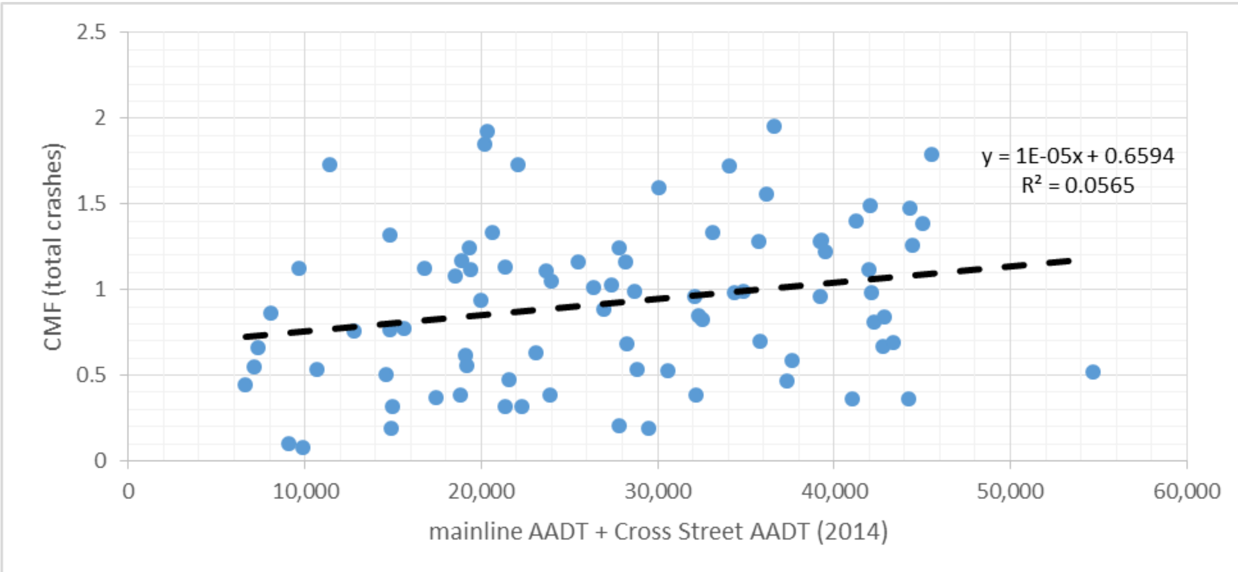
The disaggregate analysis by number of legs and number of lanes indicates that this strategy was effective for most combinations of legs and lanes. Based on the limited sample sizes for the individual categories, it appears the strategy was most effective at four-legged intersections with two-lane major roads. However, as noted above, this may be due to other correlated variables.

Table 43. Disaggregate results by number of legs and number of lanes.

Statistic	Three-Legged With Two Mainline Lanes and Two Cross-Street Lanes	Three-Legged With Four Mainline Lanes and Two Cross-Street Lanes	Four-Legged With Two Mainline Lanes and Two Cross-Street Lanes	Four-Legged With Four Mainline Lanes and Two Cross-Street Lanes
Number of intersections	5	9	15	55
Total crash CMF (standard error)	0.901 (0.113)	**0.846** (0.060)	**0.732** (0.065)	0.998 (0.027)
Fatal and injury crash CMF (standard error)	0.771 (0.202)	0.819 (0.118)	**0.746** (0.132)	0.926 (0.053)
Rear-end CMF (standard error)	0.794 (0.148)	**0.829** (0.086)	0.895 (0.114)	1.011 (0.039)
Right-angle CMF (standard error)	1.104 (0.217)	0.833 (0.099)	**0.509** (0.078)	0.928 (0.041)
Nighttime CMF (standard error)	0.809 (0.203)	1.128 (0.156)	0.914 (0.154)	0.958 (0.055)

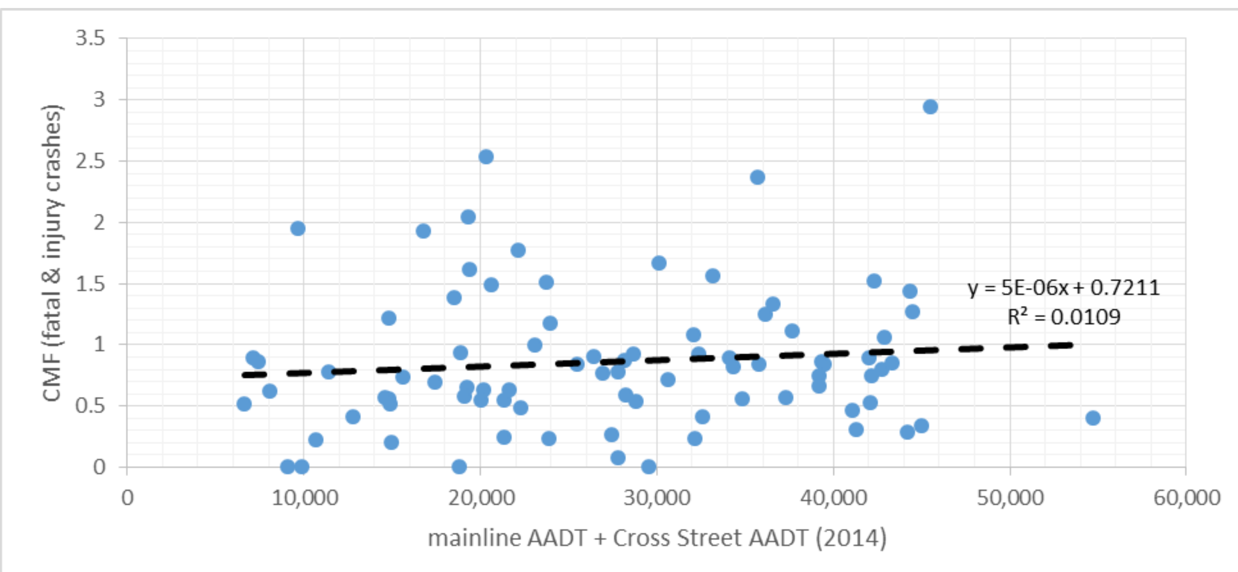
Note: Boldface indicates Statistically significant results at the 95-percent confidence level.

Figure 28 and figure 29 show the individual CMFs for total crashes and fatal and injury crashes, respectively, for each treatment site compared with the total entering traffic volume associated with the intersection. The linear trend line suggests the multiple low-cost treatments were slightly more effective on average for intersections with lower traffic volumes, and the effectiveness decreased (i.e., CMF increased) as traffic volume increased. The trend was more apparent for total crashes and nearly flat for fatal and injury crashes. The CMF in figure 28 appears to cross 1.0 when AADT is about 35,000. This suggests that the reduction potential for total crashes was better for intersections with total entering AADT under 35,000. Similarly, figure 29 suggests that the reduction potential for fatal and injury crashes was better for locations with total entering AADT under 50,000. Again, the perceived relationship may also be due to correlations with other variables.



Source: FHWA.

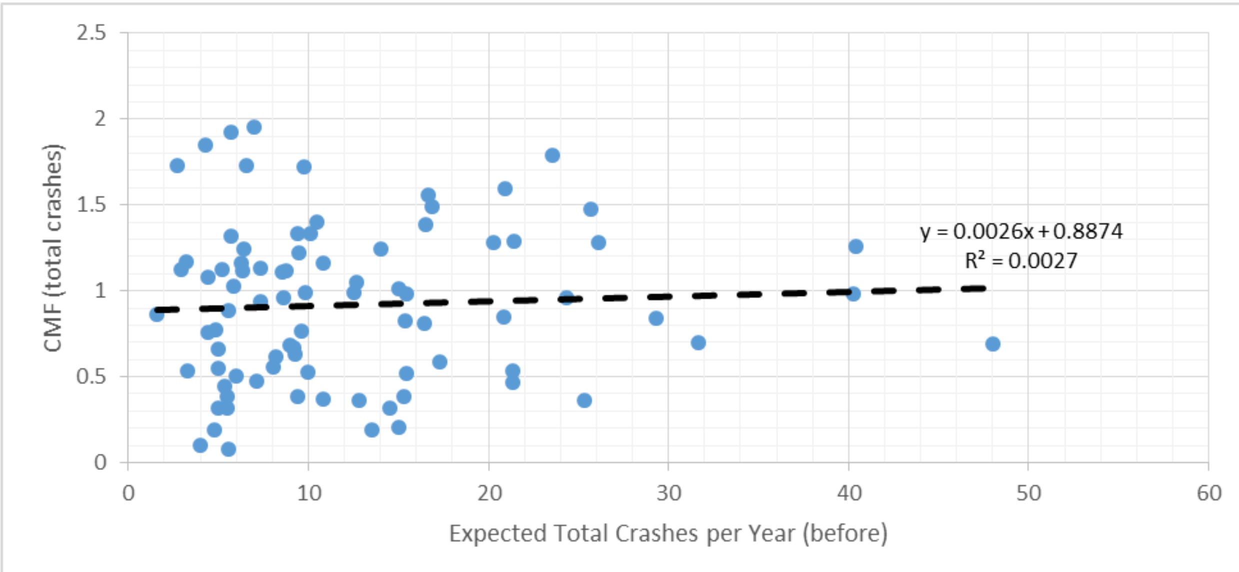
Figure 28. Chart. The relationship between CMF (total crashes) and total intersection AADT (2014).



Source: FHWA.

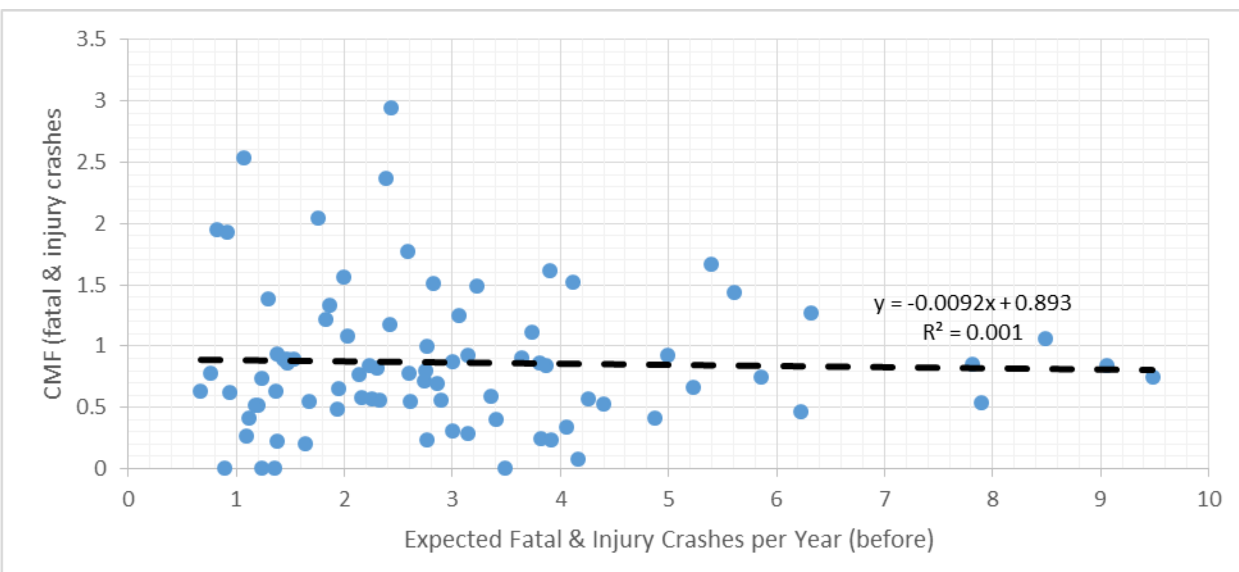
Figure 29. Chart. The relationship between CMF (fatal and injury crashes) and total intersection AADT (2014).

Figure 30 and figure 31 show the individual CMFs for total crashes and fatal and injury crashes, respectively, for each treatment site compared with the expected crashes per year in the before period. The linear trend line is nearly flat in both cases, suggesting the multiple low-cost treatments were approximately equally effective on average for intersections across the range of expected crashes per year in the before period. This confirms the need for caution when interpreting the results of the univariate analyses. Specifically, the net effect of the multiple correlations among variables investigated is a negligible effect on the expected number of crashes, which collectively captures the effects of those variables.



Source: FHWA.

Figure 30. Chart. The relationship between CMF (total crashes) and expected total crashes during the before period.



Source. FHWA.

Figure 31. Chart. The relationship between CMF (fatal and injury crashes) and expected fatal and injury crashes during the before period.

CHAPTER 9. ECONOMIC ANALYSIS

The research team conducted an economic analysis to estimate the B/C ratio for implementing various pavement marking, signing, signal, and pedestrian improvements at signalized intersections. The statistically significant aggregate reduction in total crashes was used to calculate the benefits for an average intersection. The research team performed the economic analysis of total crashes as a conservative estimate of the economic benefit.

Based on work order cost data for signalized intersections provided by SCDOT, the economic analysis assumed an average pavement marking and signing construction cost of approximately $7,000. Typical costs were roughly $13,300 for signal enhancements, $18,300 for installing pedestrian signal assemblies, and $2,500 each for curb ramps. Annual maintenance and operations costs were not available except for pedestrian signal head maintenance and were otherwise assumed to be zero (i.e., these costs will not be incurred within the service life).

PE, project management, and other general costs were not provided; however, a large portion of project planning was completed by State forces, and other costs for two contractors would have been split across all intersections if the costs were available. In future economic analyses of similar projects, all of these preliminary costs should be added to the construction costs.

The analysis assumed the useful service life for safety benefits was 7 years. Pavement markings were assumed to last roughly 4 years and all other treatments roughly 7 to 10 years with minimal maintenance. A conservative average of 7 years was used for the overall project.

The FHWA Office of Safety Research and Development suggested using the Office of Management and Budget *Circular A-4* as a resource for the real discount rate of 7 percent to calculate the present value benefits and costs of the multiple low-cost treatments over the service life.(19) With this information, the capital recovery factor was computed for all intersection types as 5.39 for a service life of 7 years.

For the benefit calculations, the most recent FHWA mean comprehensive crash costs disaggregated by crash severity and location type were used as a base.(20) These costs were developed based on 2001 crash costs, and the unit cost (in 2001 U.S. dollars (USD)) was $158,177 for fatal and injury crashes and $7,428 for PDO crashes. This was updated to 2015 USD by applying the ratio of the USDOT 2015 value of a statistical life of $9.4 million to the 2001 value of $3.8 million.(20,21) Applying this ratio of 2.474 to the unit costs for fatal and injury and PDO crashes yielded values of $391,280 and $18,375, respectively. The research team then weighted the values at approximately 20 percent fatal and injury crashes in the after period, which resulted in a total crash cost of $95,186 in 2015 USD.

When the analysis was preformed, all project costs were brought forward to 2015 USD for consistency with crash cost values based on the same 7-percent discount rate, assuming original project costs were in 2011 USD.

The total crash reduction was calculated by subtracting the actual crashes in the after period from the expected crashes in the after period had the intersection treatments 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 treatments saved 50.6 total crashes per year for the sample sites, or an average reduction of 0.6 crashes per site per year across the 84 treatment sites. Similarly, the treatments resulted in a reduction of 26.5 fatal and injury crashes, or approximately 0.3 fatal and injury crashes fewer per site per year across all 84 sites.

The annual economic benefits were calculated by multiplying the crash reduction per site per year by the cost of a crash. Total crash reduction and total crash cost were used in the calculation. The B/C ratio was calculated as the ratio of the present value of benefits to the present value of all costs. USDOT recommended a sensitivity analysis be conducted assuming values of a statistical life of 0.57 and 1.41 times the recommended 2015 value.(21) These factors were applied directly to the estimated B/C ratios to obtain a lower and upper bound of the B/C ratios. Table 44 presents the resulting B/C ratios for two scenarios: (1) assuming signing, marking, and signal improvements and (2) assuming scenario 1 plus pedestrian-related improvements.

Table 44. B/C ratios.

Treatments	Lower Bound	Average B/C	Upper Bound
Signing, marking, and signal hardware improvements	6.6	11.7	16.4
Signing, marking, signal head replacements, and pedestrian signal installation with curb ramps	2.3	4.1	5.8

These results suggest that implementation of the various intersection treatments, even with conservative assumptions of service life and the value of a statistical life, can be cost effective in reducing crashes at signalized intersections.

CHAPTER 10. SUMMARY AND CONCLUSIONS

The objective of this study was to undertake a rigorous before–after evaluation of the safety effectiveness, as measured by crash frequency, of multistrategy, low-cost improvements at signalized intersections. The study used data from a systemic intersection improvement program in South Carolina to examine the effects for the following specific crash types: total, fatal and injury, rear-end, right-angle, and nighttime. Based on the aggregate results, table 45 presents the recommended CMFs for the various crash types.

Table 45. Recommended CMFs.

Variable	Total	Fatal and Injury	Rear-End	Right-Angle	Nighttime
CMF	0.955	**0.893**	0.974	**0.883**	0.969
Standard error	0.023	0.045	0.034	0.035	0.048

Note: Boldface indicates statistically significant results at the 95-percent confidence level.

The disaggregate analysis identified specific CMFs by crash type and different conditions. The process also revealed the conditions under which the multiple low-cost treatments were more effective. Variables of interest included area type (urban or rural), number of legs (three or four), lane configuration of the mainline and the cross street, traffic volumes, and expected crashes without treatment. The disaggregate analysis indicated larger reductions of most crash types for intersections in urban areas, three-legged intersections, and intersections with two-lane major roads. For total entering volume, the disaggregate analysis indicated the strategy was slightly more effective on average for intersections with lower traffic volumes. The strategy was approximately equally effective across the range of expected crashes before treatment, suggesting the need for caution in interpreting and applying the results of the other univariate comparisons, which are likely confounded by multiple correlative effects.

The B/C ratio for intersections with pavement marking, signing, signal hardware, and pedestrian infrastructure, estimated with conservative cost and service life assumptions and considering the benefits for total crashes, was 4.1:1. With the USDOT recommended sensitivity analysis, these values could range from 2.3:1 up to 5.8:1. The B/C ratio when excluding the cost of pedestrian improvements was 11.7:1. These results suggest that the implementation of multiple low-cost treatments, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective in reducing crashes at signalized intersections.

This research demonstrates the potential effect of a systemic intersection improvement program by evaluating a program in which each site received an individualized version of a package of intersection treatments with some differences in application at each individual intersection. Although information regarding the exact treatments installed at each site was not available to the research team, such data would have value in future evaluations of multiple-strategy improvement projects. Agencies should consider how to best document and track the improvements at each site to facilitate more complete and rigorous disaggregate analyses. However, the approach used in this research was able to quantify the overall effects of an improvement program and to suggest the expected effectiveness of similar future programs.

APPENDIX. ADDITIONAL INSTALLATION DETAILS

This appendix provides a description and examples of the general work completed by SCDOT to implement the multiple-strategy improvements at signalized intersections and illustrations of the SCDOT Standard Drawings used in the project. The appendix concludes with a list of general notes related to standard review guidelines, field notes, final plans, and submissions. Most of the following text is excerpted from SCDOT project guidelines. For explanatory purposes, the authors of this report added the text in brackets.

EXAMPLE OF DOCUMENTS USED DURING THE LOW-COST INTERSECTION IMPROVEMENT PROJECT(22)

[SCDOT used the following documents during the project:]

- **General Signing and Pavement Marking Notes for all Intersections.** SCDOT included this document in each work order sent to the contractors. It contains general notes and instructions that pertain to all intersections.

- **SCDOT Standard Drawing 625-305-00.** This document shows the standard pavement markings for intersections.

- **SCDOT Standard Drawing 625-310-00.** This document shows the standard pavement markings for turn lanes.

- **SCDOT Standard Drawing 625-410-00.** This document shows the standard pavement markings for arrows and the word message "Only."

- **Additional Sign Inventory for Replacement.** SCDOT decided to replace additional warning and regulatory signs (in addition to the typical) from this table to include signs near the intersection that were considered to have notable safety impacts.

- **Unsignalized Intersection Design.** This document shows general pavement marking and sign installation information for unsignalized intersections.

- **SCDOT Traffic Engineering Guideline 20.** SCDOT Traffic Engineering designed this document to provide information on the installation of retroreflective sign post panels.

- **SCDOT Guidelines for Advance Placement of Warning Signs.** SCDOT revised this document from the Table 2C-4 from the 2009 MUTCD to show suggested placement of advanced warning signs. Proper staking has been one of the biggest issues to date so this document was used to serve as a guideline. 100 feet was added to Condition B (0) to provide additional advance notice needed for the added street name sign.

- **Intersection Typicals.** These documents are examples of intersection typicals provided to the contractor by SCDOT. They include typicals for a signalized intersection, a four-way stop controlled intersection, a cross-type stop controlled intersection, and a t-type stop controlled intersection. These typicals are revised after field inspection to create a final plan.

- **Street Name Sign Typical.** This document is an example of the SignCADD layout provided with each intersection typical.

- **Placement Dimensions for Stop Ahead. [**This document shows dimensions for placement of rumble strips preceding a Stop sign.]

GENERAL SIGNING AND PAVEMENT MARKING NOTES FOR ALL INTERSECTIONS[(22)]

[SCDOT used the following guidance for signing and pavement marking for all intersections.]

Remark all existing stop lines, crosswalks, arrows and word messages unless:

- The roadway has been resurfaced within 1 calendar year and new thermoplastic markings have been applied.

- Existing markings are uniformly reflective and above ground thickness is ≥ 90 mils.

- Otherwise directed by a district representative

Individual typicals in work orders may not show all desired markings; therefore, all turn lanes shall be marked to include the pattern of lane arrows and accompanying word message "ONLY" based on the turn lane length, in accordance with Standard Drawing 625-410-00.

As referenced in Standard Drawing 625-410-00 for signalized intersections, combination Straight and Left or Right Turn arrows shall be added on all shared usage lanes where there are two or more through lanes (exclusive or shared). For example, if an approach has an exclusive through lane AND a shared through/right turn lane, the shared lane shall have two through/right turn arrows installed in accordance with Standard Drawing 625-410-00.

Additional pavement marking details for intersections shall be followed in accordance with Standard Drawing 625-305-00 and 625-310-00. Note that all turn bays should be delineated with an extended dashed edgeline as shown in the standard drawings.

If existing lane markings and word messages are in good condition but not compliant with the typical, retain the existing marking scheme and do not install the typical layout.

For fabrication of D series signs, utilize appendix C of the blue MUTCD with 8" capital letters for 4-lane divided roadways and 6" capital letters for all other roadways.

Opposite side signs should be placed adjacent to the existing sign within a 30' tolerance.

If "STOP" pavement marking is used, place 8' letters approximately 10' in advance of stop limit line.

Install retroreflective sign post panels only on signs as indicated on Traffic Engineering Guideline TG-20 that are shown on the original typicals. Additional signs will not require sign post panels.

Do not replace Junction signs with blue border and lettering.

For electric sign mounted flashers, contact the RCE for disconnect of electric power to convert to solar flasher.

Replace all other existing signs within 500’ of the intersection that are included in the attached table entitled “Additional Sign Inventory for Replacement.”

Reinstall all pavement markings to match the existing field markings unless otherwise noted, i.e., TWLT markings should not be remarked as double yellow, dashed edge lines should not be installed for single turn lanes, etc.

STANDARD MARKINGS FOR INTERSECTIONS[22]

[The following text is transcribed from SCDOT Standard Drawing 625-305-00. Excerpts of details from the standard drawing are included as figures.]

Application of Markings at Intersections

1. Stop lines are to be applied at all signalized intersections.

2. At non-signalized intersections, the roadways which must stop are to have stoplines if centerlines are present.

3. Where stoplines are used, lane lines and center lines will terminate at the stopline. They do not extend across stoplines nor do they terminate prior to stoplines. Location of stoplines should be determined prior to marking longitudinal lines.

4. Lane lines terminating at a stopline should not be less than 10 ft in length, however they may be longer. The last lane line will be 10 to 40 ft long. The following procedure will aid in this determination:

    a. Mark a spot 50 ft in advance of stopline of each lane line approach.

    b. If a line is being applied when the spot is crossed, the striper operator permits automatic cut-off and the following 30 gap. When the next line begins, the striper operator will manually override the automatic cut-off and will extend the line to the stopline.

    c. If a line is not being applied when the spot is crossed, when the next line begins the striper operator will manually override the automatic cut-off and will extend the line to the stopline.

5. At all intersections, lane lines will normally be omitted within the intersection area where turning vehicles must maneuver.

[Figure 32 shows a detail of standard markings for intersections.]

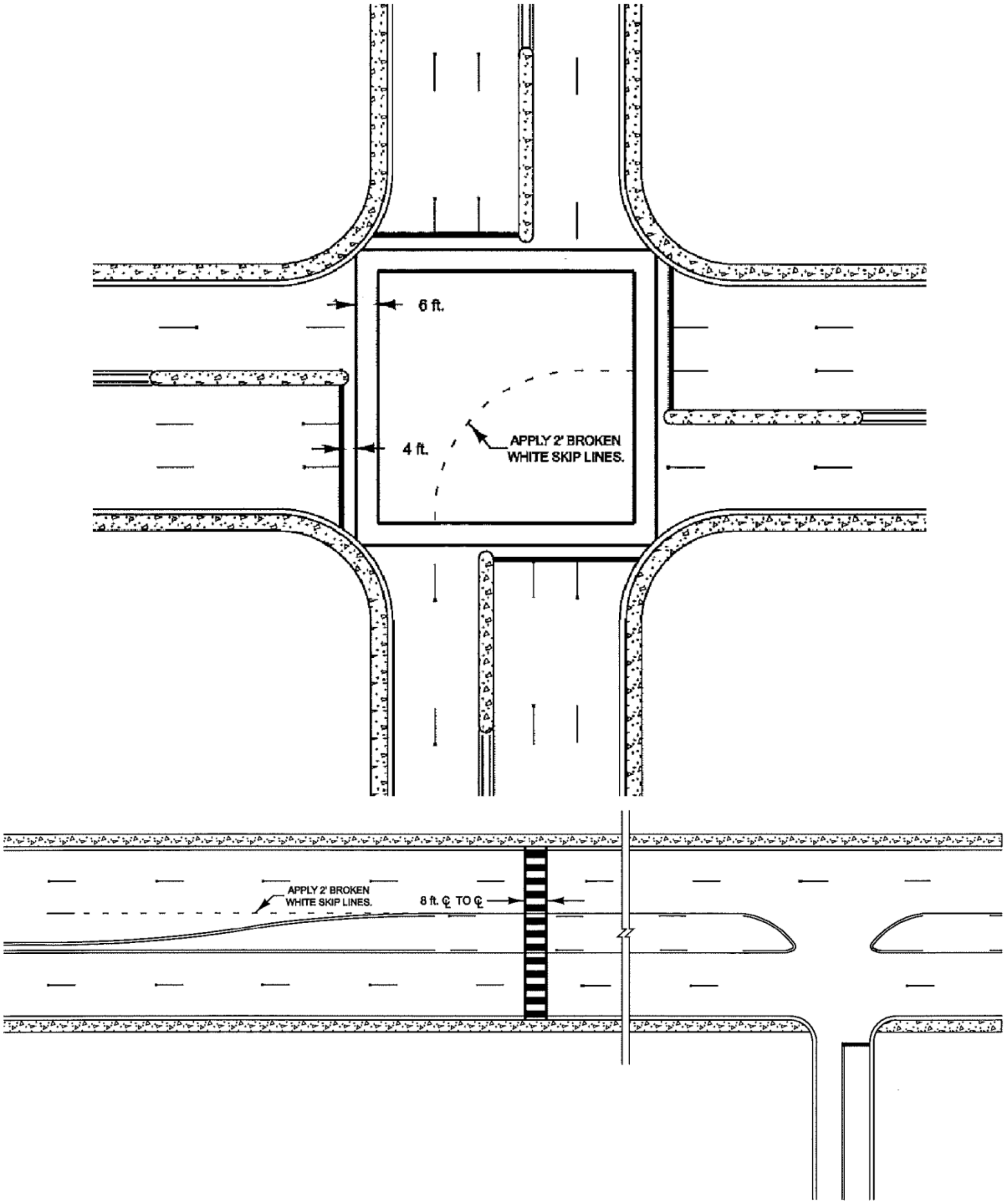


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Figure 32. Illustration. SCDOT Standard Drawing 625-305-00 excerpts for application of markings at intersections.

Arrows and Word Messages

Arrows and word messages are not typical at all turn lanes and will be placed only at locations shown on the plans or where directed by the engineer. In the absence of a marked crosswalk, the stopline should be placed at a distance of no less than 4 ft and no more than 30 ft from the where arrows supplement signs to prohibit a movement that would otherwise be legal from that lane; the arrow must be accompanied by the word “only.” All arrows and word messages shall be as indicated on standard drawings 625-410-00.

Additional Guidance through Intersections

[Figure 33 shows guidelines for applying dashed-line pavement markings through intersections.]

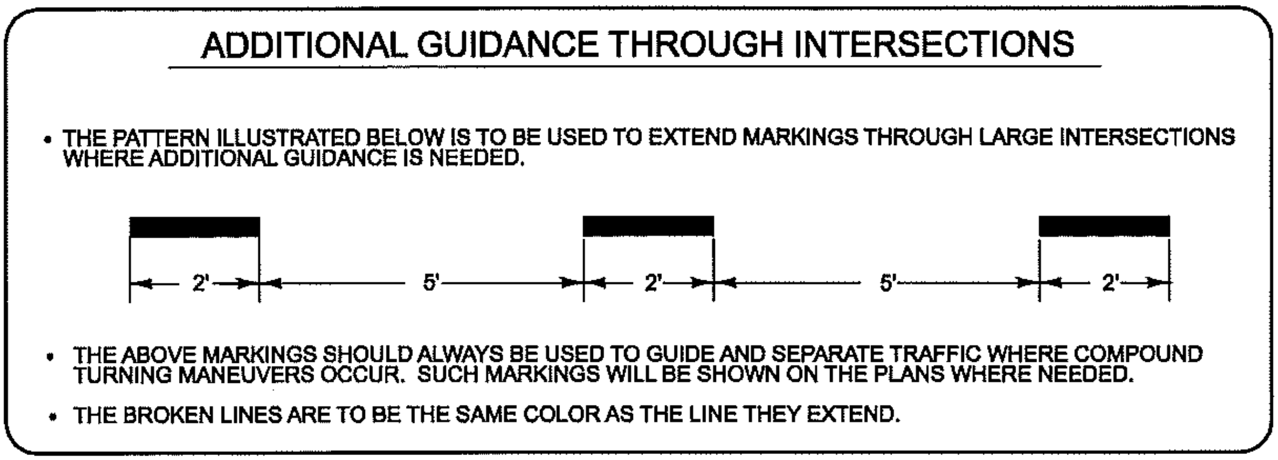

Figure 33. Illustration. SCDOT Standard Drawing 625-305-00 excerpt for guidance through intersections.

Crosswalks

All crosswalks are to be marked with 8” solid white lines. Crosswalk lines are to be spaced not less than 6 feet apart. [Figure 34 shows standards for an unsignalized school crosswalk.]

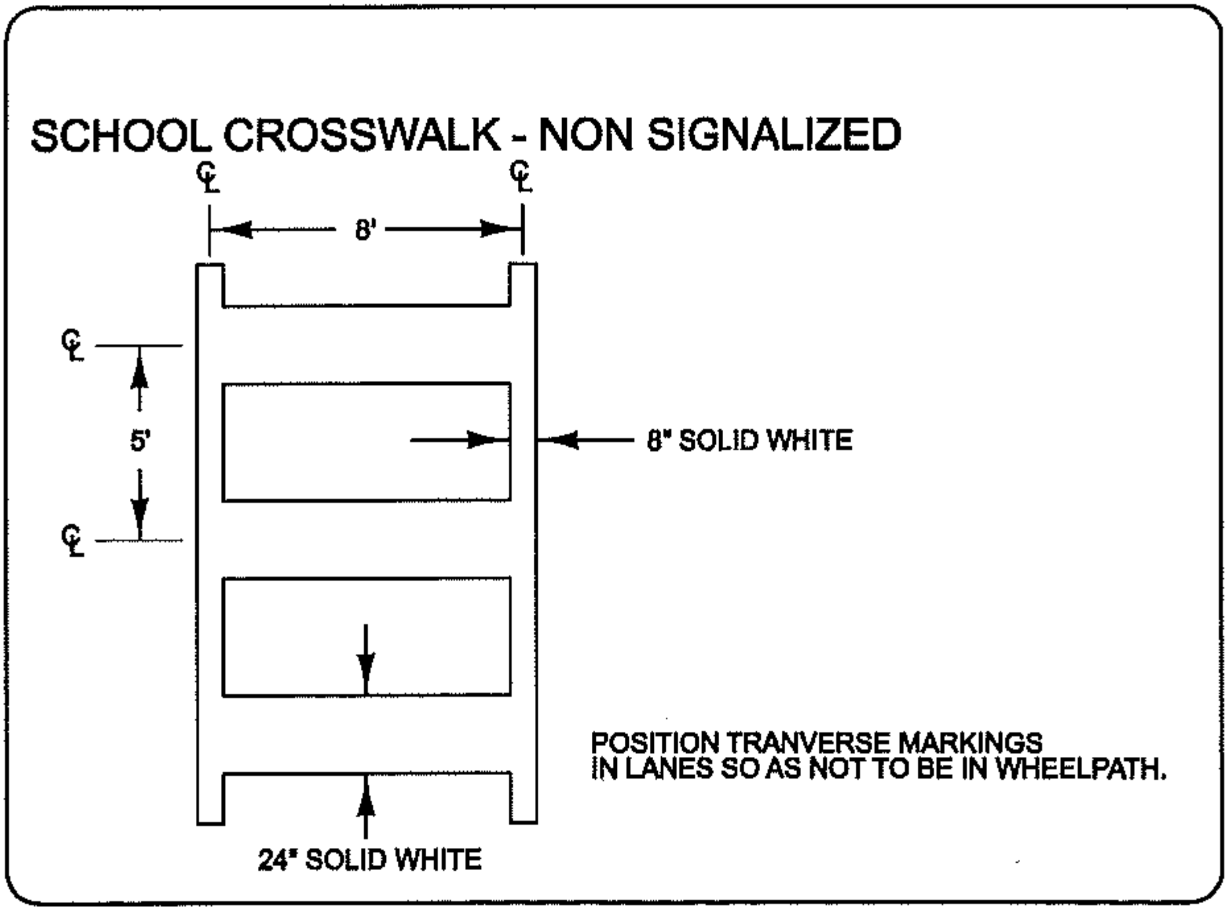

Figure 34. Illustration. SCDOT Standard Drawing 625-305-00 excerpts for crosswalk markings.

TYPICAL MARKINGS FOR TURN LANE INSTALLATIONS(22)

[The following text is transcribed from SCDOT Standard Drawing 625-310-00. Excerpts of details from the standard drawing are included as figures.]

Notes

[The following notes relate to installing typical markings for turn lanes:]

1. Length of tapers and chevrons vary. See plan sheets for dimensions.
2. Apply arrows, see Standard Drawing number 625-410-00.
3. Apply ‘only’ copy, see Standard Drawing number 625-410-00.

4. No raised markers are to be applied on chevrons.

5. Stoplines shown on mainline are to be applied only at signalized intersections.

[Figure 35 through figure 38 show details for turn lane markings from SCDOT Standard Drawing 625-310-00.]

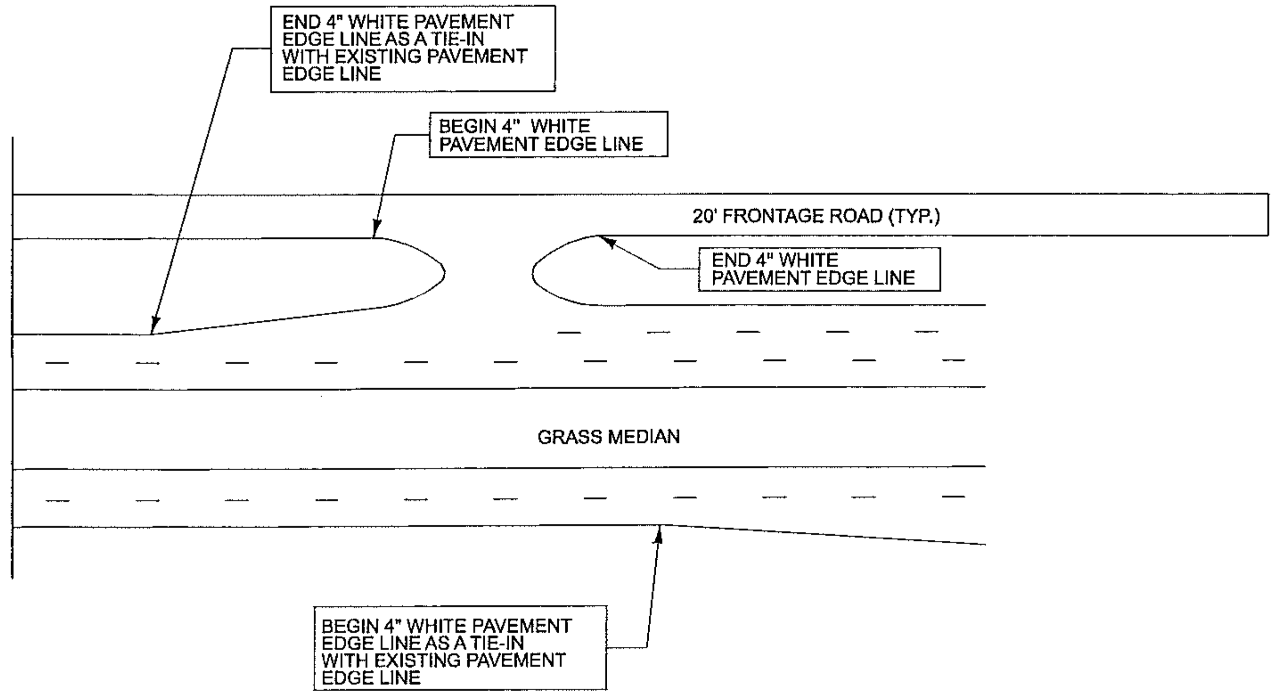

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Figure 35. Illustration. SCDOT Standard Drawing 625-310-00 excerpts for turn lane installations (part 1).

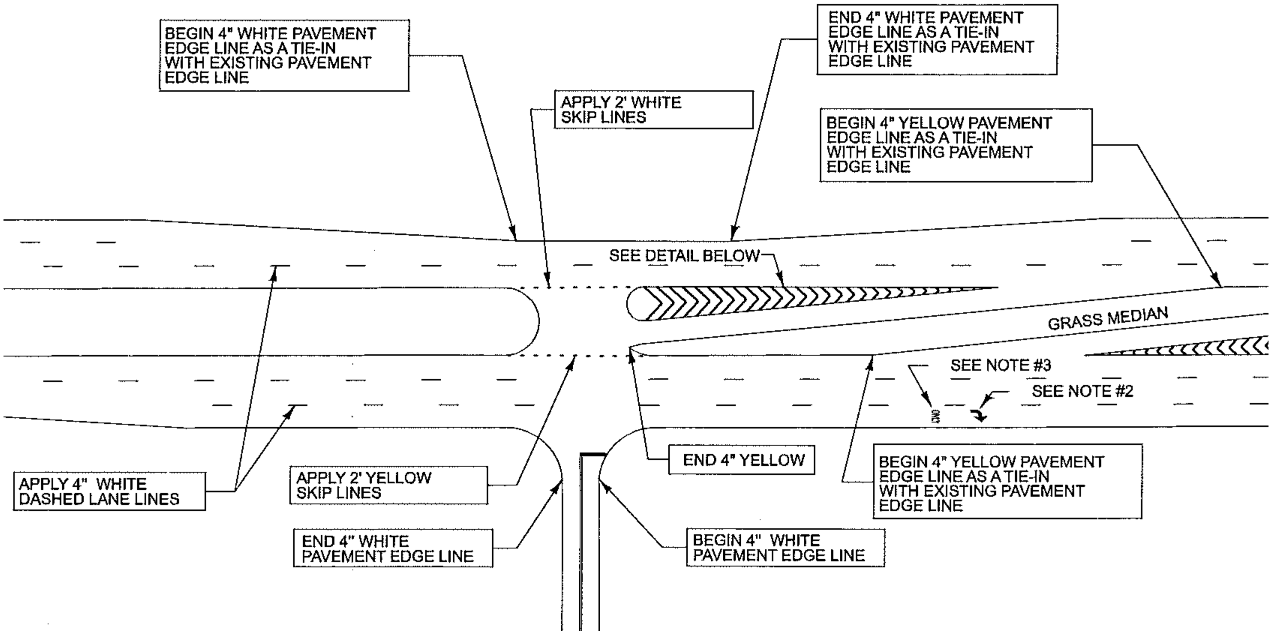


Figure 36. Illustration. SCDOT Standard Drawing 625-310-00 excerpts for turn lane installations (part 2).

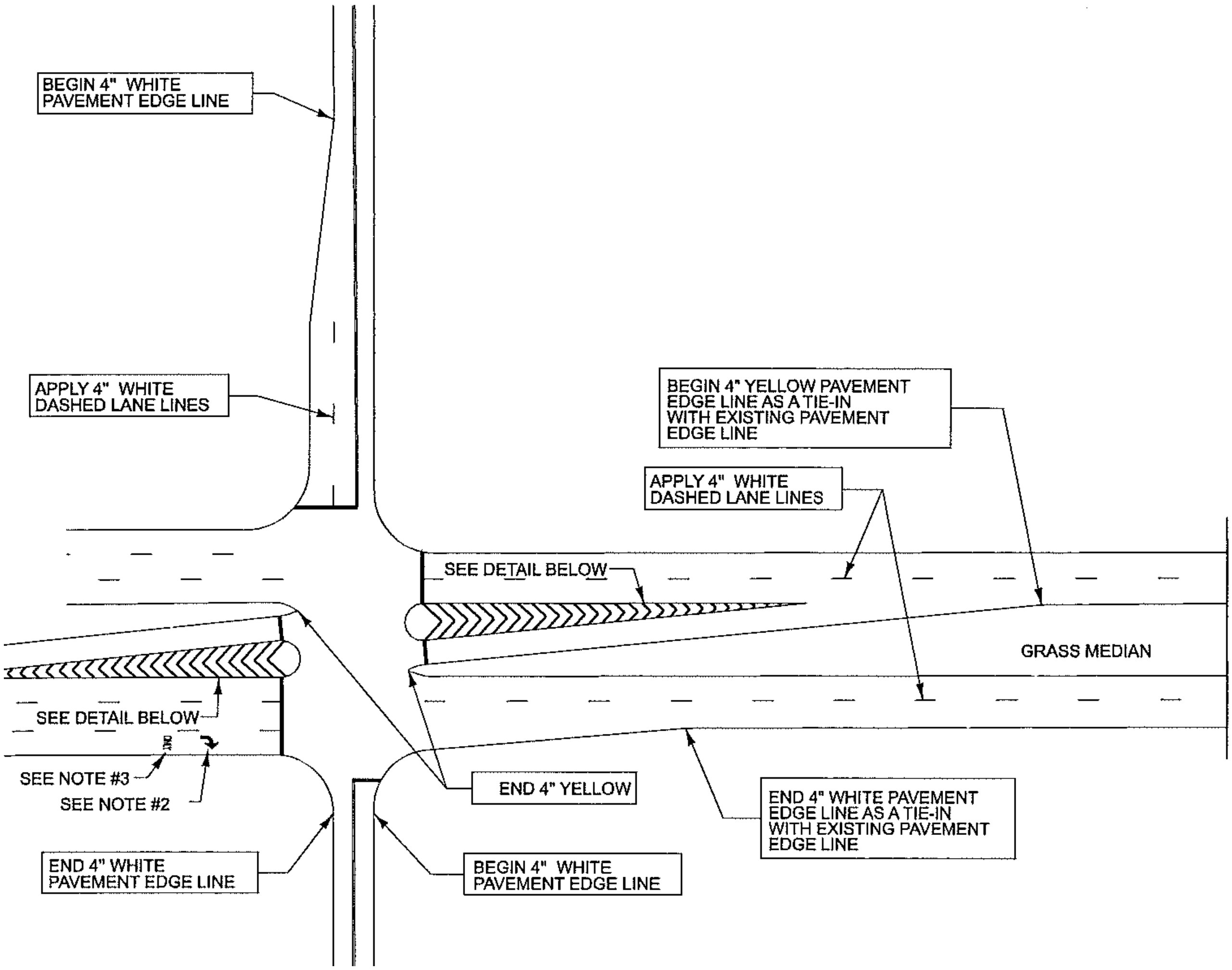


Figure 37. Illustration. SCDOT Standard Drawing 625-310-00 excerpts for turn lane installations (part 3).

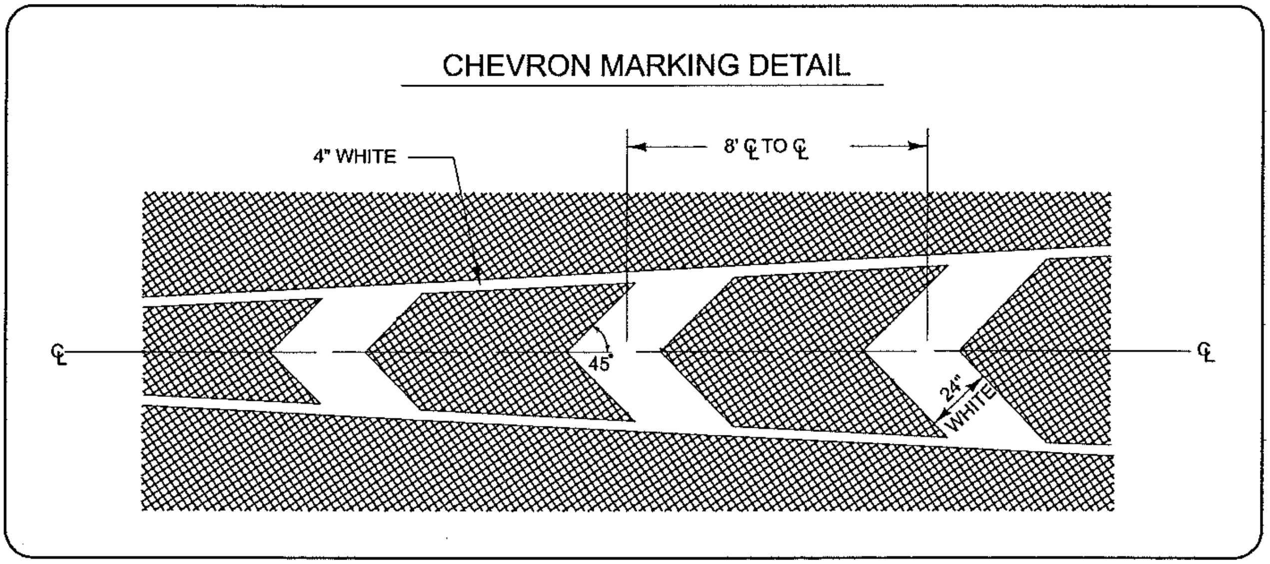


Figure 38. Illustration. SCDOT Standard Drawing 625-310-00 excerpts for chevron marking details.

STANDARD PAVEMENT MARKINGS[22]

[Figure 39 through figure 43 are excerpts of details from SCDOT Standard Drawing 625-410-00.]

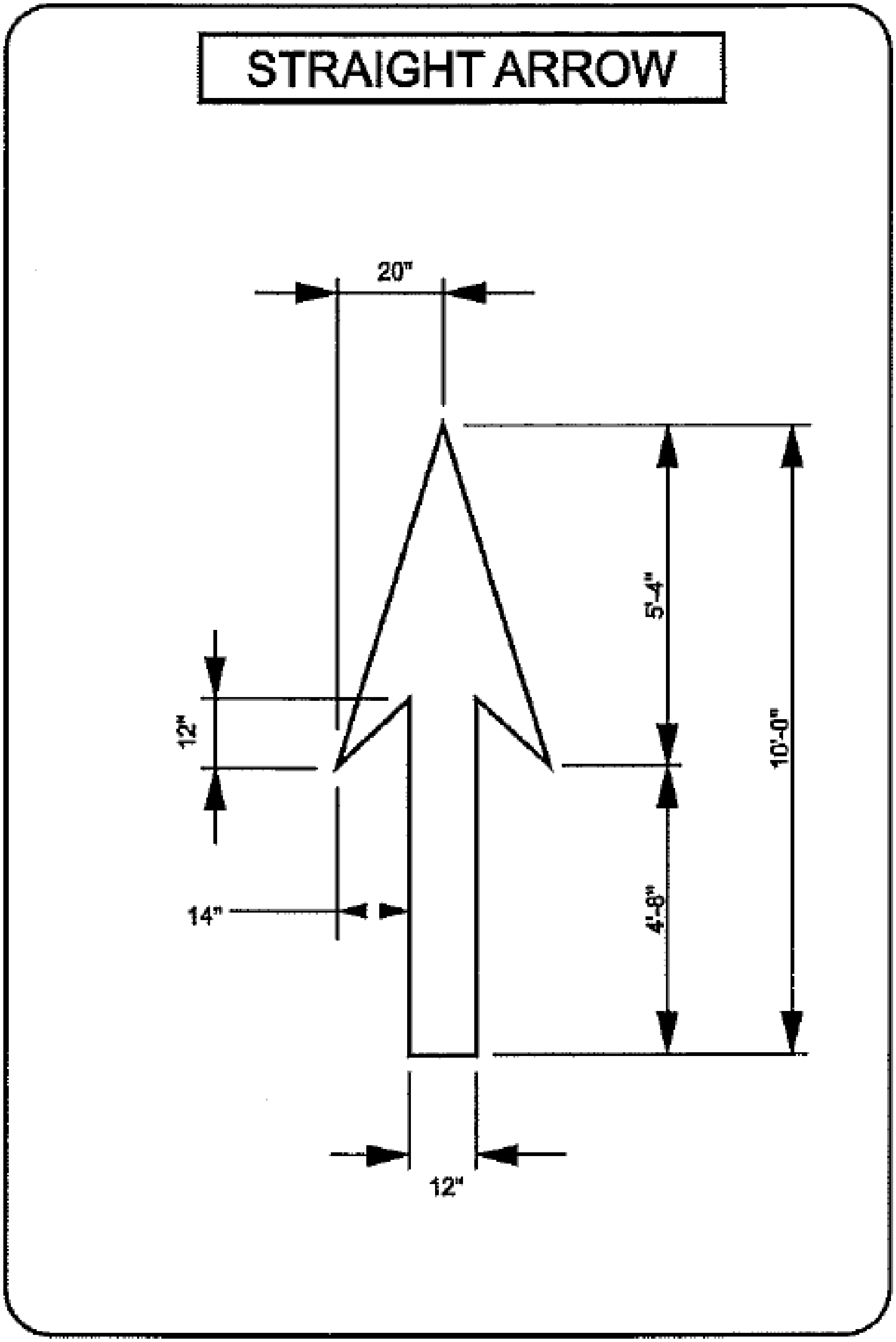


Figure 39. Illustration. SCDOT Standard Drawing 625-410-00 excerpt for straight arrow standard pavement marking.

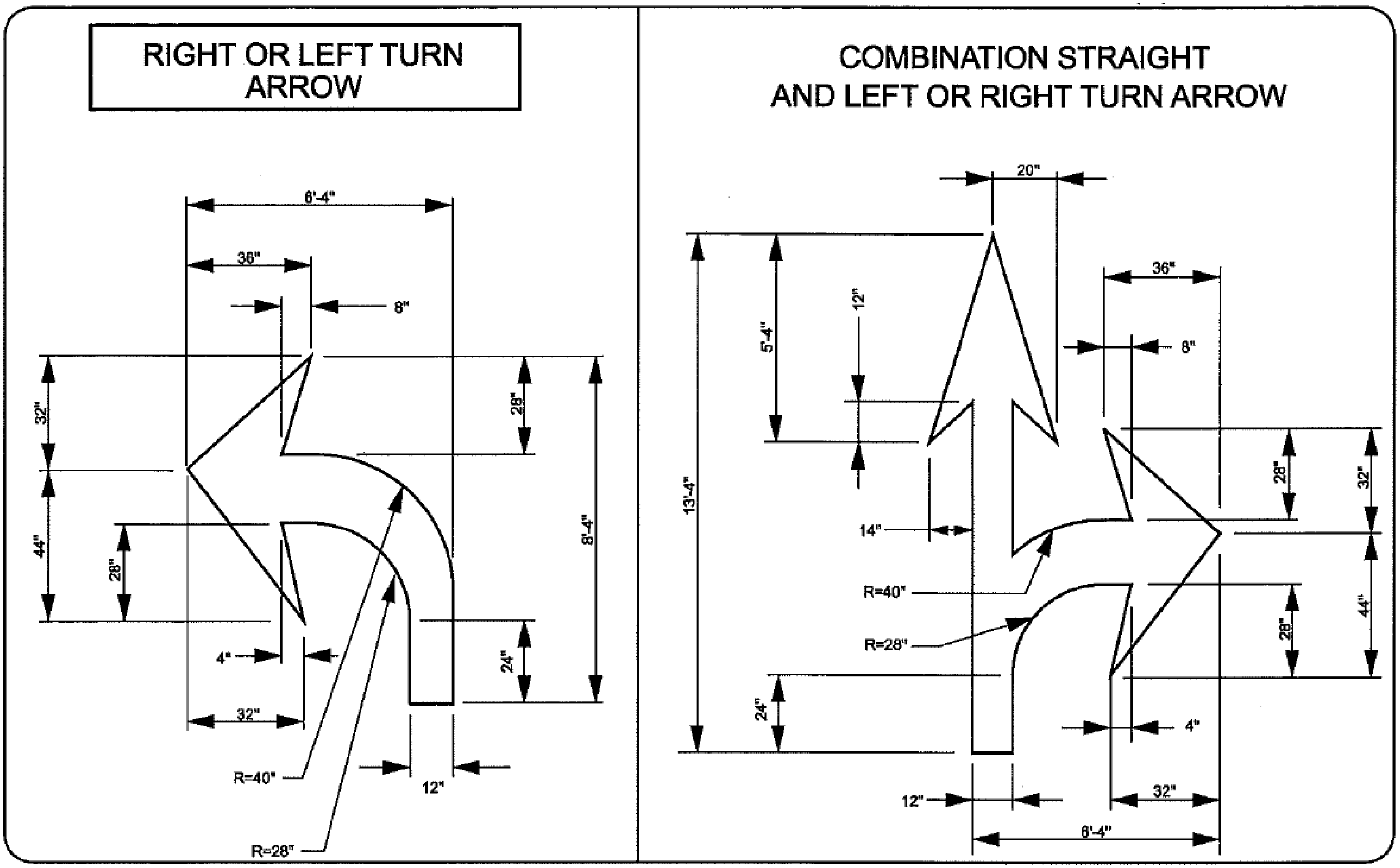


Figure 40. Illustration. SCDOT Standard Drawing 625-410-00 excerpt for right or left turn arrow and combination straight and left or right turn arrow standard pavement marking.

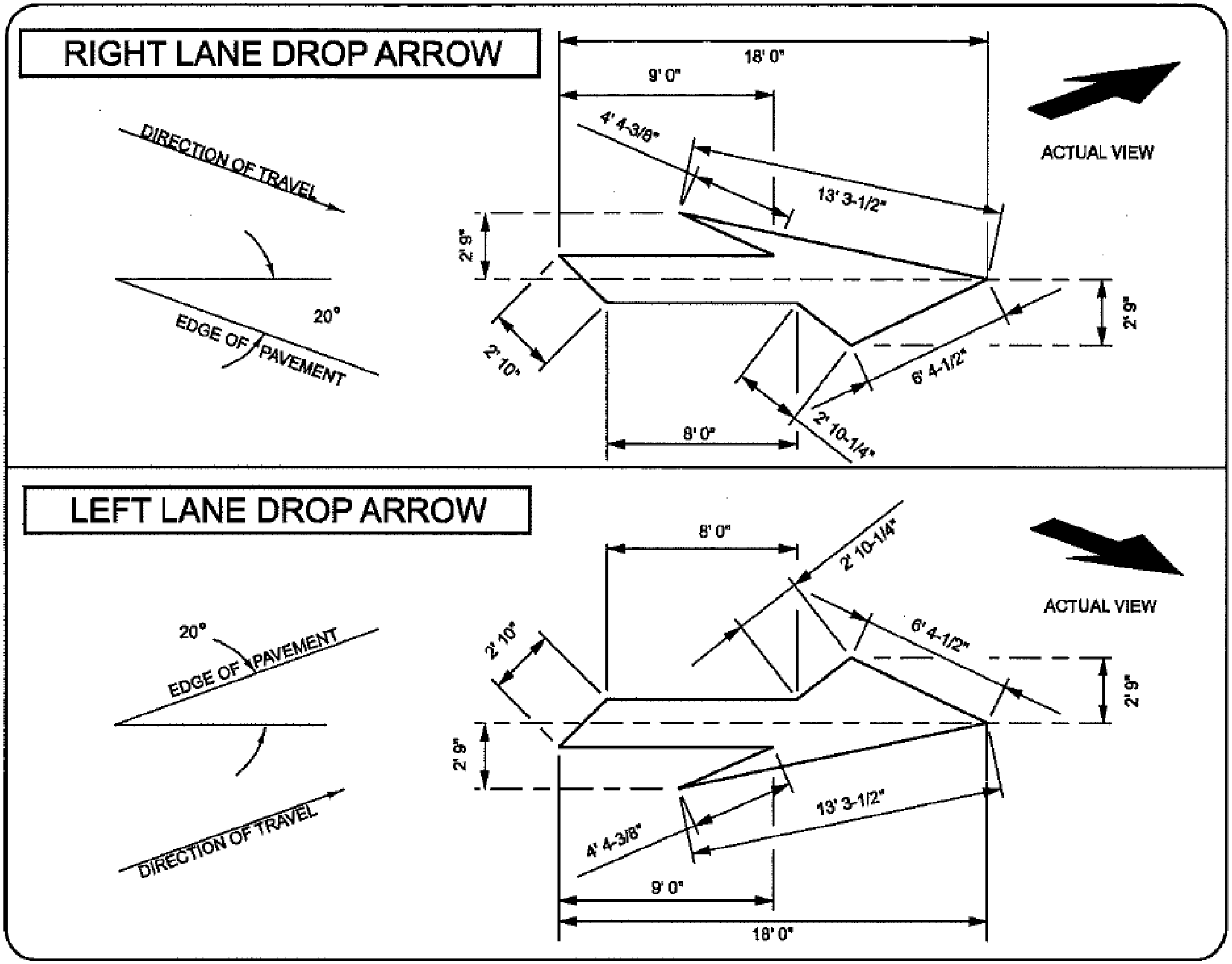


Figure 41. Illustration. SCDOT Standard Drawing 625-410-00 excerpt for right lane drop arrow and left lane drop arrow standard pavement marking.

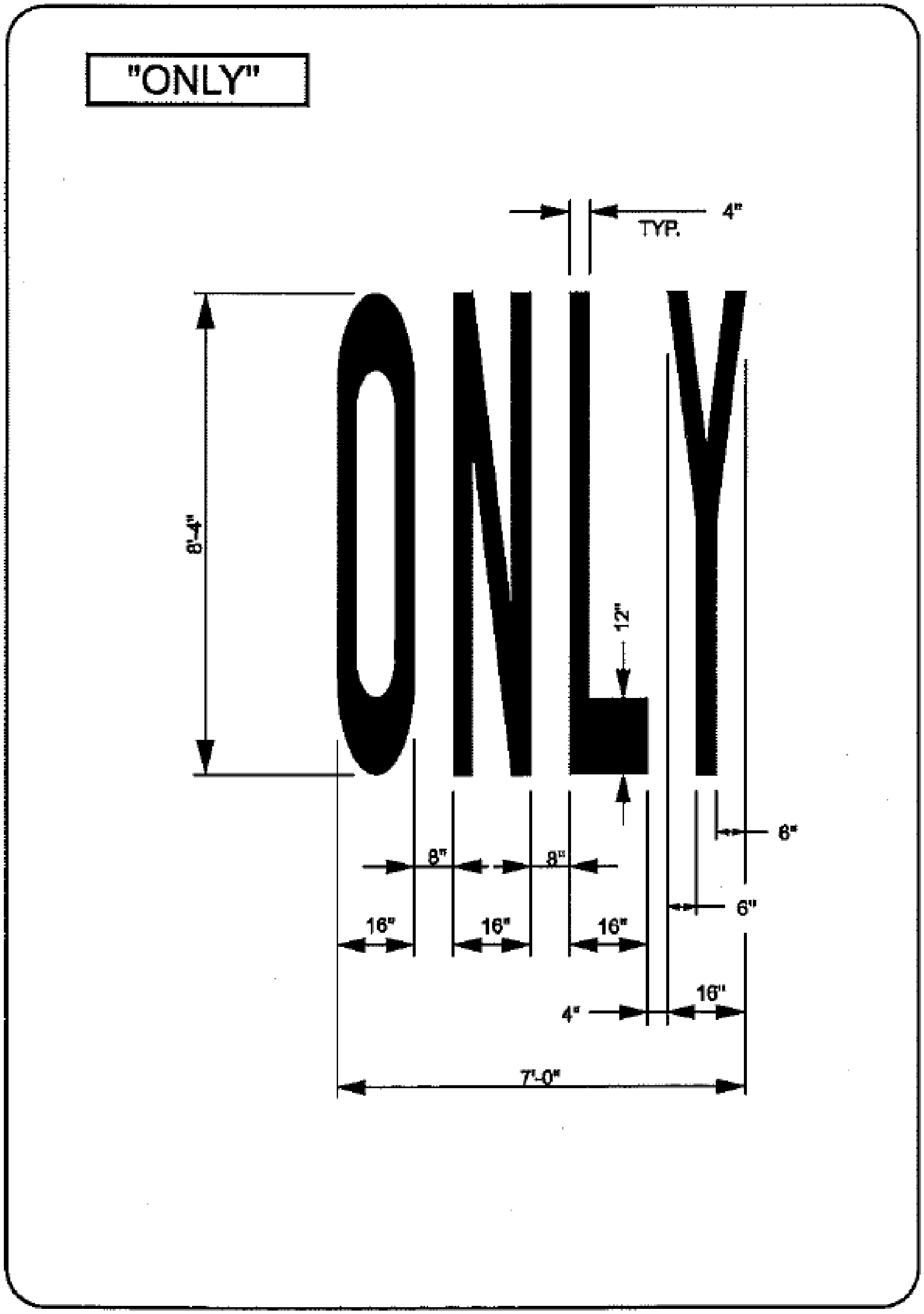


Figure 42. Illustration. SCDOT Standard Drawing 625-410-00 excerpt for "ONLY" standard pavement marking.

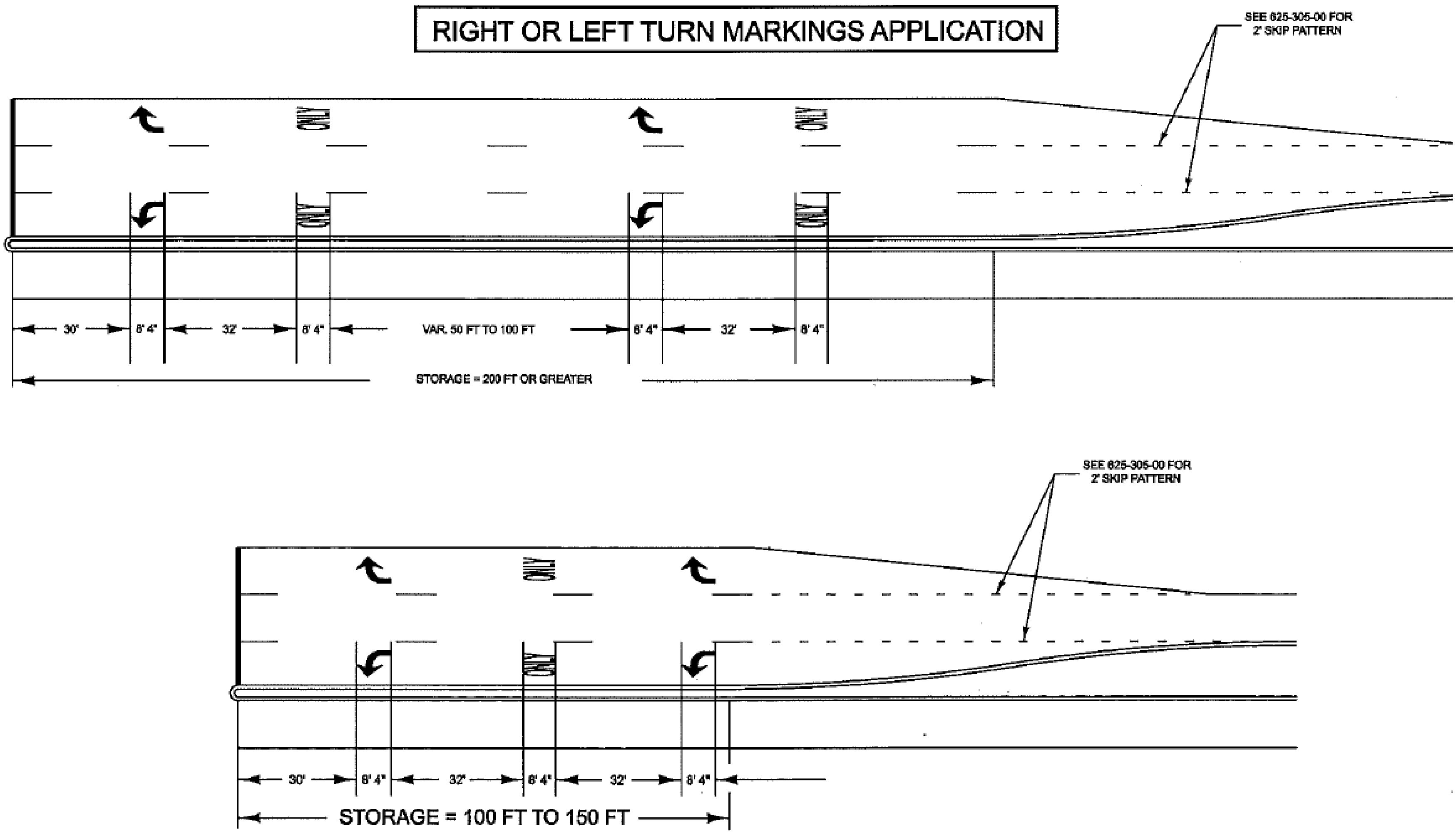


Figure 43. Illustration. SCDOT Standard Drawing 625-410-00 excerpt for right or left turn markings application.

ADDITIONAL SIGN INVENTORY FOR REPLACEMENT[22]

[SCDOT replaced additional warning and regulatory signs (in addition to the typical) shown in figure 44 through figure 47, including signs near the intersection that were considered to have notable safety impacts.]

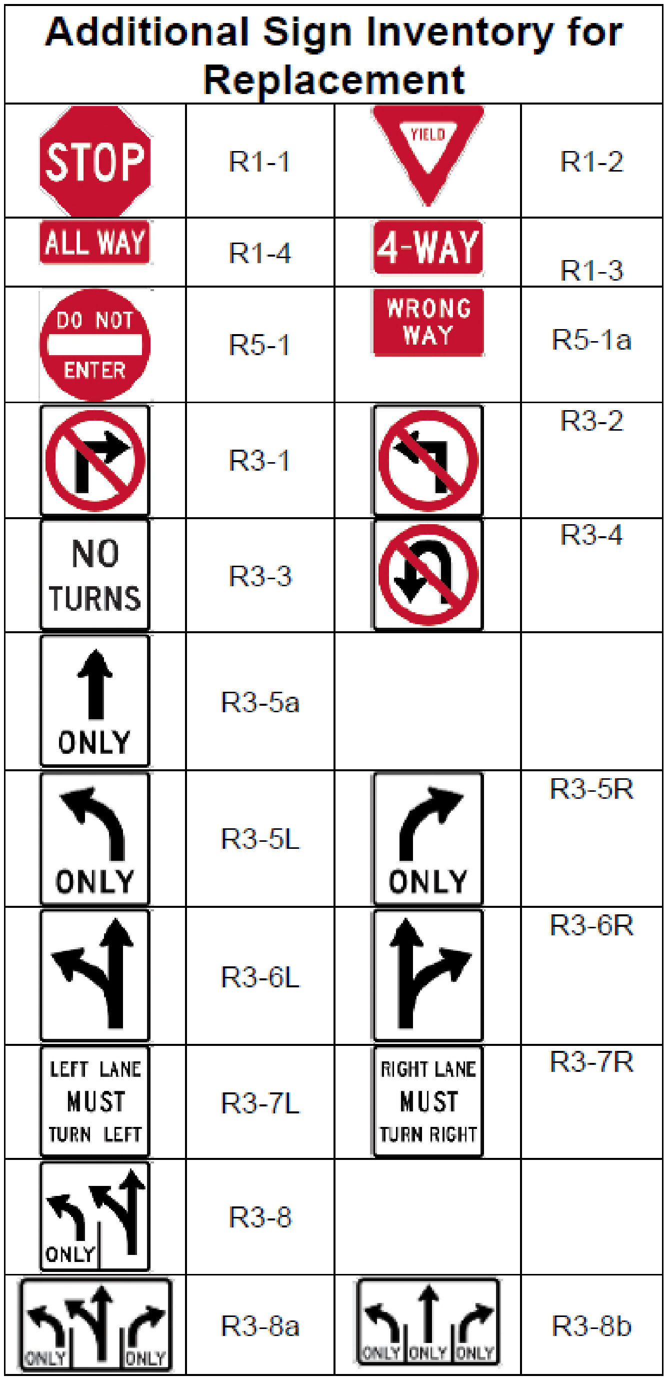


Figure 44. Illustration. Additional sign inventory for replacement (part 1).

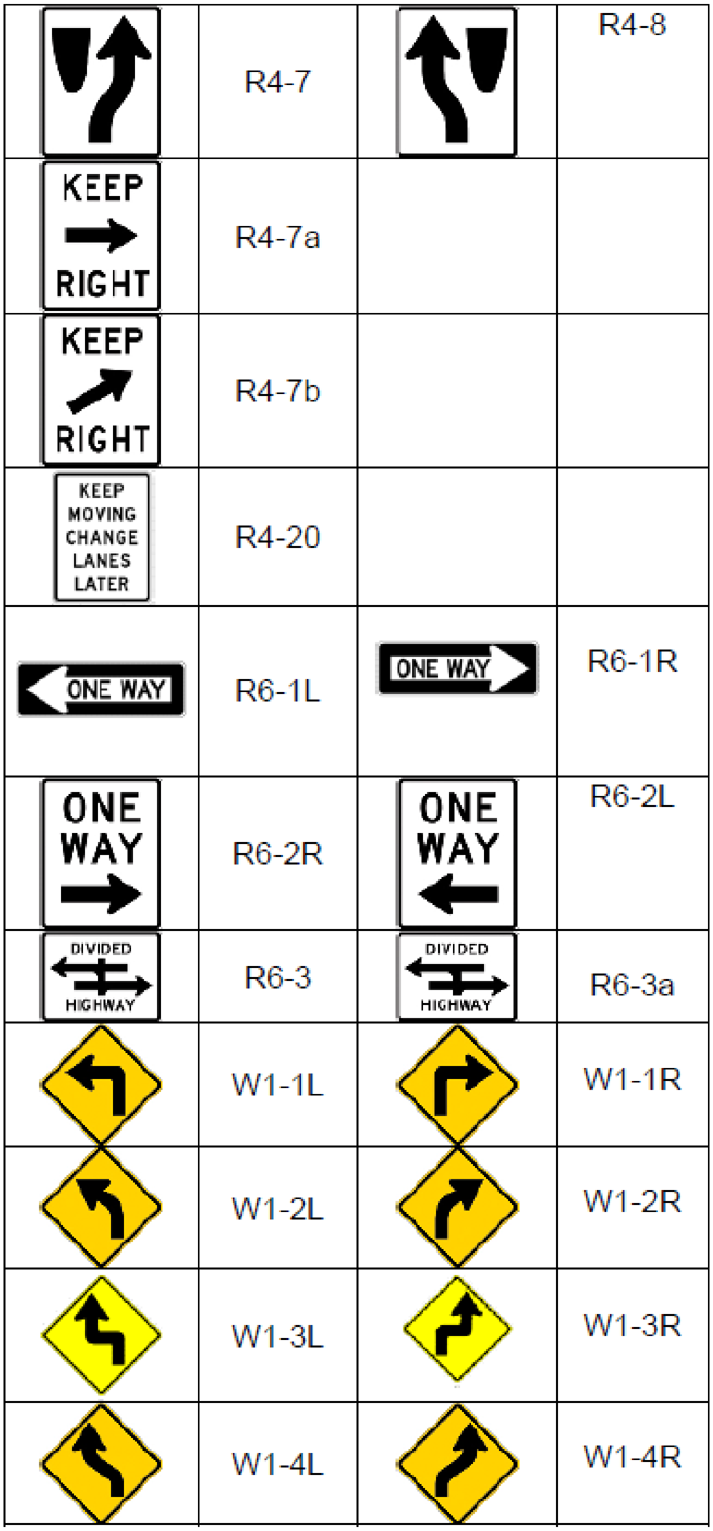


Figure 45. Illustration. Additional sign inventory for replacement (part 2).

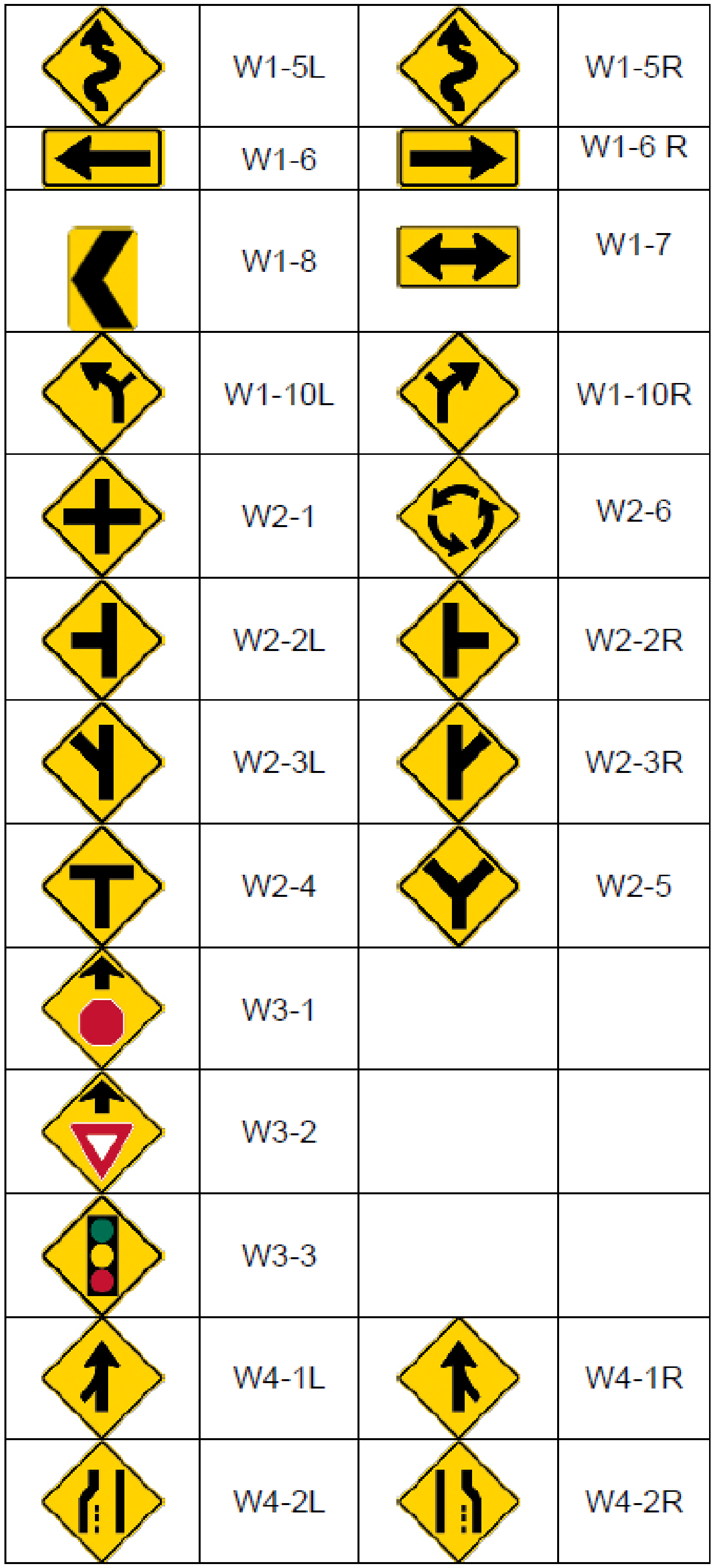


Figure 46. Illustration. Additional sign inventory for replacement (part 3).

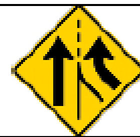
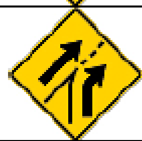
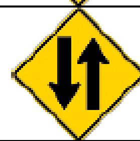
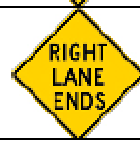
	W4-3L		W4-3R
	W4-6R		W6-3
	W9-2L		W9-2R
	W13-1		
	W16-8		

Figure 47. Illustration. Additional sign inventory for replacement (part 4).

[Table 46 shows the advance placement distance at different posted speed limits or 85-precentile speeds.]

This chart is intended as a reference with adjustments expected due to field conditions and engineering judgment.

Table 46. Advance placement distance for signal ahead, stop, or intersection warning signs.

Posted or 85th-Percentile Speed (mi/hr)	Multilane Approach* (ft)	Single Lane Approach** (ft)
20	225	200
25	325	200
30	460	200
35	565	200
40	670	225
45	775	275
50	885	350
55	990	425
60	1,100	500
65	1,200	575
70	1,250	650
75	1,350	750

Note: * These values reflect condition A from Table 2C-4 of the 2009 MUTCD and should be used as a reference for designated signs on multilane approaches.
** These values reflect condition B from Table 2C-4 of the 2009 MUTCD plus 100 ft due to the chart representing minimum guidelines and the additional advance notice needed due to the supplemental street name signs added to these sign assemblies.

RETROREFLECTIVE SIGN POST PANELS[22]

[The following guidelines on the use of retroreflective signpost panels were signed and approved by South Carolina's Director of Traffic Engineering on June 24, 2008:]

Number: TG-20

Subject: Retroreflective Sign Post Panels

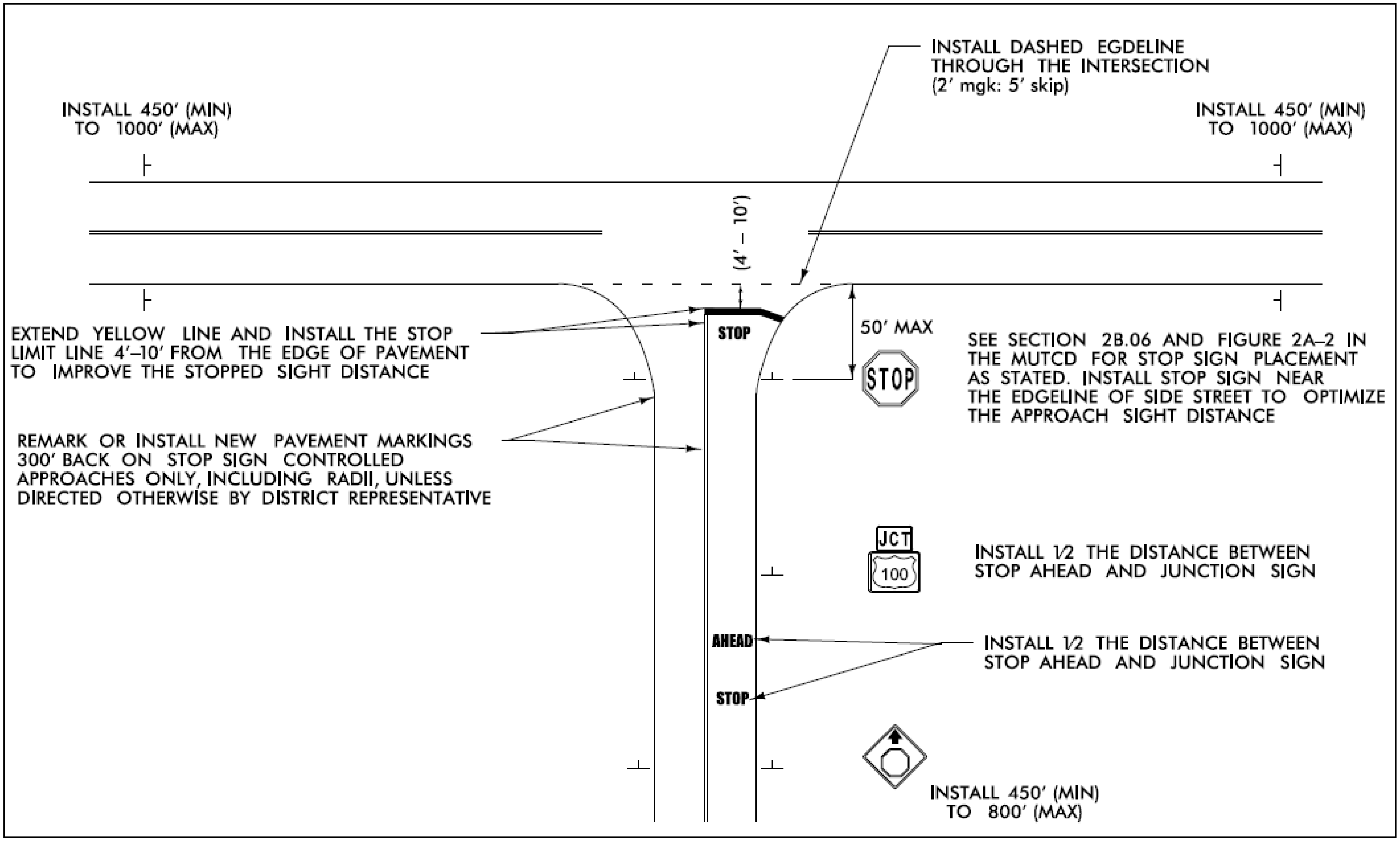
Background: Section 2A.21 of the MUTCD provides guidance on the use of Retroreflective Sign Post Panels. This section states that these panels can be applied to regulatory and warning signs where engineering judgment indicates a need for additional target enhancement during nighttime conditions. Therefore, these panels will generally be applied where crash history indicates a relatively high percentage of nighttime crashes.

Guideline: The panels shall be constructed of a nonmetallic composite or 3mm aluminum composite material approved by the SCDOT covered with a 3-inch wide type III sheeting. The panel shall be placed for the full length of the support from the sign except that the color for the "Yield" and "Do Not Enter" signs shall be red. If there are two posts supporting the sign, panels should be added to both posts.

To avoid excessive use of the Retroreflective Sign Post Panel, it is suggested that panels only be applied when needed to the regulatory signs below:

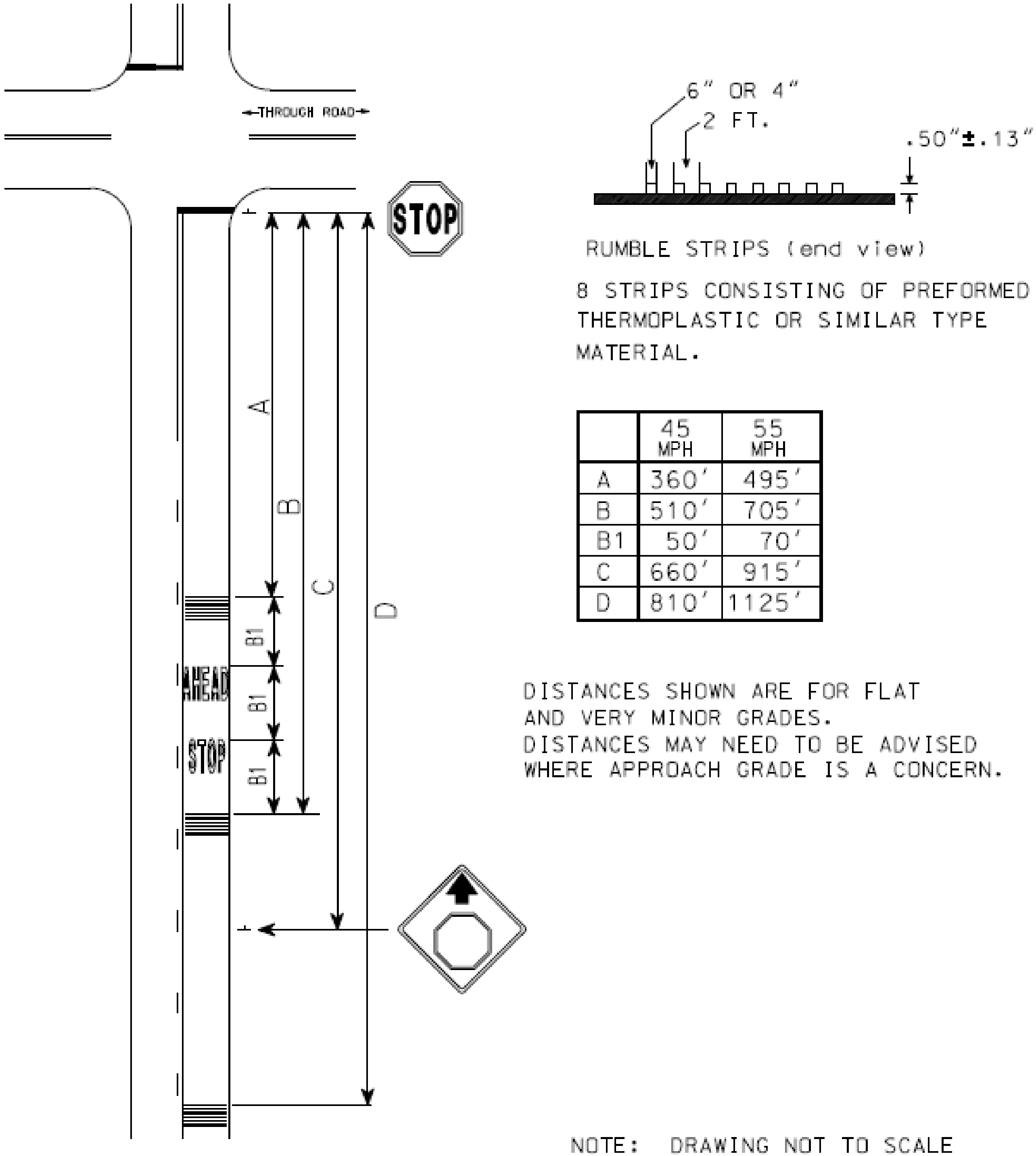
- **Red Regulatory Signs.** Stop, Yield, Do Not Enter, and Wrong Way signs—Red Panels.
- **Horizontal Alignment Signs.** Chevrons, Curve, Turn, and Large Arrow signs—Yellow Panels.
- **Advance Traffic Control Signs.** Stop Ahead, Yield Ahead, and Signal Ahead signs—Yellow Panels.
- **Intersection Warning Signs.** Cross Road, Side Road, and Two-Direction Large Arrow signs—Yellow Panels.
- **Pedestrian Signs and School Area Signs.** W11-2 and S1 Series—Fluorescent Yellow Green Panels.

[Figure 48 and figure 49 show standards for pavement marking and rumble strip placement at unsignalized intersections.]



©SCDOT

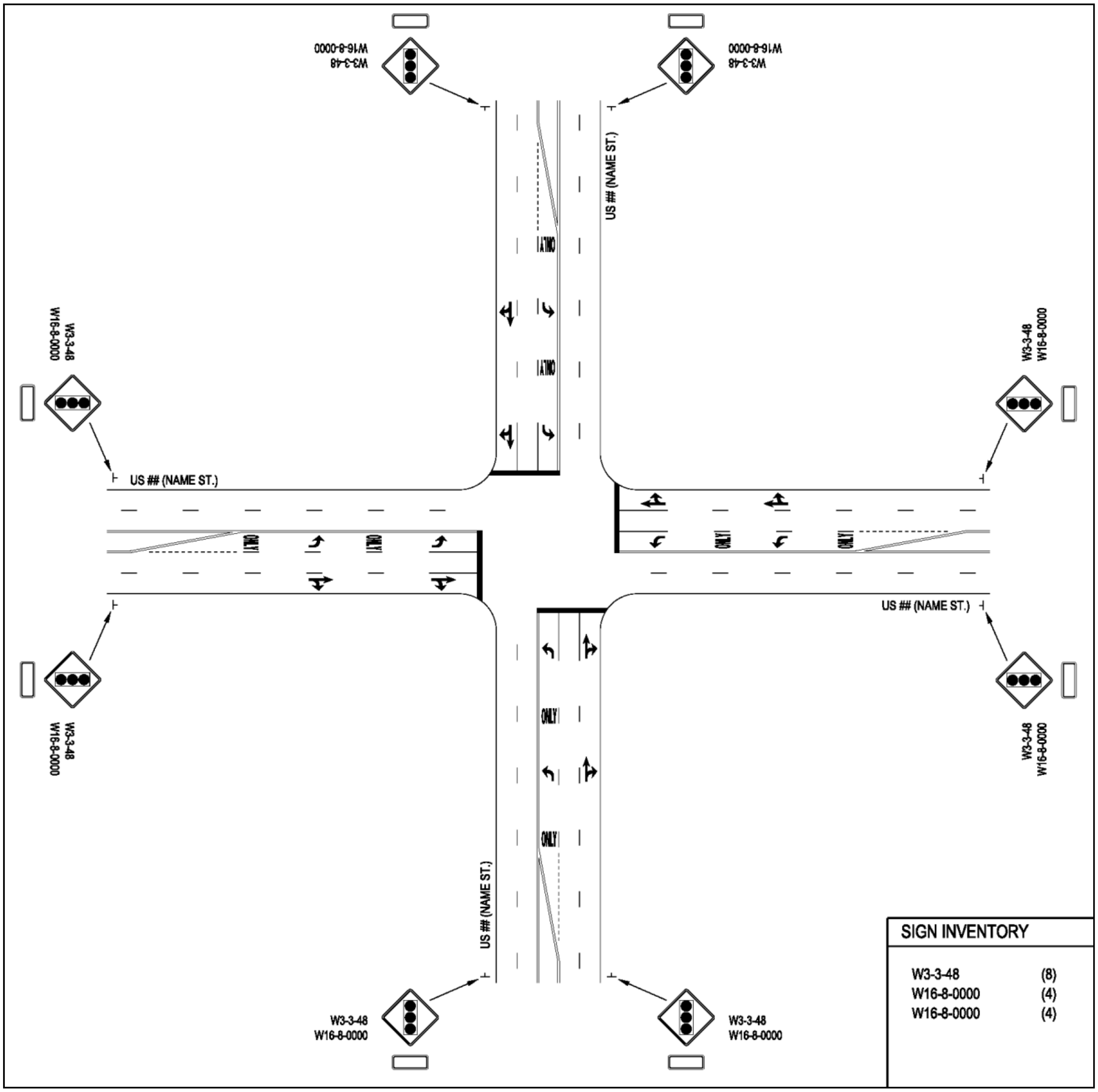
Figure 48. Illustration. SCDOT nonsignalized intersection design for pavement marking and sign installations.



	45 MPH	55 MPH
A	360′	495′
B	510′	705′
B1	50′	70′
C	660′	915′
D	810′	1125′

Figure 49. Illustration. SCDOT traffic engineering rumble strip typical.

[Figure 50 through figure 53 are examples of intersection typicals that SCDOT provided to the contractor, including a signalized intersection, a four-way stop-controlled intersection, a cross-type controlled intersection, and a t-type strop-controlled intersection.]



©SCDOT

Figure 50. Illustration. SCDOT typical for a signalized intersection.

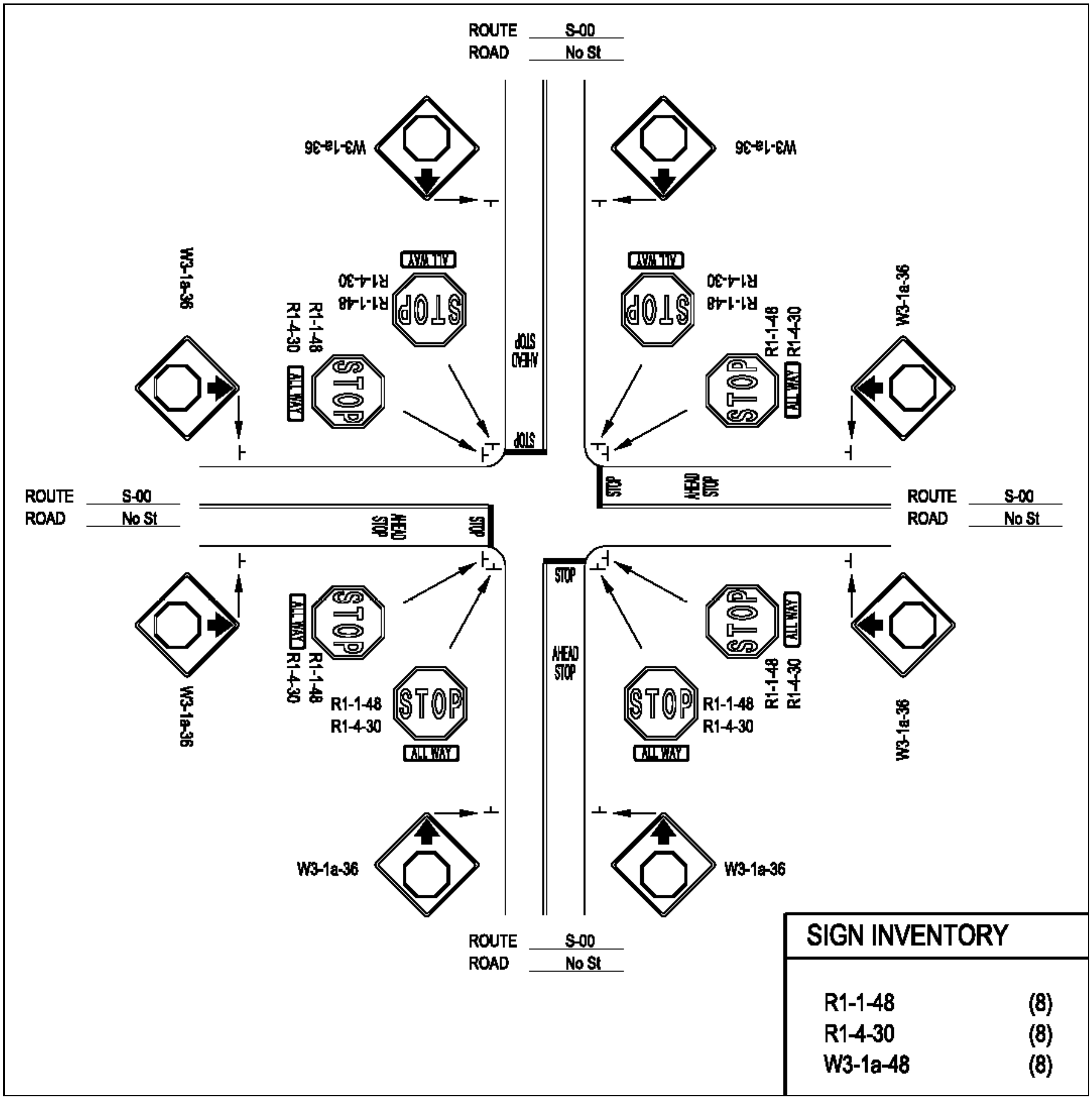


Figure 51. Illustration. SCDOT typical for a four-way stop controlled intersection.

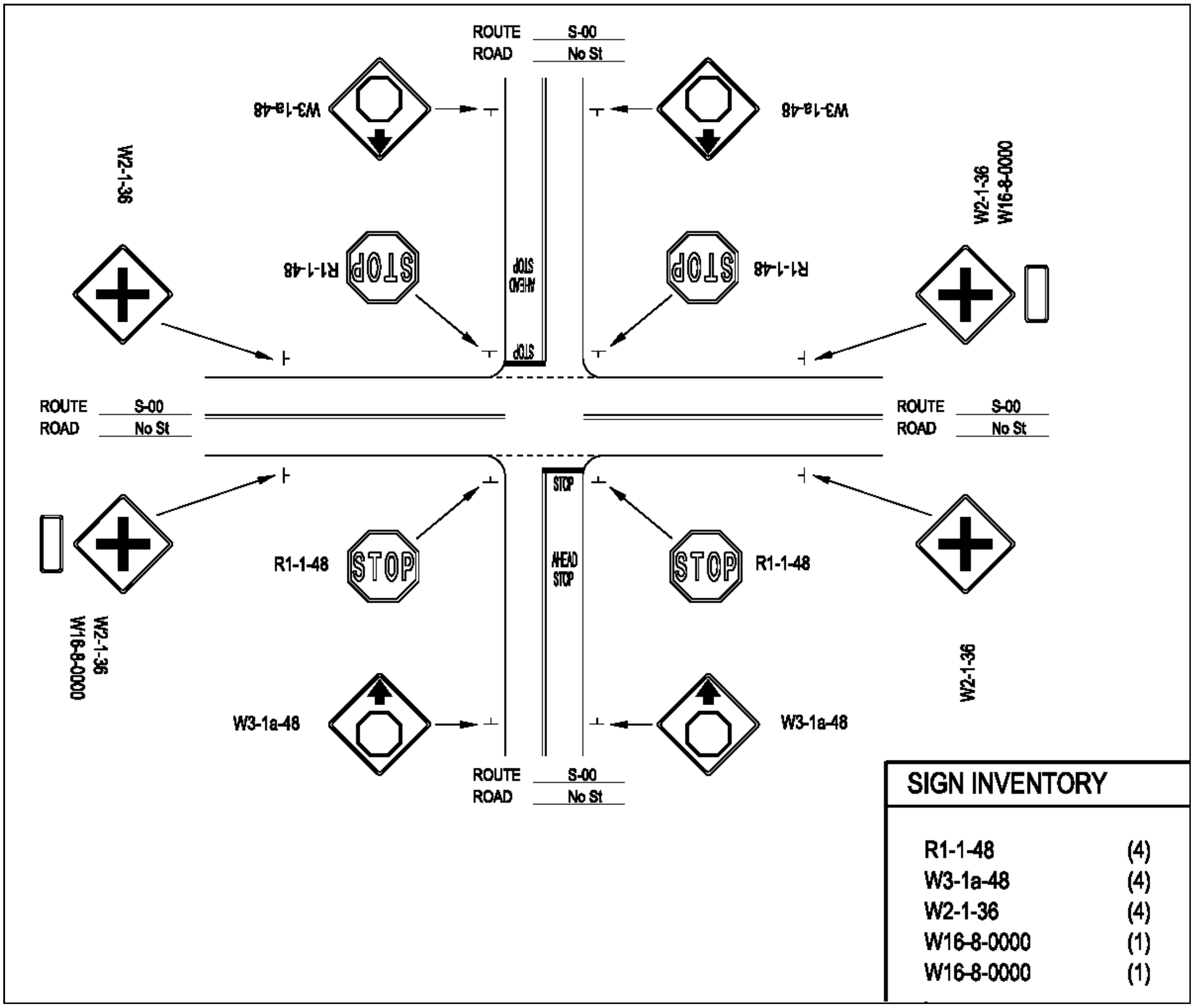


Figure 52. Illustration. SCDOT typical for a cross-type stop controlled intersection.

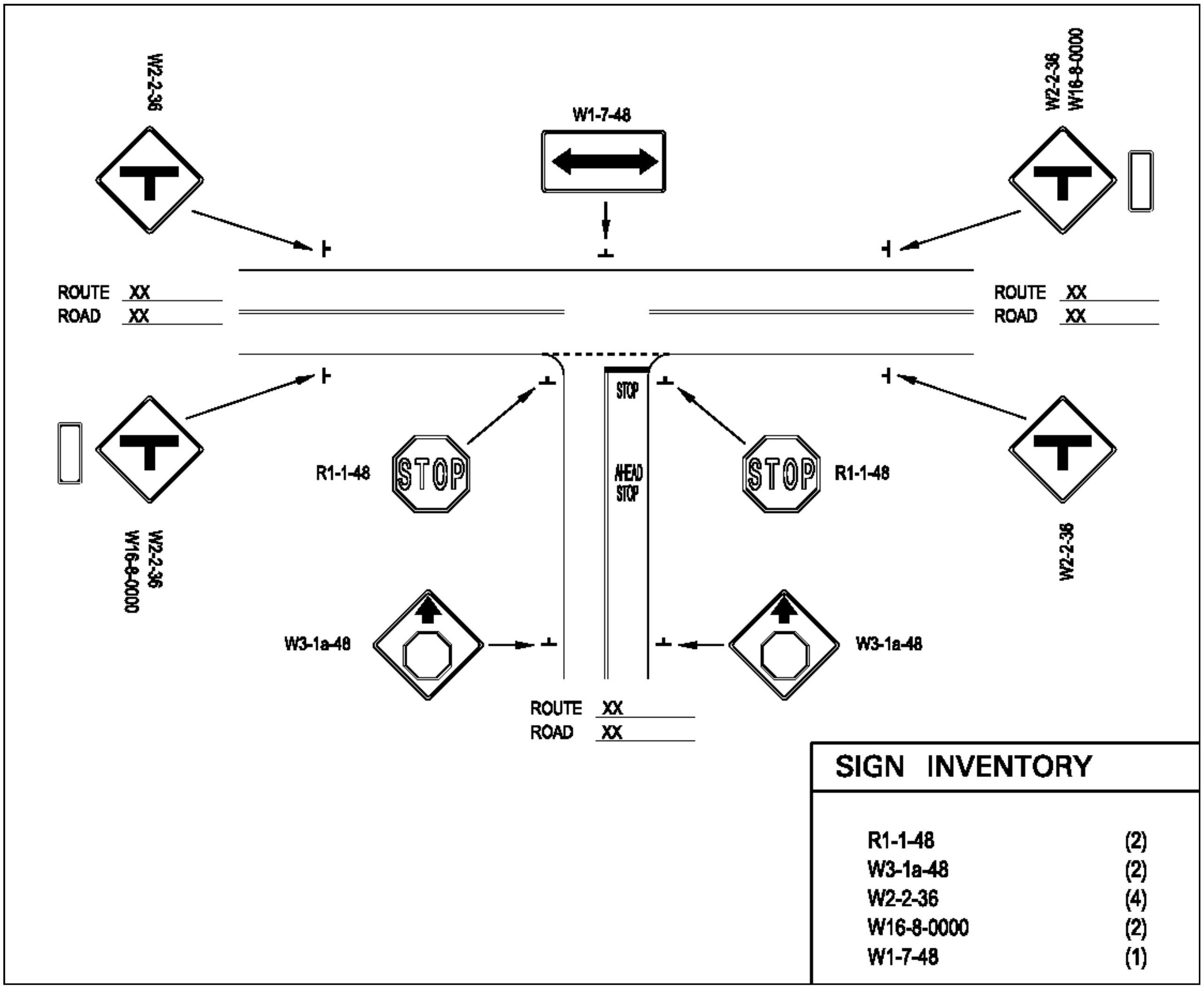
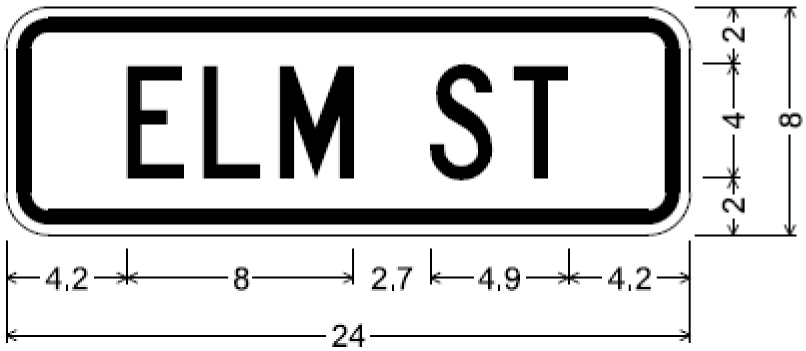


Figure 53. Illustration. SCDOT typical for a t-type stop controlled intersection.

[Figure 54 shows a street name sign typical layout.]



1.5" Radius, 0.5" Border, 0.4" Indent, Black on Yellow;
[ELM] C; [ST] C;
Table of distances between letter and object lefts.

	E	L	M	S	T	
4,2	2,7	2,7	5,3	2,9	2,0	4,2

Figure 54. Illustration. SCDOT street name sign typical.

STANDARD REVIEW GUIDELINES(23)

[The following is an excerpt from an internal SCDOT document containing standard review guidelines for reviewing installations of the treatments in this project.]

General Notes

- Speed limit signs are not to be replaced as part of this project.
- Additional Advisory Speed plaques (such as speed plaques on “Trucks Entering Hwy” sign, etc.) will not be addressed as a part of this project.
- Do not list info for retroreflective sign post panels on the plans.
- Left Turn arrow Pavement Markings shall be installed in TWLTL’s.
- Show all signs as proposed; do not shade anything to represent existing conditions.
- Any non-standard intersections, i.e., free flow interchanges or roundabouts should be sent to SCDOT Safety Office for verification and instruction.
- No Pavement Markings or signs shall be applied to routes that are not state maintained.
- All Illumination shall be upgraded to LED.
- Yield conditions shall receive yield line and skip line pavement markings.
- Place note “retain existing” for all non-MUTCD signs.

- A photo of the current street name signs in the field trumps all spelling of the street name.

- No signs should be placed in paved radii.

- Limit sign placement for dead ends, short routes, grid systems, etc.

- Engineering judgment should be used when placing all warning signs.

  - Under urban grid conditions cross road warning signs (or signal ahead signs) should not be placed.
  - Signs should not be placed near driveways (where it would obstruct sight distance) or in citizen’s front yard.
  - Signs should not be placed when an object would obscure their view (i.e., a large tree, shrubs, bridge columns, etc.).
  - Use caution when placing signs in historic districts.
  - Use caution when placing signs on interchange entrance and exit ramps.

- Guidelines for placing opposite side intersections (or signal) warning signs.

  - Do not place on roadways with more than three-lanes (three-lanes meaning two through lanes and a paved median).
  - On four-lane divided highways signs should be placed in the median.

- We will not be making upgrades to existing ramps at crosswalks.

Non-Signalized Locations

- Include estimated quantities for crosswalk, stop lines, yield lines, and skip lines on final sheet for non-signalized locations.

- Left turn Arrows and ONLY’s:

  - Less than 250’ – arrow ONLY arrow.
  - 250’ or more – arrow ONLY arrow ONLY.

- D-Signs – Make a note of the size of the letters on the signs:

  - Only need to note of existing 8” letters on 4-lane divided.

- Do not show junction signs unless they are attached to a D-sign that is being moved or replaced.

- Skip lines and yield lines must be shown at all yields.

- Overhead Flashers at a stop intersection should be treated as a signalized location and have plans made for both pavement markings/signs and signals. All flashers will be replaced with LED casings and modules. NOTE: this does not include pole-mounted flashers on a Stop sign, Stop Ahead sign or intersection warning sign.

- No NEW Flashers will be installed on Stop controlled intersections.

- All Signal Ahead, Stop Ahead, Yield and Stop signs shall be 48”. Stop and Yield signs in the median or in exclusive turn lanes can be 30”. Use engineering judgment to determine.

- Intersection warning signs shall be 36”.

- Guidelines for placing street name signs on intersection warning signs:

    - On all undivided roadways street name signs should be placed on only the right side intersection warning sign (no opposite side sign placement).
    - On four-lane divided highways street name signs should be placed on both the right side and opposite side intersection warning signs (if they are both used).
    - Word messages (such as “STOP” and “STOP AHEAD”) should be used sparingly. Only when currently in the field or engineering judgment warrants their placement (i.e., no warning signs or opposite side signs can be placed).

Signalized Locations

- **All** signal ahead signs must have street names.

- Yield and stop lines must be behind crosswalk. Indicate on plans that the stop lines/yield lines need to be eradicated and new ones installed to accommodate the crosswalk.

- Show piano lines in crosswalk **only** if they currently exist.

- Ramps will be counted as 2 if crosswalks don’t connect at the corner and 1 if they do.

- Left Turn Yield on Green (ball) sign - only installed when protected/permissive left turn (5-signal face, dog-house style head).

- There should be one 3-signal face head located in the center of each thru lane, as a minimum. A 5-signal face PT/PM head counts as one thru lane signal.

- Skip lines and yield lines must be shown at all yields.

- No NEW flashers will be installed at signalized locations.

- At intersections where Ped Heads are currently installed, if the “Walk” symbol appears automatically, then no Push Buttons are required.

- All Ped Heads shall be Countdown.

- If Ped Heads are present, propose crosswalks.

- If Push Buttons are present a crosswalk is not required.

- If a crosswalk is required, show ramps. If ramps cannot be installed mark on field notes why (i.e., catch basin).

- If ped BUTTONS are present (or proposed) = cross walks are not required.

- If ped HEADS are present (or proposed) = cross walks are required.

- If cross walks are present (or proposed) = ped heads should be present.

- Quantities for pedestrian equipment will be estimated based on the number of NEW pedestrian equipment installed.

- Number of signal heads: With permitted/protected left - 1 signal head per thru lane (5 signal face, dog-house style counts as one). With protected only left - 4 signal face, red arrows for left lane + 1 signal face per thru lane.

Field Notes

- Location information (Street names, county, etc.)

- Indicate reasons for not following regular guidelines so we know that it was not just overlooked… ped treatments, crosswalk, ramps, signs, etc.

- Any information or recommendations that may be helpful that you happen to notice while you are in the field.

- If “Signal Ahead” or “Stop Ahead” signs are determined not to be necessary, put note on field sheet as to why.

- On field notes, make mention of conflicting signs. For example, a Stop controlled intersection located between a signalized intersection and its coordinating “Signal Ahead” sign. Locations of the proposed intersection warning signs should be discussed with SCDOT.

- On field notes, note if JCT signs are black or blue.

- Note on field sheets any landscaped areas where proposed signs are to be located as well as any historic districts.

- Note on field sheets if medians or islands are pavement markings or raised. If raised, note if it is earthen or concrete.

- Street name signs on Mast Arms and Span Wire to be noted in field notes but not to be replaced.

Final Plans

- Name the intersections as they are in the list given by SCDOT.

- Consultant Company logos.

- Note NOT TO SCALE.

- Speeds from each approach.

- North arrow.

- Any changes that are made to a signalized location must be called out with an arrow pointing and a note indicating a change, i.e., Install new ped treatments (with arrows to new ped treatments only), Install NEW near-side head (with arrows to new near-side heads only), Install NEW ramp (…), Install NEW overhead signs (…), Install NEW red arrow LED head (…), etc.).

- These changes may or may not require a new PE'd plan. At a minimum, they will require an update to the signal plan if one exists. Please supply a list of signalized locations that will require a new plan to be drawn and which additions there were to the plan. (See checklist for submitting packets.)

- Example list:

    - US1 @ SC12 – nearside head, ped treatments.
    - US1 @ S-35 – ped treatments, ramps.
    - US1 @ S-1298 – additional thru lane head, ramps.

- Small maps are not necessary on Final plans (per example plan set for LCSI letting.pdf).

- Right of way does not need to be shown on plans.

- Signal Equipment box is not necessary on the Final plans.

Submissions

- Round 2 and 3 signals and stops can be submitted at the same time to cover the area all at once.

- Submit packets of approximately 50 locations at a time.

- If at all possible, do not split up a single county into two different submittals; it's best to have all locations in each county together.

- Submittals should include two packets:

    - Signal group – this packet will go to the signal group for review and contain all necessary documents spelled out below.
    - Safety group – this packet will go to the safety group for review and contain all necessary documents spelled out below.

Checklist for Submitting Packets

Initial Signal Group:

_____ Final plan – electronic version printout, may have pavement markings and signs on them

_____ Field notes plan – can be hand drawn plan or notes handwritten on electronic print, make notes for all decisions that are not following the standard recommendations (i.e., no signal ahead sign because signal nearby, no sidewalk ramp because gutter under curb, no double up on signal ahead because of somebody's beautiful garden, etc.)

_____ Quantities form – can be hand written from field as long as legible, include color of signal head/ped head casing, whether there are mast arms or not

_____ Electronic photos or ftp

_____ Electronic plans on disk or ftp

_____ Electronic list of locations needing updated signal plan

Final Signal Group Construction Packet:

_____ Coversheet

_____ Quantity sheets

_____ Drawing for each location

_____ Construction specifications with specific location information for the district

Safety Group:

_____ Electronic Documents (submitted on CD is fine) - Microstation file for each location, PDF of field notes and quantities sheet, PDF of final plan and any photos taken during the site review

_____ Cover sheet – this should include a list of all locations included in the packet (along with their signalized or stop controlled status) and all locations omitted from the packet along with the reason for omission (current project, interchange, etc.). Please also note the locations where overhead flashers (mounted on span wire or mast arms) are present. These will need to be included in both the signalized and safety packets.

_____ For signalized locations: include a hard copy of the final signing and marking plan (without signal information), a copy of the field notes and a copy of the quantities sheet.

_____ For stop controlled locations: include a hard copy of the final signing and marking plan, a copy of the field notes and a copy of the quantities sheet.

_____ For stop controlled locations with overhead flashers: include a hard copy of the final signing and marking plan (include flasher information on both the safety and signal copies for overhead flashers only), a copy of the field notes and a copy of the quantities sheet.

ACKNOWLEDGMENTS

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