Advancing Innovating Intersection Safety Treatments for Two-Lane Rural Highways

FHWA Safety Program

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16. Abstract

Intersection safety is a national, state, and local priority. Approximately 26 percent of the fatal crashes that occur in the United States are intersection or intersection-related crashes. The objective of this guide is to advance efforts to improve safety at unsignalized intersections with minor-road stop control along rural two-lane roads, by focusing on strategies that are not yet widespread. The safety effectiveness of three low-cost safety treatments was evaluated to estimate their expected effectiveness in reducing crashes. The low-cost safety treatments included: (1) single luminaire intersection lighting, (2) transverse rumble strips in advance of stop-controlled approaches, and (3) supplementary pavement markings on intersection approaches.

The effectiveness of each treatment in reducing crashes was estimated using the Empirical Bayes (EB) observational before-after safety evaluation analysis approach. Analyses were performed to estimate the effectiveness of each treatment in reducing crashes for different severity levels and crash types. An economic analysis of the treatments was also performed. Each of the treatments is effective in reducing crashes of different types and severity levels, and is economically justifiable for most traffic volumes.

The information in this report can be combined with information on other strategies to reduce intersection or intersection-related crashes at unsignalized intersections with minor-road stop control along rural two-lane roads. With such information, agencies can make informed decisions about planning and programming safety improvements at intersections under their jurisdiction.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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CHAPTER 1. INTRODUCTION

BACKGROUND

Intersection safety is a national, state, and local priority. Approximately 26 percent of the fatal crashes that occur in the United States are intersection or intersection-related crashes.[1,2] In the period between 2009 and 2013, the average number of intersection-related fatal crashes was approximately 7,960 per year.[1]

Crashes in rural areas are often more severe than in urban areas because of higher vehicle speeds, and the outcome of crashes may be more severe, in part, due to longer emergency response times. In rural areas, more fatal and severe injury crashes occur at stop-controlled intersections than at signalized intersections.[3] At stop-controlled intersections, most crashes are caused by a failure to stop at a stop-controlled approach or an acceptance of an insufficient gap when entering the intersection.[4]

OBJECTIVE

The objective of this guide is to advance efforts to improve safety at unsignalized intersections with minor-road stop control along rural two-lane roads, by focusing on strategies that are not yet widespread. The safety effectiveness of three low-cost safety treatments was evaluated to estimate their expected effectiveness in reducing crashes. The low-cost safety treatments included:

- Single luminaire intersection lighting
- Transverse rumble strips in advance of stop-controlled approaches
- Supplementary pavement markings (such as STOP AHEAD) on intersection approaches

The information in this guide can be combined with information on other strategies to reduce intersection or intersection-related crashes at unsignalized intersections with minor-road stop control along rural two-lane roads. For example, the *National Cooperative Highway Research Program (NCHRP) Report 500 Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 5: A Guide for Addressing Unsignalized Intersection Collisions* provides proven, tried, and experimental strategies for reducing crashes at unsignalized intersections.[5] The American Association of State Highway and Transportation Officials (AASHTO) *Highway Safety Manual* (HSM) provides crash prediction methods for estimating the predicted and/or expected crash frequency at unsignalized intersections on rural two-lane roads and related crash modification factors (CMFs).[6] Similarly, the online CMF Clearinghouse, sponsored by the Federal Highway Administration (FHWA), houses a web-based database of CMFs along with supporting documentation to help transportation engineers identify appropriate countermeasures for their safety needs.[7] With such information, agencies can make more informed decisions when planning and programming safety improvements at intersections under their jurisdiction. The overall goal of this guide is to increase the deployment of treatments that reduce motor vehicle fatalities and injuries at unsignalized intersections with minor-road stop control along rural two-lane roads by providing practitioners with knowledge about their installation and expected safety benefits. Throughout this guide, the term “intersections” refers to unsignalized intersections with minor-road stop control along rural two-lane roads unless otherwise stated.

HOW TO USE THIS GUIDE

This guide serves as both a technical report of the treatments evaluated in the research, and as a practical guide for practitioners who may be interested in implementing the treatments evaluated. Guidance includes, where appropriate, the conditions under which the treatment is expected to be effective and design and installation considerations.

Chapter 2 of this guide includes general information about how the research was conducted, including identification of intersections for inclusion in the research, the data that were collected, and the analysis approach.

Chapters 3 through 5 each discuss one of the three treatments evaluated as part of this research in depth: single luminaire intersection lighting, transverse rumble strips, and supplementary pavement markings. Each chapter begins with a summary table of key information about the treatment, its use, and its expected effectiveness. The chapter then includes a detailed discussion under the following subheadings:

- Description of treatment
- Safety evaluation
- Economic analysis
- Implementation

Conclusions are presented in Chapter 6.

CHAPTER 2. RESEARCH APPROACH

This Chapter describes the general approach to the research, including identification of treatments to be evaluated, selection of treatment and nontreatment sites (i.e., intersections) for inclusion in the safety evaluations, a description of the data elements collected for the safety evaluations, and descriptions of the methodological approaches used to evaluate the safety effectiveness and economic benefits of the treatments.

SELECTION OF TREATMENTS FOR EVALUATION

At the beginning of the project, the research team identified 32 low-cost safety treatments applicable to unsignalized intersections on rural two-lane roads for which limited knowledge about their safety effectiveness was available. The list of treatments was developed by gathering information through a combination of a literature review, a virtual/desktop scan of national and international experiences, and telephone discussions and email exchanges with highway agency staff and consultants. Examples of treatment types considered for evaluation as part of this research included, but were not limited to, the following:

- Geometric modifications
- Enhanced and/or dynamic forms of existing traffic control devices
- Roadside design features
- Lighting
- Pavement treatments

For each potential treatment considered for evaluation, the following information was gathered:

- Description of the treatment and the specific safety problems the treatment addresses
- The expected safety effectiveness of the treatment based upon limited previous research or anecdotal evidence
- If the treatment is included in NCHRP Report 500 (Vol. 5), status of the treatment as either “tried” or “experimental”
- If the treatment is included in the CMF Clearinghouse, the star rating of the treatment
- Potential treatment locations for data collection
- The likely performance measure(s) that would be used to evaluate the treatment
- Technical uncertainties that would be anticipated if the treatment was analyzed (e.g., Will it be difficult to identify sites where the treatment was installed? Is there a wide range of designs that may impact the effectiveness of the treatment?)
- Whether the treatment was currently being evaluated in another ongoing research project
- International experience with the treatment’s safety effectiveness
- The likelihood of developing reliable safety effectiveness estimates for the treatment given the availability of potential study sites and other data needed for analysis

After several iterations of prioritizing potential treatments, three were selected for evaluation:

- Single luminaire intersection lighting
- Transverse rumble strips in advance of stop-controlled approaches
- Supplementary pavement markings (such as STOP AHEAD) on intersection approaches

Estimating the safety effectiveness of installing a single luminaire at a stop-controlled intersection on a rural two-lane highway was identified as a high priority because safety effectiveness information for this treatment available in the HSM is general in nature and was adapted from studies that were not specific to rural intersections. HSM Chapter 10, Predictive Method for Rural, Two-Lane, Two-Way Roads*,* includes the following CMF for intersection lighting at stop-controlled intersections:[(6)]

$$CMF_{Lighting} = 1 - 0.38 \times p_{ni}$$

Figure 1. Equation. CMF for lighting.

where p_{ni} is the proportion of total crashes for unlighted intersections that occur at night.

The CMF is applicable to total crashes, and the base condition is the absence of intersection lighting. This CMF indicates that intersection lighting is expected to reduce nighttime crashes at intersections on rural two-lane roads by 38 percent. Chapter 10 of the HSM states that the CMF is adapted from crash reduction estimates presented in *The Handbook of Road Safety Measures* by Elvik and Vaa.[(8)] The *Handbook* provides the following crash reduction estimates for roadway lighting for crashes that occur in darkness based on a meta-analysis of 25 studies from several countries conducted between 1948 and 1993 (Table 1).

Table 1. Crash reduction estimates for lighting from *The Handbook of Road Safety Measures*.[(8)]

Crash severity	**Percent reduction in crashes occurring in darkness**
Fatal	64
Injury	28
Property-damage-only	17

No information specific to intersections or rural roads is presented.

HSM Chapter 14, Intersections, which provides information about intersection treatments that goes beyond what is provided in the predictive methods chapters, includes a CMF for intersection lighting. The Chapter 14 CMF for intersection lighting on nighttime crashes is 0.62 (38 percent reduction, as shown in Chapter 10), but is specified for injury crashes only. In addition, a CMF for pedestrian nighttime injury crashes of 0.58 is provided. Chapter 14 of the HSM cites four sources [(8,9,10,11)] for these intersection lighting CMFs rather than the single reference [(8)] provided in HSM Chapter 10. However, in only one of the sources [(11)] is the safety effectiveness estimate for roadway lighting based solely on data from unsignalized intersections along rural two-lane roads. The study by Preston and Schoenecker [(11)] is also cited in NCHRP Report 500 (Vol. 5), *A Guide for Addressing Unsignalized Intersection Collisions*,[(5)] which lists "Improve Visibility of the Intersection by Providing Lighting" as a "proven" safety treatment, yet the results of the Preston and Schoenecker study are not incorporated into the HSM Chapter 10 predictive methodology for intersections on rural two-lane roads.

By conducting a detailed safety evaluation for the installation of a single luminaire at stop-controlled intersections on rural two-lane roads, the intention is to develop a more reliable estimate for intersection lighting specific to the condition of interest (i.e., unsignalized intersection with minor-road stop control on rural two-lane roads) than what is currently provided in the HSM. In addition, this study includes in the analysis only intersections where a single luminaire was installed, making the results specific to this type of lighting implementation, which is currently not specified in the HSM or other available literature.

Estimating the safety effectiveness of transverse rumble strips installed on minor-road intersection approaches was identified as a high priority because it is a relatively common treatment, but reliable safety estimates specific to stop-controlled intersections on rural two-lane roads are not available. HSM Chapter 14 provides a discussion of rumble strips installed on intersection approaches, and suggests that they are frequently used to inform drivers of an upcoming change in the roadway or as traffic calming devices. The discussion notes that in-lane rumble strips appear to reduce all crash types of all severities on urban roads, but that the magnitude of the effect is not known. No information is provided regarding rural intersections. In a recent before-after study using crash data from 3- and 4-leg stop-controlled intersections in rural areas, Srinivasan et al. reported that transverse rumble strips reduce KAB (fatal and injury) crashes by 21 percent and KA (fatal and severe injury) crashes by 39 percent.(12) The results of this study are included in the CMF Clearinghouse, with star ratings ranging from 3 to 4 stars. However, it is unknown whether the analysis results from this study are based on intersections located exclusively along rural two-lane roads or a combination of sites located along rural two-lane roads and rural multilane divided highways, and due to sample size issues, no definitive conclusions were provided regarding the impacts on specific crash types. Therefore, it is desirable to develop a crash reduction estimate for transverse rumble strips specifically for unsignalized intersections with minor-road stop control on rural two-lane roads and to estimate the safety effects of this treatment on specific target crashes (e.g., angle and rear-end).

As with transverse rumble strips, supplementary pavement markings (such as STOP AHEAD) were identified as a high priority treatment for evaluation because they are relatively common treatment, but little reliable information is available regarding their impact on crashes. CMFs for STOP AHEAD pavement markings on various intersections types and for various crash types and severities are included in Chapter 14 of the HSM, but they are not incorporated into the HSM predictive chapters. Only one of the CMFs—for all crash types and severities at stop-controlled rural intersections—has a standard error low enough for it to be considered reliable. It indicates a 31 percent crash reduction when STOP AHEAD pavement markings are used. All the STOP AHEAD pavement marking CMFs in Chapter 14 of the HSM are based on a study by Gross et al.,(13) which used the Empirical Bayes before-after analysis approach. No CMF is provided specifically for unsignalized intersections with minor-road stop control on rural two-lane roads. The CMF Clearinghouse includes CMFs with ratings of 3 or 4 stars for this treatment based upon the study by Gross et al.(13) Therefore, it was desirable to develop a more reliable crash reduction estimate specifically for supplementary pavement markings (such as STOP AHEAD) for unsignalized intersections with minor-road stop control on rural two-lane roads for possible inclusion in HSM Chapter 10. It was also desirable to estimate the safety effects of this treatment on specific target crashes (e.g., angle and rear-end) for the conditions of interest.

In seeking potential study sites for this treatment, the research team did not limit the supplementary pavement marking message to STOP AHEAD only. While a majority of sites did have this message (installed on the minor approaches), several sites were identified at which a supplementary pavement marking treatment was installed on the major (uncontrolled) approaches to the intersection. Since no reliable safety effectiveness estimates were available for this specific application, a separate analysis of the safety effectiveness of this treatment was conducted as well.

SELECTION OF TREATMENT AND NONTREATMENT SITES

After selecting the three treatment types to be evaluated, the research team contacted state and county highway agencies to request location information (e.g., major-road name, minor-road name, county) for intersections at which a treatment of interest had been installed. The research team then gathered additional data for each site, including intersection geometrics and site charateristics data, traffic volumes, installation dates, and construction history to determine if each site was suitable for inclusion in the analysis. The following criteria were used to narrow the list of potential treatment sites to those included in the analysis:

- Installation year: Ideally, the treatment was installed between 2005 and 2008, allowing the research team to gather four to five years of crash data before and after the installation. Some sites were included in the safety evaluation with earlier or later installation years; these exceptions are discussed in later sections.
- Availability of crash and traffic volume data by year: In some cases, when traffic volume data were not available for all years of the study period, it was interpolated from years with known traffic volumes. Traffic volume data had to be available for both major- and minor-roads for the intersection to be included in the analysis.
- Construction history: Treatment sites were limited to those at which no substantial construction had taken place, other than installation of the treatment, during the study period.

Additional details about the data collection process are provided in the discussion on data collection later in this chapter.

Table 2 shows the states in which treatment sites included in the analysis were located.
Once the list of treatment sites for inclusion in the analysis was finalized, the research team identified nontreatment sites in each state where treatment sites were located. Nontreatment sites are used in the before-after analysis to account for crash trends over time. Potential nontreatment sites were identified by searching aerial and street-view images of rural roads in the vicinity of treatment intersections, and then expanding that search to similar, nearby routes. Nontreatment sites were selected from the potential sites using the following criteria:

- No treatment installed at site over study period (this includes the three treatments evaluated in this research)
- Crash and traffic volume data available by year
- Traffic volumes for major- and minor-roads that fall within the range of those at the treatment sites in that state
- Proportion of 3-leg and 4-leg nontreatment sites similar to that proportion for treatment sites in the same state

Table 2. States included in the safety evaluation of each treatment type.

States	Single luminaire intersection lighting	Transverse rumble strips	Supplementary pavement markings
Arkansas		Yes	Yes
Kansas		Yes	
Minnesota	Yes		Yes
Missouri		Yes	
Nebraska			Yes
North Dakota		Yes	
Oregon		Yes	
Pennsylvania			Yes
Vermont			Yes

Approximately 30 nontreatment sites were identified in each state for inclusion in the analysis. All nontreatment sites in each state were used in the analysis of all treatments in that state.

The discussion of the statistical analysis in Chapters 3, 4, and 5 includes descriptive statistics for the treatment and nontreatment sites included in the analysis.

DATA COLLECTION

The following data are critical for performing a safety evaluation of a treatment:

- Treatment installation date
- Crash data for treatment (before and after treatment installation) and nontreatment sites (matching periods)
- Traffic volume data for treatment (before and after treatment installation) and nontreatment sites (matching periods)
- Intersection characteristics data for treatment and nontreatment sites

Final selection of intersections for inclusion in the analyses was determined, in part, by the availability of such data.

Treatment Installation Date

For each potential treatment site, the research team obtained the treatment installation year from state highway agencies. This information was critical for defining the appropriate analysis period for evaluation of the treatment at the respective intersection. The goal was to include sites at which treatments were installed between 2005 and 2008 so that four to five years of crash data would be available after installation of the treatment, and before-period data would be from within the last 15 years. In cases where only a limited number of treatment sites met this criterion, exceptions were made to allow sites with fewer years of before or after data in the analysis or include “before” period crash data prior to 2000 in the analysis. In cases where the installation date of an intersection treatment was unknown, that intersection could not be included in the Empirical Bayes (EB) before-after evaluation. The EB before-after analysis methodology is discussed below, under “Analysis Approach.” .

The research team also requested information from state highway agencies as to whether substantial improvements or changes other than the installation of the treatment being evaluated were made during the study period at any of the intersections considered for inclusion in the evaluation. Intersections where other substantial improvements or changes were made were either excluded from the evaluation or the study period was adjusted to only include the years prior to or after the changes were made. Where possible, the research team used Google Earth to review images over a number of years to assess the history of changes to intersections. These images were used to gather construction history data when the highway agency was not able to provide it or to validate construction history information when it was provided. The history of changes to nontreatment intersections was assessed in the same manner.

Crash Data

The research team obtained crash data from state highway agencies for treatment and nontreatment sites in electronic form. As indicated above, the goal was to obtain crash data for four to five years before and four to five years after installation of the treatment at the treatment sites. Data were requested up to the most recent year of available data, even if this resulted in more than five years of after-period data. For a given treatment and state, crash data for nontreatment sites were requested for years covering the full range of before and after periods of the treatment sites included in the analysis. For Minnesota, some crash data were obtained from the Highway Safety Information System (HSIS) for the analysis.

Data for individual crashes were obtained at the crash and vehicle levels. The primary crash data elements of interest for the safety evaluations included:

- Crash location
- Crash date
- Time of day
- Severity level
- Number of vehicles involved
- Crash type and manner of collision
- Lighting condition
- Sequence of events (including first harmful event and most harmful event)
- Relationship to intersections/junctions

Traffic Volume Data

The research team obtained traffic volumes [annual average daily traffic (AADT)] for the major- and minor-road approaches of each treatment and nontreatment intersection. AADTs were obtained for as many years as available for the study period. If the AADTs differed for both major-road approaches to an intersection, the greater of the two AADT values was used in the analysis; AADTs for the minor-road approaches were treated in a similar fashion. If an AADT for a particular year was missing, and AADTs for years before and after that year were known, then the AADT for the missing year was estimated through interpolation. If an AADT was missing at the beginning or end of a study period, then the closest AADT was simply used for that year. If AADTs were missing for most or all study years, the intersection was excluded from the analysis.

Intersection Characteristics Data

Treatment and nontreatment site characteristics were obtained using Google Earth and Google Street View. Data for the following intersection characteristics were collected:

- Type of traffic control
- Area type
- Number of intersection legs
- Number of major-road approaches with left-turn lanes
- Number of major-road approaches with right-turn lanes
- Intersection skew angle
- Presence of lighting
- Number of light poles in the vicinity of the intersection
- Presence of transverse rumble strips
- Presence of supplementary pavement markings
- Distance of transverse rumble strips/supplementary pavement markings to intersection
- Number of treated approaches

These data were used to 1) choose the appropriate safety performance function (SPF) and CMFs to predict the expected number of crashes at the intersection, and 2) to better define the specific implementation of the treatment.

ANALYSIS APPROACH

The effectiveness of each treatment in reducing crashes was estimated using the Empirical Bayes (EB) observational before-after safety evaluation analysis approach. An economic analysis of the treatments was also performed using the safety effectiveness information developed in this research. The general approach to these analysis methodologies is described below, while specific details of how each approach was applied for the individual treatments is provided in the respective chapters.

EB Before-After Safety Evaluation Method

The collected data lent themselves to an Empirical Bayes (EB) observational before-after safety evaluation with reference sites. The EB method is now a standard approach to safety evaluations.[14,15] The EB method has been applied by members of the research team in a number of recent projects [16,17] and by others [13,18].

The EB approach overcomes the difficulties associated with conventional before-after comparisons by:

- Properly accounting for regression-to-the-mean
- Overcoming the difficulties of using crash rates in normalizing for volume differences between the before and after periods
- Reducing the level of uncertainty in the estimates of the safety effects

The specific EB approach used for this evaluation follows the steps presented in Appendix 9A in Chapter 9 of the HSM.[6] The analysis approach is comprised of four basic steps.

STEP 1**:** Calibrate the appropriate HSM SPFs within each state using the reference site data within that State. The research team also included the "before" period data for the treatment sites within that State in this step.

STEP 2**:** Estimate the expected number of crashes in the before period by taking a weighted average of the observed crash count and the predicted crash frequency calculated from the calibrated HSM SPF to estimate the EB-adjusted expected crash frequency in the before period.

STEP 3**:** Estimate the expected number of crashes in the "after" period had the treatment not been installed. This estimate is obtained by adjusting the EB-adjusted expected crash frequency from the before period (as calculated in Step 2) for the difference between before and after AADTs and between before and after number of years.

STEP 4**:** Estimate the effectiveness of the treatment by comparing the **observed** number of crashes in the after period to the **expected** number of crashes in the after period, had the treatment not been installed (as calculated in Step 3).

The effectiveness of each treatment in reducing crashes was estimated separately for the following crash severity levels and crash types:

Severity level:

- Total crashes (all severity levels combined)
- Fatal and severe (FS) crashes
- Fatal and all injury (FI) crashes
- Property-damage-only (PDO) crashes

Crash type:

- All crashes combined (excluding single luminaire)
- Nighttime crashes (single luminaire only)
- Angle crashes (excluding single luminaire)
- Rear-end crashes (excluding single luminaire)

The injury scale used in this analysis can be translated to the KABCO crash severity scale as follows:

- Total crashes = K, A, B, C and O crashes
- FS crashes = K and A crashes
- FI crashes = K, A, B and C crashes
- PDO crashes = O crashes

where:

K = fatal crash
A = disabling injury crash
B = evident injury crash
C = possible injury crash

Economic Analysis

An economic analysis was performed for each of the three intersection treatment types to estimate the benefit-cost ratio of each treatment. The benefit-cost ratio is the ratio of the present benefit of a treatment, measured in monetary terms of the number of crashes reduced due to installation of the treatment, to its construction costs. For a countermeasure to be economically justified, its benefit-cost ratio should be greater than 1.0. The most desirable countermeasures are those with the highest benefit-cost ratios. The safety effectiveness results of the three treatments were incorporated in the economic evaluations.

Implementation Cost and Service Life

The implementation costs and service lives of the safety treatments were determined based on input from State highway agencies. Costs and service lives can vary by geographic regions. For example, a cold-weather State may want to assume a shorter service life than a warm-weather State for pavement markings due to snowplows damaging the treatment. Care should be taken to select a service life appropriate to the region in which the treatment is being installed.

Crash Reduction Benefit

The annual benefits for the safety treatments were estimated as follows:

1. Estimate crash frequency by crash severity level for the existing 3-leg and 4-leg stop-controlled intersections on rural two-lane roads prior to installation of the treatment, based on the HSM Part C predictive methods.

2. Estimate the reduction in crash frequency by severity due to the treatment implementation, based on CMFs derived from this research.
3. Calculate annual crash cost savings.

Table 3 presents the crash costs used in the analysis, which are the values provided in HSM Chapter 7. Transportation agencies may use different values for crash costs that may be more current or specific to a location than the values shown in Table 3. A 2015 NHTSA report (19) estimates the economic and societal impact of a motor vehicle crash fatality to be $9,146,000, while a June 2015 memo from the Office of the Secretary of Transportation (20) provides guidance for transportation analyses to use $9.4 million as the economic value of a statistical life. Substituting higher values, such as these, for the values shown in Table 3 will only increase the calculated benefit of a given treatment. The crash cost values presented in Table 3 were used in the economic analyses for consistency with the HSM.

Table 3. Crash costs by severity level assumed for economic analysis.(6)

Crash Severity Level	Comprehensive Societal Crash Costs
Fatal (K)	$4,008,900
Disabling injury (A)	$216,000
Evident injury (B)	$79,000
Possible injury (C)	$44,900
Property damage only (O)	$7,400

The SPFs in the HSM Part C predictive methods require major- and minor-road AADTs to compute predicted crash frequencies. The intersections used to produce CMFs in this research consisted of a wide range of traffic volumes on both the major- and minor-road approaches. Annual crash reduction benefits were calculated for each treatment type by varying the major-road AADT in 1,000-veh/day increments. The minor-road AADT was varied as a percentage of the major-road AADT from 5 to 95 percent, in increments of 5 percent. Table 4 presents the major-road and minor-road AADT ranges used in the economic analysis.

Table 4. Major- and minor-road AADT ranges assumed for economic analysis.

Treatment Type	Intersection Type	Major-Road AADT Range (veh/day)	Minor-Road AADT Range (veh/day)
Single luminaire	3 legs	220 to 5,900	30 to 2,000
	4 legs	315 to 2,100	210 to 1,750
Transverse rumble strips	4 legs	200 to 5,000	90 to 3,185
Supplementary pavement markings installed on stop-controlled approach (i.e., STOP AHEAD)	3 legs	115 to 5,200	40 to 2,940
	4 legs	155 to 3,650	40 to 1,500
Supplementary pavement markings installed on uncontrolled approaches	4 legs	2,310 to 14,000	330 to 2,730

Benefit-Cost Ratio

To estimate the benefit-cost ratio of a treatment, it is necessary to convert the annual benefit of a treatment to a net present value. To do so, a discount rate or minimum attractive rate of return of 7 percent was assumed, in accordance with current Federal guidelines. The benefit-cost ratio is computed by dividing the net present value of the crash reduction benefit by the implementation cost. Results of the economic analysis for each treatment are provided in Chapters 3 through 5.

The benefit-cost ratio for a given treatment installed at 3-leg stop-controlled intersections on rural two-lane roads is calculated using the following equation:

$$\frac{B}{C}(3\ Leg) = \frac{(1-CMF)C_r e^{-9.86+0.79ln(AADT_{maj})+0.49ln(AADT_{min})}\left[\frac{(1+i)^n-1}{i(1+i)^n}\right]}{C_{Imp}+C_{Ann}\left[\frac{(1+i)^n-1}{i(1+i)^n}\right]} \times (C_K P_K + C_A P_A + C_B P_B + C_C P_C + C_O P_O)$$

Figure 2. Equation. Benefit-cost ratio for 3-leg intersections

The benefit-cost ratio for a given treatment installed at 4-leg stop-controlled intersections on rural two-lane roads is calculated using the following equation:

$$\frac{B}{C}(4\ Leg) = \frac{(1-CMF)C_r e^{-8.56+0.60ln(AADT_{maj})+0.61ln(AADT_{min})}\left[\frac{(1+i)^n-1}{i(1+i)^n}\right]}{C_{Imp}+C_{Ann}\left[\frac{(1+i)^n-1}{i(1+i)^n}\right]} \times (C_K P_K + C_A P_A + C_B P_B + C_C P_C + C_O P_O)$$

Figure 3. Equation. Benefit-cost ratio for 4-leg intersections

where:
B/C = benefit-cost ratio
CMF = crash modification factor for total intersection crashes for a given treatment or combination of treatments
C_r = calibration factor for SPF
$AADT_{maj}$ = major-road AADT
$AADT_{min}$ = minor-road AADT
i = discount rate (assumed 7 percent)
n = service life
C_{Imp} = installation cost ($)
C_{Ann} = annual operational cost of treatment ($)
C_K = fatal crash cost ($ per fatal crash)
P_K = proportion of total intersection crashes that are fatal crashes

C_A = disabling injury crash cost ($ per disabling injury crash)
P_A = proportion of total intersection crashes that are disabling injury crashes
C_B = evident injury crash cost ($ per evident injury crash)
P_B = proportion of total intersection crashes that are evident injury crashes
C_C = possible injury crash cost ($ per possible injury crash)
P_C = proportion of total intersection crashes that are possible injury crashes
C_O = property damage only crash cost ($ per property damage only crash)
P_O = proportion of total intersection crashes that are property damage only crashes

CHAPTER 3. SINGLE LUMINAIRE

Treatment Name	Single Luminaire
Description	A single luminaire is installed at an intersection to make drivers aware of the presence of the intersection at night.
States	Data from one state—Minnesota--were included in the safety evaluation of this treatment.
Safety Effectiveness	**Reduction by severity level:** The EB analysis showed a 71-percent reduction in nighttime crashes (SE = 29 percent) for all severity levels combined.
Cost and Economic Benefits	Benefit-cost ratios ranged from 0.5 to 35.0, assuming an $8,000 installation cost and $300 annual energy cost over a 20-year life. These costs assume light fixtures that used traditional wired power and the availability of a nearby power source. However, street lighting that uses solid-state LED bulbs and solar power generally have no need for a wired power source near the intersection and have no annual energy cost.
Where to Implement	This treatment should be considered at intersections with a high proportion of crashes occurring during hours of darkness, or simply at intersections with a moderate to high frequency of nighttime crashes. Intersections with patterns of nighttime crashes that suggest drivers are unaware of the presence of the intersections (such as near horizontal curves or locations with skewed approaches) may particularly benefit from this treatment.
Additional Factors for Consideration	If there is vegetation near the intersection, foliage should be trimmed and maintained on a regular basis so it does not cause shadows or reduce the visibility generated from the luminaire. Luminaire poles should have a breakaway design and should be located so as to minimize the risk of being struck by a vehicle.

TREATMENT DESCRIPTION

A single luminaire is a safety treatment used to reduce nighttime crashes by making drivers aware of the presence of an intersection that may otherwise be difficult to see at night. For drivers on a stop-controlled approach, the lighting may provide additional time for the approaching driver to perceive the need to stop by increasing the visibility of features located at the site such as pavement markings and signs. For drivers on the uncontrolled approach, the lighting may provide an indication that drivers may be entering the roadway at that location and can improve the visibility of vehicles, bicyclists, and pedestrians located near the intersection. The luminaire may be pole-mounted near one corner of the intersection, or may be wire-mounted over the intersection. Example installations of the single luminaire treatment at rural intersections are shown in Figure 4.

Figure 4. Photo. Examples of single luminaire intersection lighting (Image credit: Google Earth™ Mapping Service).[21]

SAFETY EVALUATION

The safety effectiveness of installing a single luminaire at an intersection with minor-road stop control on a rural two-lane road was estimated using the EB before-after analysis approach as discussed in Chapter 2 (Analysis Approach). The illuminance or luminance level generated from

the single luminaire was not considered in the safety evaluation as neither measure was recorded in the field at the
treatment sites. The descriptive statistics, research methodology, and analysis results of the safety evaluation are presented below.

Descriptive Statistics

A total of 27 treatment and 61 nontreatment sites in Minnesota were available for analysis of the safety effectiveness of a single luminaire installation. Their breakdown by number of intersection legs is shown in Table 5.

Table 5. Single luminaire: number of sites by number of intersection legs.

State	Number of Intersection Legs	Number of Sites	
		Treatment	Nontreatment
MN	3	21	21
	4	6	40
All legs		**27**	**61**

Crash and traffic volume data were available for varying periods before and after treatment installation, depending on treatment installation date at the individual sites. Only nighttime crashes, at four crash severity levels—total, fatal and severe injury (FS), fatal and all injury (FI), and property damage only (PDO)—were considered in the analysis of this treatment. Table 6 (treatment intersections) and Table 7 (nontreatment intersections) summarize the crash data used in the analysis. They present nighttime crash data summed across all intersections of a given configuration.

Table 6. Single luminaire: summary of nighttime crash statistics for the before and after treatment periods for treatment intersections by number of intersection legs.

State	Number of Legs	Before Period							After Period						
		Years of Data in State	Number of Sites	Number of Site-Years	Nighttime Crash Counts				Range of Years of Data in State	Number of Sites	Number of Site-Years	Nighttime Crash Counts			
					Total	FS	FI	PDO				Total	FS	FI	PDO
MN	3	5	21	105	18	0	7	11	1 to 3	21	34	1	1	1	0
	4	5	6	30	2	0	0	2	1 to 2	6	9	0	0	0	0

Table 7. Single luminaire: summary of nighttime crash statistics for the entire study period for nontreatment intersections by number of intersection legs.

State	Number of Legs	Entire Study Period						
		Years of Data in State	Number of Sites	Number of Site-Years	Nighttime Crash Counts			
					Total	FS	FI	PDO
MN	3	9	21	189	16	0	6	10
	4	8	40	320	11	0	3	8

Methodology

The safety effectiveness of installing a single luminaire was evaluated using an EB before-after method. To implement this method, the following steps were taken:

1. Select appropriate SPF: The SPFs for intersections on rural two-lane roads from Chapter 10 of the HSM were selected. These are given for total crashes only. The coefficients of these SPFs vary by number of intersection legs. Use of the intersection SPFs from Chapter 10 of the HSM provides an estimate of the intersection-related predicted crash frequency for sites included in the analysis in the absence of the treatment.

2. Obtain the proportions of target crashes (PR_1) relevant to the evaluation: The proportion of nighttime crashes to all crashes for each severity level (total, FS, FI, and PDO) were calculated using all crashes from nontreatment sites and from the before-period years of treatment sites in Minnesota. These proportions were calculated separately for 3- and 4-leg intersections. These proportions scale the total crash predictions (i.e., all crash types) to predictions for the target crashes (i.e., nighttime crashes).

3. Obtain the proportions of FS, FI, and PDO crashes (PR_2): These proportions were calculated as the ratio of all (daytime plus nighttime) FS, FI, or PDO crashes over total crashes using all crashes from the nontreatment sites and from the before-period years of treatment sites in Minnesota. These proportions were calculated separately for 3- and 4-leg intersections. These proportions scale the total crash predictions (i.e., all severity levels combined) to predicted crashes for specific severity level crashes (i.e., FS, FI, and PDO).

4. Calibrate the SPFs to the local jurisdiction: Calibration was performed using all crashes (total daytime plus nighttime crashes), separately for each intersection configuration, again using all nontreatment intersections and before-period years from treatment intersections combined. Total crash counts rather than target crashes were used due to the scarcity of nighttime crashes, especially FS and FI crashes. The calibration factor adjusts the HSM SPFs for varying conditions in the local jurisdiction such as crash reporting thresholds, environmental factors, etc.

The SPFs presented in the HSM for intersections on rural two-lane roads for total severity level (i.e., all severity levels combined) have the general form:

$$\text{Predicted crashes/yr} = \exp[a + b(\ln AADT_{maj}) + c(\ln AADT_{min})]$$

Figure 5. Equation. Base model for predicted crashes per year.

where a, b, and c are the regression coefficients shown in Table 8. These coefficients apply to base conditions and vary by number of intersection legs. For the intersection SPFs in Chapter 10 of the HSM, the base conditions are:

- Intersection skew angle: 0 degrees
- Number of intersection left-turn lanes: None on approaches without stop control
- Number of intersection right-turn lanes: None on approaches without stop control
- Presence of lighting: None

Crash modification factors (CMFs), calibration factor (C_r), proportions of nighttime crashes (PR_1), and proportions of FS, FI, and PDO crashes (PR_2) were then used to adjust for local conditions as follows:

$$\text{Predicted crashes/yr} = \{\exp[a + b(\ln AADT_{maj}) + c(\ln AADT_{min})]\} \times PR_1 \times PR_2 \times CMF_{Combined} \times C_r$$

Figure 6. Equation. Model for predicted crashes per year for specific crash types and severity levels, and accounting for local conditions.

The $CMF_{Combined}$ is the product of the CMFs from Chapter 10 of the HSM for skew angle (CMF_{1i}), number of major-road left-turn lanes (CMF_{2i}), and number of major-road right-turn lanes (CMF_{3i}), for a particular intersection configuration (note that the CMF for intersection lighting, CMF_{4i} , equals 1 in all cases for this treatment evaluation).

SPF coefficients (a, b, and c and overdispersion parameter), nighttime crash proportions (PR_1), proportions of FS, FI, and PDO crashes (PR_2), and calibration factors (Cr) are shown for each intersection configuration in Table 8. The table also shows the default proportions of PR_1 and PR_2 presented in Chapter 10 of the HSM (see HSM Tables 10-15 and 10-5, respectively). Note that PR_2 is always equal to 1 for total crashes. The decision of which proportions to use—those calculated from the data or those provided by the HSM—was based on whether calculated proportions of nighttime crashes (PR_1) were nonzero for all severity levels. If PR_1 was equal to zero for any severity level, then the default HSM proportions (both PR_1 and PR_2) were used in the EB before-after analysis. The proportions used in the analysis are indicated with an asterisk in Table 8 (HSM proportions in all cases in this analysis).

Table 8. Single luminaire: SPF coefficients, target crash proportions, and calibration factors by number of intersection legs for EB analysis.

Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Number of Crashes, Nighttime Only	Intercept (a)	$lnAADT_{maj}$ Coefficient (b)	$lnAADT_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Nighttime Crashes (PR_1)	PR_1 HSM	Proportion of FS, FI, or PDO of Total Crashes (PR_2)	PR_2 HSM	Calibration Factor (Cr)
3	315	Total	69	34	-9.86	0.79	0.49	0.54	0.49	**0.26***	1.00	**1.00***	0.60
		FS	1	0					0.00	**0.26***	0.01	**0.06***	
		FI	24	13					0.54	**0.26***	0.35	**0.42***	
		PDO	45	21					0.47	**0.26***	0.65	**0.59***	
4	390	Total	63	13	-8.56	0.60	0.61	0.24	0.21	**0.24***	1.00	**1.00***	0.23
		FS	3	0					0.00	**0.24***	0.05	**0.06***	
		FI	28	3					0.11	**0.24***	0.44	**0.43***	
		PDO	35	10					0.29	**0.24***	0.56	**0.57***	

NOTE 1: Asterisked proportions were those used in the analyses.

Safety Effectiveness

The EB analysis was based on before and after traffic volumes and crash data from 27 treatment and 61 nontreatment intersections in Minnesota, and HSM SPFs for 3- and 4-leg intersections on rural two-lane roads. Traffic volumes at the treatment sites ranged from 200 to 7,300 veh/day (3-leg intersections) and from 315 to 2,100 (4-leg intersections) on the major-road approaches and from 30 to 2,000 veh/day (3-leg intersections) and from 210 to 1,750 (4-leg intersections) on the minor-road approaches. The EB method was first applied separately to 3-leg and 4-leg intersections. However, only six 4-leg intersections were available, and none experienced any crashes in the after period. It was, therefore, decided to pool 3- and 4-leg intersections to estimate the safety effectiveness of installing a single luminaire across both 3- and 4-leg intersections combined. The EB before-after analysis results are shown in Table 9 for the following crash types and severity levels:

- Total nighttime crashes
- FI nighttime crashes
- PDO nighttime crashes

Although the analyses for FS injury crashes were performed, the analysis results were not considered reliable and are therefore not shown. The occurrence of FS crashes was too rare across all intersections in the study (both treatment and nontreatment sites).

The statistics shown in Table 9 for each crash severity are:

- Number of treatment intersections
- Percent change in nighttime crash frequency due to the treatment: estimate and standard error
- An indication of whether the treatment had a statistically significant effect on crash frequency for the crash severity level of interest at the 95- or 90-percent confidence level

A negative percent safety effectiveness indicates that crash frequencies decreased due to the treatment.

Table 9. Single luminaire: safety effectiveness on nighttime crashes for 3- and 4-leg intersections combined.

Crash Severity	Number of Treatment Sites	Safety Effectiveness (%)	SE of Treatment Effect (%)	Significance
3- and 4-Leg Intersections Combined				
Total	27	**-71**	**29**	**Significant at 95% CL**
FI		-21	79	Not significant at 90% CL
PDO		-100[a]	NC	NC

[a] Crashes recorded in before period; none in after period.

NC=Not Calculated; standard error and significance could not be estimated.

The following general observations can be made based on Table 6, Table 8, and Table 9:

- Only one nighttime crash occurred in the after period across all 27 treatment sites.
- PDO crashes decreased from 13 (before) to 0 (after), yielding a 100-percent reduction in crash counts; in such cases, the standard error of the effectiveness estimate cannot be calculated.
- The calibration factors for the SPFs are 0.23 (4-leg intersections) and 0.60 (3-leg intersections).

The EB analysis results from Minnesota sites indicate that installing a single luminaire reduced total nighttime crashes by 71 percent; this safety effect is statistically significant at the 95-percent confidence level. Although the analysis shows a 21-percent reduction in FI nighttime crashes, the result is not significant at the 90-percent confidence level due to the large standard error of the estimate.

The EB analysis made use of AADT data for the entire day. Traffic volume information for nighttime hours was not incorporated into the analyses, so interpretation of the analysis results should be taken with this analysis approach in mind.

ECONOMIC ANALYSIS

An economic analysis was conducted to calculate benefit-cost ratios to estimate the economic benefits of installing a single luminaire at 3-leg and 4-leg stop-controlled intersections on rural two-lane roads. The Economic Analysis discussion in Chapter 2 describes the procedure used to calculate the benefit-cost ratios.

The estimated crash reduction benefit is calculated using the CMF for total nighttime crashes produced in this study for installing a single luminaire at an intersection, which is 0.29 for 3- and 4-leg stop-controlled intersections combined. The following equation uses the proportion of total nighttime crashes at 3-leg and 4-leg rural stop-controlled intersections to translate the single luminaire CMF, that applies to nighttime crashes, to a CMF that applies to total crashes during the entire 24-hour day:

$$CMF_{Total} = (CMF_{Lighting} - 1) \times PR_1 + 1$$

Figure 7. Equation. CMF for total crashes.

where PR_1 is the proportion of total crashes that occur at night. The HSM provides default values for PR_1 (shown as p_{ni}). The value used in this economic evaluation is the HSM default provided in Table 10-15 in Chapter 10, which is 0.26 for 3-leg stop-controlled intersections and 0.24 for 4-leg stop-controlled intersections.

To calculate the treatment cost for the economic analysis, both installation and maintenance costs were included. The calculations assume an $8,000 installation cost for a single luminaire, an annual energy cost of $300, and a service life of 20 years. These estimates were obtained from the state DOTs that provided data for the safety analysis.

Table 10 displays the benefit-cost ratios for installing a single luminaire at a 3-leg stop-controlled intersection on rural two-lane roads. The AADTs in the table cover the range of AADTs of the study sites used for the estimation of the CMF. At very low intersection volumes, the treatment does not always produce a benefit-cost ratio above 1.0. However, single luminaire installation is economically justified at intersections with a major-road AADT at or above 1,000 veh/day, regardless of the minor-road AADT.

Table 11 presents the benefit-cost ratios for installing a single luminaire at a 4-leg stop-controlled intersection on rural two-lane roads. The AADTs in the table cover the range of AADTs of the study sites used for the estimation of the CMF. The single luminaire is economically justified at all AADT levels represented in the study, with all the benefit-cost ratios exceeding 3.0.

Table 10. Single luminaire: benefit-cost ratios for treatment at 3-leg rural stop-controlled intersection.

Major-Road AADT	% of Major-Road AADT on Minor Road													
	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	60%	70%	80%	90%
300	N/A	0.5	0.5	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.1	1.2	1.2	1.3
1,000	1.5	2.1	2.6	3.0	3.3	3.6	3.9	4.1	4.4	4.6	5.1	5.5	5.8	6.2
2,000	3.6	5.1	6.2	7.2	8.0	8.8	9.4	10.1	10.7	11.2	12.3	13.3	14.2	15.0
3,000	6.1	8.6	10.5	12.1	13.4	14.7	15.9	16.9	17.9	18.9	20.7	N/A	N/A	N/A
4,000	8.8	12.4	15.1	17.4	19.4	21.3	22.9	24.5	25.9	27.3	N/A	N/A	N/A	N/A
5,000	11.8	16.5	20.1	23.2	25.9	28.3	30.5	32.6	N/A	N/A	N/A	N/A	N/A	N/A
5,900	14.5	20.4	24.9	28.7	32.0	35.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

CMF = 0.82 (total crashes, entire day), $CMF_{Lighting}$ = 0.29 (total night crashes), PR_1 = 0.26 (proportion of nighttime crashes to total crashes)
Installation cost = $8,000
Annual energy cost = $300
Service life = 20 yrs
N/A indicates the combination of major- and minor-road AADTs was not represented in the study.

Table 11. Single luminaire: benefit-cost ratios for treatment at 4-leg rural stop-controlled intersection.

Major-Road AADT	% of Major-Road AADT on Minor Road													
	10%	15%	20%	25%	30%	40%	50%	55%	60%	70%	80%	85%	90%	95%
400	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.3	3.4	3.8	4.1	4.3	4.4	4.6
1,000	N/A	N/A	N/A	6.1	6.8	8.1	9.3	9.9	10.4	11.4	12.4	12.9	13.3	13.8
2,000	N/A	10.3	12.3	14.1	15.8	18.8	21.6	22.9	24.1	26.5	28.7	29.8	N/A	N/A
2,100	8.6	11.0	13.1	15.0	16.8	20.0	22.9	24.2	25.6	28.1	30.5	N/A	N/A	N/A

CMF = 0.83 (total crashes, entire day), $CMF_{Lighting}$ = 0.29 (total night crashes), PR_1 = 0.24 (proportion of nighttime crashes to total crashes)
Installation cost = $8,000
Annual energy cost = $300
Service life = 20 yrs
N/A indicates the combination of major- and minor-road AADTs was not represented in the study.

IMPLEMENTATION

As indicated in Volume 5 of the NCHRP Report 500 Series, *A Guide for Addressing Unsignalized Intersection Collisions* (5), the primary purposes of providing lighting at an intersection to reduce nighttime crashes are to:

- Increase drivers' awareness of the intersection
- Reduce their perception-reaction times
- Increase available sight distance
- Improve the visibility of pedestrians and bicyclists

Agencies should consider installation of a single luminaire at intersections with minor-road stop control on rural two-lane roads where the proportion of nighttime crashes to total crashes is above the statewide average for this intersection type, or simply at intersections of this type that have a moderate to high frequency of nighttime crashes. Except at intersections with very low major-road AADTs (e.g., 3-leg intersections with minor-road AADTs less than 300 veh/day), this treatment is economically justifiable. In particular, agencies may want to consider installation of a single luminaire at intersection locations where view of the intersection may be obstructed by horizontal curves or significant skew angles. (This assumes that the skew angle for an intersection is defined as the absolute value of the deviation from an intersection angle of 90 degrees.) At these locations, a single luminaire may increase driver awareness of the intersection and available sight distance.

For agencies considering installation of a single luminaire at intersections with minor-road stop control on rural two-lane roads, the *FHWA Lighting Handbook* may be a useful reference.(22) The handbook provides guidance to designers and state, city, and town officials concerning the application of roadway lighting. In particular, it includes several examples of warrants others have developed to prioritize the need for intersection lighting. For example, Table 12 illustrates a simple approach developed by Preston and Schoenecker for establishing priorities for installing lighting at rural intersections based on traffic volumes and major-road functional classification.(11)

Table 12. Prioritization of lighting at rural intersections by traffic volume and functional class.[11]

Priority	Major-Road Functional Classification			
	Principal Arterial	Minor Arterial	Collector	Local
	Major-Road Volumes in veh/day (% of Major-Street Volume that is Recommended on the Minor-Street)			
Low	0-2,000 (10%)	0-1,000 (10%)	0-5,000 (10%)	0-250 (10%)
Moderate	2,000-5,000 (15%)	1,000-2,000 (15%)	500-1,000 (15%)	250-500 (15%)
High	>5,000 (20%)	>2,000 (20%)	>1,000 (20%)	>500 (20%)

Additionally, the AASHTO *Roadway Lighting Design Guide* may serve as a useful reference.[23] While it does not provide specific information regarding the need for and design of intersection lighting, it reflects current practices in roadway lighting.

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CHAPTER 4. TRANSVERSE RUMBLE STRIPS

<table>
<tr><td>Treatment Name</td><td colspan="2">Transverse Rumble Strips</td></tr>
<tr><td>Description</td><td colspan="2">Grooves or elevated strips placed in the travel lane perpendicular to the direction of travel, generally used in sets in advance of a stop sign to bring drivers’ attention to the stop ahead condition.</td></tr>
<tr><td>States</td><td colspan="2">Data from the following states were included in the safety evaluation of this treatment: Arkansas, Kansas, Missouri, North Dakota, and Oregon.</td></tr>
<tr><td>Safety Effectiveness</td><td>Reduction by severity level:
The estimated safety effects of this treatment in reducing total crashes (all crash types combined) at 3-leg and 4-leg intersections are as follows:
3-Leg Intersections:
• 37% reduction in FI crashes (SE = 20%)
4-Leg Intersections:
• 13% reduction in total crashes (SE = 7%)
• 29% reduction in FI crashes (SE = 8%)</td><td>Reduction by crash type:
The estimated safety effects of this treatment in reducing angle and rear-end crashes at 3-leg and 4-leg intersections are as follows:
3-Leg Intersections:
Angle crashes
• 61% reduction in PDO crashes (SE = 28%)
Rear-end crashes
• 60% reduction in FI crashes (SE = 29%)
4-Leg Intersections:
Angle crashes
• 25% reduction in FI crashes (SE = 10%)
Rear-end crashes
• 56% reduction in total crashes (SE = 8%)
• 78% reduction in FI crashes (SE = 8%)
• 54% reduction in PDO crashes (SE = 10%)</td></tr>
<tr><td>Cost and Economic Benefits</td><td colspan="2">Benefit-cost ratios calculated for 4-leg intersections ranged from 1.1 to 241.1 when assuming installation costs between $1,000 and $5,000 per intersection approach.</td></tr>
<tr><td>Where to Implement</td><td colspan="2">The treatment should be considered for stop-controlled approaches to intersections where crash patterns indicate that drivers fail to recognize the stop condition (e.g., angle crashes related to stop sign violations). Rumble strips may be particularly effective on the stop-controlled approach to an intersection that is hidden from view due to horizontal or vertical curvature. Intersections following a long tangent section may also benefit from this treatment.
The economic analysis indicates this treatment is economically justifiable, even at intersections with low traffic volumes.
The proximity of the intersection to nearby residents or businesses should be considered prior to selecting this treatment for implementation, as noise generated from the rumble strips may result in complaints from nearby residents.</td></tr>
<tr><td>Additional Factors for Consideration</td><td colspan="2">Typically, transverse rumble strips are considered for implementation after less intrusive measures have been tried and failed to improve the crash experience at an intersection.
Several unintended consequences of this treatment may occur, and should be considered prior to any decision to implement this treatment, including: (a) potential loss-of-control problems for motorcyclists and bicyclists, (b) difficulties associated with snowplow operations, and (c) inappropriate driver responses such as using the opposing travel lanes to drive around the rumble strips (5).</td></tr>
</table>

TREATMENT DESCRIPTION

Transverse rumble strips are grooves in the roadway surface or elevated strips placed in the travel lane perpendicular to the direction of travel. They are designed to generate noise and vibration in the vehicle as the driver crosses over them to alert the driver to a condition that may require attention or action. The specific application of transverse rumble strips evaluated in this research is their placement on the stop-controlled approach to intersections on rural two-lane roads. The rumble strips are placed at a distance in advance of the stop sign sufficient to allow the driver time to perceive the need to stop, react to that need, and brake appropriately.

Transverse rumble strips are generally placed in sets of several closely-placed strips to form a set, and sometimes more than one set is used on a given approach. The strips may be located only in the wheel path or across the full lane width. They are often used in conjunction with stop ahead signing.

Transverse rumble strips may be rolled or grooved into asphalt, formed into fresh concrete, or created as epoxy strips on the surface of the pavement. Figure 8 shows pictures of rumble strips milled into asphalt.

SAFETY EVALUATION

The safety effectiveness of transverse rumble strips installed on the stop-controlled approaches of intersections on rural two-lane roads was estimated using the EB before-after analysis approach as discussed in Chapter 2 (Analysis Approach). The descriptive statistics, research methodology, and analysis results are presented below.

Descriptive Statistics

A total of 72 treatment and 126 nontreatment sites in five states—Arkansas, Kansas, Missouri, North Dakota, and Oregon—were available for analysis of the safety effectiveness of transverse rumble strips installed on stop-controlled approaches of intersections on rural two-lane roads. Their breakdown by state, number of intersection legs, and number of treated approaches (1 or 2; always 1 for 3-leg intersections) is shown in Table 13. Traffic volumes at the treatment sites ranged from 245 to 11,700 veh/day (3-leg intersections) and from 165 to 6,700 veh/day (4-leg intersections) on the major-road approaches and from 110 to 7,000 veh/day (3-leg intersections) and from 65 to 4,120 veh/day (4-leg intersections) on the minor-road approaches.

Crash and traffic volume data were obtained for varying before- and after-treatment installation periods, depending on treatment installation date at the individual sites. Three crash types were considered in this analysis: all collision types combined, angle crashes, and rear-end crashes.

Table 14 (treatment intersections) and Table 15 (nontreatment intersections) summarize the crash data used in the analysis. They present total, angle, and rear-end crash data summed across all intersections of a given configuration (3-leg or 4-leg) within each state.

Figure 8. Photo. Examples of transverse rumble strips placement (Image credit: Google Earth™ Mapping Service).[21]

Table 13. Transverse rumble strips: number of sites by State, number of intersection legs, and number of treated approaches.

State	Number of Intersection Legs	Number of Treated Approaches	Number of Sites	
			Treatment	Nontreatment
AR	4	1	1	19
		2	1	
KS	4	1	2	18
MO	3	1	5	6
	4	1	5	31
		2	10	
ND[a]	3	1	17	13
	4	1	20	17
		2	6	
OR	3	1	3	8
	4	1	1	14
		2	1	
All sites			**72**	**126**

[a] No control intersections were available in North Dakota; nontreatment sites from Nebraska were used in the analysis.

Table 14. Transverse rumble strips: summary crash statistics for the before and after treatment periods for treatment intersections by State and number of intersection legs.

Number of Legs	State	Before Period							After Period						
		Range of Years of Data in State	Number of Sites	Number of Site-Years	Crash Counts Total	Crash Counts FS	Crash Counts FI	Crash Counts PDO	Range of Years of Data in State	Number of Sites	Number of Site-Years	Crash Counts Total	Crash Counts FS	Crash Counts FI	Crash Counts PDO
ALL CRASHES															
3	MO	4 to 5	5	23	12	0	7	5	3 to 9	5	35	19	2	7	12
	ND	5	17	85	9	0	2	7	2 to 3	17	41	4	0	2	2
	OR	5	3	15	9	0	3	6	3 to 8	3	16	8	0	2	6
4	AR	5	2	10	14	6	10	4	9 to 10	2	19	14	2	7	7
	KS	5	2	10	4	2	2	2	1 to 2	2	3	0	0	0	0
	MO	3 to 5	15	67	75	12	42	33	4 to 10	15	111	174	28	77	97
	ND	5	26	130	14	0	7	7	2 to 3	26	62	11	0	2	9
	OR	5	2	10	14	0	7	7	8 to 9	2	17	28	3	19	9
ANGLE CRASHES															
3	MO	4 to 5	5	23	3	0	3	0	3 to 9	5	35	5	0	3	2
	ND	5	17	85	0	0	0	0	2 to 3	17	41	0	0	0	0
	OR	5	3	15	0	0	0	0	3 to 8	3	16	0	0	0	0
4	AR	5	2	10	9	3	6	3	9 to 10	2	19	7	2	4	3
	KS	5	2	10	3	2	2	1	1 to 2	2	3	0	0	0	0
	MO	3 to 5	15	67	53	11	36	17	4 to 10	15	111	115	23	56	59
	ND	5	26	130	2	0	1	1	2 to 3	26	62	4	0	1	3
	OR	5	2	10	6	0	2	4	8 to 9	2	17	9	2	9	0
REAR-END CRASHES															
3	MO	4 to 5	5	23	3	0	2	1	3 to 9	5	35	6	1	1	5
	ND	5	17	85	0	0	0	0	2 to 3	17	41	1	0	1	0
	OR	5	3	15	1	0	0	1	3 to 8	3	16	2	0	0	2
4	AR	5	2	10	2	2	2	0	9 to 10	2	19	5	0	2	3
	KS	5	2	10	0	0	0	0	1 to 2	2	3	0	0	0	0
	MO	3 to 5	15	67	9	1	3	6	4 to 10	15	111	17	0	3	14
	ND	5	26	130	5	0	2	3	2 to 3	26	62	3	0	0	3
	OR	5	2	10	0	0	0	0	8 to 9	2	17	5	0	3	2

Table 15. Transverse rumble strips: summary crash statistics for the entire study period for nontreatment intersections by State and number of intersection legs.

Number of Intersection Legs	State	Entire Study Period						
		Range of Years of Data in State	Number of Sites	Number of Site-Years	Crash Counts			
					Total	FS	FI	PDO
ALL CRASHES								
3	MO	14	6	84	8	0	2	6
	ND	9	13	117	24	3	7	17
	OR	14	8	112	71	1	42	29
4	AR	16	19	304	160	35	96	64
	KS	8	18	144	25	1	11	14
	MO	14	31	434	189	30	100	89
	ND[a]	9	17	153	41	8	26	15
	OR	15	14	210	88	0	52	36
ANGLE CRASHES								
3	MO	14	6	84	2	0	0	2
	ND	9	13	117	4	2	3	1
	OR	14	8	112	0	0	0	0
4	AR	16	19	304	98	24	63	35
	KS	8	18	144	10	1	7	3
	MO	14	31	434	102	24	65	37
	ND[a]	9	17	153	21	6	16	5
	OR	15	14	210	29	0	20	9
REAR-END CRASHES								
3	MO	14	6	84	1	0	0	1
	ND	9	13	117	2	0	0	2
	OR	14	8	112	18	0	9	9
4	AR	16	19	304	15	3	8	7
	KS	8	18	144	3	0	1	2
	MO	14	31	434	24	1	8	16
	ND[a]	9	17	153	5	2	3	2
	OR	15	14	210	15	0	8	7

[a] No control intersections were available in North Dakota; nontreatment sites from Nebraska were used in the analysis.

Methodology

The safety effectiveness of installing transverse rumble strips was evaluated using an EB method similar to that discussed in Chapter 3 for the EB evaluation of a single luminaire installation. Prior to implementing the EB method, the following points were addressed:

1. Select appropriate SPF: The SPFs for intersections on rural two-lane roads from Chapter 10 of the HSM were selected. These are given for total crashes only. The coefficients of these SPFs vary by number of intersection legs. Use of the intersection SPFs from Chapter 10 of the HSM provide an estimate of the intersection-related predicted crash frequency for sites included in the analysis in the absence of the treatment.

2. Obtain the proportion of target crashes for total, FS, FI, and PDO crashes (PR_1): The proportions of target crashes (angle and rear end) to all crashes for each severity level (total, FS, FI, and PDO) were calculated using all crashes from nontreatment sites and from the before-period years of treatment sites. These proportions were calculated separately for 3- and 4-leg intersections. These proportions scale the total crash predictions (i.e., all crash types) to predictions for the target crashes (i.e., angle and rear-end crashes).

3. Obtain the proportions of FS, FI, and PDO crashes (PR_2): These proportions were calculated as the ratio of all FS, FI, or PDO crashes over total crashes using all crashes from the nontreatment sites and from the before-period years of treatment sites. These proportions were calculated separately for 3- and 4-leg intersections. These proportions scale the total crash predictions (i.e., all severity levels combined) to predicted crashes for specific severity level crashes (i.e., FS, FI, and PDO).

4. Calibrate the SPFs to the local jurisdiction: Calibration was performed using all crashes (all collision types combined), separately for each intersection configuration within a given state, again using all nontreatment intersections and before treatment intersections combined. Total crash counts were used rather than target crashes due to the scarcity of target crashes, especially FS and FI angle and rear-end crashes. The calibration factor adjusts the HSM SPFs for varying conditions in the local jurisdiction such as crash reporting thresholds, environmental, etc.

The SPFs presented in the HSM for intersections on rural two-lane roads for total severity level (i.e., all severity levels combined) have the general form:

$$\text{Predicted crashes/yr} = \exp[a + b(\ln AADT_{maj}) + c(\ln AADT_{min})]$$

Figure 9. Equation. Base model for predicted crashes per year.

where a, b, and c are the regression coefficients shown in Table 16. These coefficients apply to base conditions and vary by number of intersection legs. For the intersection SPFs in Chapter 10 of the HSM, the base conditions are:

- Intersection skew angle: 0 degrees
- Number of intersection left-turn lanes: None on approaches without stop control
- Number of intersection right-turn lanes: None on approaches without stop control
- Presence of lighting: None

Crash modification factors (CMFs), calibration factors (C_r), proportions of angle and rear-end crashes (PR_1), and proportions of FS, FI, and PDO crashes (PR_2) were then used to adjust for local conditions as follows:

$$\text{Predicted crashes/yr} = \{\exp[a + b(\ln AADT_{maj}) + c(\ln AADT_{min})]\} \times PR_1 \times PR_2 \times CMF_{Combined} \times C_r$$

Figure 10. Equation. Model for predicted crashes per year for specific crash types and severity levels, and accounting for local conditions.

The $CMF_{Combined}$ is the product of the CMFs from Chapter 10 of the HSM for skew angle (CMF_{1i}), number of major-road left-turn lanes (CMF_{2i}), and number of major-road right-turn lanes (CMF_{3i}), for a particular intersection configuration.

SPF coefficients (a, b, and c and overdispersion parameter), target crash proportions (PR_1), proportions of FS, FI, and PDO out of total crashes (PR_2), and calibration factors (Cr) are shown for each intersection configuration in Table 16. Number of site-years, total crash counts (all severity levels), and target crash counts are also displayed. The table also shows the default proportions of PR_1 and PR_2 presented in Chapter 10 of the HSM (see Tables 10-6 and 10-5, respectively). Note that PR_2 is always equal to 1 for total crashes. The decision of which proportions to use—those calculated from the data or those provided by the HSM—was based on whether calculated proportions of target crashes (PR_1) were nonzero for all severity levels. If they were not, then the HSM proportions (both PR_1 and PR_2) were used in the EB before-after analysis. The selection of which proportions were used is indicated in Table 16 by an asterisk.

The calibration factors for the SPFs shown in Table 16 ranged from 0.53 to 6.98, meaning that several of the sites used in this analysis had substantially different crash experience than the sites used to develop the SPFs. For example, 4-leg intersections in Arkansas had a calibration factor of 6.98, indicating that those intersections experienced approximately 7 times more crashes than the 4-leg intersections used to develop the SPFs in the HSM.

Safety Effectiveness

The EB before-after method was applied to estimate the safety effectiveness of installing transverse rumble strips on stop-controlled approaches to intersections on rural two-lane roads. The analysis included treatment and nontreatment sites in Arkansas, Kansas, Missouri, Nebraska (nontreatment sites only), North Dakota (treatment sites only), and Oregon, and used HSM SPFs for 3- and 4-leg intersections on rural two-lane roads.

Table 16. Transverse rumble strips: SPF coefficients, target crash proportions, and calibration factors by State and number of intersection legs.

State	Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Target Crash Type	Number of Target Crashes	Intercept (a)	$lnAADT_{maj}$ Coefficient (b)	$lnAADT_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Target Crashes (PR_1)	PR_1 HSM	Proportion of FS, FI, or PDO of Total Crashes (PR_2)	PR_2 HSM	Calibration Factor (Cr)
AR	4	314	Total	174	Angle	107					**0.62**[*]	0.43	**1.00**[*]	1.00	
					Rear End	17					**0.10**[*]	0.24	**1.00**[*]	1.00	
			FS	41	Angle	27					**0.66**[*]	0.53	**0.24**[*]	0.06	
					Rear End	5	-8.56	0.60	0.61	0.24	**0.12**[*]	0.21	**0.24**[*]	0.06	6.98
			FI	106	Angle	69					**0.65**[*]	0.53	**0.61**[*]	0.43	
					Rear End	10					**0.09**[*]	0.21	**0.61**[*]	0.43	
			PDO	68	Angle	38					**0.56**[*]	0.35	**0.39**[*]	0.57	
					Rear End	7					**0.10**[*]	0.27	**0.39**[*]	0.57	
KS	4	154	Total	29	Angle	13					0.45	**0.43**[*]	1.00	**1.00**[*]	
					Rear End	3					0.10	**0.24**[*]	1.00	**1.00**[*]	
			FS	3	Angle	3					1.00	**0.53**[*]	0.10	**0.06**[*]	
					Rear End	0	-8.56	0.60	0.61	0.24	0.00	**0.21**[*]	0.10	**0.06**[*]	1.86
			FI	13	Angle	9					0.69	**0.53**[*]	0.45	**0.43**[*]	
					Rear End	1					0.08	**0.21**[*]	0.45	**0.43**[*]	
			PDO	16	Angle	4					0.25	**0.35**[*]	0.55	**0.57**[*]	
					Rear End	2					0.13	**0.27**[*]	0.55	**0.57**[*]	

Table 16. Transverse rumble strips: SPF coefficients, target crash proportions, and calibration factors by State and number of intersection legs (continued).

State	Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Target Crash Type	Number of Target Crashes	Intercept (a)	lnAADT$_{maj}$ Coefficient (b)	lnAADT$_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Target Crashes (PR_1)	PR_1 HSM	Proportion of FS, FI, or PDO of Total Crashes (PR_2)	PR_2 HSM	Calibration Factor (Cr)
MO	3	107	Total	20	Angle	5	-9.86	0.79	0.49	0.54	0.25	**0.24***	1.00	**1.00***	0.53
					Rear End	4					0.20	**0.28***	1.00	**1.00***	
			FS	0	Angle	0					0.00	**0.28***	0.00	**0.06***	
					Rear End	0					0.00	**0.26***	0.00	**0.06***	
			FI	9	Angle	3					0.33	**0.28***	0.45	**0.42***	
					Rear End	2					0.22	**0.26***	0.45	**0.42***	
			PDO	11	Angle	2					0.18	**0.21***	0.55	**0.59***	
					Rear End	2					0.18	**0.29***	0.55	**0.59***	
	4	501	Total	264	Angle	155	-8.56	0.60	0.61	0.24	**0.59***	0.43	**1.00***	1.00	1.01
					Rear End	33					**0.13***	0.24	**1.00***	1.00	
			FS	42	Angle	35					**0.83***	0.53	**0.16***	0.06	
					Rear End	2					**0.05***	0.21	**0.16***	0.06	
			FI	142	Angle	101					**0.71***	0.53	**0.54***	0.43	
					Rear End	11					**0.08***	0.21	**0.54***	0.43	
			PDO	122	Angle	54					**0.44***	0.35	**0.46***	0.57	
					Rear End	22					**0.18***	0.27	**0.46***	0.57	

Table 16. Transverse rumble strips: SPF coefficients, target crash proportions, and calibration factors by State and number of intersection legs (continued).

State	Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Target Crash Type	Number of Target Crashes	Intercept (a)	lnAADT$_{maj}$ Coefficient (b)	lnAADT$_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Target Crashes (PR$_1$)	PR$_1$ HSM	Proportion of FS, FI, or PDO of Total Crashes (PR$_2$)	PR$_2$ HSM	Calibration Factor (Cr)
ND	3	202	Total	33	Angle	4	-9.86	0.79	0.49	0.54	0.12	**0.24**[*]	1.00	**1.00**[*]	0.97
					Rear End	2					0.06	**0.28**[*]	1.00	**1.00**[*]	
			FS	3	Angle	2					0.67	**0.28**[*]	0.09	**0.06**[*]	
					Rear End	0					0.00	**0.26**[*]	0.09	**0.06**[*]	
			FI	9	Angle	3					0.33	**0.28**[*]	0.27	**0.42**[*]	
					Rear End	0					0.00	**0.26**[*]	0.27	**0.42**[*]	
			PDO	24	Angle	1					0.04	**0.21**[*]	0.73	**0.59**[*]	
					Rear End	2					0.08	**0.29**[*]	0.73	**0.59**[*]	
	4	283	Total	55	Angle	23	-8.56	0.60	0.61	0.24	**0.42**[*]	0.43	**1.00**	1.00	0.55
					Rear End	10					**0.18**[*]	0.24	**1.00**	1.00	
			FS	8	Angle	6					**0.75**[*]	0.53	**0.15**	0.06	
					Rear End	2					**0.25**[*]	0.21	**0.15**	0.06	
			FI	33	Angle	17					**0.52**[*]	0.53	**0.60**	0.43	
					Rear End	5					**0.15**[*]	0.21	**0.60**	0.43	
			PDO	22	Angle	6					**0.27**[*]	0.35	**0.40**	0.57	
					Rear End	5					**0.23**[*]	0.27	**0.40**	0.57	

Table 16. Transverse rumble strips: SPF coefficients, target crash proportions, and calibration factors by State and number of intersection legs (continued).

State	Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Target Crash Type	Number of Target Crashes	Intercept (a)	$lnAADT_{maj}$ Coefficient (b)	$lnAADT_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Target Crashes (PR_1)	PR_1 HSM	Proportion of FS, FI, or PDO of Total Crashes (PR_2)	PR_2 HSM	Calibration Factor (Cr)
OR	3	127	Total	80	Angle	0	-9.86	0.79	0.49	0.54	0.00	**0.24***	1.00	**1.00***	1.17
					Rear End	19					0.24	**0.28***	1.00	**1.00***	
			FS	1	Angle	0					0.00	**0.28***	0.01	**0.06***	
					Rear End	0					0.00	**0.26***	0.01	**0.06***	
			FI	45	Angle	0					0.00	**0.28***	0.56	**0.42***	
					Rear End	9					0.20	**0.26***	0.56	**0.42***	
			PDO	35	Angle	0					0.00	**0.21***	0.44	**0.59***	
					Rear End	10					0.29	**0.29***	0.44	**0.59***	
	4	220	Total	102	Angle	35	-8.56	0.60	0.61	0.24	0.34	**0.43***	1.00	**1.00***	1.79
					Rear End	15					0.15	**0.24***	1.00	**1.00***	
			FS	0	Angle	0					0.00	**0.53***	0.00	**0.06***	
					Rear End	0					0.00	**0.21***	0.00	**0.06***	
			FI	59	Angle	22					0.37	**0.53***	0.58	**0.43***	
					Rear End	8					0.14	**0.21***	0.58	**0.43***	
			PDO	43	Angle	13					0.30	**0.35***	0.42	**0.57***	
					Rear End	7					0.16	**0.27***	0.42	**0.57***	

NOTE: Asterisked proportions were those used in the analyses.

The EB before-after analysis results are shown in Table 17 for the following crash types and severity levels:

- Total crashes (all collision types combined)
  - Total crashes
  - FI crashes
  - PDO crashes
- Angle crashes
  - Total crashes
  - FI crashes
  - PDO crashes
- Rear-end crashes
  - Total crashes
  - FI crashes
  - PDO crashes

Table 17. Transverse rumble strips: safety effectiveness on target crashes by number of intersection legs.

Crash Severity	Number of Treatment Sites	Safety Effectiveness (%)	SE of Treatment Effect (%)	Significance
ALL STATES COMBINED; 3-LEG INTERSECTIONS				
ALL CRASHES				
Total	25	-18	16	Not significant at 90% CL
FI		**-37**	**20**	**Significant at 90% CL**
PDO		-13	21	Not significant at 90% CL
ANGLE CRASHES				
Total	25	-43	26	Not significant at 90% CL
FI		-44	33	Not significant at 90% CL
PDO		**-61**	**28**	**Significant at 95% CL**
REAR-END CRASHES				
Total	25	-16	29	Not significant at 90% CL
FI		**-60**	**29**	**Significant at 95% CL**
PDO		-6	37	Not significant at 90% CL
ALL STATES COMBINED; 4-LEG INTERSECTIONS				
All Crashes				
Total	47	**-13**	**7**	**Significant at 90% CL**
FI		**-29**	**8**	**Significant at 95% CL**
PDO		-14	9	Not significant at 90% CL
ANGLE CRASHES				
Total	47	-13	8	Not significant at 90% CL
FI		**-25**	**10**	**Significant at 95% CL**
PDO		-13	12	Not significant at 90% CL
REAR-END CRASHES				
Total	47	**-56**	**8**	**Significant at 95% CL**
FI		**-78**	**8**	**Significant at 95% CL**
PDO		**-54**	**10**	**Significant at 95% CL**

Although the analyses for FS injury crashes were performed, the analysis results were not considered reliable and are therefore not shown. The occurrence of FS crashes was too rare across all intersections in the study (both treatment and nontreatment sites).

The EB method was applied to all states combined based on the following reasoning: (1) only a small number of treatment sites were available in some states—individually, they could not have been used for evaluation; and (2) all EB intermediate calculations (up to the final effectiveness calculations) are performed on a state/site basis, thus using SPFs, proportions (PR_1 and PR_2), combined CMFs, and calibration factors (C_r) specific to that state. This approach, to some extent, takes differences among states into account, while increasing site and crash sample sizes.

The EB method was applied separately to 3-leg and 4-leg intersections, but at 4-leg intersections, sites with treatment installation on a single approach and on both approaches were pooled to ensure a sufficient sample size for evaluation.

The statistics shown in Table 17 for each crash severity are:

- Number of treatment intersections
- Percent change in crash frequency due to the treatment: estimate and standard error
- An indication of whether the treatment had a statistically significant effect on the crash types and severity level of interest at the 95- or 90-percent confidence level

A negative percent safety effectiveness indicates that crash frequencies decreased due to the treatment.

The following general observations can be made when looking at Table 14, Table 16, and Table 17 together:

- At 3-leg intersections, the analysis results indicate that, for all crash types combined, transverse rumble strips reduce FI crashes by 37 percent. When considering target crash types, FI rear-end crashes and PDO angle crashes were each reduced by approximately 60 percent.
- At 4-leg intersections, the analysis results indicate that, for all crash types combined, transverse rumble strips reduced total crashes by 13 percent and FI crashes by 29 percent. When evaluating target crash types, FI angle crashes were reduced by 25 percent, while total, FI, and PDO rear-end crashes were reduced by 56, 78, and 54 percent respectively. These results suggest that transverse rumble strips are more effective at reducing rear-end crashes than angle crashes.

ECONOMIC ANALYSIS

An economic analysis was conducted to estimate the economic benefits of installing transverse rumble strips at stop-controlled intersections on rural two-lane roads. The economic analysis was based on calculations assuming installation of transverse rumble strips on both stop-controlled approaches of 4-leg intersections. The Economic Analysis discussion in Chapter 2 describes the procedure used for estimating the benefit-cost ratios of the treatment. The economic benefits of this treatment were estimated using the safety effectiveness estimates developed in this research.

The estimated crash reduction benefit of the treatment was calculated using the CMF for total crashes (all severity levels and crash types combined) for 4-leg intersections (CMF = 0.87), which was statistically significant at the 90-percent level. The CMF for total crashes for 3-leg intersections was not significant at the 90-percent level.
Cost and service life of transverse rumble strips may vary by geographic region and installation type. Two scenarios were used to calculate the installation costs of transverse rumble strips in this evaluation. In the first scenario, a $5,000 installation cost per approach and a 20-year life cycle were assumed. These figures were reported by the Oregon Department of Transportation.

Table 18 presents the benefit-cost ratios as a function of major- and minor-road AADTs for a 4-leg stop-controlled intersection on a rural two-lane highway where transverse rumble strips are installed on both stop-controlled approaches. The AADTs in the table cover the range of AADTs of the study sites used for the estimation of the CMF. All the benefit-cost ratios shown are equal to or greater than 1.0, meaning that the installation of transverse rumble strips is economically justified at all AADT ranges included in this study.

Table 18. Transverse rumble strips: benefit-cost ratios for treatment on two minor-road approaches at 4-leg rural stop-controlled intersection for $10,000 installation cost and 20-yr service life.

Major-Road AADT	% of Major-Road AADT on Minor Road													
	5%	10%	20%	30%	40%	45%	50%	60%	65%	70%	75%	80%	90%	95%
200	N/A	N/A	N/A	N/A	N/A	1.1	1.1	1.3	1.3	1.4	1.5	1.5	1.6	1.7
1,000	N/A	3.0	4.5	5.8	6.9	7.5	8.0	8.9	9.3	9.8	10.2	10.6	11.4	11.8
2,000	4.5	6.9	10.5	13.5	16.1	17.2	18.4	20.6	21.6	22.6	23.6	24.5	26.3	27.2
3,000	7.4	11.3	17.2	22.0	26.2	28.2	30.0	33.6	35.3	36.9	38.5	40.0	43.0	44.4
4,000	10.4	15.9	24.3	31.2	37.1	39.9	42.6	47.6	49.9	52.2	54.5	N/A	N/A	N/A
5,000	13.7	20.9	31.9	40.8	48.6	52.3	55.7	62.3	N/A	N/A	N/A	N/A	N/A	N/A

CMF = 0.87 (total crashes)
Installation cost = $10,000 (i.e., $5,000 per approach)
Service life = 20 yrs
N/A indicates the combination of major- and minor-road AADTs was not represented in the study

In the second scenario, a $1,000 installation cost per approach and a 5-yr service life were assumed. This installation cost was reported by the Kansas Department of Transportation for milled transverse rumble strips. Kansas did not report a service life for this treatment; however, for the sake of the analysis, a shorter service life was assumed. Assuming that a longer service life will only increase the benefit of the treatment, selecting a short service life represents a conservative approach for a benefit-cost analysis.

Table 19 displays the benefit-cost ratios as a function of major- and minor-road AADTs for a 4-leg stop-controlled intersection on a rural two-lane highway where transverse rumble strips are installed on both stop-controlled approaches. The AADTs in the table cover the range of AADTs of the study sites used for the estimation of the CMF. The installation of transverse rumble strips again are economically justified at all AADT levels, all benefit-cost ratios are greater than 4.0.

Table 19. Transverse rumble strips: benefit-cost ratios for treatment on two minor-road approaches at 4-leg rural stop-controlled intersection for $2,000 installation cost and 5-yr service life.

Major-Road AADT	% of Major-Road AADT on Minor Road											
	5%	10%	20%	30%	40%	45%	50%	60%	65%	70%	75%	80%
200	N/A	N/A	N/A	N/A	N/A	4.1	4.4	4.9	5.2	5.4	5.6	5.8
1,000	N/A	11.5	17.6	22.5	26.9	28.9	30.8	34.4	36.1	37.8	39.4	41.0
2,000	17.5	26.7	40.7	52.1	62.1	66.8	71.2	79.6	83.5	87.4	91.2	94.8
3,000	28.5	43.6	66.5	85.1	101.5	109.0	116.3	130.0	136.5	142.8	148.9	154.9
4,000	40.4	61.7	94.2	120.6	143.7	154.4	164.7	184.1	193.3	202.2	210.9	N/A
5,000	53.0	80.8	123.4	158.0	188.3	202.3	215.7	241.1	N/A	N/A	N/A	N/A

CMF = 0.87 (total crashes)
Installation cost = $2,000 (i.e., $1,000 per approach)
Service life = 5 yrs
N/A indicates the combination of major- and minor-road AADTs was not represented in the study

IMPLEMENTATION

The primary purpose of installing transverse rumble strips on stop-controlled approaches to intersections on rural two-lane roads is to alert drivers to a condition that requires attention and action. In this case, the treatment is intended to increase drivers' awareness of the intersection and to the traffic control, as drivers are required to stop along the controlled approach before proceeding into the intersection. Transverse rumble strips should be considered for installation on stop-controlled approaches to intersections where a pattern of crashes is present related to a lack of driver recognition of the presence of a stop sign (e.g., angle crashes related to stop sign violations).[5] In particular, transverse rumble strips should be considered along the stop-controlled approach to an intersection that is hidden from view due to horizontal or vertical curvature.[24] In addition, transverse rumble strips should be considered along the stop-controlled approach to an intersection following a long tangent section as drivers may become less attentive to their environment or may underestimate their approach speed to the intersection having driven for a long time at a significantly higher speed. Typically, transverse rumble strips are considered for implementation after less intrusive measures have been tried and failed to improve the crash experience at an intersection. The economic analysis provided above shows that this treatment is economically justifiable, even along roads with low traffic volumes.

Noise generated from transverse rumble strips may disturb nearby residents or businesses. The proximity of the intersection to nearby residents or businesses should be considered prior to selecting this treatment for implementation.

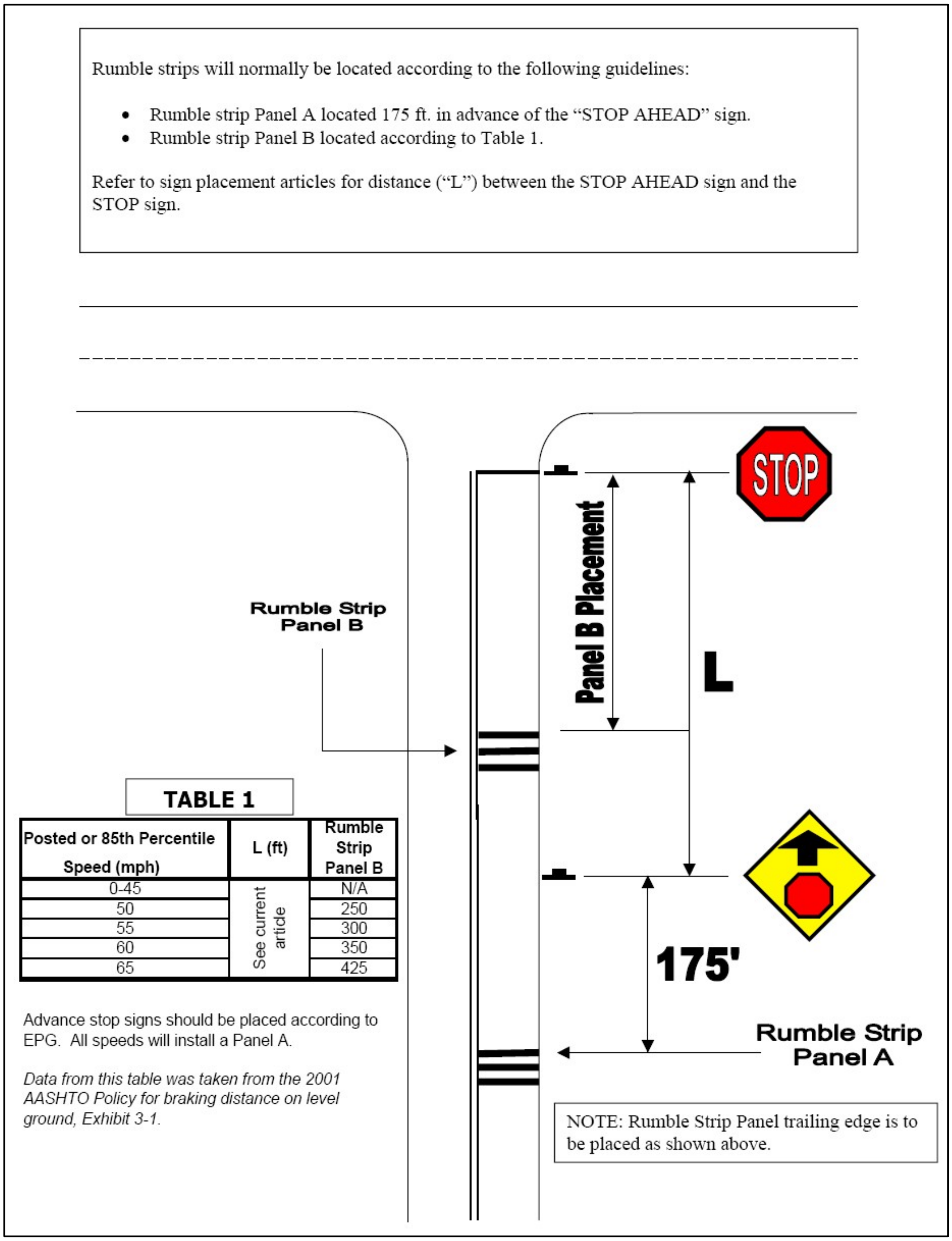
There is not a single recommended design for installing transverse rumble strips on stop-controlled approaches to intersections on rural two-lane roads. Design details are provided below from three states to serve as examples of current implementation practice. Agencies may choose to adopt or modify one of these example designs when developing their own rumble strip policy. The examples illustrate that while the dimensions of the actual rumble strips themselves are fairly consistent, there is a great deal of variation in the placement of the strips and how many individual sets of rumble strips are used in advance of a stop condition.

Figure 11 illustrates the transverse rumble strip placement guidance used by Missouri Department of Transportation (MoDOT). Design details of the rumble strips themselves are shown in Figure 12.

Figure 13 illustrates North Dakota Department of Transportation’s design details for transverse rumble strips, which includes six sets of rumble strips encountered by a driver approaching a stop condition. The dimensions of the milled rumble strips are as follows:

- Length: Varies with the width of the travel lane
- Width: 4 in
- Depth: 0.5 in to 0.625 in
- Spacing: 12 in (on-center)

Figure 14 illustrates design guidance for transverse rumble strips provided by the Kansas Department of Transportation (KDOT). KDOT’s policy is to include three sets of 25 lateral grooves provided in advance of the warning area. KDOT’s policy recommends application of transverse rumble strips at intersections where three or more right-angle collisions have occurred in a 12-month period that involve stop sign violations, where the crash rate is higher than 15 crashes per 10 million entering vehicles, and where the previous intersection on that road requiring a stop or vehicle maneuver is more than 15.5 miles prior to the intersection.


Rumble strips will normally be located according to the following guidelines:

- Rumble strip Panel A located 175 ft. in advance of the “STOP AHEAD” sign.
- Rumble strip Panel B located according to Table 1.

Refer to sign placement articles for distance (“L”) between the STOP AHEAD sign and the STOP sign.

TABLE 1

Posted or 85th Percentile Speed (mph)	L (ft)	Rumble Strip Panel B
0-45	See current article	N/A
50		250
55		300
60		350
65		425

Advance stop signs should be placed according to EPG. All speeds will install a Panel A.

Data from this table was taken from the 2001 AASHTO Policy for braking distance on level ground, Exhibit 3-1.

NOTE: Rumble Strip Panel trailing edge is to be placed as shown above.

Figure 11. Diagram. MoDOT’s design guidance for placement of transverse rumble strips.[(24)]

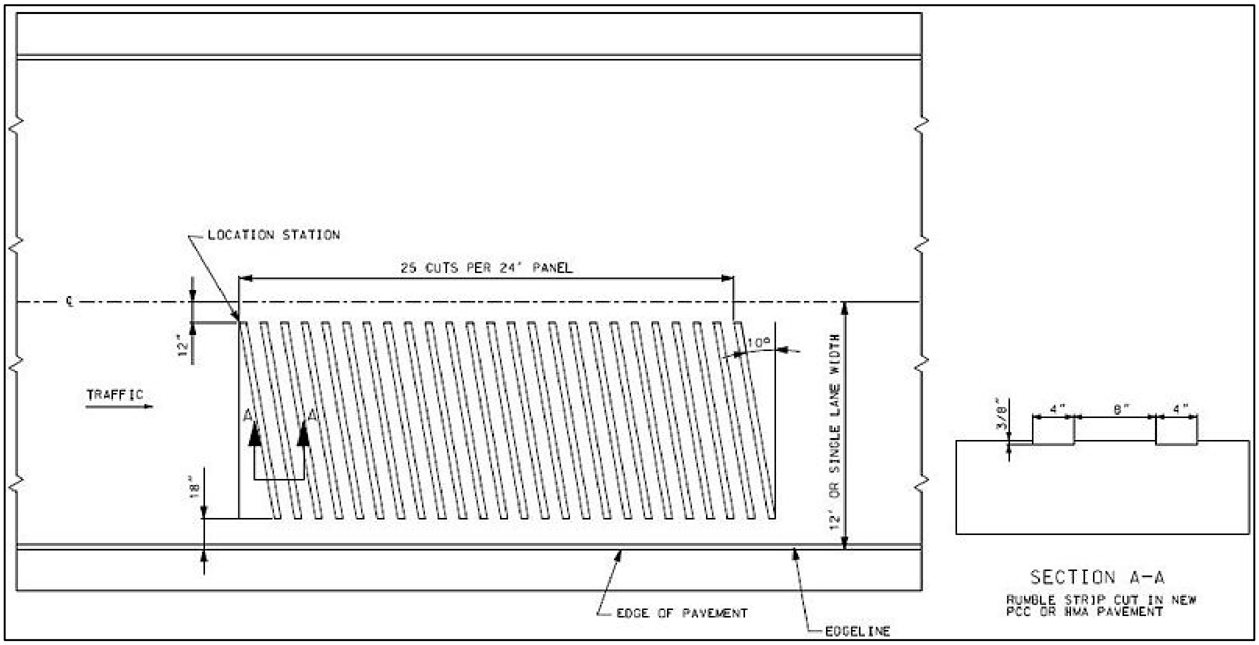


Figure 12. Diagram. MoDOT's design detail for transverse rumble strips.(24)

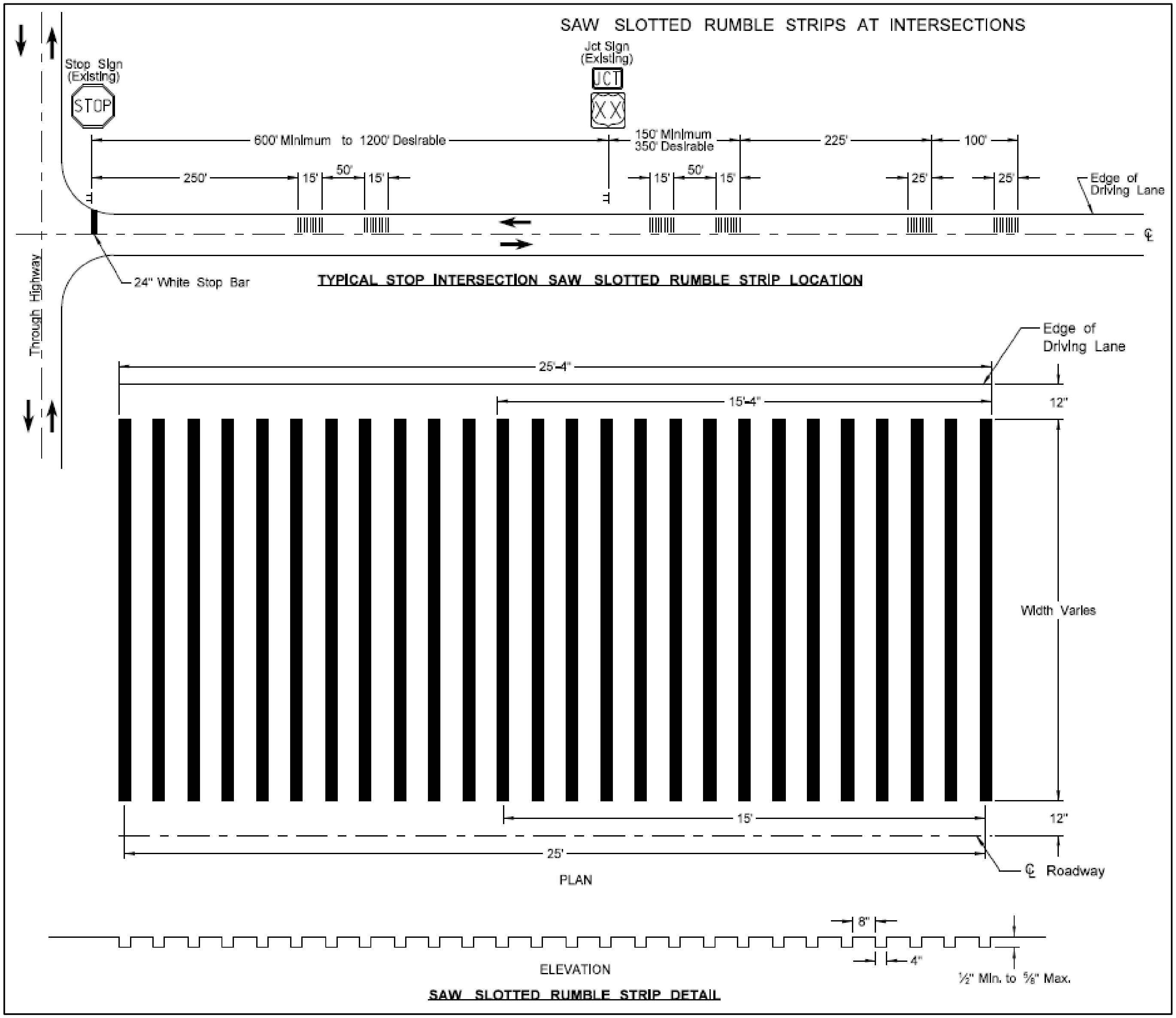


Figure 13. Diagram. North Dakota DOT's transverse rumble strip design detail.[25]

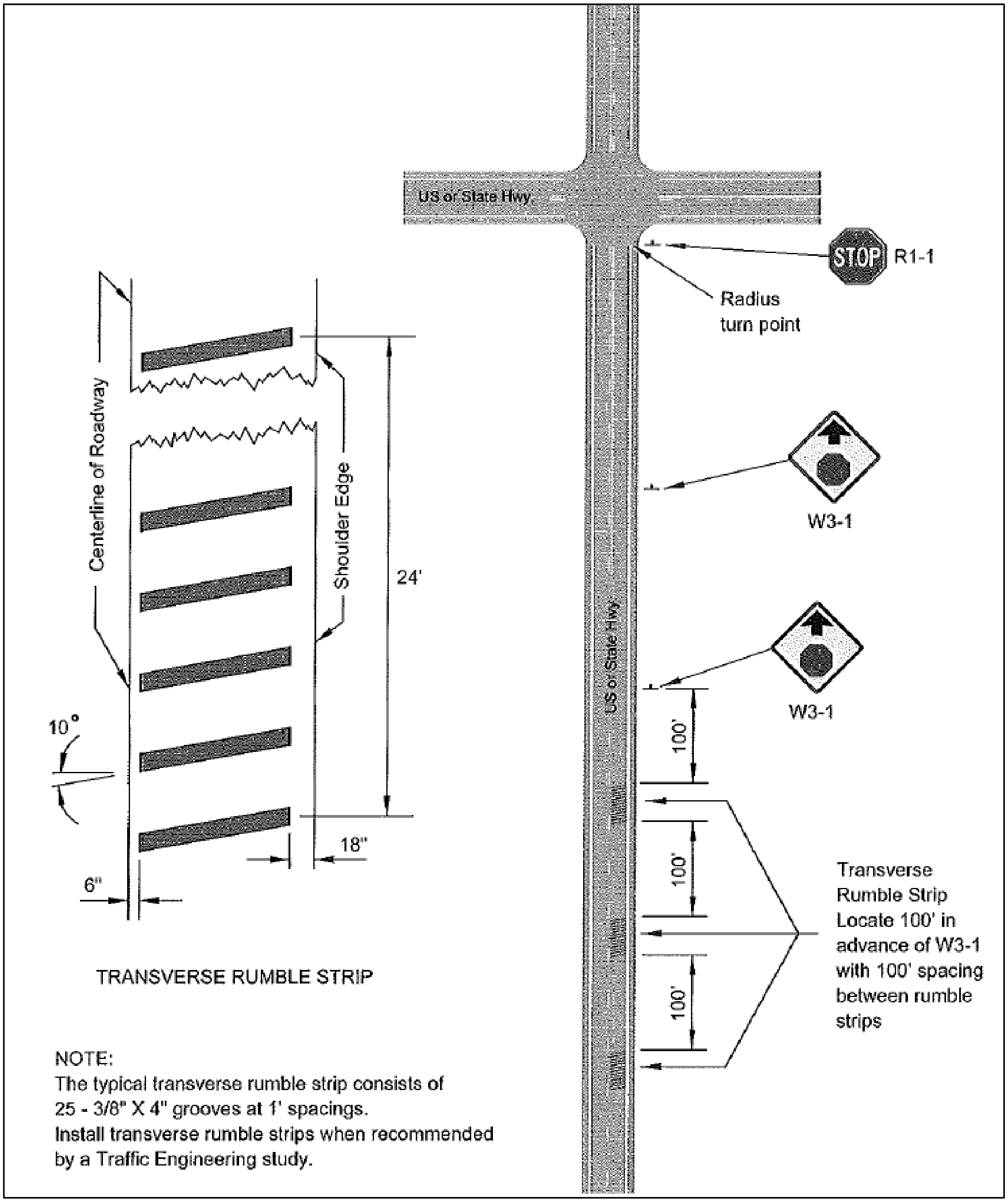


Figure 14. Diagram. KDOT transverse rumble strip installation and design detail.[26]

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CHAPTER 5. SUPPLEMENTARY PAVEMENT MARKINGS

<table>
<tr><td>Treatment Name</td><td colspan="2">Supplementary Pavement Markings</td></tr>
<tr><td>Description</td><td colspan="2">This evaluation considered two applications of supplementary pavement markings. In the first application, STOP AHEAD pavement markings were installed on the stop-controlled approach to an intersection. These markings are used to alert drivers of the presence of the intersection and the need to stop before proceeding into the intersection. These markings are intended to reduce crashes related to a failure to stop at the intersection.

In the second application, supplementary pavement markings were installed on uncontrolled approaches to an intersection. These pavement markings include a graphical depiction of the intersection with one of the following symbols: ┼, ├, or ┤, and are used to alert drivers of the presence of the intersection and of the potential for vehicles turning onto or off the roadway at that location.</td></tr>
<tr><td>States</td><td colspan="2">Data from the following states were included in the safety evaluation of this treatment: Arkansas, Minnesota, Nebraska, Pennsylvania, and Vermont.</td></tr>
<tr><td>Safety Effectiveness</td><td>Reduction by severity level:
The estimated safety effects of this treatment in reducing total crashes (all crash types combined) at 3-leg and 4-leg intersections are as follows:

<u>Markings on stop-controlled approaches</u>
3-Leg Intersections:
• 67% reduction of total crashes (SE = 7%)
• 76% reduction in FI crashes (SE = 7%)
• 72% reduction in PDO crashes (SE = 7%)

4-Leg Intersections:
• 66% reduction in total crashes (SE = 4%)
• 69% reduction in FI crashes (SE = 5%)
• 77% reduction in PDO crashes (SE = 4%)</td><td>Reduction by crash type:
The estimated safety effects of this treatment in reducing angle and rear-end crashes at 3-leg and 4-leg intersections are as follows:

<u>Markings on stop-controlled approaches</u>
3-Leg Intersections:
Angle Crashes
• 92% reduction in total crashes (SE = 5%)
• 88% reduction in FI crashes (SE = 7%)

Rear-End Crashes
• 95% reduction in total crashes (SE = 4%)
• 96% reduction in FI crashes (SE = 5%)
97% reduction in PDO crashes (SE = 3%)

4-Leg Intersections:
Angle Crashes
• 74% reduction in total crashes (SE = 4%)
• 71% reduction in FI crashes (SE = 5%)
• 88% reduction in PDO crashes (SE = 3%)

Rear-End Crashes
• 89% reduction in total crashes (SE = 3%)
• 86% reduction in FI crashes (SE = 5%)
• 95% reduction in PDO crashes (SE = 2%)</td></tr>
</table>

<table>
<tr><td>Treatment Name</td><td colspan="2">Supplementary Pavement Markings</td></tr>
<tr><td>Safety Effectiveness</td><td>Reduction by severity level:
<u>Markings on uncontrolled approaches</u>
3-Leg and 4-Leg Intersections Combined
• 46% reduction in total crashes (SE = 5%)
• 49% reduction in FI crashes (SE = 7%)
• 50% reduction in PDO crashes (SE = 6%)</td><td>Reduction by crash type:
<u>Markings on uncontrolled approaches</u>
3-Leg and 4-Leg Intersections Combined
Angle Crashes
• 38% reduction in total crashes (SE = 7%)
• 42% reduction in FI crashes (SE = 8%)
• 35% reduction in PDO crashes (SE = 10%)

Rear-End Crashes
• 69% reduction in total crashes (SE = 7%)
• 76% reduction in FI crashes (SE = 9%)
• 75% reduction in PDO crashes (SE = 8%)</td></tr>
<tr><td>Cost and Economic Benefits</td><td colspan="2">To estimate benefit-cost ratios, assumed installation costs for painting supplementary pavement markings (i.e., STOP AHEAD) on a stop-controlled approach to an intersection ranged from $300-$750. The assumed cost for installing supplementary pavement markings on both uncontrolled approaches to an intersection with thermoplastic markings was $10,000 (cost per intersection treatment). Benefit-cost ratios calculated for installing supplementary pavement markings (i.e., STOP AHEAD) on stop-controlled approaches to intersections ranged from 1.8 to 528.9, and benefit-cost ratios for installing supplementary pavement markings on uncontrolled approaches to intersections ranged from 15.1 to 138.7.</td></tr>
<tr><td>Where to Implement</td><td colspan="2">The treatment should be considered at intersections with a crash pattern related to a lack of driver awareness of the presence of the intersection.</td></tr>
<tr><td>Additional Factors for Consideration</td><td colspan="2">Supplementary pavement markings may not be visible during winter conditions with snow and ice. Supplementary pavement markings may have a lower coefficient of friction compared to the rest of the intersection approach, especially during wet conditions [(5)].</td></tr>
</table>

TREATMENT DESCRIPTION

Supplementary pavement markings may be used as a safety treatment at unsignalized intersections with minor-road stop control on rural two-lane roads. This study considered two distinct types of supplementary pavement markings: markings on stop-controlled approaches and markings on uncontrolled approaches. These two types of markings are discussed in greater detail below.

Supplementary pavement markings installed on stop-controlled approaches alert drivers of the presence of the intersection and the need to stop before proceeding into the intersection. At all of the study locations included in the evaluation of supplementary pavement markings installed on stop-controlled approaches to an intersection, the supplementary pavement markings read "STOP AHEAD." Figure 15 shows two images of supplementary pavement markings on stop-controlled approaches.

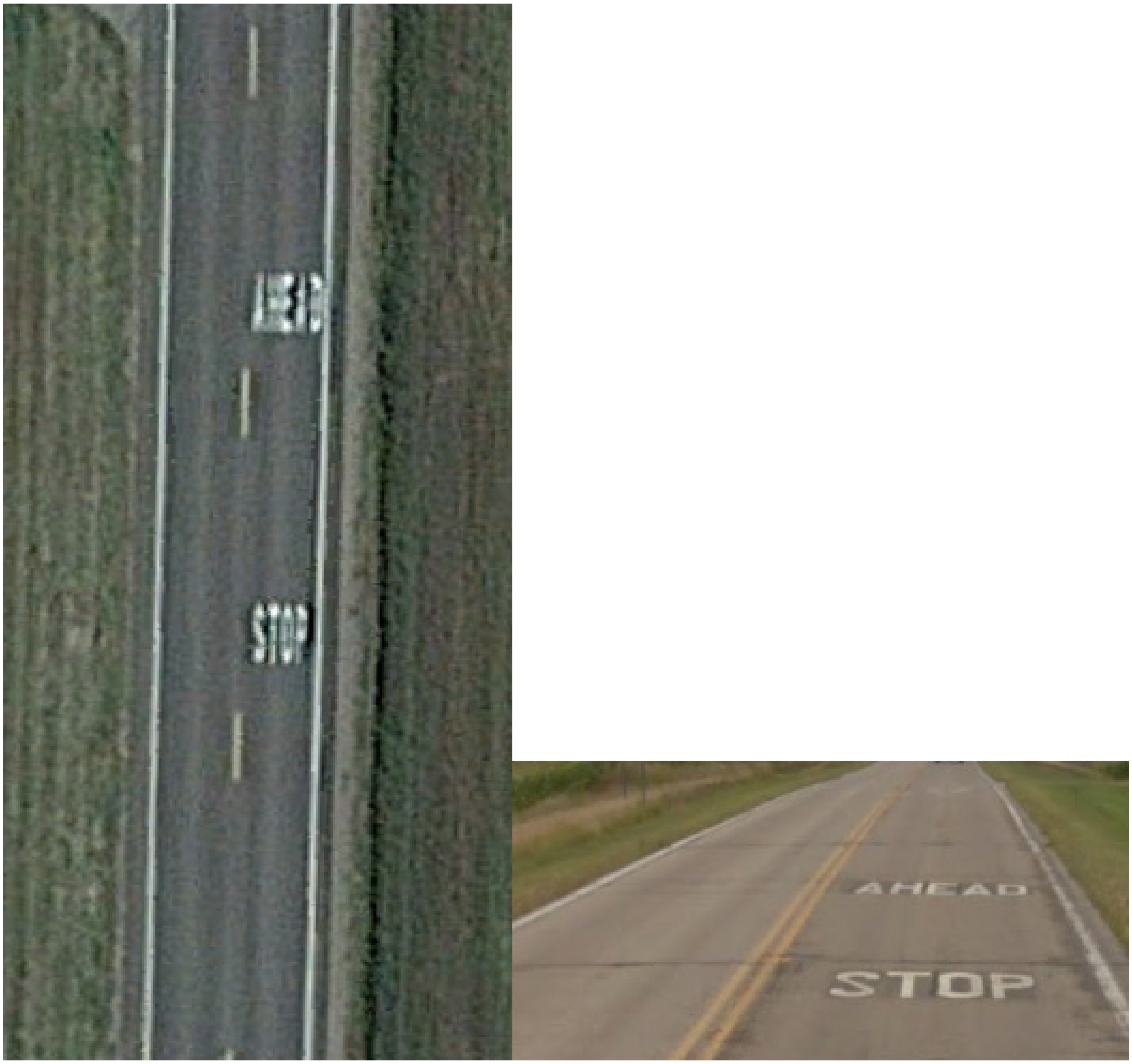


Figure 15. Photo. Aerial view and street view of supplementary pavement markings on stop-controlled approach (Image credit: Google Earth™ Mapping Service).[(21)]

At uncontrolled approaches, the Pennsylvania Department of Transportation deployed a unique set of supplementary pavement markings on the major-road approaches (i.e., uncontrolled approaches) at intersections with minor-road stop control. These markings are intended to alert drivers of the presence of the intersection and of the potential for vehicles and other road users entering or exiting the roadway at that location. Figure 16 shows the pavement markings on the uncontrolled approach to an intersection that is located over the crest of the vertical curve. The treatment consists of two sets of pavement markings. In the direction of travel, the first set of markings warns drivers to slow to the speed limit of the roadway (e.g., “SLOW, XX MPH,”). The second set of markings illustrates the configuration of the upcoming intersection as either 4 legs or 3 legs with one of the following symbols: ┼, ├, or ┤. For 3-leg intersections, the symbol indicates the side of the roadway from which the minor road intersects the major road. In

Figure 16, the supplementary pavement markings warn drivers to slow down to a speed of 30 mph as they are approaching a 4-leg intersection.

Figure 16. Photo. Supplementary pavement markings on uncontrolled approach.
(Image credit: Pennsylvania DOT)

SAFETY EVALUATION

The safety effectiveness of supplementary pavement markings was evaluated separately for markings installed on stop-controlled approaches of intersections and those installed on uncontrolled approaches, because the two types of installations are very different in their mechanism for reducing crashes. In the first case, drivers are being reminded that they must take action at the intersection—the treatment is aimed at reducing crashes related to a failure to stop at the intersection. In the second case, drivers are being warned to use caution while approaching the intersection as other vehicles or road users may be entering the roadway, slowing to exit the roadway, or making a left-turn in front of the driver; however, no specific action is necessarily required. The EB before-after analysis approach was used in both cases, as discussed in Chapter 2 (Analysis Approach). The descriptive statistics, research methodology, and analysis results of the safety evaluations are presented below.

Descriptive Statistics

A total of 76 treatment and 140 nontreatment sites in four states—Arkansas, Minnesota, Nebraska, and Vermont—were available for analysis of the safety effectiveness of supplementary pavement markings on stop-controlled intersection approaches. Their breakdown by state, number of intersection legs, and number of treated approaches is shown in Table 20. The treatment was always installed on one minor-road approach at 3-leg intersections and either one or two minor-road approaches at 4-leg intersections. Traffic volumes at the treatment sites ranged from 90 to 5,700 veh/day (3-leg intersections) and from 105 to 4,800 veh/day (4-leg intersections) on the major-road approaches and from 40 to 3,000 veh/day (3-leg intersections) and from 25 to 1,770 veh/day (4-leg intersections) on the minor-road approaches.

In Pennsylvania, 11 treatment sites and 28 nontreatment sites were available for analysis of supplementary pavement markings on uncontrolled intersection approaches. Supplementary pavement markings were installed on both major-road approaches at all intersections included in the evaluation. Their breakdown by number of intersection legs and number of treated approaches is also shown in Table 20. Traffic volumes at the treatment sites ranged from 1,890 to 14,020 veh/day (3-leg intersections) and from 2,310 to 16,270 veh/day (4-leg intersections) on the major-road approaches and from 180 to 5,380 veh/day (3-leg intersections) and from 330 to 3,480 veh/day (4-leg intersections) on the minor-road approaches.

Table 20. Supplementary pavement markings: number of sites by State, number of intersection legs, and number of treated approaches.

State	Number of Intersection Legs	Number of Treated Approaches	Number of Sites	
			Treatment	Nontreatment
Treatment on Stop-Controlled Approach(es)				
AR	3	1	1	11
	4	1	1	19
		2	1	
MN	3	1	29	21
	4	1	21	40
		2	9	
NE	3	1	3	13
	4	1	4	17
		2	2	
VT	3	1	2	9
	4	2	3	10
All sites			**76**	**140**
Treatment on Uncontrolled Approaches				
PA	3	2	3	8
	4		8	20
All sites			**11**	**28**

Crash and traffic volume data were obtained for varying periods before and after treatment installation, depending on the treatment installation date at the individual sites and crash data availability. Three crash types were considered in the analyses: all collision types combined, angle crashes, and rear-end crashes.

Table 21 (treatment intersections) and Table 22 (nontreatment intersections) summarize the crash data incorporated into the analysis of supplementary pavement markings installed on stop-controlled approaches to intersections on rural two-lane roads. They present total, angle, and rear-end crash data summed across all intersections of a given configuration (number of intersection legs) within each state.

Table 23 (treatment intersections) and Table 24 (nontreatment intersections) summarize the corresponding data incorporated into the analysis of supplementary pavement markings installed on uncontrolled approaches to intersections on rural two-lane roads.

Methodology

The safety effectiveness of installing supplementary pavement markings was evaluated using an EB method similar to that discussed in the EB evaluation of installing transverse rumble strips in Chapter 4. The safety effectiveness of supplementary pavement markings was evaluated separately for markings installed on stop-controlled approaches of intersections and those installed on uncontrolled approaches. Prior to implementing the EB method, the following points were addressed:

1. Select appropriate SPF: The SPFs for intersections on rural two-lane roads from Chapter 10 of the HSM were selected. These are given for total crashes only. The coefficients of these SPFs vary by number of intersection legs. Use of the intersection SPFs from Chapter 10 of the HSM provide an estimate of the intersection-related predicted crash frequency for sites included in the analysis in the absence of the treatment.

2. Obtain the proportion of target crashes for total, FS, FI, and PDO crashes (PR_1): The proportions of target crashes (angle and rear end) to all crashes for each severity level (total, FS, FI, and PDO) were calculated using all crashes from nontreatment sites and from the before-period years of treatment sites. These proportions were calculated separately for 3- and 4-leg intersections. These proportions scale the total crash predictions (i.e., all crash types) to predictions for the target crashes (i.e., angle and rear-end crashes).

3. Obtain the proportions of FS, FI, and PDO crashes (PR_2): These proportions were calculated as the ratio of all FS, FI, or PDO crashes over total crashes using all crashes from the nontreatment sites and from the before-period years of treatment sites. These proportions were calculated separately for 3- and 4-leg intersections. These proportions scale the total crash predictions (i.e., all severity levels combined) to predicted crashes for specific severity level crashes (i.e., FS, FI, and PDO).
4. Calibrate the SPFs to the local jurisdiction: Calibration was performed using all crashes (all collision types combined), separately for each intersection configuration within a

given state, again using all nontreatment intersections and before treatment intersections combined. Total crash counts were used rather than target crashes due to the scarcity of target crashes, especially FS and FI angle and rear-end crashes. The calibration factor adjusts the HSM SPFs for varying conditions in the local jurisdiction such as crash reporting thresholds, environmental, etc.

Table 21. Supplementary pavement markings installed on stop-controlled approaches: summary crash statistics for the before and after treatment periods for treatment intersections by State and number of intersection legs.

Number of Intersection Legs	State	Before Period							After Period						
		Range of Years of Data in State	Number of Sites	Number of Site-Years	Crash Counts				Range of Years of Data in State	Number of Sites	Number of Site-Years	Crash Counts			
					Total	FS	FI	PDO				Total	FS	FI	PDO
All Crashes															
3	AR	5	1	5	1	1	1	0	9	1	9	0	0	0	0
	MN	5	29	145	14	0	7	6	9	29	261	17	0	10	7
	NE	3	3	9	2	1	2	0	16	3	48	13	2	5	8
	VT	5	2	10	8	1	1	7	1 to 2	2	3	2	0	0	2
4	AR	4 to 5	2	9	4	1	1	3	9 to 12	2	21	27	6	16	11
	MN	5	30	150	24	6	17	4	9	30	270	26	1	14	12
	NE	3	6	18	10	1	7	3	16	6	96	40	7	24	16
	VT	5	3	15	11	0	3	8	2 to 7	3	11	7	0	3	4
Angle Crashes															
3	AR	5	1	5	1	1	1	0	9	1	9	0	0	0	0
	MN	5	29	145	1	0	0	1	9	29	261	1	0	1	0
	NE	3	3	9	0	0	0	0	16	3	48	2	1	2	0
	VT	5	2	10	1	1	1	0	1 to 2	2	3	0	0	0	0
4	AR	4 to 5	2	9	0	0	0	0	9 to 12	2	21	14	5	12	2
	MN	5	30	150	11	0	8	2	9	30	270	7	0	5	2
	NE	3	6	18	7	0	4	3	16	6	96	22	6	17	5
	VT	5	3	15	5	0	1	4	2 to 7	3	11	3	0	0	3
Rear-End Crashes															
3	AR	5	1	5	0	0	0	0	9	1	9	0	0	0	0
	MN	5	29	145	1	0	0	1	9	29	261	0	0	0	0
	NE	3	3	9	0	0	0	0	16	3	48	2	0	1	1
	VT	5	2	10	0	0	0	0	1 to 2	2	3	0	0	0	0
4	AR	4 to 5	2	9	2	0	0	2	9 to 12	2	21	4	0	2	2
	MN	5	30	150	2	2	2	0	9	30	270	4	0	3	1
	NE	3	6	18	0	0	0	0	16	6	96	3	0	2	1
	VT	5	3	15	3	0	0	3	2 to 7	3	11	1	0	1	0

Table 22. Supplementary pavement markings installed on stop-controlled approaches: summary crash statistics for the entire study period for nontreatment intersections by State and number of intersection legs.

Number of Intersection Legs	State	Entire Study Period						
		Range of Years of Data in State	Number of Sites	Number of Site-Years	Crash Counts			
					Total	FS	FI	PDO
ALL CRASHES								
3	AR	15	11	165	119	14	64	55
	MN	15	21	315	56	2	24	30
	NE	20	13	260	71	5	23	48
	VT	8	9	72	22	0	6	16
4	AR	17	19	323	161	35	96	65
	MN	15	40	600	106	4	47	55
	NE	20	17	340	123	22	65	58
	VT	13	10	130	58	1	27	31
ANGLE CRASHES								
3	AR	15	11	165	28	5	17	11
	MN	15	21	315	4	0	3	1
	NE	20	13	260	10	3	5	5
	VT	8	9	72	2	0	0	2
4	AR	17	19	323	98	24	63	35
	MN	15	40	600	31	2	17	11
	NE	20	17	340	70	18	44	26
	VT	13	10	130	35	0	18	17
REAR-END CRASHES								
3	AR	15	11	165	36	2	21	15
	MN	15	21	315	4	0	2	2
	NE	20	13	260	5	0	2	3
	VT	8	9	72	4	0	1	3
4	AR	17	19	323	16	3	8	8
	MN	15	40	600	21	1	8	13
	NE	20	17	340	14	2	7	7
	VT	13	10	130	5	0	0	5

Table 23. Supplementary pavement markings installed on uncontrolled approaches: summary crash statistics for the before and after treatment periods for treatment intersections by State and number of intersection legs.

Number of Intersection Legs	State	Before Period							After Period						
		Range of Years of Data in State	Number of Sites	Number of Site-Years	Crash Counts				Range of Years of Data in State	Number of Sites	Number of Site-Years	Crash Counts			
					Total	FS	FI	PDO				Total	FS	FI	PDO
ALL CRASHES															
3	PA	5	3	15	14	3	11	3	2	3	6	6	0	5	1
4	PA	4 to 5	8	37	94	8	50	44	2 to 12	8	52	156	5	74	82
ANGLE CRASHES															
3	PA	5	3	15	7	1	5	2	2	3	6	3	0	2	1
4	PA	4 to 5	8	37	62	7	38	24	2 to 12	8	52	122	5	62	60
REAR-END CRASHES															
3	PA	5	3	15	1	0	1	0	2	3	6	1	0	1	0
4	PA	4 to 5	8	37	13	0	5	8	2 to 12	8	52	19	0	7	12

Table 24. Supplementary pavement markings installed on uncontrolled approaches: summary crash statistics for the entire study period for nontreatment intersections by State and number of intersection legs.

Number of Intersection Legs	State	Entire Study Period						
		Range of Years of Data in State	Number of Sites	Number of Site-Years	Crash Counts			
					Total	FS	FI	PDO
ALL CRASHES								
3	PA	8	8	64	28	4	20	8
4	PA	17	20	340	324	24	188	136
ANGLE CRASHES								
3	PA	8	8	64	5	1	3	2
4	PA	17	20	340	201	20	121	80
REAR-END CRASHES								
3	PA	8	8	64	5	0	4	1
4	PA	17	20	340	39	0	22	17

The SPFs presented in the HSM for intersections on rural two-lane roads for total severity level (i.e., all severity levels combined) have the general form:

$$\text{Predicted crashes/yr} = \exp[a + b(\ln AADT_{maj}) + c(\ln AADT_{min})]$$

Figure 17. Equation. Base model for predicted crashes per year.

where a, b, and c are the regression coefficients shown in Table 25 for the analysis associated with markings installed on stop-controlled approaches of intersections and in Table 27 for the analysis associated with markings installed on uncontrolled approaches. These coefficients apply to base conditions and vary by number of intersection legs. For the intersection SPFs in Chapter 10 of the HSM, the base conditions are:

- Intersection skew angle: 0 degrees
- Number of intersection left-turn lanes: None on approaches without stop control
- Number of intersection right-turn lanes: None on approaches without stop control
- Presence of lighting: None

Crash modification factors (CMFs), calibration factors (C_r), proportions of angle and rear-end crashes (PR_1), and proportions of FS, FI, and PDO crashes (PR_2) were then used to adjust for local conditions as follows:

$$\text{Predicted crashes/yr} = \{\exp[a + b(\ln AADT_{maj}) + c(\ln AADT_{min})]\} \times PR_1 \times PR_2 \times CMF_{Combined} \times C_r$$

Figure 18. Equation. Model for predicted crashes per year for specific crash types and severity levels, and accounting for local conditions.

The $CMF_{Combined}$ is the product of the CMFs from Chapter 10 of the HSM for skew angle (CMF_{1i}), number of major-road left-turn lanes (CMF_{2i}), and number of major-road right-turn lanes (CMF_{3i}), for a particular intersection configuration.

SPF coefficients (a, b, and c and overdispersion parameter), target crash proportions (PR_1), proportions of FS, FI, and PDO out of total crashes (PR_2), and calibration factors (Cr) are shown for each intersection configuration in Table 25 and Table 26. Number of site-years, total crash counts (all severity levels), and target crash counts are also displayed. The tables also show the default proportions of PR_1 and PR_2 presented in Chapter 10 of the HSM (see Tables 10-6 and 10-5, respectively). Note that PR_2 is always equal to 1 for total crashes. The decision of which proportions to use—those calculated from the data or those provided by the HSM—was based on whether calculated proportions of target crashes (PR_1) were nonzero for all severity levels. If they were not, then the HSM proportions (both PR_1 and PR_2) were used in the EB before-after analysis. The selections of which proportions were used are indicated in Table 25 and Table 26 by an asterisk.

Safety Effectiveness

The EB before-after method was applied to estimate the safety effectiveness of installing supplementary pavement markings at rural stop-controlled intersections. The analysis of the safety effectiveness of supplementary pavement markings installed on stop-controlled approaches to intersections included treatment and nontreatment sites in Arkansas, Minnesota, Nebraska, and Vermont, and used HSM SPFs for 3- and 4-leg intersections on rural two-lane roads. The analysis of the safety effectiveness of supplementary pavement markings installed on uncontrolled approaches to intersections was based on treatment and nontreatment intersections in Pennsylvania.

Table 25. Supplementary pavement markings installed on stop-controlled approaches: SPF coefficients, target crash proportions, and calibration factors by State and number of intersection legs.

State	Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Target Crash Type	Number of Target Crashes	Intercept (a)	lnAADT$_{maj}$ Coefficient (b)	lnAADT$_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Target Crashes (PR_1)	PR_1 HSM	Proportion of FS, FI, or PDO of Total Crashes (PR_2)	PR_2 HSM	Calibration Factor (Cr)
AR	3	170	Total	120	Angle	29					**0.24***	0.24	**1.00***	1.00	
					Rear End	36					**0.30***	0.28	**1.00***	1.00	
			FS	15	Angle	6					**0.40***	0.28	**0.13***	0.06	
					Rear End	2	-9.86	0.79	0.49	0.54	**0.13***	0.26	**0.13***	0.06	13.68
			FI	65	Angle	18					**0.28***	0.28	**0.54***	0.42	
					Rear End	21					**0.32***	0.26	**0.54***	0.42	
			PDO	55	Angle	11					**0.20***	0.21	**0.46***	0.59	
					Rear End	15					**0.27***	0.29	**0.46***	0.59	
	4	332	Total	165	Angle	98					**0.59***	0.43	**1.00***	1.00	
					Rear End	18					**0.11***	0.24	**1.00***	1.00	
			FS	36	Angle	24					**0.67***	0.53	**0.22***	0.06	
					Rear End	3	-8.56	0.60	0.61	0.24	**0.08***	0.21	**0.22***	0.06	9.18
			FI	97	Angle	63					**0.65***	0.53	**0.59***	0.43	
					Rear End	8					**0.08***	0.21	**0.59***	0.43	
			PDO	68	Angle	35					**0.52***	0.35	**0.41**	0.57	
					Rear End	10					**0.15***	0.27	**0.41**	0.57	

Table 25. Supplementary pavement markings installed on stop-controlled approaches: SPF coefficients, target crash proportions, and calibration factors by State and number of intersection legs (continued).

State	Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Target Crash Type	Number of Target Crashes	Intercept (a)	$lnAADT_{maj}$ Coefficient (b)	$lnAADT_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Target Crashes (PR_1)	PR_1 HSM	Proportion of FS, FI, or PDO of Total Crashes (PR_2)	PR_2 HSM	Calibration Factor (Cr)
MN	3	460	Total	70	Angle	5	-9.86	0.79	0.49	0.54	0.07	**0.24***	1.00	**1.00***	1.35
					Rear End	5					0.07	**0.28***	1.00	**1.00***	
			FS	2	Angle	0					0.00	**0.28***	0.03	**0.06***	
					Rear End	0					0.00	**0.26***	0.03	**0.06***	
			FI	31	Angle	3					0.10	**0.28***	0.44	**0.42***	
					Rear End	2					0.07	**0.26***	0.44	**0.42***	
			PDO	36	Angle	2					0.06	**0.21***	0.51	**0.59***	
					Rear End	3					0.08	**0.29***	0.51	**0.59***	
	4	750	Total	130	Angle	42	-8.56	0.60	0.61	0.24	**0.32***	0.43	**1.00***	1.00	1.24
					Rear End	23					**0.18***	0.24	**1.00***	1.00	
			FS	10	Angle	2					**0.20***	0.53	**0.08***	0.06	
					Rear End	3					**0.30***	0.21	**0.08***	0.06	
			FI	64	Angle	25					**0.39***	0.53	**0.49***	0.43	
					Rear End	10					**0.16***	0.21	**0.49***	0.43	
			PDO	59	Angle	13					**0.22***	0.35	**0.45***	0.57	
					Rear End	13					**0.22***	0.27	**0.45***	0.57	

Table 25. Supplementary pavement markings installed on stop-controlled approaches: SPF coefficients, target crash proportions, and calibration factors by State and number of intersection legs (continued).

State	Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Target Crash Type	Number of Target Crashes	Intercept (a)	lnAADT$_{maj}$ Coefficient (b)	lnAADT$_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Target Crashes (PR_1)	PR_1 HSM	Proportion of FS, FI, or PDO of Total Crashes (PR_2)	PR_2 HSM	Calibration Factor (Cr)
NE	3	269	Total	73	Angle	10	-9.86	0.79	0.49	0.54	0.14	**0.24**[*]	1.00	**1.00**[*]	8.80
					Rear End	5					0.07	**0.28**[*]	1.00	**1.00**[*]	
			FS	6	Angle	3					0.50	**0.28**[*]	0.08	**0.06**[*]	
					Rear End	0					0.00	**0.26**[*]	0.08	**0.06**[*]	
			FI	25	Angle	5					0.20	**0.28**[*]	0.34	**0.42**[*]	
					Rear End	2					0.08	**0.26**[*]	0.34	**0.42**[*]	
			PDO	48	Angle	5					0.10	**0.21**[*]	0.66	**0.59**[*]	
					Rear End	3					0.06	**0.29**[*]	0.66	**0.59**[*]	
	4	358	Total	133	Angle	77	-8.56	0.60	0.61	0.24	**0.58**[*]	0.43	**1.00**[*]	1.00	7.57
					Rear End	14					**0.11**[*]	0.24	**1.00**[*]	1.00	
			FS	23	Angle	18					**0.78**[*]	0.53	**0.17**[*]	0.06	
					Rear End	2					**0.09**[*]	0.21	**0.17**[*]	0.06	
			FI	72	Angle	48					**0.67**[*]	0.53	**0.54**[*]	0.43	
					Rear End	7					**0.10**[*]	0.21	**0.54**[*]	0.43	
			PDO	61	Angle	29					**0.48**[*]	0.35	**0.46**[*]	0.57	
					Rear End	7					**0.12**[*]	0.27	**0.46**[*]	0.57	

Table 25. Supplementary pavement markings installed on stop-controlled approaches: SPF coefficients, target crash proportions, and calibration factors by State and number of intersection legs (continued).

State	Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Target Crash Type	Number of Target Crashes	Intercept (a)	lnAADT$_{maj}$ Coefficient (b)	lnAADT$_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Target Crashes (PR$_1$)	PR$_1$ HSM	Proportion of FS, FI, or PDO of Total Crashes (PR$_2$)	PR$_2$ HSM	Calibration Factor (Cr)
VT	3	82	Total	30	Angle	3					0.10	**0.24***	1.00	**1.00***	
					Rear End	4					0.13	**0.28***	1.00	**1.00***	
			FS	1	Angle	1					1.00	**0.28***	0.03	**0.06***	
					Rear End	0	-9.86	0.79	0.49	0.54	0.00	**0.26***	0.03	**0.06***	1.82
			FI	7	Angle	1					0.14	**0.28***	0.23	**0.42***	
					Rear End	1					0.14	**0.26***	0.23	**0.42***	
			PDO	23	Angle	2					0.09	**0.21***	0.77	**0.59***	
					Rear End	3					0.13	**0.29***	0.77	**0.59***	
	4	145	Total	69	Angle	40					0.58	**0.43***	1.00	**1.00***	
					Rear End	8					0.12	**0.24***	1.00	**1.00***	
			FS	1	Angle	0					0.00	**0.53***	0.01	**0.06***	
					Rear End	0	-8.56	0.60	0.61	0.24	0.00	**0.21***	0.01	**0.06***	2.44
			FI	30	Angle	19					0.63	**0.53***	0.44	**0.43***	
					Rear End	0					0.00	**0.21**	0.44	**0.43***	
			PDO	39	Angle	21					0.54	**0.35***	0.57	**0.57***	
					Rear End	8					0.21	**0.27***	0.57	**0.57***	

NOTE: Asterisked proportions were those used in the analyses.

Table 26. Supplementary pavement markings installed on uncontrolled approaches: SPF coefficients, target crash proportions, and calibration factors by State and number of intersection legs.

State	Number of Legs	Number of Site-Years	Severity Level	Number of Crashes, All	Target Crash Type	Number of Target Crashes	Intercept (a)	$lnAADT_{maj}$ Coefficient (b)	$lnAADT_{min}$ Coefficient (c)	Overdispersion Parameter	Proportion of Target Crashes (PR_1)	PR_1 HSM	Proportion of FS, FI, or PDO of Total Crashes (PR_2)	PR_2 HSM	Calibration Factor (Cr)
PA	3	79	Total	42	Angle	12	-9.86	0.79	0.49	0.54	0.29	**0.24***	1.00	**1.00***	1.05
					Rear End	6					0.14	**0.28***	1.00	**1.00***	
			FS	7	Angle	2					0.29	**0.28***	0.17	**0.06***	
					Rear End	0					0.00	**0.26***	0.17	**0.06***	
			FI	31	Angle	8					0.26	**0.28***	0.74	**0.42***	
					Rear End	5					0.16	**0.26***	0.74	**0.42***	
			PDO	11	Angle	4					0.36	**0.21***	0.26	**0.59***	
					Rear End	1					0.09	**0.29***	0.26	**0.59***	
	4	377	Total	418	Angle	263	-8.56	0.60	0.61	0.24	0.63	**0.43***	1.00	**1.00***	2.82
					Rear End	52					0.12	**0.24***	1.00	**1.00***	
			FS	32	Angle	27					0.84	**0.53***	0.08	**0.06***	
					Rear End	0					0.00	**0.21***	0.08	**0.06***	
			FI	238	Angle	159					0.67	**0.53***	0.57	**0.43***	
					Rear End	27					0.11	**0.21***	0.57	**0.43***	
			PDO	180	Angle	104					0.58	**0.35***	0.43	**0.57***	
					Rear End	25					0.14	**0.27***	0.43	**0.57***	

NOTE: Asterisked proportions were those used in the analyses.

The EB before-after analysis results are shown for the following crash types and severity levels:

- Total crashes (all collision types combined)
  - Total crashes
  - FI crashes
  - PDO crashes
- Angle crashes
  - Total crashes
  - FI crashes
  - PDO crashes
- Rear-end crashes
  - Total crashes
  - FI crashes
  - PDO crashes

Although the analyses for FS injury crashes were performed, the analysis results were not considered reliable and are therefore not shown. The occurrence of FS crashes was too rare across all intersections in the study (both treatment and nontreatment sites).

For the analysis of the safety effectiveness of supplementary pavement markings installed on stop-controlled approaches to intersections, the EB method was applied to all states combined based on the following reasoning: (1) a small number of treatment sites were available in Arkansas and Vermont—individually, they could not have been used for evaluation; and (2) all EB intermediate calculations (up to the final effectiveness calculations) are performed on a state/site basis, thus using SPFs, proportions (PR_1 and PR_2), combined CMFs, and calibration factors (C_r) specific to that state/site. This approach, to some extent, took state-to-state variability into account while increasing site and crash sample sizes. Additionally, the EB method was initially applied separately to 3-leg and 4-leg intersections and whether the treatment was installed on one or two stop-controlled approaches to the intersection. However, due to sample size issues, it was decided to pool across the number of treated approaches and perform the EB analysis separately for 3- and 4-leg intersections for the pooled data from the four states.

For the analysis of the safety effectiveness of supplementary pavement markings installed on uncontrolled approaches to intersections, the data for 3- and 4-leg intersections were combined and analyzed together to have a sufficient sample size for analysis.

The analysis results of the safety effectiveness estimates for supplementary pavement markings installed on stop-controlled approaches to intersections are shown in Table 27. The statistics shown for each crash severity are:

- Number of treatment intersections
- Percent change in crash frequency due to the treatment: estimate and standard error
- An indication of whether the treatment had a statistically significant effect on the crash types and severity level of interest at the 95-percent confidence level

A negative percent safety effectiveness indicates that crash frequencies decreased due to the treatment.

The analysis results of the safety effectiveness estimates for supplementary pavement markings installed on uncontrolled approaches to intersections are shown in Table 28.

Table 27. Supplementary pavement markings installed on stop-controlled approaches: safety effectiveness on target crashes by number of intersection legs.

Crash Severity	Number of Treatment Sites	Safety Effectiveness (%)	SE of Treatment Effect (%)	Significance
ALL STATES COMBINED; 3-LEG INTERSECTIONS				
ALL CRASHES				
Total	**35**	**-67**	**7**	**Significant at 95% CL**
FI		**-76**	**7**	**Significant at 95% CL**
PDO		**-72**	**7**	**Significant at 95% CL**
ANGLE CRASHES				
Total	**35**	**-92**	**5**	**Significant at 95% CL**
FI		**-88**	**7**	**Significant at 95% CL**
PDO		-100[a]	NC	NC
REAR-END CRASHES				
Total	**35**	**-95**	**4**	**Significant at 95% CL**
FI		**-96**	**5**	**Significant at 95% CL**
PDO		**-97**	**3**	**Significant at 95% CL**
ALL STATES COMBINED; 4-LEG INTERSECTIONS				
ALL CRASHES				
Total	**41**	**-66**	**4**	**Significant at 95% CL**
FI		**-69**	**5**	**Significant at 95% CL**
PDO		**-77**	**4**	**Significant at 95% CL**
ANGLE CRASHES				
Total	**41**	**-74**	**4**	**Significant at 95% CL**
FI		**-71**	**5**	**Significant at 95% CL**
PDO		**-88**	**3**	**Significant at 95% CL**
REAR-END CRASHES				
Total	**41**	**-89**	**3**	**Significant at 95% CL**
FI		**-86**	**5**	**Significant at 95% CL**
PDO		**-95**	**2**	**Significant at 95% CL**

[a] Crashes recorded in before period; none in after period.

NC=Not Calculated; standard error and significance could not be estimated.

Table 28. Supplementary pavement markings installed on uncontrolled approaches: safety effectiveness on target crashes.

Crash Severity	Number of Treatment Sites	Safety Effectiveness (%)	SE of Treatment Effect (%)	Significance
3- and 4-Leg Intersections Combined				
All Crashes				
Total	11	-46	5	Significant at 95% CL
FI		-49	7	Significant at 95% CL
PDO		-50	6	Significant at 95% CL
Angle Crashes				
Total	11	-38	7	Significant at 95% CL
FI		-42	8	Significant at 95% CL
PDO		-35	10	Significant at 95% CL
Rear-End Crashes				
Total	11	-69	7	Significant at 95% CL
FI		-76	9	Significant at 95% CL
PDO		-75	8	Significant at 95% CL

In general, the EB analysis results for supplementary pavement markings installed on stop-controlled approaches to intersections yielded statistically significant results for most of the crash types and severity levels analyzed for both 3- and 4-leg intersections. The results show that the overall effectiveness of this treatment (for all crash types and severities combined) is nearly identical for 3-leg and 4-leg intersections. Also, greater reductions were estimated for target crashes (i.e., angle and rear-end crashes) than for total crashes (i.e., all crash types combined).

The EB analysis results for supplementary pavement markings installed on uncontrolled approaches to intersections also show statistically significant reductions in crashes for all of the crash types and severity levels analyzed. The analysis results also show greater reductions in rear-end crashes compared to total (i.e., all crash types combined) and angle crashes.

ECONOMIC ANALYSIS

An economic analysis was conducted to estimate the economic benefits of installing supplementary pavement markings at unsignalized intersections with minor-road stop control on rural two-lane roads. Separate economic analyses were conducted for supplementary pavement markings installed on stop-controlled approaches and uncontrolled approaches. The Economic Analysis discussion in Chapter 2 describes the procedure for estimating the benefit-cost ratios of the treatments. The economic benefits of these treatments were estimated using the safety effectiveness estimates developed in this research.

The economic analysis produced two separate benefit-cost ratio tables for installing supplementary pavement markings on stop-controlled approaches: one for 3-leg intersections and the second for 4-leg intersections on rural two-lane roads. The safety evaluation produced CMFs for total crashes on both 3-leg and 4-leg intersections, and these CMFs were used to determine the expected annual benefit. This particular analysis assumes that one STOP AHEAD supplementary pavement marking is installed on each stop-controlled approach.

Kansas Department of Transportation reports the average cost of a STOP AHEAD pavement marking to be $750 per approach. For the sake of the analysis, a 1-yr service life was assumed. Longer service lives will only increase the benefit of a treatment, so assuming a shorter service life is conservative for a benefit-cost analysis. Table 29 and Table 30 present the benefit-cost ratios for installing a STOP AHEAD pavement marking on the stop-controlled approaches of a 3-leg and 4-leg rural intersection, respectively. The AADTs in the table cover the range of AADTs of the study sites used for the estimation of the CMF. For both intersection types, the benefit-cost ratio exceeds 1.0 for all AADT combinations, indicating that installation of a STOP AHEAD pavement marking on stop-controlled approaches is economically justified at all AADT levels. At higher-volume intersections, the benefit can be 100 or more times the cost.

Table 29. Benefit-cost ratios for installing STOP AHEAD pavement marking on the stop-controlled approach of a 3-leg intersection for $750 installation cost and 1-yr service life.

Major-Road AADT	% of Major-Road AADT on Minor Road											
	5%	10%	15%	20%	25%	30%	40%	50%	60%	70%	80%	90%
200	N/A	N/A	N/A	1.8	2.0	2.2	2.5	2.8	3.1	3.3	3.5	3.7
1,000	7.1	10.0	12.2	14.0	15.6	17.1	19.7	22.0	24.0	25.9	27.6	29.3
2,000	17.3	24.2	29.6	34.0	38.0	41.5	47.8	53.3	58.3	62.9	67.1	71.1
3,000	29.0	40.7	49.7	57.2	63.8	69.8	80.3	89.6	98.0	105.7	112.8	119.5
4,000	41.9	58.9	71.8	82.7	92.2	100.8	116.1	129.5	141.6	152.7	N/A	N/A
5,000	55.8	78.3	95.5	110.0	122.7	134.1	154.5	172.3	N/A	N/A	N/A	N/A
5,200	58.6	82.3	100.4	115.6	129.0	141.1	162.4	181.2	N/A	N/A	N/A	N/A

CMF = 0.33 (total crashes)
Installation cost = $750 (i.e., $750 per approach)
Service life = 1 yr
Shaded cells indicate the combination of major- and minor-road AADTs was not represented in the study

Table 30. Benefit-cost ratios for installing STOP AHEAD pavement markings on the stop-controlled approaches of a 4-leg intersection for $1,500 installation cost and 1-yr service life.

Major-Road AADT	% of Major-Road AADT on Minor Road											
	5%	10%	15%	20%	25%	30%	40%	50%	60%	70%	80%	90%
200	N/A	N/A	N/A	1.9	2.2	2.5	3.0	3.4	3.8	4.2	4.5	4.8
1,000	5.8	8.9	11.4	13.6	15.6	17.4	20.7	23.7	26.5	29.1	31.6	34.0
2,000	13.5	20.6	26.3	31.4	36.0	40.2	47.9	54.9	61.4	67.4	N/A	N/A
3,000	22.0	33.6	43.0	51.3	58.8	65.7	78.3	89.7	N/A	N/A	N/A	N/A
3,600	27.5	41.9	53.7	64.0	73.3	81.9	97.6	N/A	N/A	N/A	N/A	N/A

CMF = 0.34 (total crashes)
Installation cost = $1,500 (i.e., $750 per approach)
Service life = 1 yr
N/A indicates the combination of major- and minor-road AADTs was not represented in the study

Vermont Department of Transportation reports the average cost of a STOP AHEAD pavement marking to be between $300 and $500 per approach with a service life of 2 years. Table 31 and Table 32 present the benefit-cost ratios for installing a STOP AHEAD pavement marking on the stop-controlled approaches of a 3-leg and 4-leg intersection, respectively. The AADTs in the table cover the range of AADTs of the study sites used for the estimation of the CMF. For both intersection types, the benefit-cost ratio exceeds 5.0 for all AADT combinations.

Table 31. Benefit-cost ratios for installing STOP AHEAD pavement marking on the stop-controlled approach of a 3-leg intersection for $500 installation cost and 2-yr service life.

Major-Road AADT	% of Major-Road AADT on Minor Road											
	5%	10%	15%	20%	25%	30%	40%	50%	60%	70%	80%	90%
200	N/A	N/A	N/A	5.2	5.8	6.4	7.3	8.2	8.9	9.6	10.3	10.9
1,000	20.7	29.1	35.5	40.9	45.6	49.9	57.5	64.1	70.1	75.6	80.7	85.5
2,000	50.4	70.7	86.3	99.4	110.8	121.2	139.5	155.7	170.2	183.6	196.0	207.6
3,000	84.6	118.9	145.0	167.0	186.2	203.7	234.5	261.6	286.0	308.5	329.3	348.9
4,000	122.3	171.8	209.6	241.3	269.2	294.3	338.9	378.0	413.4	445.8	N/A	N/A
5,000	162.8	228.6	278.8	321.1	358.1	391.6	450.9	503.0	N/A	N/A	N/A	N/A
5,200	171.1	240.4	293.2	337.6	376.6	411.8	474.1	528.9	N/A	N/A	N/A	N/A

CMF = 0.33 (total crashes)
Installation cost = $500 (i.e., $500 per approach)
Service life = 2 yrs
Shaded cells indicate the combination of major- and minor-road AADTs was not represented in the study

Table 32. Benefit-cost ratios for installing STOP AHEAD pavement markings on the stop-controlled approaches of a 4-leg intersection for $1,000 installation cost and 2-yr service Life.

Major-Road AADT	% of Major-Road AADT on Minor Road											
	5%	10%	15%	20%	25%	30%	40%	50%	60%	70%	80%	90%
200	N/A	N/A	N/A	5.6	6.4	7.2	8.6	9.8	11.0	12.1	13.1	14.1
1,000	16.9	25.8	33.1	39.4	45.1	50.4	60.1	68.9	77.0	84.6	91.8	98.6
2,000	39.1	59.7	76.5	91.1	104.4	116.7	139.1	159.4	178.1	195.7	N/A	N/A
3,000	63.9	97.5	124.9	148.8	170.5	190.6	227.2	260.3	N/A	N/A	N/A	N/A
3,600	79.7	121.6	155.7	185.6	212.6	237.7	283.3	N/A	N/A	N/A	N/A	N/A

CMF = 0.34 (total crashes)
Installation cost = $1,000 (i.e., $500 per approach)
Service life = 2 yrs
N/A indicates the combination of major- and minor-road AADTs was not represented in the study

The Pennsylvania Department of Transportation was the only state in the study that installed supplementary pavement markings on uncontrolled approaches to intersections. The Pennsylvania Department of Transportation reports the average cost of installation to be $10,000 with a service life of 5 years. This cost is based on the use of thermoplastic pavement marking material and cost of the treatment for the entire intersection. Table 33 shows the benefit-cost ratios for the supplementary pavement markings on uncontrolled approaches at a 4-leg stop-controlled intersection on rural two-lane roads. The ranges of the AADTs in the table are within the minimum and maximum AADTs of the study sites used in the safety evaluation. All the benefit-cost ratios exceed 15, meaning the installation of supplementary pavement markings on uncontrolled approaches is economically justified across the entire AADT range evaluated in this study.

Table 33. Benefit-cost ratios for installing supplementary pavement markings on uncontrolled approaches at 4-leg stop-controlled intersections.

Major-Road AADT	% of Major-Road AADT on Minor Road										
	5%	10%	15%	20%	30%	40%	50%	60%	70%	80%	90%
2,400	N/A	N/A	15.1	18.0	23.0	27.4	31.4	35.1	38.6	41.8	45.0
3,000	N/A	N/A	19.7	23.5	30.1	35.9	41.1	46.0	50.5	54.8	58.9
4,000	N/A	21.8	28.0	33.3	42.7	50.9	58.3	65.1	N/A	N/A	N/A
5,000	N/A	28.6	36.6	43.7	55.9	66.6	76.3	N/A	N/A	N/A	N/A
6,000	N/A	35.7	45.7	54.4	69.7	83.1	N/A	N/A	N/A	N/A	N/A
7,000	28.2	43.0	55.0	65.6	84.0	N/A	N/A	N/A	N/A	N/A	N/A
8,000	33.1	50.5	64.7	77.1	98.7	N/A	N/A	N/A	N/A	N/A	N/A
9,000	38.2	58.2	74.6	88.9	113.8	N/A	N/A	N/A	N/A	N/A	N/A
10,000	43.3	66.2	84.7	101.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
11,000	48.6	74.2	95.1	113.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A
12,000	54.0	82.5	105.6	125.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A
13,000	59.5	90.9	116.4	138.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A
14,000	65.1	99.4	127.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

CMF = 0.54 (total crashes)
Installation cost = $10,000
Service life = 5 yrs
N/A indicates the combination of major- and minor-road AADTs was not represented in the study

IMPLEMENTATION

The primary purpose of installing supplementary pavement markings on stop-controlled approaches to intersections on rural two-lane roads is to alert drivers of a stop ahead. The treatment is intended to increase drivers' awareness of the intersection and to the traffic control. Supplementary pavement markings should be considered for installation on stop-controlled approaches to intersections with a pattern of crashes related to a lack of driver recognition of the presence of the intersection (e.g., angle crashes related to stop sign violations).[5] In particular, supplementary pavement markings should be considered for installation along the stop-controlled approach to an intersection that is hidden from view due to horizontal or vertical curvature or where the traffic control is hidden from view as the driver approaches the intersection.

The primary purpose of supplementary pavement markings on uncontrolled approaches to intersections on rural two-lane roads is to increase driver awareness of the intersection and reduce speeds of vehicles on the major road near the intersection. Supplementary pavement markings on uncontrolled approaches to intersections should be considered on approaches to intersections where it is difficult to recognize the presence of the crossroad(s) and/or at intersections where speeds on the major-road approaches are higher than desired for the conditions.

The economic analyses provided above show that both types of supplementary pavement markings are economically justifiable, even along roads with low traffic volumes.

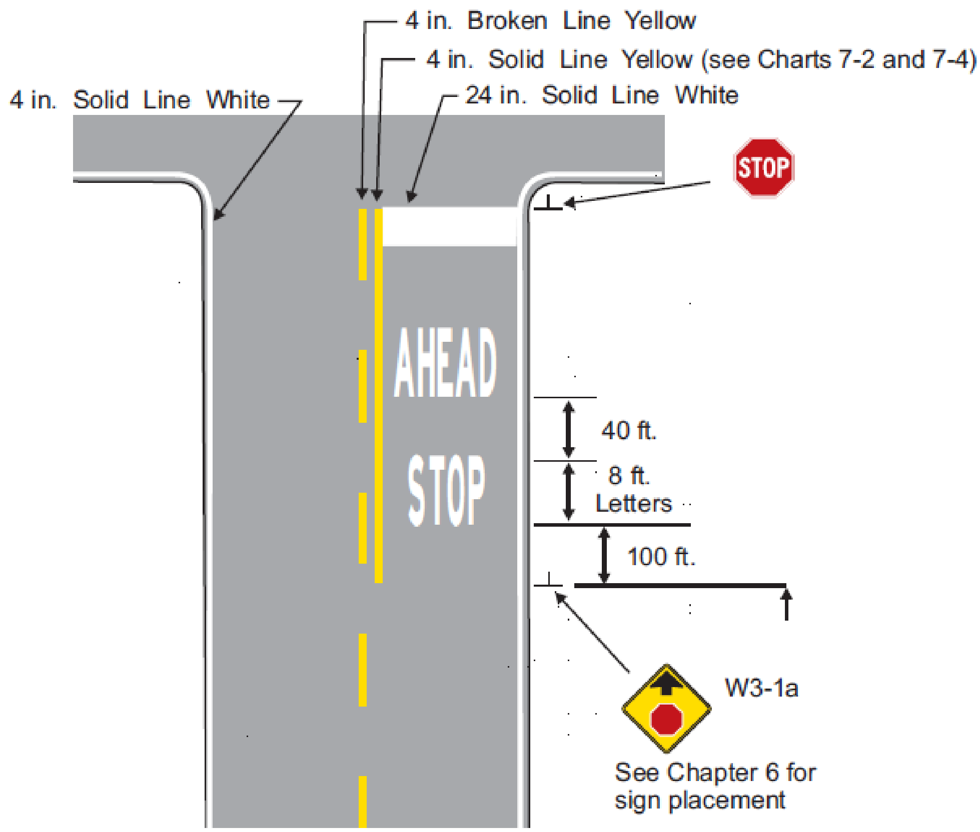
Both types of supplementary pavement markings should be implemented in accordance with the *Manual on Uniform Traffic Control Devices* (MUTCD). The MUTCD gives little guidance about the design and placement of supplementary pavement markings. Section 3B.20 of the MUTCD gives support for the use of markings, stating, "These pavement markings can be helpful to road users in some locations by supplementing signs and providing additional emphasis for important regulatory, warning, or guidance messages, because the markings do not require diversion of the road user's attention from the roadway surface.[27]" Section 3B.20 also includes recommended sizes for words on the pavement and states that "STOP AHEAD" may be used to supplement signs.

The following paragraphs present several example design details on the use of supplementary pavement markings. The information was provided by several state agencies.

As indicated, the MUTCD permits the use of the phrase "STOP AHEAD" on pavement to warn drivers of an upcoming stop. Figure 19 and Figure 20 are from the Minnesota *Traffic Engineering Manual* and provide guidance on the placement of the supplementary pavement marking. Figure 19 shows that the placement of the pavement marking is dependent on the placement of the W3-1a advance warning sign. Figure 20 indicates the placement of the W3-1a sign relative to the location of the stop bar.

Vermont Department of Transportation recommends installing the STOP AHEAD pavement marking at the location of the W3-1a sign (stop ahead sign). The distance to the stop bar is usually 200-250 ft; however, engineering judgment in the field is used to make sure sight obstructions such as crest vertical curves do not warrant longer distances.

Figure 21 shows design details for the placement and size of the supplementary pavement markings on the uncontrolled approach. It is recommended that this treatment not be used in areas with significant grade differences. The placement of the markings relative to the intersection is dependent on the posted speed of the roadway (see Table 34 for distances). These markings are part of a comprehensive intersection treatment that includes unique signage. See Appendix A for additional guidance from the Pennsylvania Department of Transportation regarding this treatment.



NOTES:

1. Do not install a STOP AHEAD pavement message if the intersection has adequate lighting.
2. Install only one set of STOP AHEAD pavement messages. If a Stop Ahead sign needs to be installed more than 1000 feet from the STOP sign, contact the district traffic engineer to determine if, and where, a second set of STOP AHEAD pavement messages should be installed.
3. The stop line should ordinarily be placed 4 feet in advance of and parallel to the nearest crosswalk line. In the absence of a marked crosswalk, the stop line should be placed at the desired stopping point, and in no case no more than 30 feet or less than four feet from the nearest edge of the intersecting curb line or the near edge of the thru lane.

   If a stop line is used in conjunction with a stop sign, it should ordinarily be placed in line with the stop sign. However, if the sign cannot be located exactly where vehicles are expected to stop, the stop line should be placed at the stopping point.

Figure 19. Diagram. Minnesota guidance for placement of STOP AHEAD pavement marking relative to W3-1a sign.[28]

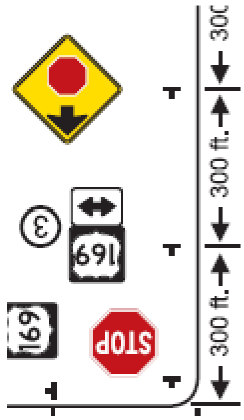


Figure 20. Diagram. Minnesota guidance for placement of W3-1a sign relative to stop bar.[28]

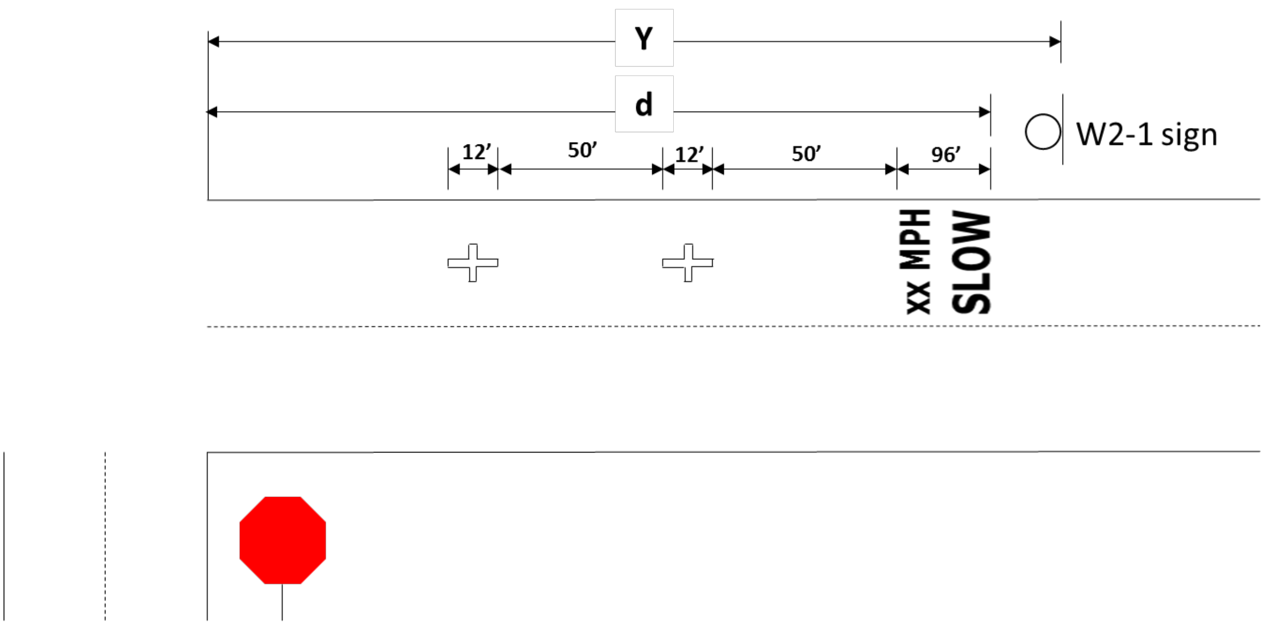


Figure 21. Diagram. Placement guidance for supplementary pavement markings on uncontrolled approach.[29]

Table 34. Placement of supplementary pavement markings relative to intersection by posted speed.[29]

Posted Speed (mph)	d, Pattern Length (ft)	Y, Distance to Sign (ft)
25	265	340
30	300	380
35	340	450
40	375	500
45	410	550
50	450	600
55	485	650

CHAPTER 6. CONCLUSIONS

The objective of this research is to advance efforts to improve safety at intersections with minor-road stop control along rural two-lane roads. The safety effectiveness of three low-cost safety treatments was evaluated to estimate their expected effectiveness in reducing crashes. The low-cost safety treatments included:

- Single luminaire intersection lighting
- Transverse rumble strips in advance of stop-controlled approaches
- Supplementary pavement markings on intersection approaches

The effectiveness of each treatment in reducing crashes was estimated using the Empirical Bayes (EB) observational before-after safety evaluation analysis approach. In addition, economic analyses were performed to estimate the benefit-cost ratio of each treatment, incorporating safety effectiveness results from the EB analyses.

The safety and economic analyses show that the treatments are effective in reducing crashes of different types and severity levels and are economically justifiable for installation at intersections with patterns of crashes that suggest drivers are unaware of the presence of the intersection. The expected safety effectiveness (and standard error) of each treatment in reducing crashes of different types and severities are shown in Table 35.

Table 35. Summary of treatment effectiveness by treatment and intersection type and crash type and crash severity level.

Intersection Type	Crash Type	Severity Level	Crash Reduction (%) (SE (%))
Single Luminaire			
3 or 4 Legs	Total nighttime	Total	71 (29)
Transverse Rumble Strips			
3 Legs	All	FI	37 (20)
	Angle	PDO	61 (28)
	Rear End	FI	60 (29)
4 Legs	All	Total	13 (7)
		FI	29 (8)
	Angle	FI	25 (10)
	Rear End	Total	56 (8)
		FI	78 (8)
		PDO	54 (10)

Table 36. Summary of treatment effectiveness by treatment and intersection type and crash type and crash severity level (continued).

Intersection Type	**Crash Type**	**Severity Level**	**Crash Reduction (%) (SE [%])**
Supplementary Pavement Markings on Stop-Controlled Approaches (i.e., STOP AHEAD)			
3 Legs	All	Total	67 (7)
		FI	76 (7)
		PDO	72 (7)
	Angle	Total	92 (5)
		FI	88 (7)
	Rear End	Total	95 (4)
		FI	96 (5)
		PDO	97 (3)
4 Legs	All	Total	66 (4)
		FI	69 (5)
		PDO	77 (4)
	Angle	Total	74 (4)
		FI	71 (5)
		PDO	88 (3)
	Rear End	Total	89 (3)
		FI	86 (5)
		PDO	95 (2)
Supplementary Pavement Markings on Uncontrolled Approaches			
3 or 4 Legs	All	Total	46 (5)
		FI	49 (7)
		PDO	50 (6)
	Angle	Total	38 (7)
		FI	42 (8)
		PDO	35 (10)
	Rear End	Total	69 (7)
		FI	76 (9)
		PDO	75 (8)

The information in this research can be combined with information on other strategies to reduce crashes at intersections with minor-road stop control along rural two-lane roads. With this information, agencies can make informed decisions about planning and programming safety improvements at intersections under their jurisdiction

CHAPTER 7. REFERENCES

1. National Highway Traffic Safety Administration (NHTSA). *Fatality Analysis Reporting System (FARS)*. [cited September 2015]
2. Federal Highway Administration (FHWA), Focused Approach to Safety. http://safety.fhwa.dot.gov/fas/. [cited September 2015]
3. Federal Highway Administration (FHWA), *Example Intersection Safety Implementation Plan*, US Department of Transportation, 2009.
4. Preston, H., R. Storm, M. Donath, and C. Shankwitz, Review of Minnesota's Rural Intersection Crashes: Methodology for Identifying Intersections for Intersection Decision Support (IDS), Report No. MN/RC-2004-31, Minnesota Department of Transportation, 2004.
5. Neuman, T. R., R. Pfefer, K. L. Slack, K. K. Hardy, D. W. Harwood, I. B. Potts, D. J. Torbic, and E. R. Kohlman Rabbani, Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 5: A Guide for Addressing Unsignalized Intersection Collisions, NCHRP Report 500, Volume 5, Transportation Research Board, 2003.
6. American Association of State Highway and Transportation Officials (AASHTO), *Highway Safety Manual*, Washington, DC, 2010.
7. Federal Highway Administration (FHWA), Crash Modification Factors Clearinghouse. http://www.cmfclearinghouse.org/. [cited July 2015]
8. Elvik, R., and T. Vaa. *The Handbook of Road Safety Measures*. Elsevier Science, Burlington, MA, 2004.
9. Elvik, R. Meta-Analysis of Evaluations of Public Lighting as Accident Countermeasure. In *Transportation Research Record 1485.* TRB, National Research Council, Washington, DC, 1995.
10. Griffith, M.S. Comparison of the Safety of Lighting Options on Urban Freeways. *Public Roads*, Vol. 58, No. 2, 1994.
11. Preston, H., and T. Schoenecker. *Safety Impacts of Street Lighting at Rural Intersections*. Minnesota Department of Transportation, 1999.
12. Srinivasan, R., J. Baek, and F. Council, Safety Evaluation of Transverse Rumble Strips on Approaches to Stop Controlled Intersections in Rural Areas, Presented at the 89th Annual Meeting of the Transportation Research Board, Washington, DC, 2010.
13. Gross, F., R. Jagannathan, B. Persaud, C. Lyon, K. Eccles, N. Lefler, and R. Amjadi, *Safety Evaluation of STOP Ahead Pavement Markings*, Report No. FHWA-HRT-08-043, Federal Highway Administration, 2007.
14. Hauer, E. *Observational Before-After Studies in Road Safety*, Pergamon/Elsevier Science, Inc., Tarrytown, New York, 1997.
15. Hauer, E., D. W. Harwood, F. M. Council, and M. S. Griffith, "Estimating Safety by the Empirical Bayed Method: A Tutorial," presented at the 81st annual meeting of the Transportation Research Board, January 2002.

16. Torbic, D. J., J. M. Hutton, C. D. Bokenkroger, K. M. Bauer, D. W. Harwood, D. K. Gilmore, J. M. Dunn, J. J. Ronchetto, E. T. Donnell, H. J. Sommer III, P. Garvey, B. Persaud, and C. Lyon, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, NCHRP Report 641, Transportation Research Board, Washington DC, 2009.

17. Torbic, D. J., K. M. Bauer, and J. M. Hutton, "*Delta Region Transportation Development Program: Rural Safety Innovation Program Evaluation,"* Report FHWA-SA-14-029, Federal Highway Administration, 2014.

18. Srinivasan, R., D. Carter, K. Eccles, B. Persaud, N. Lefler, C. Lyon, and R. Amjadi, *Safety Evaluation of Flashing Beacons at STOP-Controlled Intersections*, Report No. FWHA-HRT-8-044, Federal Highway Administration, 2007.

19. Blincoe, L. J., Miller, T. R., Zaloshnja, E., & Lawrence, B. A. The economic and societal impact of motor vehicle crashes, 2010. (Revised). Report No. DOT HS 812 013. Washington, DC: National Highway Traffic Safety Administration, 2015.

20. United States Department of Transportation (US DOT). "Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses-2015 Adjustment." Office of the Secretary of Transportation Memorandum, June 17, 2015. Accessed September 11, 2015.

21. Google Earth™ Mapping Service.

22. Lutkevich, P., D. McLean, and J. Cheung. *FHWA Lighting Handbook*, Federal Highway Administration, Washington, DC, 2012.

23. American Association of State Highway and Transportation Officials (AASHTO), *Roadway Lighting Design Guide*, Washington, DC, 2005.

24. Missouri Department of Transportation. MoDOT Engineering Policy Manual. Section 626.4 Transverse Rumble Strips. http://epg.modot.org/index.php?title=626.4_Transverse_Rumble_Strips [cited March 2015]

25. North Dakota Department of Transportation. CADD Standard Drawings. Standard No. D760-05, Saw Slotted Rumble Strips at Intersections. https://www.dot.nd.gov/divisions/design/docs/standards/D760-05.pdf

26. Kansas Department of Transportation. *Highway Sign Manual*. 2007.

27. Federal Highway Administration (FHWA). *Manual on Uniform Traffic Control Devices*. U.S. Department of Transportation. Washington, DC, 2009A.

28. Minnesota Department of Transportation. *Traffic Engineering Manual*. 2015 http://www.dot.state.mn.us/trafficeng/publ/tem/

29. Pennsylvania Department of Transportation. *District Highway Safety Guidance Manual*. 2014.

30. SAS Institute Inc. 2011. *SAS/STAT® 9.3 User's Guide*. Cary, NC:SAS Institute Inc.

For More Information:

Visit http://fhwa.safety.dot.gov/intersection/

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