# Project No. 17-66

# GUIDANCE FOR SELECTION OF APPROPRIATE COUNTERMEASURES FOR OPPOSITE DIRECTION CRASHES

## FINAL REPORT

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Report Developed by:
Karen Dixon, Texas A&M Transportation Institute (TTI)
Srinivas Geedipally, TTI
Eun Sug Park, TTI
Raghavan Srinivasan, Highway Safety Research Center (HSRC) at UNC
Bo Lan, HSRC
Marcus Brewer, TTI
Subasish Das, TTI
Lingtao Wu, TTI
Charles Zegeer, HSRC
Emira Rista, TTI

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# LIST OF FREQUENTLY USED ABBREVIATIONS

For your convenience, this table includes the following list of abbreviations that are used within the content of this report.

| | |
|---|---|
| A | Incapacitating crash |
| AADT | Annual average daily traffic |
| AASHTO | American Association of State Highway and Transportation Officials |
| ADT | Average Daily Traffic |
| B | Non-incapacitating crash |
| C | Possible injury crash |
| CMF | Crash Modification Factor / Function |
| ConnDOT | Connecticut Department of Transportation |
| CRF | Crash Reduction Factor |
| CRIS | Crash Records Information System |
| EB | Empirical Bayes |
| FARS | Fatal Analysis Reporting System |
| FHWA | Federal Highway Administration |
| FI | Fatal and Injury (Crashes) |
| ft | Feet |
| GEE | Generalized Estimating Equations |
| GPS | Global Referencing System |
| HSIP | Highway Safety Improvement Plan |
| HSIS | Highway Safety Information System |
| HSM | *Highway Safety Manual* |
| IL | Illinois |
| K | Fatal crash |
| KS | Kansas |
| MI | Michigan |
| mi | Miles |
| mph | Miles per hour |
| NB | Negative binomial |
| NCHRP | National Cooperative Highway Research Program |
| NHTSA | National Highway Traffic System Administration |
| NLMIXED | Mixed non-linear regression procedure |
| OD | Opposite Direction |
| PDO | Property Damage Only |
| RHINO | Roadway Highway Inventory Network Offload (Texas) |
| SAS | Statistical Analysis System |
| SD | Standard Deviation |
| SLOSSS | Suggested list of surveillance study sites |
| SPF | Safety Performance Function |
| SRMP | State route milepost |
| SVROR | Single vehicle run off road |
| TRB | Transportation Research Board |
| TWLTL | Two-way left-turn lane |
| TxDOT | Texas Department of Transportation |
| VMT | Vehicle Miles Traveled |
| WSDOT | Washington State Department of Transportation |

# CHAPTER 1 Introduction and Overview

## Problem Statement

According to the NHTSA Fatal Analysis Reporting System (FARS), from 2016 through 2018, there were over 19,200 vehicles involved in opposite direction crashes that resulted in a fatality. Approximately 68 percent of these crashes occurred on two-lane roadways. Countermeasures, such as rumble strips/stripes, delineators, and barriers have proven to reduce both total crashes and serious injury crashes; however, there is limited guidance on the specific performance for many of these treatments as they directly relate to opposite direction crashes. Improved guidance is needed on when and what type of countermeasure is appropriate, and what roadway factors may lead to higher opposite direction crash frequency rates. For the purposes of this study, an opposite direction crash occurs between two or more vehicles that were traveling in opposing directions prior to the crash and were not attempting to execute a turning maneuver at the time of the crash. In this report, crashes that are opposite direction sideswipe and head-on are designated as OD crashes.

Although many opposite direction crash countermeasures have been studied individually, guidance on selecting from a wide range of opposite direction countermeasures does not exist. Median barriers for divided roads and centerline rumble strips for undivided roads have been the most studied countermeasures, but other countermeasures, such as reallocating lane width to create a small buffer median between opposing lanes, may be appropriate in some applications. A comprehensive guide on opposite direction crash countermeasures combined with a better understanding of what roadway factors increase opposite direction crash risk would aid transportation agencies to cost-effectively invest in countermeasures to reduce crashes on their road systems.

## Goal and Objectives

The objective of the research documented in this report was to develop a guidance document for the identification, prioritization, and selection of effective countermeasures to reduce or eliminate opposite direction crashes. The guidance document is intended for future possible adoption by the AASHTO Technical Committee on Roadside Safety as an update to content included in the AASHTO *Roadside Design Guide*. The guidance document addresses:

1. Locations and roadway factors that influence the frequency of opposite direction crashes, such as but not limited to average daily traffic (ADT), geometric features (e.g., tangents, horizontal and vertical curves, cross-sectional features), topography, geographical areas, and operating speeds.
2. Selection of countermeasures (low and high cost) that can be implemented individually or in combination, such as but not limited to: rumble strips/stripes, delineators, raised pavement markings, separation between opposing lanes, and barriers. Where feasibly, the guideline document also identifies countermeasure effectiveness under various roadway factors.
3. Any adverse impacts that may result from implementation of the countermeasures such as an increase of other crash types, operational impacts, and if the countermeasures impact

other road users (such as bicyclists and motorcyclists) as well as adjacent properties (e.g., noise from rumble strips/stripes and surface treatments).

For the purpose of this research, the focus is for two-lane undivided roadways; however, results may have application to other types of undivided roadways and shall be noted. This report documents the information used to support the companion Guideline document (developed as a standalone resource).

**Report Organization**

This final report includes a review of three completed rural two-lane highway assessments identified as follows:

- Chapter 2: Safety Effects of Wider Edge Lines on Opposite Direction Crashes.
- Chapter 3: Safety Effects of Centerline Buffers on Opposite Direction.
- Chapter 4: Safety Evaluation of the Effect of Curve Delineation on Head-on and Opposite Direction Crashes.
- Chapter 5: Safety Effects of Shoulder Widening on Opposite Direction Crashes.

Chapter 6 provides a summary overview of the findings from all four evaluations. This report concludes with a list of references, Appendix 1 (review of the Empirical Bayes or EB method), and Appendix 2 (separated standalone Guideline document).

# CHAPTER 2. Safety Effects of Wider Edge Lines on Opposite Direction Crashes (Rural Two-lane Highways)

Information documenting the safety effects related to opposite direction crashes is limited. For this study, therefore, the research team identified existing databases that could be subjected to additional analysis related to opposite direction crashes. The evaluation of the safety effects of wider edge lines on opposite direction crashes is based on one of these pre-existing databases. The analysis conducted, therefore, is bounded by the available data as compiled by other researchers. In some cases, additional assessment of crash types for existing study sets can have sample size limitations because the research design was not originally intended to subdivide the data to include additional crash types. In addition, opposite direction crashes tend to be rare events and so robust data sets focused directly on opposite direction crashes cannot be extracted from studies with relatively small sample sizes.

The purpose of this chapter is to summarize the results of the analyses of safety effects of wider edge lines on opposite direction crashes for rural, two-lane highways. This analysis utilized crash databases developed as part of a previous Federal Highway Administration (FHWA) project titled Pavement Marking Demonstration Projects: State of Alaska and State of Tennessee (1). For this assessment the analysis explored data from Kansas (KS), Michigan (MI), and Illinois (IL). The opposite direction crashes included those coded as head-on or sideswipe opposite direction. Where possible, the dataset further identified opposite direction fatal plus injury crashes, opposite direction night crashes, and opposite direction wet crashes. The analysis focused on non-intersection/interchange crashes and the influence of the wider edge lines. For regions such as MI and IL where the edge lines could potentially be obstructed by snow during winter months, the research team considered a crash dataset consisting of non-winter period crashes (excluding crashes that occurred during the winter months, November-March) as well as a larger dataset including winter-period crashes in an effort to minimize potential confounding results due to snow crashes in those northern states.

Due to the unique characteristics of the data, this evaluation included three separate analyses adapted for the individual state edge line conversion characteristics. Items considered included how, when, and to what extent the states made the transition to wider lines, and how long it took the state to complete the transition. The first analysis is an EB before-after analysis of rural, two-lane segments in Kansas for which the edge line width was changed from four inches to six inches in multiple years (mostly in 2005 and 2006). The second is a piecewise regression analysis of interrupted time series design with the change from four inches to six inches in 2004 treated as an intervention for Michigan data. The third is a cross-sectional safety comparison of rural two-lane segments with five inch center lines and edge lines to segments with four inch center lines and edge lines for Illinois.

### Analysis of Safety Performance for Kansas Rural Two-Lane Roadway Edge Line

The Kansas crash data consist of non-intersection/interchange crash counts obtained from 2,767 rural, two-lane road segments (corresponding to 2178.2 mi) in the District 2 and District 6 for years 2001–2007. Using an EB approach, the research team evaluated the influence of the wider edge line for the Kansas crash data (opposite direction and opposite direction fatal plus injury crashes). Appendix 1 summarizes the steps for the EB procedure. Note that in this evaluation, safety performance functions (SPFs) are calibrated for each year of the before and after periods (rather than just for each before or after total period).

There were two treatment groups, Group 1 consisting of 1,213 segments (803.8 mi) with 2005 as the implementation year and Group 2 consisting of 402 segments (361.5 mi) with 2006 as the implementation year. The analysis excluded 718 segments for which the implementation year was not known. Table 1 shows the number of segments and the corresponding miles for each treatment group used in the EB analysis for Kansas

**Table 1. Kansas Sites - Wider Edge Lines in Treatment Groups**

| Treatment Group | Implementation Year | Number of Segments | Total Miles |
|---|---|---|---|
| Group 1 | 2005 | 1,213 | 803.8 |
| Group 2 | 2006 | 402 | 361.5 |
| | Total | 1,615 | 1,165.3 |

The EB method uses SPFs that have been developed based on data from reference sites to estimate the predicted crash frequencies at the treated sites if the treatments had not been applied. While the success of an EB approach largely depends on reliable estimation of SPFs, it is often hard to identify a reference group that is similar enough to the treatment group. The number of segments and mileage for the Kansas reference group (used in the EB analysis) are 261 segments (158.1 miles). Table 2 provides the descriptive statistics for the treatment group and the reference group, respectively.

**Table 2. Descriptive Statistics for Kansas Rural Two-Lane Highway Segments**

| Segment variable | Treatment Group 1,615 segments (1,165.3 mi) | | | Reference Group 261 segments (158.1 mi) | | |
|---|---|---|---|---|---|---|
| | Minimum | Maximum | Average | Minimum | Maximum | Average |
| Length (mi) | 0.002 | 8.1 | 0.72 | 0.005 | 6.16 | 0.61 |
| Average daily traffic (vehicles per day (vpd)) | 65 | 12,800 | 1,036 | 40 | 4,745 | 746 |
| Daily commercial traffic (trucks per day) | 3 | 1,790 | 217 | 5 | 540 | 148 |
| Lane width (ft) | 10 | 14 | 11.8 | 11 | 15 | 11.5 |
| Shoulder width (ft) | 1 | 10 | 4.7 | 0 | 10 | 4.1 |
| Paved shoulder width (ft) | 0 | 10 | 1.4 | 0 | 8 | 0.7 |
| Speed limit (mph) | 20 | 65 | 60.2 | 25 | 65 | 58.4 |

The research team used a negative binomial regression model with a categorical variable for the Kansas District 2 and Kansas District 3 and year (2001-2007) to develop the SPFs (based on the reference sites). The model controlled for general trends by considering the shoulder width, log of the annual average daily traffic (AADT), and log of the segment length as independent variables. Although some other roadway characteristic variables such as lane width and speed limit were also available in the database, there was minimal variation attributed to those features and so they were not ultimately included in the model. Due to an issue of the small sample size, however, the coefficients for the SPFs could not be directly estimated for the opposite direction crashes or the opposite direction fatal plus injury crashes. The coefficients for opposite direction crashes and opposite direction fatal plus injury crashes were therefore obtained by applying a multiplier $\alpha_f$ (computed as the number of crashes of opposite direction crashes divided by the total number of crashes for the reference group for example) to the SPF for total crashes as in Bahar et al. (*2*). The estimated coefficients for SPFs for total crashes and the multipliers ($\alpha_f$) for opposite direction crashes and opposite direction fatal plus injury crashes are presented in Table 3 and Table 4, respectively.

**Table 3. Coefficient Estimates for Kansas Reference Group SPFs**

| Variable | | Total |
|---|---|---|
| District | 2 | –3.6538 |
| | 6 | –4.3942 |
| Year | 2001 | −0.2680 |
| | 2002 | −0.4696 |
| | 2003 | −0.3080 |
| | 2004 | −0.2427 |
| | 2005 | −0.4324 |
| | 2006 | −0.2561 |
| | 2007 | 0.0000 |
| Shoulder Width | | −0.0483 |
| Log(AADT) | | 0.5417 |
| Log(Length) | | 0.9344 |
| Dispersion | | 0.2777 |
| Pearson chi-square/DF | | 1.0700 |

Note: Based on a reference group consisting of 261 segments (158.1 mi) for rural two-lane roadways in Kansas.

**Table 4. Ratio of the Kansas Study Crashes to the Total Number for the Reference Group**

| Crash Type | Crash Counts | $\alpha_f$ |
|---|---|---|
| Total | 424 | 1.000 |
| Opposite direction | 14 | 0.033 |
| Opposite direction fatal plus injury | 10 | 0.024 |

Table 5 includes the results of the EB before-after evaluation based on the Kansas crash data. It can be observed from Table 5 that both opposite direction crashes and opposite direction fatal plus injury crashes resulted in statistically significant (at the 95 percent confidence level) crash reduction estimates regardless of the small sample sizes. In the previous FHWA project for assessing the safety effects of wider edge lines, the focus of the analysis was single vehicle crashes on rural two-lane highways and the study provided evidence to suggest the positive safety effects of wider edge lines on those crashes. (The results for total, fatal plus injury, single vehicle, and single vehicle fatal plus injury crashes from the previous FHWA project are also shown in Table 5 for comparison purposes.) The results of Table 5 support consistent safety effects of wider edge lines for opposite direction crashes and opposite direction fatal plus injury crashes.

**Table 5. Results of Kansas EB Before-After Evaluations for Rural Two-Lane Roadways**

| Crash Type | Crashes in the After Period | | $\hat{\theta}$ (S.E.) | 95% Confidence Interval for $\theta$ | Crash Reduction (%) |
|---|---|---|---|---|---|
| | Observed (L) | EB Estimate ($\hat{\pi}$) | | | |
| Total | 1021 | 1234.07 | 0.827 (0.028) | (0.772, 0.882) | 17.3 |
| Fatal plus Injury | 156 | 242.01 | 0.644 (0.053) | (0.541, 0.748) | 36.6 |
| Single Vehicle | 273 | 368.97 | 0.739 (0.048) | (0.644, 0.834) | 26.1 |
| Single Vehicle Fatal plus Injury | 113 | 176.63 | 0.640 (0.061) | (0.519, 0.760) | 36.0 |
| Opposite Direction | 20 | 35.23 | 0.568 (0.127) | (0.318, 0.817) | 43.2 |
| Opposite Direction Fatal plus Injury | 12 | 25.58 | 0.469 (0.136) | (0.203, 0.735) | 53.1 |

Notes:

1. EB estimate is the predicted number of crashes during after period had wider lines not been installed.
2. $\hat{\theta}$: Estimated index of effectiveness.
3. Percent Crash Reduction = $100\left(1-\hat{\theta}\right)$.
4. SE: Standard Error.
5. Statistically significant percent crash reductions at 95 percent confidence level are shown in bold.
6. Data based on non-intersection/interchange opposite direction crashes obtained from 1615 segments (1165.3 mi) on rural two-lane roadways

**Analysis of Safety Performance for Michigan Rural Two-Lane Roadway Edge Line**

The Michigan crash data consist of non-intersection/interchange crash counts obtained from 238 rural, two-lane road segments (corresponding to 787.8 mi) for years 2001–2009. To address the issue of potential confounding effects related to wider lines obscured by snow in Michigan, the research team analyzed two datasets, a dataset consisting of only non-winter period crashes (excluding crashes that occurred during the winter months, November-March) and a larger dataset that included winter-period crashes. Table 6 and Table 7 show the annual aggregated non-winter period crash counts and the annual aggregated crash counts (including winter crashes) from 238 segments for opposite direction and opposite direction fatal plus injury crashes. For information purposes, the annual aggregated crash counts for total, fatal plus injury, single vehicle, and single vehicle fatal plus injury crashes are also included in the tables.

**Table 6. Annual Aggregated Non-Winter Michigan Crashes (2001 – 2009)**

| Crash Type | Year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
| Total | 943 | 981 | 1106 | 1119 | 905 | 1010 | 1034 | 1006 | 1007 |
| Fatal plus injury | 127 | 149 | 127 | 146 | 125 | 99 | 121 | 124 | 115 |
| Single Vehicle | 778 | 811 | 946 | 953 | 775 | 894 | 915 | 890 | 891 |
| Single Vehicle fatal plus injury | 73 | 90 | 80 | 91 | 88 | 60 | 77 | 79 | 63 |
| Opposite direction | 30 | 24 | 32 | 30 | 22 | 14 | 15 | 29 | 27 |
| Opposite direction fatal plus injury | 10 | 12 | 13 | 11 | 5 | 8 | 10 | 16 | 17 |

Note:

1. Crashes in 2004 are excluded from the subsequent safety analysis because 2004 is the year of wider line installation.
2. Crash counts represent 238 segments (787.8 mi) of rural two-lane roadways in Michigan for the years of 2001 to 2009.

**Table 7. Annual Aggregated Crashes (2001 – 2009)**

| Crash Type | Year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
| Total | 2027 | 2039 | 2263 | 2356 | 2250 | 2069 | 2179 | 2236 | 2187 |
| Fatal plus injury | 224 | 257 | 242 | 276 | 247 | 202 | 220 | 243 | 219 |
| Single Vehicle | 1719 | 1724 | 1963 | 2046 | 1982 | 1834 | 1947 | 1999 | 1969 |
| Single Vehicle fatal plus injury | 134 | 158 | 149 | 179 | 168 | 120 | 139 | 158 | 134 |
| Opposite direction | 63 | 54 | 61 | 69 | 52 | 45 | 45 | 68 | 53 |
| Opposite direction fatal plus injury | 26 | 20 | 26 | 26 | 18 | 21 | 25 | 33 | 31 |

Note:

1. Crashes in 2004 are excluded from the subsequent safety analysis because 2004 is the year of wider line installation.
2. Crash counts represent 238 segments (787.8 mi) of rural two-lane roadways in Michigan from 2001 to 2009.

Table 8 and Table 9 summarize descriptive statistics for the primary segment variables considered in the Michigan data analysis.

**Table 8. Descriptive Statistics for Continuous Michigan Segment Variables**

| Segment variable | 238 segments (787.8 mi) with 4-in. edge lines for three years (2001–2003) and 6-in. lines for five years (2005–2009) | | |
|---|---|---|---|
| | **Minimum** | **Maximum** | **Average** |
| Length (mi) | 0.04 | 12.69 | 3.31 |
| Average daily traffic (vehicles per day) | 196 | 18,597 | 4,436 |
| Daily commercial traffic (trucks per day) | 7 | 2,169 | 337 |
| Lane width (ft) | 10 | 12 | 11.5 |
| Shoulder width (ft) | 3 | 12 | 8.1 |
| Paved shoulder width (ft) | 0 | 12 | 4.2 |
| Posted speed (mph) | 25 | 55 | 53.3 |

**Table 9. Descriptive Statistics for a Categorical Michigan Segment Terrain Variable**

| Terrain | 238 segments (787.8 mi) with 4-in. edge lines for three years (2001–2003) and 6-in. lines for five years (2005–2009) | |
|---|---|---|
| | **Frequency** | **Percent** |
| Level terrain (1) | 156 | 65.5% |
| Rolling terrain (2) | 82 | 34.5% |

The comprehensive conversion from 4-in. to 6-in. edge lines on almost all of the state-owned Michigan roads (i.e., all facility types) in 2004 left very few sites within the state available for a reference group that is needed for an EB before-after evaluation. The researchers employed an alternative approach, an interrupted time series analysis, to perform a safety evaluation of Michigan rural 2-lane roadway crash data. An interrupted time series analysis is a quasi-experimental method used to determine the impact of an intervention. Here the intervention is the statewide installation of wider lines that took place in 2004. Because 2004 was the installation year of wider lines, crashes from year 2004 were excluded from the subsequent safety analysis. The assessment utilized a negative binomial regression model that introduced 1) *Time* as a variable to control for overall trend and 2) *Intervention* (installation of wider lines) as a variable to estimate the effect of the wider lines. For *Time*, the years prior to the installation of wider lines are coded as negative integers starting at −1 in descending order, and the years after the installation of wider lines are coded as positive integers starting at 1 in ascending order. For *Intervention*, the years corresponding to the after period are coded 1, and the years in the before period are coded as 0. At road segment *i,* the log of the expected number of annual crashes in year *t* ($\mu_{it}$) can be expressed as follows:

$$\log \mu_{it} = \beta_0 + \beta_1 * \mathrm{Time}_t + \beta_2 * \mathrm{Intervention}_t + \beta_3 X_{i,3t} \cdots + \beta_k X_{i,kt},$$

where $X_{i,kt}$ is the value of the *k*th predictor variable measured at road segment *i* in time *t*. The underlying assumption for the above model is that the relationship between the log mean annual crash count and *Time* is linear within each segment of time period (i.e., for the time period before the *Intervention* and independently for the time period after the *Intervention*). The intercept $\beta_0$ represents the baseline level of the log mean annual crash count, and $\beta_1$ represents the baseline trend that corresponds to the change in the log mean annual crash count that occurs with each year. The coefficient $\beta_2$ represents the level change (i.e., the change in the intercept) in the log mean annual crash count immediately after the intervention. The key parameter of interest is $\beta_2$, which can measure the effect of *Intervention*, while $\beta_0$ and $\beta_1$ play the role of controlling for baseline level and trend. In addition to *Time* and *Intervention*, lane width, paved shoulder width, terrain, Log(AADT), and Log(segment length) were also included as predictors in the Negative Binomial regression model. The Generalized Estimating Equations (GEE) were employed as an estimation method to account for correlation in crash counts obtained for multiple years from the same segment.

Table 10 contains the estimated coefficients for the negative binomial regression models fitted for the non-winter period crash data and the corresponding percent crash reduction estimates. For comparison purposes, the results for total, fatal plus injury, single vehicle, and single vehicle fatal plus injury crashes are also shown in Table 10. It can be observed from Table 10 that statistically significant crash reductions occurred for total, single vehicle, opposite direction, and opposite direction fatal plus injury crashes, statistically significant (at the 95 percent confidence level).

**Table 10. Interrupted Time Series Analysis applied to the Michigan Non-Winter Crashes**

| Variable | Total | Fatal plus Injury | Single Vehicle | Single Vehicle Fatal plus Injury | Opposite direction | Opposite Direction Fatal plus Injury |
|---|---|---|---|---|---|---|
| Intercept | **-2.6900** | **-7.6647** | **-2.1199** | **-5.6089** | **-15.1610** | **-20.3627** |
| Time | **0.0440** | 0.0121 | **0.0533** | -0.0198 | *0.1053* | **0.2703** |
| Intervention | **-0.2115** | -0.1718 | **-0.2033** | 0.0219 | **-0.7843** | **-1.3874** |
| Lane width | **-0.1745** | -0.0494 | **-0.1818** | -0.0603 | 0.1079 | 0.3969 |
| Paved shoulder width | **0.0448** | 0.0350 | **0.0395** | 0.0261 | 0.0258 | 0.0289 |
| Terrain | **0.2104** | 0.1421 | **0.2302** | 0.1154 | 0.0929 | 0.2130 |
| Log(AADT) | **0.5357** | **0.7419** | **0.4465** | **0.4374** | **1.2356** | **1.3449** |
| Log(Length) | **1.1264** | **1.0387** | **1.1758** | **1.1072** | **1.1925** | **1.2583** |
| Percent crash reduction | **19.1** | 15.8 | **18.4** | -2.2 | **54.4** | **75.0** |

Notes:
1. GEE approach was used as an estimation method.
2. Percent crash reduction estimates are obtained by $\{1-\exp(\beta_I)\}\times 100$ where $\beta_I$ represents the estimated coefficient of the intervention variable.
3. Statistically significant results at 95 percent confidence level are shown in **bold**.
4. Statistically significant results at 90 percent confidence level are shown in *italic*.
5. Crashes are non-intersection/interchange non-winter crashes for 238 segments (787.8 mi) of rural two-lane roadways with 3 years (2001 to 2003) of pre-intervention and 5 years (2005 to 2009) of post-intervention data.

Table 11 contains the estimated coefficients for negative binomial regression models fitted to the yearly crash data (including winter-period crashes) summarized in Table 7 and the corresponding percent crash reduction estimates. Note that while the number of crashes significantly increases with inclusion of winter period crashes, many unrelated crashes such as snow crashes might also have been included and masked the effect of wider lines. As expected, the effects of *Intervention* are now much weaker (the magnitude of the coefficient for *Intervention* is much smaller although the sign is still negative), possibly due to the inclusion of many unrelated crashes (as previously noted). A statistically significant crash reduction only occurred for the opposite direction fatal plus injury crashes (significant at the 90 percent confidence level). It is deemed that inclusion of winter crashes in Michigan does appear to obscure the effects of wider edge lines.

**Table 11. Interrupted Time Series Analysis applied to the Michigan Yearly Crash Data**

| Crash Type | Total | Fatal plus Injury | Single Vehicle | Single Vehicle Fatal plus Injury | Opposite Direction | Opposite Direction Fatal plus Injury |
|---|---|---|---|---|---|---|
| Intercept | **-2.6227** | **-7.8460** | **-2.1834** | **-6.5992** | **-13.3329** | **-16.9409** |
| Time | **0.0278** | 0.0137 | **0.0364** | 0.0012 | 0.0479 | **0.1375** |
| Intervention | -0.0632 | -0.0977 | -0.0593 | -0.0034 | -0.3229 | *-0.5847* |
| Lane width | **-0.1954** | -0.0613 | **-0.2100** | -0.0500 | 0.1184 | 0.3144 |
| Paved shoulder width | **0.0465** | 0.0304 | **0.0469** | *0.0332* | -0.0133 | -0.0448 |
| Terrain | **0.2770** | *0.1529* | **0.3155** | **0.2306** | 0.0869 | -0.0614 |
| Log(AADT) | **0.6279** | **0.8464** | **0.5638** | **0.5921** | **1.1245** | **1.2250** |
| Log(Length) | **1.1258** | **1.0617** | **1.1643** | **1.1320** | **1.0519** | **1.0841** |
| Percent crash reduction | 6.1 | 9.3 | 5.8 | 0.3 | 27.6 | *44.3* |

Notes:
1. GEE approach was used as an estimation method.
2. Percent crash reduction estimates are obtained by $\{1-\exp(\beta_I)\}\times100$ where $\beta_I$ represents the estimated coefficient of the intervention variable.
3. Statistically significant results at 95 percent confidence level are shown in **bold**.
4. Statistically significant results at 90 percent confidence level are shown in *italic*.
5. Crashes are non-intersection/interchange yearly crashes for 238 segments (787.8 mi) of rural two-lane roadways with 3 years (2001 to 2003) of pre-intervention and 5 years (2005 to 2009) of post-intervention data.

### Analysis of Safety Performance for Illinois Rural Two-Lane Roadway Edge Line

The Illinois analysis evaluated crash data (years 2001 to 2006) for 6531 segments, roughly corresponding to 1733 mi of rural, two-lane highways. Out of the 6531 segments of two-lane highways in Illinois, 5343 (corresponding to 1446 mi) had 4-in edge lines and 4-in centerlines and 1,188 (corresponding to 287 mi) had 5-in edge lines with 5-in centerlines. The research team used the cross-sectional data analysis procedure to compare crashes that occurred at the segments with 4-in edge and center lines to those that occurred at the segments with 5-in edge and center lines. The analysis excluded any crashes that occurred at intersections or interchanges. To minimize the issue of potential confounding results due to the effect of wider lines obscured by snow, the researchers analyzed two datasets: 1) a dataset consisting of only non-winter period crashes (excluding crashes that occurred during the winter months November-March), and 2) a larger dataset the included winter period crashes.

In the previous FHWA project for which this database was developed, it was revealed during the course of data analysis that about 50 percent of total crashes (about 60 percent of PDO crashes, 60 percent of single-vehicle crashes, and 10 percent of fatal plus injury crashes) in the Illinois data involved animal collisions. While animal collisions were deemed to be unrelated for assessing safety effects of wider edge lines, the proportion of animal collisions in the Illinois data was significant. Therefore, the researchers conducted cross-sectional analyses for two different 2001–2006 Illinois datasets: 1) one with animal collisions included, and 2) the other with animal collisions excluded from the data (in a manner similar to that of the previous FHWA project). The crash counts for opposite direction crashes, however, are identical for both the dataset with animal collisions included and the dataset without animal collisions. This observation demonstrates that none of the opposite direction crashes in the dataset containing animal collisions appeared to involve animals. Note that the Illinois data analyses for other crash types in this report are all based on the crash data without animal collisions.

Table 12 and Table 13 summarize the 2001–2006 Illinois crash datasets used for the analyses. Table 12 shows the aggregated non-winter period crash counts for six years for opposite direction, opposite direction fatal plus injury, and opposite direction night crashes categorized by edge line width for Illinois rural two-lane highways. For information purposes, the crash counts for total, fatal plus injury, single vehicle, single vehicle fatal plus injury, and single vehicle night crashes are also shown in the table. Table 13 shows the aggregated crash counts for six years including winter period crashes. In addition to the crash types in Table 12, opposite direction wet crashes were also available in this dataset and the aggregated crash counts by edge line width are reported in Table 13.

**Table 12. Summary of Non-Winter Crash Data without Animal Collisions (IL 2001-2006)**

| Crash Type | Edge line width | |
|---|---|---|
| | 4-in | 5-in |
| Total | 3397 | 342 |
| Fatal plus Injury | 1451 | 137 |
| Single vehicle | 1942 | 203 |
| Single vehicle fatal plus injury | 884 | 90 |
| Single vehicle night | 810 | 90 |
| Opposite direction | 262 | 36 |
| Opposite direction fatal plus injury | 166 | 15 |
| Opposite direction night | 74 | 9 |

**Table 13. Summary of Annual Crash Data without Animal Collisions (IL 2001-2006)**

| Crash Type | Edge line width | |
|---|---|---|
| | 4-in | 5-in |
| Total | 6332 | 700 |
| Fatal plus Injury | 2495 | 260 |
| Single vehicle | 3907 | 439 |
| Single vehicle fatal plus injury | 1555 | 175 |
| Single vehicle night | 1759 | 203 |
| Opposite direction | 488 | 72 |
| Opposite direction fatal plus injury | 292 | 32 |
| Opposite direction night | 157 | 18 |
| Opposite direction wet | 46 | 5 |

To distinguish the effect of edge line width from other important roadway characteristics, the researchers applied negative binomial regression models to the associated cross-sectional data. The general form of the expected number of crashes in a Negative Binomial regression model can be given as follows:

$$\mu_i = \exp\left(\beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_k X_{ki}\right)$$

where $\mu_i$ is the expected number of crashes at segment $i$, $X_{1i}, \ldots, X_{ki}$ are the covariates/predictors corresponding to roadway characteristics of segment $i$, and $\beta_0$, $\beta_1$, $\beta_2$,…, $\beta_k$ are the regression coefficients. Table 14 and Table 15 each summarizes the descriptive statistics for the primary segment variables considered in the Illinois data analysis.

**Table 14. Descriptive Statistics -- Continuous Variables (IL rural, two-lane segments)**

| Segment variable | 5,343 segments (1,446 mi) with 4-in wide markings | | | 1,188 segments (287 mi) with 5-in wide markings | | |
|---|---|---|---|---|---|---|
| | Minimum | Maximum | Average | Minimum | Maximum | Average |
| Length (mi) | 0.01 | 5.45 | 0.27 | 0.01 | 2.51 | 0.24 |
| Average daily traffic (vehicles per day) | 108 | 20,250 | 3,316 | 102 | 9017 | 2340 |
| Daily commercial traffic (trucks per day) | 0 | 2,708 | 379 | 0 | 917 | 281 |
| Lane width (ft) | 8 | 16 | 11.7 | 9 | 16 | 11.6 |
| Shoulder width (ft) | 0 | 14 | 6.5 | 0 | 12 | 6.0 |
| Paved shoulder width (ft) | 0 | 14 | 3.7 | 0 | 12 | 4.3 |
| Speed limit | 25 | 55 | 51.5 | 25 | 55 | 51.0 |
| Number of rainy days per year | 88 | 124 | 112.5 | 88 | 122 | 108.5 |
| Number of snowy days per year | 13 | 48 | 26.2 | 17 | 27 | 22.9 |
| Number of days with fog per year | 17 | 73 | 32.1 | 17 | 36 | 26.5 |

**Table 15. Descriptive Statistics – Categorical Variables (IL segments at horizontal curves)**

| Presence of horizontal curve sharper than 2.5 degrees | 5,343 segments (1,446 mi) with 4-in. wide markings | | 1,188 segments (287 mi) with 5-in. wide markings | |
|---|---|---|---|---|
| | Frequency | Percent | Frequency | Percent |
| Present (1) | 961 | 18.0% | 140 | 11.8% |
| Not present (0) | 4382 | 82.0% | 1048 | 88.2% |

After exploring various regression model forms with different predictors and interaction terms, the model including wider edge line (coded as 1 when edge line width = 5 in and 0 when edge line width = 4 in), lane width, shoulder width, log of AADT, presence of horizontal curve with degree of curve greater than 2.5 degrees (1: present, 0: not present), log of segment length, the number of rainy days, and the number of days with fog, as predictors seemed to be most appropriate for these data. The horizontal curve indicator variable was created using the non-zero entries for horizontal curve beginning and ending mileposts contained in the Highway Safety Information System (HSIS) road files. A comparison of the curve mileposts to the road segment mileposts indicated that the entire road segment with the curve presence indicator variable equal to a value of one was located inside the boundaries of the horizontal curve.

Table 16 and Table 17 each presents the estimates of the negative binomial regression model coefficients for opposite direction, opposite direction fatal plus injury, opposite direction night crashes, and opposite direction wet crashes (Table 17 only) for the dataset excluding winter period crashes and the dataset including winter period crashes, respectively. The model coefficients for total, fatal plus injury, single vehicle, single vehicle fatal plus injury, and single vehicle night crashes are also included in the tables for comparison purposes. It can be observed that the signs of the coefficients for lane width, shoulder width, log of AADT, and curve presence are consistent with intuition in most cases. For example, the negative signs of lane width and shoulder width coefficients imply that crashes tend to decrease as lane width or shoulder width increases, and the positive sign of curve presence implies that crashes tend to increase when there is a curve or curves as compared to when there is no horizontal curve present.

The percent crash reduction estimates were computed by $\{1-\exp(\beta_{edge})\}\times 100$ where $\beta_{edge}$ represents the estimated coefficient of wider edge line. The regression coefficient for wider edge line was negative and statistically significant at $\alpha = 0.05$, which indicates a positive safety effect of wider edge lines (i.e., a smaller number of crashes is associated with wider edge lines) for total, fatal plus injury, single vehicle, single vehicle fatal plus injury, and single vehicle night crashes. Unlike those crash types, the effects of wider edge lines on opposite direction, opposite direction fatal plus injury, and opposite direction night crashes were not statistically significant. This observation suggests the need for more data before drawing any definitive conclusions on those crash types from the Illinois data. Comparison of the coefficients for wider edge line in Table 16 and Table 17 indicates that the effects of wider edge lines were less impactful for the crash data that included winter period crashes. This observation may be due to the inclusion of some unrelated crashes such as snow crashes. One exception is opposite direction wet crashes (see Table 17) which automatically excludes snow crashes by definition and are not adversely affected by the inclusion of winter period crashes.

**Table 16. Estimates of Regression Coefficients and Percent Crash Reduction for Illinois Non-Winter Crashes (2001-2006)**

| Variable | Crash Type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Total** | **Fatal plus injury** | **Single vehicle** | **Single vehicle fatal plus injury** | **Single vehicle night** | **Opposite direction** | **Opposite direction fatal plus injury** | **Opposite direction night** |
| Intercept | **-7.3660** | **-6.9218** | **-4.6379** | **-4.1822** | **-6.0189** | **-12.3078** | **-12.6018** | **-12.3234** |
| Wider edge line | **-0.3834** | **-0.4662** | **-0.4892** | **-0.5496** | ***-0.4073*** | -0.0044 | -0.2709 | -0.1581 |
| Lane width | **-0.0617** | **-0.0763** | -0.0223 | -0.0344 | 0.0031 | **-0.2823** | **-0.2651** | -0.3011 |
| Paved shoulder width | **-0.0290** | **-0.0370** | **-0.0364** | **-0.0403** | **-0.0323** | 0.0127 | -0.0099 | 0.0599 |
| Log(AADT) | **1.0098** | **0.8969** | **0.6624** | **0.5357** | **0.7408** | **1.4709** | **1.4468** | **1.3350** |
| Presence of curve | **0.3696** | **0.7171** | **0.7031** | **0.9817** | **1.0010** | 0.3005 | **0.6250** | -0.5481 |
| Log(Length) | **0.7734** | **0.8533** | **0.8323** | **0.8673** | **0.9040** | **0.7859** | **0.9006** | **0.7913** |
| No. of rainy days | **-0.0102** | **-0.0116** | **-0.0185** | **-0.0195** | **-0.0219** | -0.0016 | -0.0004 | -0.0020 |
| No. of days with fog | 0.0013 | 0.0025 | **0.0036** | **0.0052** | 0.0025 | 0.0011 | -0.0028 | 0.0005 |
| Pearson chi-square/DF | 1.0832 | 1.0988 | 1.0946 | 1.0959 | 1.0614 | 1.0731 | 1.0598 | 1.0656 |
| Percent crash reduction | **31.8** | **37.3** | **38.7** | **42.3** | *33.5* | 0.4 | 23.7 | 14.6 |

Notes:

1. Percent crash reduction estimates are obtained by $\{1-\exp(\beta_{edge})\}\times 100$ where $\beta_{edge}$ represents the estimated coefficient of the edge line width variable.
2. Statistically significant results at 95 percent confidence level are shown in bold.
3. Statistically significant results at 90 percent confidence level are shown in italic.
4. Crashes are non-intersection/interchange non-winter crashes (excludes animal collisions) for 6531 segments (1732.8 mi) based on data for 6 years (2001 to 2006).

**Table 17. Estimates of Regression Coefficients and Percent Crash Reduction for Illinois Yearly Crashes (2001-2006)**

| Variable | Crash Type | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Total** | **Fatal plus injury** | **Single vehicle** | **Single vehicle fatal plus injury** | **Single vehicle night** | **Opposite direction** | **Opposite direction fatal plus injury** | **Opposite direction night** | **Opposite direction wet** |
| Intercept | **-6.6716** | **-6.3460** | **-4.2308** | **-4.1234** | **-5.6667** | **-12.6010** | **-12.1993** | **-12.7338** | **-9.1681** |
| Wider edge line | **-0.2636** | **-0.3693** | **-0.3955** | **-0.4159** | **-0.3267** | 0.2131 | -0.1544 | -0.1012 | -0.3846 |
| Lane width | *-0.0404* | **-0.0695** | -0.0143 | -0.0344 | -0.0167 | **-0.1332** | **-0.1376** | -0.1636 | -0.2645 |
| Paved shoulder width | **-0.0240** | **-0.0296** | **-0.0318** | **-0.0387** | **-0.0329** | 0.0153 | -0.0021 | 0.0499 | -0.0025 |
| Log(AADT) | **0.9805** | **0.8723** | **0.6679** | **0.5465** | **0.7579** | **1.4203** | **1.3841** | **1.4132** | **1.1591** |
| Presence of curve | **0.4004** | **0.6249** | **0.6576** | **0.8751** | **0.8777** | **0.4602** | **0.3084** | 0.2240 | -0.0550 |
| Log(Length) | **0.7825** | **0.8541** | **0.8284** | **0.8784** | **0.8696** | **0.7868** | **0.8376** | **0.8070** | **0.8041** |
| No. of rainy days | **-0.0106** | **-0.0106** | **-0.0164** | **-0.0148** | **-0.0169** | -0.0051 | -0.0071 | -0.0114 | -0.0208 |
| No. of days with fog | -0.0005 | 0.0010 | 0.0005 | 0.0024 | 0.0005 | -0.0003 | -0.0064 | -0.0004 | -0.0057 |
| Pearson chi-square/DF | 1.1596 | 1.1048 | 1.1648 | 1.2689 | 1.1673 | 1.1630 | 1.0974 | 1.0614 | 1.4958 |
| Percent crash reduction | **23.2** | **30.9** | **32.7** | **34.0** | **27.9** | -23.8 | 14.3 | 9.6 | 31.9 |

Notes:

1. Percent crash reduction estimates are obtained by $\{1-\exp(\beta_{edge})\}\times 100$ where $\beta_{edge}$ represents the estimated coefficient of the edge line width variable.
2. Statistically significant results at 95 percent confidence level are shown in bold.
3. Statistically significant results at 90 percent confidence level are shown in italic.
4. Crashes are non-intersection/interchange yearly crashes (excludes animal collisions) for 6531 segments (1732.8 mi) based on data for 6 years (2001 to 2006).

### Consolidated Results and Discussion for Edge Line Safety Performance

Table 18 presents consolidated results for estimations of the percent crash reductions for the five separate analyses previously summarized in this chapter. Note that only non-intersection/ interchange crashes were considered for all three states. For Michigan and Illinois, the analysis considered both the non-winter period crash data and the yearly crash data (including winter period crashes).

**Table 18. Percent crash reduction estimates for wider edge lines on rural, two-lane highways based on the crash data from three states.**

| Crash Type | Percent Crash Reduction | | | | |
|---|---|---|---|---|---|
| | **KS** | **MI (non-winter period)** | **MI (all year)** | **IL (non-winter period)** | **IL (all year)** |
| Opposite direction | **43.2** | **54.4** | 27.6 | 0.4 | -23.8 |
| Opposite direction fatal plus injury | **53.1** | **75.0** | *44.3* | 23.7 | 14.3 |
| Opposite direction night | | | | 14.6 | 9.6 |
| Opposite direction wet | | | | | 31.9 |
| Total | **17.3** | **19.1** | 6.1 | **31.8** | **23.2** |
| Fatal plus injury | **36.6** | 15.8 | 9.3 | **37.3** | **30.9** |
| Single vehicle | **26.1** | **18.4** | 5.8 | **38.7** | **32.7** |
| Single vehicle fatal plus injury | **36.1** | -2.2 | 0.3 | **42.3** | **34.0** |
| Single vehicle night | | | | *33.5* | **27.9** |

Note: Estimates in **bold** and in *italic* are significant at 95% confidence level and at 90% confidence level, respectively.

As part of the analysis, the researchers were constrained by the small number of opposite direction crashes and how this limited sample size adversely impacted a robust statistical analysis for assessing the safety effects of wider lines. Although the magnitudes of crash reductions are somewhat different from state to state, the estimated safety effects of wider edge lines for opposite direction fatal plus injury crashes were consistently positive. Also, regardless of the small sample size of target crashes, statistically significant positive safety effects for opposite direction fatal plus injury crashes were observed for Kansas and Michigan. Opposite direction night crashes and opposite direction wet crashes could be extracted from the existing database for the Illinois data. A positive safety effect of wider edge line was observed for those crash types of interest although the result was not statistically significant.

# CHAPTER 3. Safety Effects of Centerline Buffers on Opposite Direction Crashes (Rural Two-lane Texas Highways)

The creation of a lateral separation between opposing vehicles, often achieved by reallocating available lane width, can be expected to help reduce the likelihood of opposite direction crashes. For undivided rural highways, in particular, this centerline buffer separation may also help to alleviate headlight glare from opposing vehicles during nighttime conditions. Figure 1 depicts an application of this type of centerline buffer for a rural two-lane highway in Texas. The widespread applications for this treatment are limited, so there is a need to determine the safety effects associated with this countermeasure. This chapter, therefore, summarizes safety performance evaluations for the centerline buffer with a goal to determine if (and by how much) this treatment can help to reduce opposite direction crashes.

**Figure 1. Centerline Buffer on a Rural Two-Lane Road in Texas**

## Methodology

The centerline buffer is a small median buffer created between opposing lanes and deployed with the expectation that this pavement marking configuration can facilitate a greater lateral offset between opposing direction vehicles. For this analysis, the researchers acquired site information so as to develop a new database to use for a statistical analysis. In addition, the data collection effort also included identification of comparison sites similar to the treatment sites in all aspects except for the centerline buffer. The compiled data included information related to crash, traffic, and roadway geometric characteristics.

For the treatment sites, each site included a centerline buffer as part of the initial construction, so a before-after analysis could not be conducted. Consequently, the subsequent analysis required the application of a cross-sectional study approach. Cross-sectional studies include those where one is comparing the safety of a group of locations having a common feature to the safety of a different but similar group of locations that do not have that feature. The Crash Modification Factor/Function (CMF) developed from cross sectional studies is not negatively affected by the regression-to-the-mean. Regression to the mean is the statistical tendency for locations chosen because of high crash histories to have lower crash frequencies in subsequent years even without treatment. The methodology described in this section is further divided into evaluation methods and a framework for cross-sectional modeling.

### *Evaluation Methods*

The main objective of the analysis reviewed in this chapter was to develop a CMF for the centerline buffer. A CMF is a multiplicative factor or function that can be used to reflect or capture changes in the expected number of crashes when a given countermeasure or a modification in geometric and operational characteristics of a specific site is implemented (*3, 4*). This evaluation considered the safety benefit of centerline buffers for opposite direction (OD) crashes as well as single-vehicle run-off-road (SVROR) crashes. The SVROR crashes are considered so as to assess if the reallocation of space to the centerline buffer, in many cases achieved by narrowing the shoulder, has an impact on safety.

CMFs play a significant role in roadway safety management, including safety effect evaluation, crash prediction, hotspot identification, and countermeasure selection. Several methods are available for the development of CMFs including techniques that are based on before-after methods, cross-sectional studies (e.g., regression models and case-control), and expert panel studies among others (5).

The two most common ways to develop the CMFs are before-after studies and cross-sectional study methods. Before-after studies (using EB or other appropriate statistical procedures) refer to methods by which one may study the safety of a change that has been implemented for a group of sites. Appendix 1 of this report provides more detail about the EB procedure. Cross-sectional studies include those where one is comparing the safety of a group of locations having a common feature to the safety of a different group of locations not having that feature. Cross-sectional studies typically involve the use of regression type models (typically, negative binomial regression models) that estimate the predicted crash frequency as a function of site characteristics where one or more of these site characteristics may be the presence/absence of the treatment under consideration. It is generally accepted that well designed, statistically robust before-after studies would provide more reliable CMFs compared to cross-sectional studies, although recent work has shown that before-after studies, both using a control group and the EB method, can also be negatively affected by the site selection bias, a distinct bias that can potentially be more problematic than the regression-to-the-mean (6). Nevertheless, to conduct a well-designed before-after study, it is important to have accurate records on when a treatment was installed. Due to this limitation, a before-after analysis was not a practical option for the centerline buffer evaluation since the treatment was present for the entire study period duration.

Cross sectional studies naturally produce CMFs (generally in a function format) because they are equations rather than single values and are not negatively affected by the regression-to-the-mean. CMFs from cross sectional studies may not always be reliable due to a wide variety of issues including aggregation and omitted variable bias. One common example of the use of cross sectional models is to determine the safety of horizontal curvature. It is generally very difficult to find a sufficient number of sites where horizontal curvature has been modified to conduct a before-after study to determine the safety effect specific only to the changes in curvature.

***Cross-Sectional Model Framework***

For the cross-sectional analysis of the centerline buffer, the number of crashes on each roadway segment is considered as a dependent variable and traffic volume, centerline buffer width, and other geometric characteristics are considered as explanatory variables. Given that the dependent variable is count data, the most basic count data models such as the Poisson and Poisson-gamma (also known as the negative binomial, or NB) should be considered. Both models belong to the family of generalized linear models. For the Poisson model to be appropriate for a given dataset, the mean has to be approximately equal to the variance. However, in practice, it has been found that count data often exhibit over-dispersion, meaning that the variance is larger than the mean (*7*). On rare occasions, the data or modeling output may show characteristics of under-dispersion (*8, 9*). To overcome the problem related to the over-dispersion, the Poisson-gamma model has been proposed as a viable alternative to the Poisson model (*10*). The Poisson-gamma model has become very popular because it has a closed-form equation (i.e., the mathematical manipulations can be performed manually; for example, it can be shown that the Poisson-gamma mixture leads to the NB distribution), and the mathematics to manipulate the relationship between the mean and the variance are relatively simple (*11*). Furthermore, most statistical software packages have incorporated a NB function that simplifies the analysis of count data.

The Poisson-gamma model commonly used for highway safety applications has been shown to have the following probabilistic structure: the number of crashes at the $i$-th entity (grid) and $t$-th time period, $Y_{it}$, when conditional on its mean, $\theta_{it}$, is assumed to be Poisson distributed and independent over all grids and time periods as follows (*13*):

$$Y_{it} \mid \theta_{it} \sim Po(\theta_{it}) \qquad i = 1, 2, \ldots, i \text{ and } t = 1, 2, \ldots, t$$

The mean of the Poisson is structured as:

$$\theta_{it} = \mu_{it} \exp(\varepsilon_{it})$$

Where:

$\mu_{it}$ = a function of the covariates ($X$) (e.g., $\mu_{it} = \exp\left(\beta_0 + \beta_1 X_{it1} + \beta_2 X_{it2} + \cdots + \beta_p X_{itp}\right)$ where p is the number of covariates).

$\beta$ = a vector of unknown coefficients.

$\varepsilon_{it}$ = the model error independent of all the covariates.

It is usually assumed that $\exp(\varepsilon_{it})$ is independent and gamma distributed with a mean equal to 1 and a variance $1/\phi$ for all $i$ and $t$ (here $\phi$ is the inverse dispersion parameter, with $\phi > 0$). With this characteristic, it can be shown that $Y_{it}$, conditional on $\mu_{it}$ and $\phi$, is distributed as a Poisson-gamma random variable with a mean $\mu_{it}$ and a variance $\mu_{it}(1+\mu_{it}/\phi)$, respectively.

## Site Identification

This following content documents the identification process of the treatment and comparison for subsequent safety analysis.

### *Treatment Sites*

The research team sent a questionnaire to the Texas Department of Transportation (TxDOT) districts requesting the location and installation dates of any centerline buffer locations. Based on feedback from seven districts, the research team then reviewed characteristics for candidate sites using Google Earth. The street view feature of Google Earth provided confirmation whether the site did include a centerline buffer or if the configuration actually functioned as a two-way left-turn lane (TWLTL) constructed to facilitate left-turn maneuvers. The TWLTL sites were then excluded so that the final database only contained centerline buffer sites. In addition, segments with a centerline buffer greater than 12 ft were excluded so that sites not intended as TWLTL locations but that could still be used for this purpose or for passing would not be considered for the centerline buffer analysis. The researchers also obtained the control section number and the reference markers associated with each study location (based on the TxDOT planning map). This site information then enabled segmentation of homogeneous study sections based on TxDOT's Road-Highway Inventory Network Offload database. The homogenous segments included variables such as ADT, surface width, shoulder width, number of lanes, and functional classification. This analysis resulted in a total number of 135 Texas treatment sites with centerline buffers (see Table 19).

**Table 19. Centerline Buffer Summary Statistics for Treatment and Comparison Sites**

| Site | No. of Segments | Variable | Min. | Max. | Mean | Std. Dev | Sum |
|---|---|---|---|---|---|---|---|
| Treatment | 135 segments (42.06 mi) | ADT (vpd) | 2386 | 17,989 | 8942 | 5891 | -- |
| | | Lane Width (ft) | 11 | 13.5 | 12.0 | 0.2 | -- |
| | | No. of Lanes | 2 | 4 | 3.7 | 0.7 | -- |
| | | Centerline Buffer (ft) | 4 | 12 | 6.6 | 3.5 | -- |
| | | Posted Speed Limit (mph) | 40 | 75 | 62.2 | 10.5 | -- |
| | | Shoulder Width (ft) | 0 | 10 | 7.4 | 2.5 | -- |
| | | OD Crashes | 0 | 3 | 0.2 | 0.5 | 28 |
| | | SVROR Crashes | 0 | 29 | 1.1 | 3.5 | 156 |
| Comparison | 407 segments (124.78 mi) | ADT (vpd) | 560 | 22,919 | 6824 | 5071 | -- |
| | | Lane Width (ft) | 6 | 16 | 12.8 | 1.7 | -- |
| | | No. of Lanes | 2 | 4 | 3.7 | 0.7 | -- |
| | | Posted Speed Limit (mph) | 30 | 75 | 55.6 | 12.0 | -- |
| | | Shoulder Width (ft) | 0 | 14 | 6.1 | 3.9 | -- |
| | | OD Crashes | 0 | 6 | 0.1 | 0.5 | 54 |
| | | SVROR Crashes | 0 | 21 | 0.7 | 2.2 | 295 |

### *Comparison Sites*

Based on the identified treatment sites, the selected comparison sites were as identical as possible to the treatment sites with the exclusion of a centerline buffer or median. Specifically, the identification criteria were based on highway functional class, number of lanes, and traffic volume (i.e., ADT). The ideal comparison sites had ADT values that were within ±500 vpd of the matched treatment site.

The research team attempted to locate comparison sites where the segment length was greater than the length for the respective treatment sites. In the case the total length of a comparison site was less than the treatment site, the researchers then applied a relaxation coefficient k ($0 < k < 1$) for ADT. In other words, a site with ADT between "$k \times$ ADT of treatment site" and "$\frac{1}{k} \times$ ADT of treatment site" could still be considered as a comparison site. In this study, the comparison site selection process assumed a k value of 0.8. For a few treatment sites, comparison sites were still insufficient. For these sites, the research team further relaxed the inclusion criteria for functional class. In total, the research team identified 407 comparison sites as shown in Table 19.

## Data Collection

The following content describes the source databases used to provide information about the crash, traffic, and geometric data

### *Crash Data*

The research team acquired crash data for the years 2010 to 2014 from the TxDOT Crash Records Information System (CRIS). This information included crash, unit, and person level information associated with each crash. In addition, each crash file further identified the highway area type, crash type, location, severity, lighting, weather condition, and time of crash. The unit data included information about vehicle type, vehicle model, crash contributing factors, etc. The person file contained data related to the driver/passenger age, gender, and crash contributing factors including driving under the influence, fatigue, and driver vision defects.

Crash data information included the total target crashes as well as crash frequency by severity level including:

- Fatal (K),
- Incapacitating injury (A),
- Non-incapacitating injury (B),
- Minor injury (C), and
- Property damage only (PDO).

### *Roadway and Traffic Data*

In addition to acquiring data from the TxDOT Road-Highway Inventory Network database for the year 2014, the research team also confirmed the centerline buffer width, shoulder width, and lane width based on Google Earth measurements. The resulting database, therefore, included spatial and temporal cross references based on crash, traffic, and geometric records. The Texas linear referencing system (based on section numbers and distances from the origin) provided supplemental spatial confirmation. Table 19 presents the summary of candidate variables for both the treatment and comparison sites.

## Data Analysis

This section documents the crash rate comparisons and the cross-sectional model results.

### *Crash Rates*

The researchers calculated the crash rate for each segment by dividing the number of crashes in any given crash category by the product of total mileage and traffic volume, in this case, the total length in miles multiplied by the annual traffic volume, or vehicle miles. Because the number of crashes relative to the number of vehicle miles is very small, the rates are expressed per 100 million vehicle miles.

Crash rates may be interpreted as the probability (based on past events, in this case what occurred from 2010 to 2014) of being involved in a crash per instance of the exposure measure. Observed crash rates are often used as a tool to identify and prioritize sites in need of modifications and for evaluation of the effectiveness of treatments.

The researchers calculated the crash rate for each segment as:

$$Crash\ rate = \frac{Number\ of\ total\ crashes\ \times 100{,}000{,}000}{Length \times Number\ of\ years \times 365 \times Average\ Daily\ Traffic}$$

This analysis only considered the target crashes (i.e. OD crashes + SVROR crashes). The average crash rates are based on the centerline buffer median width. Table 20 presents the crash rate comparisons between treatment and comparison sites.

**Table 20. Comparison of Crashes and Crash Rates**

| No. of lanes | Treatment sites | | | | Comparison sites[1] | | |
|---|---|---|---|---|---|---|---|
| | Median width[2] (ft) | Total mileage (mi) | Number of Crashes | Target crash rate[3] (100 million VMT) | Total mileage (mi) | Number of Crashes | Target crash rate[3] (100 million VMT) |
| 2 | 4 | 11.06 | 66 | 50.24 | 25.05 | 49 | 16.78 |
| | 8 | 0.31 | 0 | 0.00 | | | |
| | 12 | 0.52 | 1 | 18.15 | | | |
| | **ALL** | **11.89** | **67** | **26.72** | | | |
| 4 | 4 | 18.44 | 57 | 17.45 | 99.73 | 300 | 23.70 |
| | 5 | 0.44 | 1 | 9.86 | | | |
| | 6 | 0.27 | 0 | 0.00 | | | |
| | 8 | 0.55 | 0 | 0.00 | | | |
| | 11 | 2.45 | 2 | 2.10 | | | |
| | 12 | 8.02 | 57 | 17.56 | | | |
| | **ALL** | **30.17** | **117** | **14.84** | | | |

Notes:
1. Comparison sites have a median width of zero.
2. Measured in Google earth.
3. Target crashes are OD + SVROR crashes.

### *Cross-sectional Models*

The research team separately developed the statistical models for two-lane and four-lane roads separately due to their difference in safety performance. Table 21 presents the sample size by the number of lanes.

**Table 21. Centerline Buffer Summary by Number of Lanes**

| No. of Lanes | Site Type | No. of Segments | Mileage (mi) | OD Crashes | SVROR Crashes |
|---|---|---|---|---|---|
| 2 | Treatment | 7 | 11.89 | 3 | 64 |
| | Comparison | 56 | 25.05 | 13 | 36 |
| 4 | Treatment | 128 | 30.16 | 25 | 92 |
| | Comparison | 351 | 99.73 | 41 | 259 |

The research team initially evaluated the following model functional form:

$$N_i = N_{base,i} \times CMF_1 \times CMF_2 \times \ldots \times CMF_n;\ i\text{=2 or 4}$$

$$N_{base} = L \times n \times e^{b_0 + b_{adt} \ln(AADT)};\ n = no\ of\ years$$

Where,

$N_i$ = predicted annual average crash frequency for model $i$ ($i$ =2 or 4 lanes),

$N_{base,i}$ = predicted annual average crash frequency at base conditions, and

$CMF_1, CMF_2, \ldots CMF_n$ = CMFs for various road segment features (1, 2, …, $n$).

The variables can potentially take on differing shapes related to the dependent variable and so the analysis first explored these candidate functional forms. This analysis resulted in the form shown below. This configuration reflects the findings from several preliminary regression analyses. The base conditions for the lane width and shoulder width are 12-foot and 8-foot respectively.

$$N = N_{base} \times CMF_{lw} \times CMF_{sw} \times CMF_{cb}$$

With:

$$CMF_{lw} = e^{b_{lw}(W_l - 12)}$$

$$CMF_{sw} = e^{b_{lsw}(W_s - 8)}$$

$$CMF_{cb} = e^{b_{cb}(W_{cb})}$$

Where:

$CMF_{lw}$ = lane width CMF.

$CMF_{sw}$ = shoulder width CMF.

$CMF_{cb}$ = centerline buffer width CMF.

$W_l$ = average lane width, ft.

$W_{ls}$ = average shoulder width, ft.

$W_{cb}$ = centerline buffer width, ft.

$b_i$ = calibrated coefficients.

The predictive model calibration process consisted of the simultaneous calibration of two-lane and four-lane models and CMFs using the aggregate model. This simultaneous calibration approach was necessary because the lane width and shoulder width CMFs were common to two-lane and four-lane undivided roads.

Based on this approach, the researchers developed two types of models: 1) OD, and 2) SVROR crashes. These crash types were combined so that the model results correspond to "target" (OD+SVROR) crashes that are likely to be preventable based on the application of the centerline buffer. A second analysis separately modeled OD and SVROR crashes. Simultaneous calibration was adopted so that the effect of lane and shoulder widths remained the same irrespective of the number of lanes or collision type.

The inverse dispersion parameter, $K$ (which is the inverse of the overdispersion parameter $\alpha$), is allowed to vary with the segment length. The inverse dispersion parameter is calculated using:

$$K = L \times e^{k}$$

Where:

$K$ = inverse dispersion parameter.

$k$ = calibration coefficient for inverse dispersion parameter.

The basis for estimating the proposed model coefficients was the mixed nonlinear regression procedure (NLMIXED) in the Statistical Analysis System (SAS) software. This procedure was used because the proposed predictive model is both nonlinear and discontinuous. The log-likelihood function for the NB distribution was used to determine the best-fit model coefficients.

Table 22 contains the modeling results for the target crashes. The coefficient for ADT shows that target crashes increased as the ADT increased for both two-lane and four-lane highways. The coefficient for the shoulder width is significant at the five percent level and shows that the increase in shoulder width is aligned with a decrease in the target crashes. The coefficient for the centerline buffer width shows that the variable is not significant in influencing the overall target crashes at four-lane roads but appears to be positive and significant for two-lane highways.

Upon closer inspection, it is notable that the shoulder is always wider for the two-lane highways (see

Table 23) and it is possible that all the reduction may be captured by the shoulder width variable only. Second, the sample size is quite small and there is not enough variability in the data to capture the effect. The OD and SVROR crash types may respond differently to a centerline buffer and it is likely that they should be independently addressed. In fact, Geedipally et al. (*12*) recommended developing models by collision type because the influential variables are unique to each collision type.

**Table 22. Parameter Estimates for the Target Crashes**

| Variable | Parameter | Estimate | Standard Error | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | $b_{0\_2}$ | -12.719 | 5.443 | 0.020 |
| | $b_{0\_4}$ | -7.273 | 1.013 | <.0001 |
| ADT | $b_{adt\_2}$ | 1.390 | 0.635 | 0.029 |
| | $b_{adt\_4}$ | 0.741 | 0.113 | <.0001 |
| Lane width | $b_{lw}$ | 0.003 | 0.042 | 0.947 |
| Shoulder width | $b_{sw}$ | -0.068 | 0.020 | 0.001 |
| Centerline buffer width | $b_{bmw\_2}$ | 0.136 | 0.069 | 0.048 |
| | $b_{bmw\_4}$ | 0.026 | 0.020 | 0.191 |
| Dispersion | $k_2$ | 0.921 | 0.505 | 0.069 |
| | $k_4$ | 1.258 | 0.219 | <.0001 |

**Table 23. Shoulder Width Distribution by Site Type**

| No. of Lanes | Site Type | No. of Segments | Shoulder Width (ft) | | | |
|---|---|---|---|---|---|---|
| | | | Mean | Std. Dev | Minimum | Maximum |
| 2 | Treatment | 7 | 9.43 | 0.97 | 8 | 10 |
| | Comparison | 56 | 6.90 | 3.32 | 0 | 11 |
| 4 | Treatment | 128 | 7.34 | 2.47 | 0 | 10 |
| | Comparison | 350* | 5.96 | 4.02 | 0 | 14 |

Note:
* One site removed from analysis due to outlier status (resulting in 350 comparison sites rather than 351).

Table 24 summarizes the parameter estimates for OD and SVROR crashes separately (Model 1). The coefficient for the ADT shows that SVROR crashes increase with an increase in ADT for two-lane highways. OD crashes (i.e. opposite direction sideswipe and head-on) have a similar response for both two-lane and four-lane highways. However, the increase in ADT increases SVROR at a decreasing rate on four-lane highways. The lane and shoulder width are found to have a positive effect in decreasing the OD and SVROR crashes but the coefficients are statistically insignificant.

**Table 24. Parameter Estimates for the OD and SVROR Crashes Separately - Model 1**

| Variable | Parameter | OD Crashes | | | SVROR Crashes | | |
|---|---|---|---|---|---|---|---|
| | | Est. | Std. Err | Pr > \|t\| | Est. | Std. Err | Pr > \|t\| |
| Intercept | $b_{0\_2}$ | -13.721 | 1.966 | <.0001 | -10.244 | 6.417 | 0.1107 |
| | $b_{0\_4}$ | -14.725 | 2.111 | <.0001 | -7.251 | 1.016 | <.0001 |
| ADT (vpd) | $b_{adt\_2}$ | 1.34 | 0.226 | <.0001 | 1.067 | 0.752 | 0.156 |
| | $b_{adt\_4}$ | 1.34 | 0.226 | <.0001 | 0.721 | 0.113 | <.0001 |
| Dispersion | $k_2$ | 3.924 | 5.647 | 0.4874 | 0.394 | 0.493 | 0.424 |
| | $k_4$ | 3.021 | 4.946 | 0.5415 | 1.487 | 0.281 | <.0001 |
| Lane width (ft) | $b_{lw}$ | -0.005 | 0.037 | 0.8956 | -0.005 | 0.037 | 0.8956 |
| Shoulder width (ft) | $b_{sw}$ | -0.02 | 0.019 | 0.2859 | -0.020 | 0.019 | 0.2859 |
| Centerline median width (ft) | $b_{bmw\_2}$ | -0.236 | 0.158 | 0.1343 | 0.218 | 0.092 | 0.0187 |
| | $b_{bmw\_4}$ | 0.054 | 0.027 | 0.0499 | 0.019 | 0.020 | 0.3519 |

The results from Table 24 show that the centerline buffer does not statistically influence the number of SVROR crashes for four-lane highways. The OD crashes for four-lane highways appear to slightly increase, though the variable estimate is close to zero (a value of 0.054).

For two-lane highways, the centerline buffer does have a positive effect on reducing the OD crashes on two-lane roads with a coefficient statistically significant at the 15 percent level. The coefficient for centerline buffer for the SVROR indicates an increase in crashes for two-lane highways. These contrasting findings (increase in SVROR and decrease in OD crashes) suggest that the factors critical to SVROR crashes are different than those that influence OD crashes and may merit additional investigation. Figure 2 presents the CMF for the two-lane highway centerline buffer width for OD crashes.

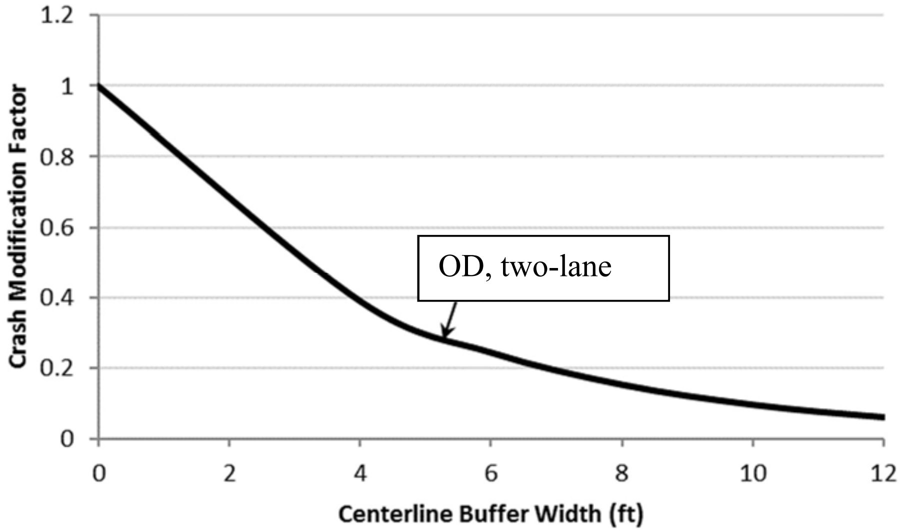



**Figure 2. Crash Modification Factor for Centerline Buffer**

Given that the above results show that the buffer median width appears to have a positive effect on SVROR crashes on two-lane roads, the research team separated the width into two categories to investigate if there is any influence due to wider buffer widths. Model 2 is based on two centerline buffer categories: 1) Centerline buffers less than 8 ft wide, and 2) centerline buffers greater than or equal to 8-ft wide. As shown in Table 25, the analysis results show that the buffer median width, when separated into two distinct width categories, resulted in variables that are not statistically significant. Though not statistically significant, the buffer median width did retain the positive effect on reducing OD and SVROR crashes on two-lane roads when the buffer width is at least 8-ft wide.

**Table 25. Parameter Estimates for the OD and SVROR Crashes Separately - Model 2**

| Variable | Parameter | OD Crashes | | | SVROR Crashes | | |
|---|---|---|---|---|---|---|---|
| | | Est. | Std. Err | Pr > \|t\| | Est. | Std. Err | Pr > \|t\| |
| Intercept | $b_{0\_2}$ | -14.137 | 1.998 | <.0001 | -11.953 | 6.567 | 0.069 |
| | $b_{0\_4}$ | -14.836 | 2.136 | <.0001 | -7.308 | 1.033 | <.0001 |
| ADT (vpd) | $b_{adt\_2}$ | 1.359 | 0.229 | <.0001 | 1.316 | 0.761 | 0.084 |
| | $b_{adt\_4}$ | 1.359 | 0.229 | <.0001 | 0.731 | 0.115 | <.0001 |
| Dispersion | $k_2$ | 3.694 | 6.234 | 0.554 | -0.009 | 0.428 | 0.983 |
| | $k_4$ | 2.516 | 2.126 | 0.237 | 1.477 | 0.280 | <.0001 |
| Lane width (ft) | $b_{lw}$ | -0.011 | 0.036 | 0.756 | -0.011 | 0.036 | 0.756 |
| Shoulder width (ft) | $b_{sw}$ | -0.016 | 0.019 | 0.379 | -0.016 | 0.019 | 0.379 |
| Centerline median width (1 if ≥ 8-ft, 0 if < 8-ft) | $b_{bmw\_2}$ | -2.171 | 5.735 | 0.705 | -0.180 | 1.553 | 0.908 |
| | $b_{bmw\_4}$ | 0.514 | 0.328 | 0.117 | 0.099 | 0.240 | 0.681 |

Notes:
OD = Opposite direction crashes
SVROR = Single Vehicle Run-off-road crashes

To summarize, in general the centerline buffer has a positive effect on reducing OD crashes on two-lane highways and no measurable effect on four-lane highways. These findings should be interpreted with caution due to the small sample size (*14*). It is also well known that the cross-sectional analysis establishes associations between the independent variables and the outcome (target crashes) but not the causal relationships. Thus, the effect shown by the centerline buffer variable may also be correlated to other variables (e.g. lane width).

# CHAPTER 4 Safety Evaluation of the Effect of Curve Delineation on Opposite Direction Crashes

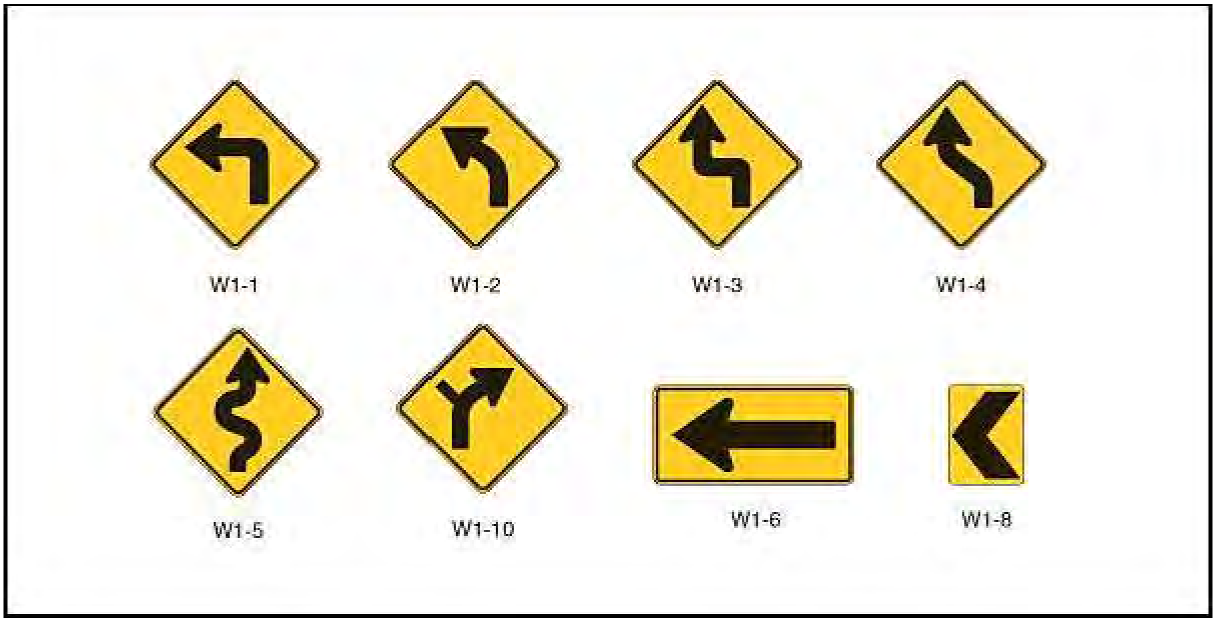
This chapter provides a summary of the results of the evaluation to investigate the safety effects of improved curve delineation on head-on and opposite direction sideswipe crashes on rural two lane roads. This effort was conducted as part of NCHRP Project 17-66. Two data sets were used in this evaluation: one was from Connecticut and other from Washington. The treatment in Connecticut varied by site and included new chevrons, horizontal arrows, and advance warning signs as well as the improvement of existing signs using fluorescent yellow sheeting. The treatment in Washington included addition of new chevrons. Both evaluations were based on the EB before-after evaluation method, and used data from a prior evaluation that was conducted for the FHWA (*15*). In the prior evaluation for FHWA, the primary target crashes were lane departure crashes and crashes during dark. In NCHRP Project 17-66, the researchers evaluated the effect of this treatment on head on and opposite direction sideswipe crashes. The rest of this chapter provides an overview of the data, methodology, and the results from the two states.

## Safety Performance for Connecticut Rural Two-Lane Roadway Curve Delineation

### *Data*

A summary of the data including installation and site characteristics are provided here based on the prior FHWA study report. The Connecticut Department of Transportation (ConnDOT) used fluorescent yellow sheeting to improve signing at horizontal curves between 2002 and 2006. These curves were selected through a regular program called the Suggested List of Surveillance Study Sites (SLOSSS). SLOSSS uses crash data, traffic volumes, and roadway characteristics to identify intersections and road segments with higher than expected crash rates. District engineers indicated which of the SLOSSS were located on horizontal curves, and these curve locations were then treated with improved signing. After these sites were implemented, the ConnDOT received positive feedback from enforcement officials who then asked to have these installed at additional curves.

The treatments used in Connecticut consisted of improved signing using fluorescent yellow sheeting. This included installing new signs or replacing existing signs. The signs in question were either warning signs (e.g., curve ahead or suggested speed limit) and/or curve delineation signs (e.g., chevrons or horizontal arrows). Figure 3 shows the types of signs used in the treatment. Signs W1-1, W1-2, W1-3, W1-4, W1-5, and W1-10 were classified as warning signs in this study. Signs W1-6 and W1-8 were classified as curve delineation signs.




*Source: Adapted from Figure 2C-1, p. 109. Manual on Uniform Traffic Control Devices, USDOT FHWA, December 2009 Edition with Revision Numbers 1 and 2 (incorporated May 2012) (Reference 16)*

**Figure 3. Chart Sign Types used for Connecticut Horizontal Curve Treatments**

Installation Data

ConnDOT provided information on 34 curve treatment projects; each project had between one and 16 individual horizontal curves, providing a total of 91 treated horizontal curves. Two curves were excluded from the analysis because their curve radii could not be obtained. This resulted in a sample of 89 curves for further analysis. Service memorandums for each project gave details on the treatment description, installation date, treatment cost, and the number of warning and curve delineation signs that were replaced or newly installed.

Reference Sites

An EB before-after evaluation requires the use of reference sites. Reference sites were curves that were similar to the treatment sites but did not receive the improved signing treatment. Reference sites were identified in this study by first identifying curves that were located within 1.55 mi of the treatment curves. These curves were then further evaluated based on certain exclusion criteria. These criteria ensured that the final list of reference sites would be an appropriate match to the group of treatment sites. Curves that were not included in the final group of reference sites contained the following characteristics:

- Right-turn lane.
- Left-turn lane.
- Center-turn lane (two-way left-turn lane).
- Median.
- More than two travel lanes.

- Radius under 32.8 ft or over 3,280 ft.
- Heading change of less than 2 degrees.

The final group of reference sites included 334 horizontal curves for a total segment length of the curves in the reference group of 23.6 mi.

Roadway Data

Roadway characteristics data were collected by an instrumented vehicle that drove the entirety of the Connecticut State highway system. One of the most useful pieces of data from this vehicle was the photolog. The vehicle equipment took photos every 32.8 ft along the route in each direction. The photolog was used to visually obtain data for the following items:

- Number of lanes (through, right-turn, left-turn, and center-turn lanes).
- Number of driveways and public street access points.
- Median presence and type.
- Shoulder type and width.
- Roadside hazard rating (RHR) (1-7 scale).
- Speed limit (regulation).
- Suggested curve speed (if any).
- Cable barrier/guardrail.

Another key piece of data collected by the vehicle was horizontal alignment data. Geographic positioning system (GPS) coordinates taken at regular intervals allowed the vehicle to track the horizontal alignment of the road. The researchers then processed the GPS data, via an algorithm, to divide the road into segments and determine where tangents, arcs, and spirals began and ended. This tool also calculated the curve radius and degree of heading change from one tangent to the next.

The vehicle equipment also acquired readings for superelevation and grade at regular intervals. Superelevation data were only available for 40 out of 91 treatment sites and 194 out of 334 reference sites and so was not subsequently included in the evaluation. Vertical grade data were available for all sites.

Traffic Data

Traffic volume counts are performed once every three years for each Connecticut road. These values are recorded on ADT maps. Maps from 1997 to 2005 were made available to the research team in addition to an electronic file of 2006 ADT data. Team members located each treatment site on the map and determined the nearest ADT count point. In the case of a site lying between two ADT count points, the researchers used the average value. Since reference sites were chosen in close proximity to treatment sites, any particular reference site was assumed to have the same ADT as its treatment site.

Crash Data

For the prior FHWA study, Connecticut crash data from 1995 to 2006 were obtained from the University of Connecticut. The project team investigated the possibility of obtaining more recent crash data, but no information was available on whether other changes were made to the treated sites since 2006. For the NCHRP 17-66 work, the research team extracted head-on and opposite-direction sideswipe crashes.

### *Summary of Data*

In Srinivasan et al., (*15*) the researchers compiled data for the following crash types:

- Total non-intersection crashes: A non-intersection crash was defined based on the information by the police officer on the location of the crash.
- Non-intersection injury and fatal crashes: This included all non-intersection crashes where there was at least one non-fatal injury or one fatal injury.
- Non-intersection lane departure crashes: Lane departure crashes included sideswipe, overturn, head-on, jackknife, and run off road.
- Non-intersection crashes during dark: This category included crashes for which the light condition was coded as 'dark-not lighted' or 'dark-lighted'.
- Non-intersection lane departure crashes during dark: This category included crashes that were lane departure but with the light condition coded as 'dark-not lighted' or 'dark lighted'.

For NCHRP Project 17-66, the researchers extracted non-intersection head-on and opposite-direction sideswipe crashes. The possibility of evaluating fatal and injury head-on and opposite-direction sideswipe crashes was explored, but with the limited sample of sites and crashes, the project team felt that such an analysis would not provide useful results. Table 26 shows the summary of the data collected in Connecticut.

**Table 26. Data Summary for Connecticut (89 curves, 7.08 miles).**

| Variable | Before | After |
|---|---|---|
| Mile-Years | 45.80 | 21.60 |
| Minimum AADT (vpd) | 895 | 920 |
| Average AADT (vpd) | 4,381 | 4,741 |
| Maximum AADT (vpd) | 19,945 | 20,479 |
| Non-Intersection Crashes per mile per year (Average) | 9.01 | 7.19 |
| Non-Intersection Lane Departure Crashes per mile per year (Average) | 7.66 | 6.08 |
| Non-Intersection Crashes that are Injury or Fatal (K,A,B,C) per mile per year (Average) | 3.43 | 1.95 |
| Non-Intersection Crashes During Dark per mile per year (Average) | 3.99 | 2.18 |
| Non-Intersection Lane Departure Crashes During Dark per mile per year (Average) | 3.54 | 1.86 |
| Non-Intersection head-on and opposite-direction sideswipe crashes (Average) | 0.90 | 0.74 |

### *Safety Performance Functions*

This section presents the approach used to estimate the SPFs. The SPFs are used in the EB methodology to estimate the safety effectiveness of this strategy. The team applied generalized linear modeling techniques to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the state of research in developing these models. The over-dispersion parameter (k) is also estimated in the model calibration process. The over-dispersion parameter relates the mean and variance of the SPF estimate and is such that the smaller its value, the better a model is for a given set of data. Thus it is a useful criterion in comparing candidate models.

The form of the SPFs is:

$$\text{Crashes/year} = \exp(\beta_0 + \sum_{i=1}^{n} \beta_i X_i)$$

where X's are the independent variables and $\beta$'s are parameters to be estimated.

With head-on and opposite direction sideswipe crashes, the sample of crashes is limited compared to other types of crashes. Hence, estimating SPFs just of this type can sometimes be challenging and the resulting SPFs may not be reliable. So, two options were considered. The first option was to derive an estimate for head-on and opposite direction crashes by starting with the SPF for lane departure crashes that were estimated in Srinivasan et al. (15) and multiplying that with the proportion of lane departure crashes that were head-on and opposite direction sideswipe crashes. The second option was to estimate SPFs directly for head-on and opposite direction sideswipe crashes. The SPF for lane departure crashes (from Srinivasan et al. (15)) and the SPF that was specifically estimated for head-on and opposite-direction sideswipe crashes are presented in Table 27.

**Table 27. Safety Performance Functions from Connecticut**

| Variable | Non-intersection lane departure crashes | Head-on and opposite direction sideswipe |
|---|---|---|
| | Estimate (S.E.) | Estimate (S.E.) |
| Intercept | 2.3637 (0.3091) | 0.3209 (0.7060) |
| Ln(section length in miles) | 0.9898 (0.09439) | 0.6439 (0.2364) |
| Ln(AADT/10000) | 0.7003 (0.07719) | 1.5762 (0.2222) |
| Radius (in meters) | -0.00206 (0.00024) | -0.00378 (0.000748) |
| 1, if Roadside Hazard Rating is 1-4, 0 otherwise | | |
| 1, if Roadside Hazard Rating is 5, 0 otherwise | | |
| 1, if Roadside Hazard Rating is 1-5, 0 otherwise | | |
| 1, if Roadside Hazard Rating is 6, 0 otherwise | | |
| Roadside Hazard Rating = 7 (Reference case) | | |
| Number of driveways in the arc portion of the section | | |
| 1, if there is a cable barrier in the inside of the curve, 0 otherwise | 0.3343 (0.1136) | |
| 1, if there is a cable barrier on the outside of the curve, 0 otherwise | | |
| 1, if there is a guardrail in the inside of the curve, 0 otherwise | 0.2446 (0.05538) | |
| 1, if there is a guardrail on the outside of the curve, 0 otherwise | | |
| Average distance to next curve (in km) | -0.8101 (0.4666) | |
| 1, if there is a curb and gutter in the shoulder, 0 otherwise | | |
| Grade in the middle of the arc portion of the section | | |
| k (over-dispersion parameter) | 1.3859 (0.1732) | 1.3327 (0.4150) |
| Crashes in the Reference Group | 910 | 143 |
| Proportion of head-on and opposite direction crashes | 0.157 | |

***Results***

Table 28 shows the results of the EB before-after evaluation from Connecticut. The middle column (Option 1) shows the results that were derived based on the SPF predictions that were estimated as a proportion of lane departure crashes. The Option 2 column shows the results that were obtained based on SPFs that were specifically estimated for head-on and opposite direction sideswipe crashes. Due to the limited sample of crashes, the standard errors are relatively high indicating that the CMF is not statistically different from 1.0 at the 0.05 significance level.

**Table 28. Results from Connecticut Sites for Head-On and Opposite Direction Sideswipe Crashes**

| | SPF Option 1 | SPF Option 2 |
|---|---|---|
| EB estimate of crashes expected in the after period without strategy | 16.9 | 16.8 |
| Count of crashes observed in the after period | 16 | 16 |
| CMF | 0.937 | 0.936 |
| Standard error of CMF | 0.253 | 0.257 |

**Safety Performance for Washington Rural Two-Lane Roadway Curve Delineation**

***Background***

Unlike Connecticut, the treatments in WA involved the installation of chevrons (W1-8 signs) on horizontal curves. WSDOT provided information on the location of chevrons. Information on traffic volume, roadway characteristics, and crashes were obtained from the Highway Safety Information System (HSIS). The cost of each chevron sign was estimated to be about $100.

Installation Data

The State of Washington provided the research team with information about locations where chevrons were installed in the last 15 years. In order to determine where these chevrons were located, the project team tried to match the location of the chevrons with the beginning and ending mileposts of horizontal curves that are available from HSIS. The first attempt at this matching seemed to indicate that a significant percentage of chevrons were not located within horizontal curves. It was then found that the beginning and ending mileposts of roadway segments in HSIS are recorded in the accumulated route mileage mileposting system whereas the information about the location of the chevrons was recorded in the state route milepost linear referencing system (it is important to note that a particular point on a roadway can have a different accumulated route mileage during time periods especially if there have been changes in the alignment upstream of that point on the same route). HSIS staff worked with WSDOT to learn how to convert between accumulated route mileage mileposts for each year in the study period with the state route milepost. Using the information provided by WSDOT and with support from HSIS staff, the research team was able to identify 139 curves on rural two lane roads where chevrons were installed sometime between 1994 and 2006.

***Reference Sites***

HSIS data were used to identify curves on rural two-lane roads that could serve as reference sites. The initial set of reference sites including about 4,000 curves that experienced about 8,000 crashes between 1993 and 2007. Several alternative reference groups were examined to obtain the reference group most similar to the treatment group in its characteristics.

Roadway Data

From HSIS, the team compiled the following information for each reference curve over the study period:

- AADT
- Curve length
- Curve radius
- Shoulder width
- Lane width
- Percent grade
- Terrain

In situations where a particular characteristic (e.g., shoulder width) varied within a curve, an average value was computed for each curve. In addition to these variables that were directly available from the HSIS inventory files, it was felt that it will be useful to obtain information about the distance between consecutive curves since there is some evidence to indicate that curves separated by short tangent sections may have more crashes compared to curves that are separated by long tangent sections. The initial effort to obtain the distance between curves seemed to find a large number of long tangent sections (tangent sections exceeding five miles). Further review indicated that this observation was because of gaps in the data due to coinciding routes. Coinciding routes are two routes that share the roadway section, but the roadway inventory and crash information is available only for one of the routes. Identifying the coinciding routes required the project team and HSIS staff to review individual roadway sections from the raw data provided by WSDOT.

Traffic Data

The team acquired exposure data, in the form of AADT, from HSIS for the treatment and reference sites. AADT data was not available from 1999 to 2001. To fill in the missing data, members of the project team used an algorithm developed by Lord (*17*). Upon a cursory review of the AADT, there were several curves where AADT changed dramatically from year to year (one site had an AADT of 138 in 2005 and 7,325 in 2006). A decision was made to only include curves where the difference between the AADT for two consecutive years was less than 20%.

Crash Data

The team also acquired crash data from HSIS for the study period starting from 1993 and ending in 2007. Crash data for 1997 and 1998 were not provided to HSIS by WSDOT and hence not available for analysis in this effort.

Data Manipulation and Reduction in Treatment Sample

A review of the crash data from the reference sites revealed that the number of head-on and opposite-direction sideswipe crashes increased significantly in 2002. WSDOT staff indicated that there were some changes made to their crash type definitions in 2002, but were not sure if those changes could have resulted in more counts of these crash types being reported. Given this situation, the researchers decided to exclude the data before 2002. Since a significant number of treatment sites had the chevrons implemented before 2002, the list of treatment sites had to be reduced to 37, from the original list of 139 sites. Table 29 shows the summary statistics for the treatment sites from Washington.

**Table 29. Data Summary for Washington (37 curves, 3.7 miles).**

| Variable | Before | After |
|---|---|---|
| Mile-Years | 10.08 | 8.42 |
| Minimum AADT (vpd) | 503 | 482 |
| Average AADT (vpd) | 2,833 | 2,947 |
| Maximum AADT (vpd) | 7,691 | 8,330 |
| Non-Intersection head-on and opposite-direction sideswipe crashes (Average) | 0.496 | 0.475 |

### *Safety performance functions*

Similar to the SPFs for Connecticut, the researchers use the following functional form to estimate the SPFs using the reference group from Washington:

$$\text{Crashes/year} = \exp(\beta_0 + \sum_{i=1}^{n} \beta_i X_i)$$

where X's are the independent variables and $\beta$'s are parameters to be estimated.

The resulting SPFs for head-on and opposite-direction sideswipe crashes were based on data from 4344 reference curves that had 220 crashes of this type from 2002 to 2007.

Table 30 provides the safety performance function from Washington for head-on and opposite direction-sideswipe crashes.

**Table 30. Safety Performance Function from Washington**

| Parameter | Estimate (Standard Error) |
|---|---|
| Intercept | -13.2389 (2.3147) |
| *ln*(AADT) | 1.9210 (0.2969) |
| AADT/1000 | -0.1425 (0.0577) |
| *ln*(radius in feet) | -0.6249 (0.1057) |
| *ln*(length in miles) | 0.8795 (0.1072) |
| k (overdispersion) | 0.1613 (0.1207) |

### *Results*

The resulting single value CMF for the installation of chevrons (W1-8 signs) was estimated to be 0.747 with a standard error of 0.378. The observed crashes in the after period were 4, and expected crashes without the treatment were 5.29. Due to the limited sample, the standard error is relatively high indicating that the CMF is not statistically different from 1.0 at the 0.05 level.

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# CHAPTER 5. Effect of Shoulder Widths on Opposite Direction Crashes

This chapter evaluates the safety effectiveness of providing or widening shoulders for rural two-lane highways in Texas. The research team selected study sites where shoulder widening occurred during the time period 2011 to 2015 as part of the Highway Safety Improvement Program (HSIP). Team members collected traffic and roadway geometric data for treatment segments from the Texas Department of Transportation's (TxDOT) Road-Highway Inventory Network Offload (RHiNO) database. Similarly, they obtained crash data from TxDOT's Crash Records Information System (CRIS). The team used Google Earth to supplement this data with additional information not available in the Texas road characteristic database (e.g., presence of rumble strips, passing lane, number of driveways). Although the TxDOT road characteristic database does include shoulder width data, the team confirmed these before/after dimensions and the construction period using Google earth historic maps. The target crashes are those crashes that are influenced by the shoulder improvements. In this study, opposite direction head-on and sideswipe crashes (referred to as OD in the modeling process) and single-vehicle run-off-road (SVROR) collisions are collectively considered as target crashes.

The empirical Bayes (EB) before-after study has been recognized as a robust method for developing CMFs. The EB approach estimates the safety of a site by combining the observed number of crashes at the site and the predicted number of crashes at similar sites (also known as reference sites). The predicted number of crashes is usually derived from a Safety Performance Function (SPF), which is a statistical model developed or calibrated with the reference sites. The SPF plays an important role in the EB method. Thus, either a robust SPF needs to be developed or an existing and widely accepted SPF such as the one found in the Highway Safety Manual (HSM) can be used (*18*). This study adopted the two-lane rural SPF from the HSM. The EB method is able to account for the regression-to-the-mean bias, other changes over time not due to the treatment, and to reduce the level of uncertainty in the estimates of safety effect. However, the EB method assumes the yearly expected number of crashes at a given site remains the same if all the variables considered in the SPF remain the same in the before and after periods. In other words, the conventional EB approach is unable to capture temporal instability of highway crash data (*19*), if the annual adjustment factor is not included in the SPF, as is the case with the HSM SPF. Previous studies have revealed that economic recession from 2008 to about 2010 had influence on traffic crashes *(20, 21*). Without considering the economic effect, safety evaluation involving periods of the recession may be biased. The effect of economic change on crashes needs to be considered while estimating the CMF of an engineering treatment. To overcome this limitation of the conventional EB method, this project considered the change in safety at a few reference sites during- and post-economic recession and used it in the evaluation of safety effectiveness of the shoulder widening.

## Methodology

The conventional EB approach is summarized in Appendix 1 of this report. To fully capture conditions at the site, the EB method must incorporate the calibration process and assumed economic effect.

### *SPF Calibration*

The EB approach combines the following two sources of safety information for a site:

(1) Predicted crashes determined using an SPF.

(2) Observed crash frequency.

The conventional EB approach uses one SPF for all the study periods. The use of a single SPF with a single calibration factor assumes the expected crashes for a given site are relatively stable and have not experienced any significant changes in terms of traffic volume and roadway characteristics. However, this may not be the case when the study periods include an economic recession. To address this problem, the research team calibrated the SPF with reference sites in two stages: one during the economic recession (i.e., 2008 to 2010), and the other post the economic recession (i.e., 2012 to 2014). This approach enables the analyst to incorporate two calibration factors. The economic effect is then captured by using one calibration factor for “before” conditions and a second calibration factor for “after” conditions.

The team developed the calibration factors based on the procedure documented in Part C of the HSM (*18*). The brief steps are as follows:

**Step 1**: Calculate the annual predicted number of crashes at each reference site with default calibration factor (i.e., 1.0).

**Step 2**: Obtain the observed number of crashes at each site.

**Step 3**: Estimate the calibration factor by dividing the sum of observed crash number by the sum of predicted numbers.

The research team separately applied these three steps to the periods of 2008 to 2010 (i.e., years of economic recession), and 2012 to 2014 (i.e., years following the economic recession). This analysis resulted in one calibration factor for each time period. The analyst then applied these two calibration factors as part of the EB process so as to properly address the economic effect.

### Treatment Sites

TxDOT provided a list of the highway projects that were submitted for shoulder widening during the time period 2011 to 2015 as part of the HSIP funding. The research team used the TxDOT road inventory database, supplemented by Google earth historic maps, to verify the construction period and the shoulder widths for both the before and after periods. The research team excluded from consideration any projects that could not be verified with this approach. Team members next extracted homogenous road segments and associated information related to lane width, and AADT for each segment. To improve prediction accuracy, segments longer than two miles were split into shorter ones, and those shorter than 0.1 mile were excluded from the dataset. This resulted in 252 segments for a total of 245.0 miles. The analysts also used Google Earth’s aerial and street views to acquire information about the presence of centerline rumble strips, shoulder rumble strips, passing lane, and roadside lateral clearance (i.e., distance from edge line marking to the roadside obstacles). The team enhanced the data with OD and SVROR crash frequency information for the before and after periods at each segment. The crash data included the following two crash severity levels: (1) fatal and injury (FI); and (2) property damage only (PDO). Table 31 summarizes the variables of the treatment segments.

**Table 31. Summary Statistics of Treated Sites (252 Sites)**

| Variable | Average | Min | Max | SD* |
|---|---|---|---|---|
| Length (mi) | 0.972 | 0.105 | 1.975 | 0.590 |
| Lane Width (ft) | 11.0 | 10.0 | 12.5 | 0.7 |
| Driveway Density (number per mi) | 7.6 | 0.0 | 30.4 | 6.3 |
| Roadside Lateral Clearance (ft) | 26.6 | 2.1 | 30.0 | 5.2 |
| AADT – Before (vpd) | 1902 | 100 | 9306 | 1,424.1 |
| AADT – After (vpd) | 1817 | 75 | 10,104 | 1,358.8 |
| Shoulder Rumble Strips Present | 4.3% | | | |
| Centerline Rumble Strips Present | 5.5% | | | |
| Passing Lane Present | 0%† | | | |

Notes:

* SD = standard deviation;

† No passing lanes were observed at the study segments.

The crash frequency and crash rates in the before and after periods are shown in Table 32. According to the crash rate comparisons, FI[OD+SVROR] crash rates decreased by about 5.4 percent, PDO[OD+SVROR] crash rates increased by about 48 percent, and All[OD+SVROR] crash rates increased by about 18 percent following shoulder widening. The OD crash rates increased regardless of the severity level. Specifically, FI[OD], PDO[OD], and All[OD] crash rates increased by 72.5, 128.7, and 93.7 percent, respectively.

The results based on the crash rates have a few limitations. First, the crash rate method completely depends on the observed crash data, in this case from law enforcement reports submitted to the state. The issue of data quality and accuracy arises due to the limitations in recording, reporting, and measuring crash data with accuracy and consistency in different time periods. Second, crash rates presume a linear relationship between crash frequency and the measure of exposure, which is typically not true.

**Table 32. Crash Frequency and Crash Rate in the Before and After Periods (252 Sites)**

| Target Crash | Before (3 Years) | | After* | | Change in Crash Rate |
|---|---|---|---|---|---|
| | Frequency | Crash Rate† | Frequency | Crash Rate† | |
| FI[OD+SVROR] | 151 | 12.5 | 109 | 11.9 | -5.4% |
| PDO[OD+SVROR] | 117 | 9.7 | 132 | 14.3 | 47.8% |
| All[OD+SVROR] | 268 | 22.2 | 241 | 26.2 | 17.8% |
| FI[OD] | 13 | 1.08 | 17 | 1.86 | 72.5% |
| PDO[OD] | 8 | 0.66 | 14 | 1.52 | 128.7% |
| All[OD] | 21 | 1.74 | 31 | 3.37 | 93.7% |

Notes:

† Crash rate is defined as number of target crashes (i.e., OD+SVROR) divided by 100 x $10^6$ vehicle miles of traveling (VMT). The VMT values for the before and after period are 1,204,818.8 and 919,451.1, respectively.

* The duration of after period at each segment varies.

Although the majority of the treatment segments did not have a paved shoulder prior to the treatment, a few of them had a 1-ft shoulder during the before period. The widths of shoulders in the after period varied from 2-ft to 10-ft. Table 33 depicts the shoulder width distribution for the 252 segments.

**Table 33. Distribution of Shoulder Width in the Before and After Periods**

| After / Before | 2-ft | 3-ft | 4-ft | 5-ft | 8-ft | 10-ft | Total |
|---|---|---|---|---|---|---|---|
| **0 (No Shoulder)** | 34 | 99 | 79 | 2 | 7 | - | 221 |
| **1-ft** | - | 13 | 6 | - | - | 12 | 31 |
| **Total** | 34 | 112 | 85 | 2 | 7 | 12 | 252 |

Different shoulder widths may potentially have different safety effects and so obtaining a single effect may not provide a complete picture. Consequently, the research team considered the following six different scenarios for this study.

- **Scenario I**:
  Before – Narrow shoulder (i.e. 9 to 1 feet in width).
  After – All 252 locations and varying shoulder widths.
- **Scenario II:**
  Before – No shoulder.
  After – Provide a narrow shoulder (i.e., 2 or 3 feet in width).
- **Scenario III:**
  Before – No shoulder.
  After – Provide a wider shoulder (i.e., 4 feet or wider).
- **Scenario IV:**
  Before – Narrow shoulder (i.e. 1 to < 4 feet in width).
  After – Provide a wider shoulder (i.e., 4 feet or wider).
- **Scenario V:**
  Before – No shoulder or narrow shoulder present (i.e. 0 to 1 feet in width).
  After – Provide a narrow shoulder (i.e., widen to < 4 feet).
- **Scenario VI:**
  Before – No shoulder or narrow shoulder present (i.e. 0 to 1 feet in width).
  After – Provide a wider shoulder (i.e., 4 feet or wider).

These six scenarios and the database threshold values are summarized in Table 34.

**Table 34. Database Thresholds for Shoulder Improvement Scenarios**

| Scenario | | Shoulder Width (ft) | | Sample Size (# of Segments) |
|---|---|---|---|---|
| **No.** | **Description** | **Before*** | **After** | |
| I. | Shoulder widening (all segments) | 0 or 1 | 2,3,4,5,8 or10 | 252 |
| II. | No shoulder to 2 or 3 ft | 0 | 2 or 3 | 135 |
| III. | No shoulder to 4 ft or wider | 0 | 4, 5 or 8 | 88 |
| IV. | Widening shoulder from 1 ft to 3, 4, or 10 ft | 1 | 3, 4 or 10 | 31 |
| V. | Providing/Widening shoulder to less than 4 ft | 0 | 2 or 3 | 148 |
| | | 1 | 3 | |
| VI. | Providing/Widening shoulder to 4 ft or more | 0 | 4, 5 or 8 | 106 |
| | | 1 | 4 or 10 | |

**Reference Sites**

In order to assess the economic effect on crash occurrence, this study identified reference sites. The research team selected comparison sites as identical as possible to the treatment sites. Specifically, the identification criteria were based on highway functional class, number of lanes, and traffic volume (i.e., AADT). The study periods for comparison sites included time periods during the economic recession (2008-2010) and following the economic recession (2012 to 2014). There were no safety treatments implemented on the sites from 2008 to 2014. All other variables (e.g., lane width, shoulder width, median type and width, etc.) were the same or very similar.

In total, the reference site identification included 300 locations. The summary statistics of the reference sites are shown in Table 35.

**Table 35. Summary Statistics of Reference Sites (300 Sites)**

| Variable | Average | Min | Max | SD* |
|---|---|---|---|---|
| Length (mi) | 0.614 | 0.100 | 1.995 | 0.487 |
| AADT (2008-2010) (vpd) | 1,130 | 290 | 4,100 | 617.9 |
| AADT (2012-2014) (vpd) | 1,101 | 238 | 3,892 | 612.8 |

Note:
* SD = standard deviation.

The crash frequency and crash rates in the before and after periods at the reference sites are presented in Table 36.

**Table 36. Crash Frequency and Rate for the Reference Sites (300 Locations)**

| Target Crash | Before (2008 to 2011) | | After (2012 to 2014) | | Change in Crash Rate |
|---|---|---|---|---|---|
| | Frequency | Crash Rate† | Frequency | Crash Rate† | |
| FI[OD+SVROR] | 84 | 14.0 | 89 | 15.2 | 8.6% |
| PDO[OD+SVROR] | 70 | 11.7 | 93 | 15.8 | 35.0% |
| All[OD+SVROR] | 154 | 25.7 | 182 | 31.0 | 20.6% |

Notes:
† Crash rate is defined as number of target crashes (i.e., OD+SVROR) divided by $100 \times 10^6$ vehicle miles of traveling (VMT). The VMT in the two periods are 599,471.2 and 587,610.1, respectively.

A simple or naïve comparison of the crash rates (last column in Table 36) indicates that the All[OD+SVROR] crash rate increased by 20.6% following the economic recession.

**Results**

The research team conducted the analysis by calibrating the HSM SPF and estimated CMFs for shoulder improvements for the six scenarios. The results are documented in the following sections.

***Calibration Factors***

The HSM requires that the calibration factor should be adjusted for local conditions. This study followed the procedure documented in Part C of the HSM and estimated the calibration factor. The data for all references sites for the two previously identified time periods were used to estimate the calibration factor.

There were a total of 154 OD and SVROR crashes during the period of economic recession. The predicted number of crashes for this time period, based on a default calibration factor (i.e., 1.0), results in the value of 128.7. Thus, the calibration factor during the period of economic recession was estimated has a value of 1.20 (i.e., 154/128.7). There were 182 observed OD and SVROR crashes after the economic recession and this value corresponds to a predicted number of 126.1. The calibration factor for this time period of post-economic recession was estimated as 1.44 (i.e., 182/126.1).

The difference between the two calibration factors indicates that the influence of economic change on collisions cannot be assumed to be negligible. Without any changes, a site is expected to experience 20 percent ($1.44/1.20 - 1 = 0.20$) more crashes during the time period after the economic recession. This result confirms the findings with the crash rate analysis presented in Table 36.

***All Shoulder Improvements (Scenario I)***

The results for Scenario I, which include all segments with any type of shoulder improvements, are shown in Table 37. It can be seen that there were in total 241 OD and SVROR crashes reported in the after period for these 252 locations. The analysis results indicate that if the shoulder had not been provided or widened, the predicted number of the target crashes would have been 294.5 during the after period. The **predicted** numbers of FI[OD+SVROR] crashes and PDO[OD+SVROR] crashes during the after period would have been 141.8 and 152.7, respectively, had the shoulders not been provided or improved. This value is then compared to the **observed** crash frequency during the after period which is 109 and 132, respectively. Overall, the results show that the OD+SVROR crashes decreased after shoulder improvements. It is estimated that the shoulder improvements decreased OD+SVROR crashes (all severity) by 18.3 percent. The standard deviation is 0.4 percent which makes the estimate statistically significant at the 95 percent level. The estimated CMF for FI[OD+SVROR] crashes is 0.77, and the standard deviation is 0.01, meaning that the crash reduction factor (CRF) is 23.4 percent. This result is statistically significant at the 95 percent level. For PDO crashes, the CRF is 13.8 percent, also statistically significant at the 95 percent level.

Table 37 shows the estimated results for OD crashes separately. FI[OD] crashes increased by 22.9 percent after shoulder improvements, and the standard deviation is 13.2 percent. This result is not statistically significant at the 95 percent level. PDO[OD] crashes increased by 47.8 percent, and All[OD] crashes increased by 35.7 percent. Both are statistically significant at 95 percent level. Since the sample size is quite small, the results related to the OD crashes should be interpreted with caution. The increase in OD crashes may not actually be related to the shoulder widening but might have occurred randomly.

**Table 37. Results of All Segments (Scenario I) – 252 Sites**

| Crash Type | Variables | Crash Severity Levels | | |
|---|---|---|---|---|
| | | FI (SE) | PDO (SE) | All (SE) |
| OD+SVROR | Predicted Crashes | 141.8 (11.9) | 152.7 (12.4) | 294.5 (17.2) |
| | Observed Crashes | 109 (10.4) | 132 (11.5) | 241 (15.5) |
| | CMF | <u>0.77 (0.01)</u> | <u>0.86 (0.01)</u> | <u>0.82 (0.01)</u> |
| | Crash Reduction Factor (%) | <u>23.4 (0.7)</u> | <u>13.8 (0.8)</u> | <u>18.3 (0.4)</u> |
| OD | Predicted Crashes | 13.4 (3.7) | 9.0 (3.0) | 22.4 (4.7) |
| | Observed Crashes | 17 (4.1) | 14 (3.7) | 31 (5.6) |
| | CMF | 1.23 (0.13) | <u>1.48 (0.24)</u> | <u>1.36 (0.09)</u> |
| | Crash Reduction Factor (%) | -22.9 (13.2) | <u>-47.8 (24.2)</u> | <u>-35.7 (9.4)</u> |

Notes:
Underline indicates statistically significant at the 95% level. Value in the parenthesis is the standard error of the estimate.

***Providing a Paved Shoulder (Scenarios II and III)***

The estimated results for providing a shoulder (i.e., Scenarios II and III) when none existed are shown in Table 38. In both scenarios, PDO[OD+SVROR] crashes decreased. Specifically, FI[OD+SVROR] crashes decreased by 9.9 percent after providing a 2-ft or 3-ft shoulder, and 32.2 percent after providing a 4-ft or wider shoulder. PDO[OD+SVROR] crashes decreased by 15.8 percent after providing a 2-ft or 3-ft shoulder, and 21.1 percent after providing a 4-ft or wider shoulder. All[OD+SVROR] crashes decreased by 12.6 and 26.0 percent, respectively, in the two scenarios. All the results are statistically significant at the 95 percent level.

An analysis related to the OD crashes for Scenarios II and III is also presented in Table 38. Providing a shoulder showed mixed results for FI[OD] crashes in the two scenarios. OD crashes increased by 104.0 percent after providing a 2-ft or 3-ft shoulder, but decreased by 35.7 percent after providing a 4-ft or wider shoulder. The latter is statistically significant at 95 percent level, but the former is not. PDO[OD] and All[OD] crashes increased in both scenarios. Only the CMF for All[OD] crashes in Scenario II is statistically significant at the 95 percent level. This contrasting result is likely due to the low number of OD crashes.

**Table 38. Results for Providing a Shoulder (Scenarios II and III)**

| Crash Type | Variables | Crash Severity Levels | | |
|---|---|---|---|---|
| | | FI (SE) | PDO (SE) | All (SE) |
| **Scenario II: No shoulder to 2 or 3 ft – 135 Sites** | | | | |
| OD+SVROR | Predicted Crashes | 65.0 (8.1) | 67.3 (8.2) | 132.3 (11.5) |
| | Observed Crashes | 59 (7.7) | 57 (7.5) | 116 (10.8) |
| | CMF | 0.90 (0.02) | 0.84 (0.02) | 0.87 (0.01) |
| | CRF (%) | 9.9 (1.9) | 15.8 (1.6) | 12.6 (0.9) |
| OD | Predicted Crashes | 4.5 (2.1) | 5.2 (2.3) | 9.7 (3.1) |
| | Observed Crashes | 10 (3.2) | 8 (2.8) | 18 (4.2) |
| | CMF | 2.04 (0.64) | 1.42 (0.36) | 1.78 (0.28) |
| | CRF (%) | -104.0 (64.1) | -42.5 (36.2) | -77.9 (28.3) |
| **Scenario III: No shoulder to 4 ft or wider – 88 Sites** | | | | |
| OD+SVROR | Predicted Crashes | 62.9 (7.9) | 71.7 (8.5) | 134.5 (11.6) |
| | Observed Crashes | 43 (6.6) | 57 (7.5) | 100 (10.0) |
| | CMF | 0.68 (0.01) | 0.79 (0.02) | 0.74 (0.01) |
| | CRF (%) | 32.2 (1.4) | 21.1 (1.5) | 26.0 (0.8) |
| OD | Predicted Crashes | 7.2 (2.7) | 3.1 (1.8) | 10.3 (3.2) |
| | Observed Crashes | 5 (2.2) | 6 (2.4) | 11 (3.3) |
| | CMF | 0.64 (0.10) | 1.64 (0.66) | 1.01 (0.13) |
| | CRF (%) | 35.7 (9.9) | -64.2 (66.3) | -1.0 (13.3) |

Notes:
Underline indicates statistically significant at the 95% level. Value in the parenthesis is the standard error of the estimate.

### *Widening Shoulders (Scenario IV)*

Table 39 shows the estimated results for widening shoulders (i.e., Scenario IV). After widening shoulders, FI[OD+SVROR] crashes decreased by 50.3 percent, but PDO crashes increased by 29.5 percent. All[OD+SVROR] crashes decreased by 9.7 percent. All of these were statistically significant at the 95 percent level but the sample size for this scenario was very small (only 31 sites).

Because no OD crashes were reported that aligned with this scenario, the results related to OD crash type are not available.

**Table 39. Results of Widening Shoulder (Scenario IV) – 31 Sites**

| Crash Type | Variables | Crash Severity Levels | | |
|---|---|---|---|---|
| | | FI (SE) | PDO (SE) | All (SE) |
| OD+SVROR | Predicted Crashes | 13.8 (3.7) | 13.6 (3.7) | 27.4 (5.2) |
| | Observed Crashes | 7 (2.6) | 18 (4.2) | 25 (5.0) |
| | CMF | <u>0.50 (0.04)</u> | <u>1.29 (0.12)</u> | <u>0.90 (0.04)</u> |
| | CRF (%) | <u>50.3 (3.9)</u> | <u>-29.5 (12.5)</u> | <u>9.7 (4.1)</u> |

Notes:
Underline indicates statistically significant at the 95% level. Value in the parenthesis is the standard error of the estimate.

### *Improving to Narrow Shoulders (Scenario V)*

Table 40 presents the estimated results for improving to narrow shoulders (i.e., Scenario V). After providing a relative narrow shoulder (2 or 3ft) or widening the shoulder from 1ft to 3ft, OD+SVROR crashes decreased. Specifically, FI[OD+SVROR] crashes decreased by 9.5 percent, PDO crashes increased by 11.8 percent, and total decreased by 10.4 percent. All of them are statistically significant at the 95 percent level.

An analysis related to OD crashes for this scenario shows that the FI[OD] crashes increased by 92.7 percent, PDO[OD] crashes increased by 37.5 percent, and All[OD] crashes increased by 69.6 percent. Only the CMF for All[OD] crashes is statistically significant at the 95 percent level.

**Table 40. Results of Improving to Narrow Shoulders (Scenario V) – 148 Sites**

| Crash Type | Variables | Crash Severity Levels | | |
|---|---|---|---|---|
| | | FI (SE) | PDO (SE) | All (SE) |
| OD+SVROR | Predicted Crashes | 68.1 (8.3) | 71.0 (8.4) | 139.1 (11.8) |
| | Observed Crashes | 62 (7.9) | 63 (7.9) | 125 (11.2) |
| | CMF | 0.91 (0.02) | 0.88 (0.02) | 0.90 (0.01) |
| | CRF (%) | 9.5 (1.8) | 11.8 (1.7) | 10.4 (0.9) |
| OD | Predicted Crashes | 4.8 (2.2) | 5.4 (2.3) | 10.2 (3.2) |
| | Observed Crashes | 10 (3.2) | 8 (2.8) | 18 (4.2) |
| | CMF | 1.93 (0.56) | 1.37 (0.33) | 1.70 (0.25) |
| | CRF (%) | -92.7 (56.0) | -37.5 (33.3) | -69.6 (25.2) |

Notes:
Underline indicates statistically significant at the 95% level. Value in the parenthesis is the standard error of the estimate.

### *Improving to Wider Shoulders (Scenario VI)*

Table 41 presents the results of Scenario VI, i.e. improving to relatively wider shoulders. In this scenario, a 4-ft or wider shoulder has been provided or the shoulder has been widened to 4-ft or more from 1-ft. Estimated results indicate that FI[OD+SVROR] crashes decreased by 36.5 percent, PDO[OD+SVROR] crashes decreased by 15.9 percent, and All[OD+SVROR] decreased by 2.7 percent. All of them are statistically significant at the 95 percent level.

Table 41 also shows the estimating results for OD crashes after improving to relatively wider shoulders. In this scenario, FI[OD] crashes decreased by 22.6 percent with standard deviation of 10.9 percent, which makes the results statistically significant at the 95 percent level. However, PDO[OD] crashes and All[OD] crashes increased by 45.8 and 2.7 percent, respectively. Both are not statistically significant at the 95 percent level.

**Table 41. Results of Improving to Relatively Wider Shoulders (Scenario VI) – 106 Sites**

| Crash Type | Variables | Crash Severity Levels | | |
|---|---|---|---|---|
| | | **FI (SE)** | **PDO (SE)** | **All (SE)** |
| OD+SVROR | Predicted Crashes | 73.6 (8.6) | 81.5 (9.0) | 155.1 (12.5) |
| | Observed Crashes | 47 (6.9) | 69 (8.3) | 116 (10.8) |
| | CMF | <u>0.63 (0.01)</u> | <u>0.84 (0.01)</u> | <u>0.75 (0.01)</u> |
| | CRF (%) | <u>36.5 (1.1)</u> | <u>15.9 (1.5)</u> | <u>25.5 (0.7)</u> |
| OD | Predicted Crashes | 8.5 (2.9) | 3.6 (1.9) | 12.1 (3.5) |
| | Observed Crashes | 7 (2.6) | 6 (2.4) | 13 (3.6) |
| | CMF | <u>0.77 (0.11)</u> | 1.46 (0.50) | 1.03 (0.12) |
| | CRF (%) | <u>22.6 (10.9)</u> | -45.8 (50.0) | -2.7 (11.6) |

Notes:
Underline indicates statistically significant at the 95% level. Value in the parenthesis is the standard error of the estimate.

***Summary***

The findings from the shoulder widening analysis results are summarized as follows:

(1) Generally, OD+SVROR crashes decreased after shoulder improvements. The effect is more noticeable for FI crashes than on PDO crashes.
(2) There is no conclusive evidence about the effect of shoulder improvements for OD crashes. This is likely due to a small number of reported OD crashes.
(3) The economic recession had an effect on traffic crashes. The crashes increased by about 20 percent following the recession.
(4) Providing or widening shoulders to 4-ft or more is expected to have more safety effect on OD+SVROR crashes than providing or widening shoulders to 3-ft or less.

This study proposed an alternative method for capturing the economic effect that influences the estimation of safety for engineering treatments. The researchers identified reference sites and used the safety data for conditions during the economic recession as well as following the economic recession. This time-based economic assessment resulted in two calibration factors.

Compared to other studies that have utilized EB method for estimating treatment effects, this study has attempted to adopt HSM SPFs and CMFs rather than developing a SPF based on reference sites. This eliminated the low sample size bias in developing SPFs as was shown in many previous studies. However, previous studies have pointed out that the selection of SPFs in the EB method will affect the CMF estimation results. Further research needs to be conducted to explore the issues related to the SPF selection.

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# CHAPTER 6. Findings and Conclusions

The objective of this research effort was to identify, where available, the known effect of safety treatments for opposite direction crashes where a crash occurs between two or more vehicles that were traveling in opposing directions prior to the crash and were not attempting to execute a turning maneuver at the time of the crash.

The rare and random nature of opposite direction crashes creates challenges when statistically assessing the influence of a safety treatment on the reduction in this crash type. For this evaluation, the research team evaluated four unique treatment configurations. These potential safety treatments included:

- Wider edgeline.
- Centerline buffers.
- Enhanced curve delineation.
- Increased shoulder width.

The wider edgeline and curve delineation evaluations were based on datasets previously assembled for prior work. These previous studies did not directly focus on opposite direction crashes and so sample size limitations for re-application of this data presented some challenges. The research team assembled new databases for the centerline buffers as well as the increased shoulder width treatments.

The general observations related to opposite direction crashes are summarized for each of the individual treatments below.

<u>Wider edgelines</u> (for two-lane highways):

- Results vary but consistently indicate a reduction in opposite direction crashes (see Table 18).
- The effect could not be assessed accurately for wider edgelines on two-lane highways in regions with extreme winter weather.

<u>Centerline buffer</u>:

- Centerline buffers reduce opposite direction crashes for two-lane highways with greater reductions achieved for wider buffers (see Figure 2).
- Centerline buffers do not have a measurable effect for reduction of opposite direction crashes on four-lane highways.

Curve delineation (for two-lane highways):

- The effectiveness of enhanced curve delineation varied with a reduction in opposite direction crashes of six percent (CMF = 0.94, SE = 0.25) up to a 25 percent (CMF = 0.75, SE = 0.38) reduction.

Increased shoulder width:

- A combination of opposite direction and single vehicle run-off-road crashes decreased following shoulder improvements. This effect was more significant for shoulder widening of 4-ft or more.
- Due to a small sample size of opposite direction crashed, it is not clear if the shoulder width directly influenced opposite direction crashes.

A final notable observation identified as part of the shoulder width evaluation is that the evaluation of before and after time periods that included the years of the Great Recession (2007 to 2009) should be adjusted to explicitly assess the impact of the Recession on the number of crashes. Stated another way, a simple observation of all crashes during the Great Recession compared to crashes after the Great Recession will result in an increase in crashes that is not related to the performance of a safety treatment but rather is a result of driver behavior during constrained economic conditions.

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# APPENDIX 1. Steps of the Empirical Bayes Procedure

Step 1. Develop a Safety Performance Function (SPF) and estimate the regression coefficients and a negative binomial dispersion parameter ($k$) using data from the reference group.

Step 2. Estimate the expected number of crashes $E\left(\kappa_{iy}\right)$ for each year ($y$) in the before period at each treatment site using the SPF developed in Step 1.

Step 3. Compute the sum of the annual SPF predictions during the before period at each treatment site by summing $E\left(\kappa_{iy}\right)$ for before years:

$$P_i = \sum_{y=1}^{y_{0i}-1} \hat{E}\left(\kappa_{iy}\right)$$

where $y_{0i}$ denotes the year during which the countermeasure was installed at site $i$.

Step 4. Obtain an estimate of the expected number of crashes ($M_i$) before implementation of the countermeasure at each treatment site and an estimate of variance of $M_i$. The estimate $M_i$ is given by combining the sum of the annual SPF predictions during the before period ($P_i$) with the total count of crashes during the before period as follows:

$$M_i = w_i P_i + \left(1 - w_i\right) K_i$$

where $K_i$ is the total crash counts during the before period at site $i$ and the weight $w_i$ is given by

$$w_i = \frac{1}{1 + kP_i}$$

where $k$ is the estimated dispersion parameter of the Negative Binomial regression model developed in Step 1. An estimated variance of $M_i$ is given by:

$$\hat{Var}\left(M_i\right) = \left(1 - w_i\right) M_i .$$

Step 5. Determine SPF predictions $\hat{E}\left(\kappa_{iy}\right)$ for each year in the after period at each treatment site, and compute $C_i$, the ratio of the sum of the annual SPF predictions for the after period ($Q_i$) and the sum of the annual SPF predictions for the before period ($P_i$).

$$C_i = \frac{\sum_{y=y_{0i}+1}^{Y} \hat{E}\left(\kappa_{iy}\right)}{\sum_{y=1}^{y_{0i}-1} \hat{E}\left(\kappa_{iy}\right)} = \frac{Q_i}{P_i} .$$

Step 6. Obtain the predicted crashes ($\hat{\pi}_i$) and its estimated variance during the after period that would have occurred without implementing the countermeasure. The predicted crashes ($\hat{\pi}_i$) are given by:

$$\hat{\pi}_i = C_i M_i$$

The estimated variance of $\hat{\pi}_i$ is given by:

$$\hat{Var}\left(\hat{\pi}_i\right) = C_i^2 \hat{Var}\left(M_i\right) = C_i^2 \left(1 - w_i\right) M_i .$$

Step 7. Compute the sum of the predicted crashes over all sites in a treatment group of interest and its estimated variance by:

$$\hat{\pi} = \sum_{i=1}^{I} \hat{\pi}_i$$

$$V\hat{a}r(\hat{\pi}) = \sum_{i=1}^{I} V\hat{a}r(\hat{\pi}_i)$$

where $I$ is the total number of sites in a treatment group of interest.

Step 8. Compute the sum of the observed crashes over all sites in a treatment group of interest by:

$$L = \sum_{i=1}^{I} L_i$$

where $L_i$ is the total crash counts during the after period at site $i$.

Step 9. The index of effectiveness of the countermeasure is estimated by:

$$\hat{\theta} = \frac{L}{\hat{\pi}\left(1 + \mathrm{var}(\hat{\pi})/\hat{\pi}^2\right)}.$$

The percent change in the number of crashes at site $i$ is given by $100\left(1-\hat{\theta}\right)$. If $\hat{\theta}$ is less than 1 then the countermeasure has a positive effect on safety.

Step 10. Compute the estimated variance and standard error of the index of effectiveness and the approximate 95% confidence interval for $\theta$. The estimated variance and standard error of the index of effectiveness are given by

$$V\hat{a}r\left(\hat{\theta}\right) = \hat{\theta}^2 \frac{\left(1/L + V\hat{a}r(\hat{\pi})/\hat{\pi}^2\right)}{\left(1 + V\hat{a}r(\hat{\pi})/\hat{\pi}^2\right)^2}$$

$$s.e.\left(\hat{\theta}\right) = \sqrt{V\hat{a}r\left(\hat{\theta}\right)}$$

The approximate 95% confidence interval for $\theta$ is given by adding and subtracting $1.96\, s.e.\left(\hat{\theta}\right)$ from $\hat{\theta}$. If the confidence interval contains the value 1, then no statistically significant effect has been observed. This does not mean that a safety effect does not exist, so all indices that were estimated are reported in this paper to show a complete picture of safety effects. A confidence interval placed below 1 (i.e., the upper limit of the interval is less than 1) implies that the countermeasure has a significant positive effect (i.e., a reduction in crashes) on safety. The confidence interval placed above 1 (i.e., the lower limit of the interval is greater than 1) implies that the countermeasure has a significant negative effect (i.e., an increase in crashes) on safety.

# APPENDIX 2. Guidelines for Treatments to Mitigate Opposite Direction Crashes

This appendix is published as *NCHRP Research Report 995: Guidelines for Treatments to Mitigate Opposite Direction Crashes*.