Safety Evaluation of Horizontal Curve Realignment on Rural, Two-Lane Roads

PUBLICATION NO. FHWA-HRT-17-066 APRIL 2018

U.S. Department of Transportation
Federal Highway Administration

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

FOREWORD

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

This study evaluates the safety effectiveness of horizontal curve realignment by increasing the radius of curved roadway segments on two-lane rural roads. One objective of this strategy is to reduce lane departure crashes, especially run-off-road crashes. The evaluation results showed substantial and significant reduction in crashes (total, injury and fatal crashes, run-off-road, and fixed object crashes, dark crashes, and wet-road crashes). The economic analysis revealed that increasing the radius of a horizontally curved roadway segment on two-lane, rural roads is a cost-effective safety improvement for reducing all types of crashes. This document is intended for safety engineers, highway designers, planners, and practitioners at State and local agencies involved with AASHTO Strategic Highway Safety Plan implementation.

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

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-17-066	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Safety Evaluation of Horizontal Curve Realignment on Rural, Two-Lane Roads		5. Report Date April 2018 6. Performing Organization Code
7. Author(s) Raghavan Srinivasan, Daniel Carter, Craig Lyon, and Matthew Albee		8. Performing Organization Report No.
9. Performing Organization Name and Address VHB 8300 Boone Blvd., Ste. 700 Vienna, VA 22182-2626 Highway Safety Research Center University of North Carolina Chapel Hill, NC 27599-3430		10. Work Unit No. 11. Contract or Grant No. DTFH61-13-D-0001
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Highway Administration 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Safety Evaluation; August 2013–November 2016 14. Sponsoring Agency Code HRDS-20

15. Supplementary Notes
The Federal Highway Administration (FHWA) Office of Safety Research and Development managed this study under the Development of Crash Modification Factors program. The FHWA Office of Safety Research and Development Program and Task Manager was Roya Amjadi (HRDS-20).

16. Abstract
The Development of Crash Modification Factors program conducted safety evaluation of horizontal curve realignment on rural, two-lane roads for the Evaluation of Low Cost Safety Improvements Pooled Fund Study. The goal of this evaluation is to evaluate the safety effectiveness of this strategy. This strategy sought to reduce lane departure crashes, especially run-off-road crashes. This study determined the crash modification factors (CMFs) associated with curve realignment using the before–after empirical Bayes method and compared the results from published CMFs from cross-sectional studies. This evaluation used data from rural, two-lane roads in California, North Carolina, and Ohio. The evaluation revealed a 68-percent reduction in total crashes, a 74-percent reduction in injury and fatal crashes, a 78-percent reduction in run-off-road and fixed object crashes, a 42-percent reduction in dark crashes, and an 80-percent reduction in wet crashes, all of which were statistically significant at the 95-percent confidence level. The results pertain to a range of site characteristics, the most important of which is the range of the before and after degree of curve. The average degrees of curve in the before and after periods were 18.1 (with a minimum of 3.2 and a maximum of 52.1) and 6.9 (with a minimum of 0.0 and a maximum of 16.3), respectively. The average central angle of the curves was approximately 42 degrees (with a minimum of 1 and a maximum of 117). The average annual average daily traffic at the treated sites was about 3,500 (with a minimum of 465 and a maximum of 11,917). The average length of the realigned segments was 0.15 mi (with a minimum of 0.03 and a maximum of 0.60). This study compared the total crash CMFs with the results from previous cross-sectional studies. The CMFs from this before–after evaluation are lower compared to CMFs estimated from two previous cross-sectional studies. The economic analysis revealed a benefit–cost ratio of 3.17:1 with a range of 1.75:1 to 4.38:1. There is a need for further research with a larger sample of sites to assess the reliability of the CMFs obtained from this before–after evaluation.

17. Key Words Horizontal curve, rural two-lane roads, realignment, radius, degree of curve, lane departure crashes, safety improvements, safety evaluations, empirical Bayesian, run-off-road, crash modification factors, crash modification functions, cross-sectional studies		18. Distribution Statement No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages: 54	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed pages authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AADT	annual average daily traffic
B/C	benefit–cost
CMF	crash modification factor
CMFunction	crash modification function
DCMF	Development of Crash Modification Factors (program)
EB	empirical Bayes
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FHWA	Federal Highway Administration
GIS	geographic information system
HSIS	Highway Safety Information System
HSM	*Highway Safety Manual*, first edition
NCDOT	North Carolina Department of Transportation
PDO	property-damage-only
RTM	regression-to-the-mean
SPF	safety performance function
TAC	technical advisory committee
USDOT	U.S. Department of Transportation

EXECUTIVE SUMMARY

The Federal Highway Administration established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes. The ultimate goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and promote those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit–cost (B/C) ratios through research. State transportation departments and other transportation agencies need to have objective measures for safety effectiveness and B/C ratios before investing in new strategies for statewide safety improvements. Forty State transportation departments provided technical feedback on safety improvements to the DCMF program and implemented new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements-Pooled Fund Study, which functions under the DCMF program. This study evaluated the effectiveness of horizontal curve realignment on rural, two-lane roads. One objective of this strategy is to reduce lane departure crashes, especially run-off-road crashes.

This evaluation developed crash modification factors (CMFs) for curve realignment on rural, two-lane roads using state-of-the-art before–after empirical Bayes methods and compared the results with previously developed CMFs from cross-sectional studies. The data included 39 realigned locations from California, North Carolina, and Ohio, and 56 untreated reference curves.

Table 1 presents the recommended CMFs for curve realignment on rural, two-lane roads. The results pertain to a range of site characteristics, the most important of which is the range of before and after degree of curve. The average degrees of curve in the before and after periods were 18.1 (with a minimum of 3.2 and a maximum of 52.1) and 6.9 (with a minimum of 0.0 and a maximum of 16.3), respectively. The average central angle of the curves was approximately 42 degrees (with a minimum of 1 and a maximum of 117). The average annual average daily traffic at the treated sites was about 3,500 (with a minimum of 465 and a maximum of 11,917). The average length of the realigned segments was 0.15 mi (with a minimum of 0.03 and a maximum of 0.60).

Table 1. Recommended CMFs.

Metric	Total	Injury and Fatal	Run-Off-Road Plus Fixed Object	Dark	Wet-Road
Estimate of CMF	**0.315**	**0.259**	**0.216**	**0.584**	**0.204**
Standard error of estimate of CMF	0.064	0.086	0.068	0.176	0.079

Note: Bold text indicates that CMFs are statistically significant at the 95-percent confidence level.

Crash modification functions (CMFunctions) that were estimated showed that safety benefits may be greater for curves with a larger central angle and where the difference in radius between the before- and after-period conditions is larger.

In addition to developing the CMFs through a before–after evaluation, this study also compared the total crash CMFs with the results from previous cross-sectional studies. The CMFs derived through this before–after evaluation are lower compared to CMFs estimated by two previous cross-sectional studies. The economic analysis revealed a B/C ratio of 3.17:1 with a range of 1.75:1 to 4.38:1. There is a need for further research with a larger sample of sites to assess the reliability of the CMFs obtained from this before–after evaluation.

CHAPTER 1. INTRODUCTION

BACKGROUND ON STRATEGY

Horizontal curves have consistently been an area of concern for road safety practitioners, particularly for single-vehicle crashes. A 2010 report from the Bureau of Transportation Statistics showed that one-third of fatal single-vehicle crashes occur at curves.[1] Most crashes at curves involve a vehicle leaving the roadway and striking a fixed object or overturning.[2,3] To counter this problem, transportation departments employ many strategies ranging from low-cost improvements of enhanced signs, delineations, or high friction surfacing to higher-cost strategies such as realignment of the curve or improving the superelevation.

The American Association of State Highway and Transportation Officials Guide for Reducing Collisions on Horizontal Curves lists "increasing the radius of a horizontal curve" as one strategy for reducing the likelihood of a vehicle leaving its lane and either crossing the roadway centerline or leaving the roadway at a horizontal curve.[3] The guide acknowledges that modifying the horizontal alignment is the longest-term, highest-cost strategy because it involved reconstructing the roadway, as well as other considerations such as right-of-way acquisition and environmental review. However, many States employ this strategy. From 2013 to 2015, 23 States reported using Highway Safety Improvement Program funds to implement horizontal curve realignment via 83 projects.[4]

BACKGROUND ON STUDY

The Federal Highway Administration (FHWA) established the Development of Crash Modification Factors (DCMF) program in 2012 to address highway safety research needs for evaluating new and innovative safety improvement strategies by developing reliable quantitative estimates of their effectiveness in reducing crashes. The ultimate goal of the DCMF program is to save lives by identifying new safety strategies that effectively reduce crashes and to promote those strategies for nationwide implementation by providing measures of their safety effectiveness and benefit–cost (B/C) ratios through research. State transportation departments and other transportation agencies need objective measures for safety effectiveness and B/C ratios before investing in broad applications of new strategies for safety improvements. Forty State transportation departments provide technical feedback on safety improvements to the DCMF program and implement new safety improvements to facilitate evaluations. These States are members of the Evaluation of Low-Cost Safety Improvements-Pooled Fund Study (ELCSI-PFS), which functions under the DCMF program.

Typically, researchers have based studies on the effect of horizontal curve radius on a cross-sectional analysis, where they compare the safety performance of curves of different radii. This methodology allows for a larger potential sample of curves because there is not a need to know a conversion/installation date such as is needed in a before–after study. It allows the use of an entire State's database of curved road sections, as was the case with Washington State data in the Bauer and Harwood and the Saleem and Persaud studies.[5,6]

However, before–after methodology is preferable to cross-sectional for evaluating the safety effect of an infrastructure modification.[7] Before–after studies are conducted for many other evaluations of safety improvements and provide the best estimate of the effect of the improvement. Typically, the most difficult aspect of before–after studies is identifying where and when the safety improvement was implemented.

The advantage to this study was the assistance provided by the Technical Advisory Committee (TAC) of the ELCSI-PFS. This committee consists of safety engineers and representatives from more than 40 States. The TAC served as a source of knowledge for projects where horizontal curves were realigned, making the before–after methodology possible. Using the information gained from the ELCSI-PFS TAC, this study sought to conduct a before–after study of curve realignments using an empirical Bayes (EB) methodology.

LITERATURE REVIEW

Several studies have produced crash modification factors (CMFs) and crash modification functions (CMFunctions) for curve radius on rural, two-lane roads. Several other studies, also listed, provide CMFs for curve radius for other roadway types.

The Highway Safety Manual (HSM), first edition, chapter for rural, two-lane roads includes a CMF for horizontal curvature (pp. 10–27).[8] The HSM based this CMF on regression analysis done by Zegeer et al.[9] The base condition of the HSM predictive model for rural, two-lane roads is a tangent, and the CMF for a curve is calculated as shown in figure 1:

$$CMF = \frac{(1.55L) + \left(\frac{80.2}{R}\right) - (0.012S)}{(1.55L)}$$

Figure 1. Equation. CMF for horizontal curvature on rural, two-lane roads from HSM.

Where:

L = length of horizontal curve in mi, including spiral transitions.
R = radius of curve in feet.
S = 1 if spiral transition present; 0 if not; 0.5 if present only on one end of curve.

A study by Bauer and Harwood focused on the interaction of horizontal curvature and vertical curvature and grade for rural, two-lane highways.[5] The authors conducted a cross-sectional analysis of roadway segments from Washington State. They used 3,457 mi of road and 6 yr of crash data to produce a series of CMFunctions that quantify the safety performance of various combinations of vertical and horizontal alignment.

Their study classified horizontal alignment of roadway segments as follows:

- Tangent.
- Horizontal curve.

Their study classified vertical alignment of roadway segments as follows:

- Level.
- Straight grade (constant grade of 1 percent or more).
- Type 1 or 2 crest vertical curve.
- Type 1 or 2 sag vertical curve.

Figure 2 shows one of the CMFunctions produced by Bauer and Harwood. The function calculates a CMF for fatal and injury crashes for a horizontal curve that occurs on a straight grade (i.e., no vertical curvature). The study produced other CMFunctions for other conditions (e.g., horizontal curve on a type 1 vertical crest).

$$CMF = e^{\left[0.044+0.19 ln\left(2\times\frac{5730}{R}\right)+4.52\left(\frac{1}{R}\right)\left(\frac{1}{L_C}\right)\right]}$$

Figure 2. Equation. Bauer and Harwood CMFunction for injury and fatal crashes for safety effect of horizontal curve on straight grade.[(5)]

Where:

G = absolute value of percent grade (0 percent for level tangents, ≥1 percent otherwise.
R = curve radius (ft) (missing for tangents).
L_c = horizontal curve length (mi) (not applicable for tangents).

Saleem and Persaud built on the work for two-lane highways to explore the development of a CMFunction where they explored different designs to flatten an existing horizontal curve.[(6)] They focused on horizontal curves only on level grade (less than 3 percent). They used 440 curves from Washington State with radii between 100 and 11,000 ft to conduct a cross-sectional analysis and develop CMFunctions. Their functions show that CMFs decreased (fewer crashes occured) for scenarios in which a larger radius is entertained. They furthermore found that the level of annual average daily traffic (AADT) on the subject segment did not influence the effect.

The following studies have produced CMFs related to horizontal curve radius but focused on other types of crash or roadway conditions:

- Schneider et al. estimated CMFs for horizontal curvature on two-lane highways but focused on truck-involved crashes.[(10)]

- Banihashemi, Fitzpatrick et al., and Graham et al. produced CMFs involving horizontal curve radius but focused on rural, multilane highways.[(11–13)]

- Pratt et al. and Choi et al. produced CMFs for horizontal alignment but focused on freeways.[(14,15)]

Summary of Literature Review

Previous studies have generally shown that higher curve radius is associated with fewer crashes. However, all the published studies that have examined the safety effect of horizontal curvature were based on cross-sectional studies that may not always provide reliable CMFs. This illustrates the need for before–after studies, even if researchers must base those studies on a small sample to verify the results that cross-sectional studies have obtained.

CHAPTER 2. OBJECTIVE

The objective of this study was to develop a CMF for horizontal curve realignment, where increasing the radius of a curved roadway segment served to flatten the curve. Most previous studies used cross-sectional models to develop CMFs, and this evaluation used the EB before-evaluation method to develop CMFs and verify the results with the cross-sectional studies. The evaluation used data from California, Ohio, and North Carolina. The evaluation included the following crash types:

- Total.
- Injury and fatal.
- Run-off-road and fixed object.
- Crashes during dark.
- Wet crashes.

In addition to determining the overall safety effect of the treatment(s), a further objective was to address the following questions:

- Do effects vary by level of traffic volume?
- Do effects vary by the frequency of crashes before treatment?
- How do the effects vary based on a change in radius from the before to the after periods?

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

CHAPTER 3. STUDY DESIGN

When planning a before–after safety evaluation study, it is vital to ensure that enough data are included to statistically detect the expected change in safety. Even though those designing the study do not know the expected change in safety in the planning stage, it is still possible to make a rough determination of how many sites are required based on the best available information about the expected change in safety. Alternatively, one could estimate the statistically detectable change in safety for the number of available sites. For a detailed explanation of sample size considerations, as well as estimation methods, see chapter 9 of Hauer.[16] The sample size analysis cases presented in this section address how large a sample is required to statistically detect an expected change in safety and the change in safety that can be detected with available sample sizes.

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

For this analysis, the project team assumed that the study used a conventional before–after study with comparison group design, because available sample size estimation methods are based on this assumption. The sample size estimates from this method would be conservative in that the EB methodology proposed would likely require fewer sites. To facilitate the analysis, the project team also assumed that the number of comparison sites is equal to the number of treatment sites, which again, is a conservative assumption.

Table 2 provides the crash rate assumptions used for total, injury and fatal, and run-off-road plus fixed-object crashes based on data from California, North Carolina, and Ohio. The project team obtained these rates by taking the before crash rate from the treated sites and reducing them by 25 percent. This was based on the suggestion in Bahar to account for possible bias due to regression-to-the-mean (RTM).[16] Because the sample of realignments is limited, the project team used an overall crash rate instead of individual rates from different States.

Table 2. Before-period crash rate assumptions.

Crash Type	Crash Rate per mi-yr
Total	4.47
Injury and Fatal	2.46
Run-off-road plus fixed-object	2.98

Table 3 provides estimates of the required number of before- and after-period mile-years (mi-yr) for statistical significance at both a 90- and 95-percent confidence levels. Because the safety effects of realignment depend on many factors, including the specific change in the radius from the before to the after period, the expected reduction values in the table need to reflect the expected change in radius from the before to the after periods. Based on the initial data that the team obtained from the three States, the average radius in the before period was about 400 ft, the average radius in the after period was about 1,000 ft, and the average curve length was about 0.15 mi. Using this information and results from Zegeer et al. and Bauer and Harwood, the CMF for total crashes for this change is expected to range from 0.65 to 0.75, i.e., a 25- to 35-percent reduction in total crashes.[5,9] The reduction for injury and fatal crashes and run-off-road crashes could be higher.

Table 3. Minimum required before-period mi-yr.

Crash Type and Expected Percent Reduction in Crashes	95-Percent Confidence	90-Percent Confidence
All 20	58	41
All 30	**21**	**15**
All 40	9	6
Injury and fatal 20	106	75
Injury and fatal 30	**38**	**27**
Injury and fatal 40	17	12
Run-off-road plus fixed-object 20	87	62
Run-off-road plus fixed-object 30	**31**	**22**
Run-off-road plus fixed-object 40	14	10

Note: Assumes equal number of mi-yr for treatment and comparison sites and equal length of before and after periods. Bold text indicates recommended sample size.

The minimum sample indicates the level for which a study seems worthwhile; that is, it is feasible to detect with the level of confidence the largest effect that one may reasonably expect based on current knowledge about the strategy. The project team based these sample size calculations on the methodology in Hauer and on specific assumptions regarding the number of crashes per mile and years of available data.[15] Mi-yr are the number of miles where the strategy was implemented, multiplied by the number of years of data before or after implementation. For example, if a State implemented a strategy over 10 mi, and data are available for 4 yr since implementation, then there is a total of 40 mi-yr of after-period data available for the study.

In table 3, bold text indicates the sample size values recommended in this study. The project team recommends these values based on the likeliness of obtaining the estimated sample size as well as the anticipated effects of the treatment. As noted, the sample size estimates provided are conservative in that the state-of-the-art EB methodology proposed for the evaluations would require fewer sites than the less robust conventional before–after study with a comparison group that had to be assumed for the calculations. Estimates may be predicted with greater confidence, or a smaller reduction in crashes will be detectable, if there are more site-years of data available in the after period.

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

The standard deviations of the estimated percent change in safety describe the statistical accuracy attainable for a given sample size. From this, one can estimate p-values for various sample sizes and expected change in safety for a given crash history based on the method in Hauer.[16]

For the available data in the three States in this evaluation, the research team estimated the minimum percentage changes in crash frequency that could be statistically detectable at 90- and 95-percent significance levels (see table 4). The results indicate that the data should be able to detect the recommended crash reduction values from table 3 if such an effect were present. Using these results, the authors decided to proceed with the evaluation using the data available at that time.

Table 4. Sample analysis for crash effects.

Crash Type	**Mi-yr in Before Period**	**Mi-yr in After Period**	**Minimum Percent Reduction Detectable for Crash Rate Assumption* *P* = 0.10**	**Minimum Percent Reduction Detectable for Crash Rate Assumption* *P* = 0.05**
Total	33	19	25	29
Injury and fatal	33	19	32	36
Run off road plus fixed object	33	19	30	34

Note: Results are to nearest 1 percent.
*Crash rate assumption is based on crash rates in table 3.

CHAPTER 4. METHODOLOGY

This methodology accounts for RTM using a reference group of similar but untreated sites, giving it a reputation for being especially rigorous. In the process, the project team uses safety performance functions (SPFs) to address the following issues:

- Overcoming the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- Accounting for time trends.
- Reducing the level of uncertainty in the estimates of safety effect.
- Properly accounting for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

The methodology also provides a foundation for developing guidelines for estimating the likely safety consequences of a contemplated strategy. Researchers can use the SPFs for roadways that have not undergone a curve realignment with observed crash histories to estimate the number of crashes without treatment. Researchers can then apply the CMFs developed to this number to estimate the number with treatment.

Figure 3 shows the equation used in the EB approach to find the estimated change in safety for a given crash type at a site.

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

Figure 3. Equation. Estimated change in safety.

Where:

λ = expected number of crashes that would have occurred in the after period without the strategy.

π = number of reported crashes in the after period.

In estimating λ, the effects of RTM and changes in traffic volume are explicitly accounted for using SPFs, which relate crashes of different types to traffic flow and other relevant factors for each jurisdiction based on untreated sites (reference sites). Researchers can calibrate annual SPF multipliers to account for temporal effects on safety, such as variation in weather, demography, and crash reporting.

In the EB procedure, researchers first use the SPF to estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the one being analyzed (i.e., reference sites). The sum of these annual SPF estimates (P) is then combined with the count of crashes (x) in the before period at a strategy site to obtain an estimate of the expected number of crashes (m) before strategy. Researchers then calculate this estimate of m using the equation in figure 4.

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

Figure 4. Equation. EB estimate of expected crashes.

Where *w* is estimated from the mean and variance of the SPF estimate using the equation in figure 5.

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

Figure 5. Equation. EB weight.

Where *k* is the constant for a given model and is estimated from the SPF calibration.

In estimating the SPF, a negative binomial distributed error structure is assumed with *k* being the overdispersion parameter of this distribution.

A factor is then applied to *m* to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period divided by *P*, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance of λ.

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

The index of effectiveness (θ) is estimated using the equation in figure 6.

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

Figure 6. Equation. Index of effectiveness.

The standard deviation of θ is given by the equation in figure 7.

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

Figure 7. Equation. Standard deviation of index of effectiveness.

The percent change in crashes is calculated as $100(1 - \theta)$; thus, a value of $\theta = 0.70$ with a standard deviation of 0.12 indicates a 30-percent reduction in crashes with a standard deviation of 12 percent.

CHAPTER 5. DATA COLLECTION

SITE IDENTIFICATION

The initial list of potential treatment sites was assembled based on information obtained from the TAC. The State safety engineers provided lists of curve-related projects that were either changes in horizontal radius or changes in superelevation of the curve. Given the focus of this evaluation, the team pursued only those projects involving an increase to horizontal radius. The State personnel also provided a date when they realigned the curve, typically presented as the construction start date and construction end date.

The following five States initially provided lists of curves where they had increased the radius:

- California—4 sites (supplemented with others as described below).
- Kentucky—16 sites.
- North Carolina—11 sites.
- Ohio—15 sites.
- South Carolina—6 sites.

California staff provided a list of four sites of curve realignments. The project team used the State Safety Improvements Project Database developed by the Highway Safety Information System (HSIS) to identify an additional 32 curve realignment projects in California. That database listed no additional curve realignment projects for North Carolina or Ohio.

Figure 8 presents an example of a horizontal curve that a State realigned. The solid red line on the aerial image illustrates the old alignment.

Source: Esri, DigitalGlobe, Earthstar Geographics, CNES/Airbus DS, GeoEye, USDA FSA, USGS, Getmapping, Aerogrid, IGN, IGP, and the GIS User Community.

Figure 8. Photo. Example of horizontal curve realignment.

The project team focused on sites in California, North Carolina, and Ohio, because these States represented some of the largest sample sizes, and all three of these States have data that are available through HSIS. The use of HSIS data was an advantage not only because it facilitates the process of obtaining the crash and roadway data, but also because it enabled the team to obtain annual values for the traffic volume.

The project team identified reference sites by visually inspecting the roadway network at the area of each treatment curve and selecting one or two other curves nearby on the same route as reference curves. The team preferred curves with smaller radii in order to better match the "before" condition of the treatment sites. The team inspected a timeline of aerial imagery to ensure that no significant changes had taken place at these reference curves. The project team used the same timeline of imagery to verify (and occasionally correct) the installation year for the treatment sites.

ROADWAY CHARACTERISTICS AND TRAFFIC VOLUME

The project team used HSIS to obtain data on roadway characteristics and traffic volume. Although the States provided location data for the treated curves, it was often fairly general information, such as the milepost range for an entire roadway project, or simply a description (e.g., "SR 1100 from 0.4 mile to 0.2 mile west of US 13 Bypass, west of Windsor"). In order to request data from HSIS, the team had to determine the exact start and end mileposts of the treatment.

The team first located the treatment and reference sites in Google® Earth™, then overlaid that file on a geographic information system (GIS)-based road network from each State. The project team used the GIS road file to identify the start and end mileposts of each curve, as well as verify or obtain other pieces of data that they needed to identify the road section, such as route number and county. This process was fairly straightforward for sites in Ohio and North Carolina. The process for the California sites proved to be more complicated, because California identifies route sections by a complex combination of district, route, route suffix, county, postmile prefix, and postmile. The main issue for this project was that the GIS road file did not contain all these required data. The team worked with several members of the California Department of Transportation (Caltrans) staff to resolve this issue and accurately identify the treatment and reference curves on the California network.

HSIS requested the following roadway characteristics:

- Right and left shoulder width.
- Right and left shoulder type.
- Number of lanes.
- Rural/urban designation.
- Annual average daily traffic.

Given the large range of installation dates of the curve realignments, the team requested these data for the following time spans:

- California—1997 to 2011.
- North Carolina—2003 to 2013.
- Ohio—2000 to 2013.

In addition to data from HSIS, the team also collected data from the GIS road files and aerial imagery (Google® Earth™). These included the following:

- **Curve radius before and after.** The team used a GIS-based tool to measure the radius of the curve before and after realignment. Typically, the GIS linework represented either the before or after alignment (depending on how recently the realignment occurred and how up-to-date the GIS file was). The team used aerial imagery to obtain a measurement of the other period.

- **Distance to previous and next curve.** The team noted the distance from the start of the study curve to the end point of the next curve and the distance from the end of the study curve to the start point of the next curve. They collected this to enable the analysis to distinguish isolated curves from grouped curves.

- **Intersection in curve.** Some curves had an intersection of a public road in the curve section or very near the endpoints of the curve. The team noted this intersection presence as a data variable.

Table 5 provides a list of all treatment sites (curves where radius was modified) with the before and after radius measurements. Table 6 provides a summary of characteristics for both treatment and reference sites. Appendix A provides a complete list of all site characteristics for treatment and reference sites.

Table 5. Before and after curve radii for treatment sites.

Treatment Curve ID	Curve Radius Before (ft)	Curve Radius After (ft)	Amount of Radius Increase (ft)	Proportion of After to Before Radius
CA002A	110	362	252	3.29
CA018-A	157	1,588	1,431	10.11
CA002B	158	446	288	2.82
OH001	177	955	778	5.4
CA030-A	187	20,000*	19,813	106.95
CA018-B	190	1,079	889	5.68
CA018-C	190	1,657	1,467	8.72
CA018-D	200	441	241	2.21
NC008	206	351	145	1.7
CA022	228	446	218	1.96
CA011	229	1,640	1,411	7.16
OH011	259	700	441	2.7
OH012	282	800	518	2.84
NC006	307	512	205	1.67
CA003-A	335	500	165	1.49
NC004-A	337	433	96	1.28
NC004-B	380	415	35	1.09
OH004	387	1,069	682	2.76
CA013-D	390	809	419	2.07
NC002-C	398	698	300	1.75
CA026-D	405	1,902	1,497	4.7
CA013-2	419	684	265	1.63
CA013-C	429	602	173	1.4
CA013-A	440	742	302	1.69
NC003	445	842	397	1.89
NC002-A	470	20,000*	19,530	42.55
CA030-B	475	875	400	1.84
CA027	500	1,200	700	2.4
CA028-C	500	1,312	812	2.62
CA034-B	533	1,409	876	2.64
CA005	545	872	327	1.6
NC005	554	818	264	1.48
CA015-A	566	1,102	536	1.95
NC009	570	1,023	453	1.79
NC010	579	1,146	567	1.98
CA025-B	851	4,495	3,644	5.28
CA025-A	903	1,312	409	1.45
CA034-A	964	20,000*	19,036	20.75
CA003-D	1,781	10,000	8,219	5.61

*Locations with a radius of 20,000 in the after period are those where the curve was realigned to a straight segment. Instead of showing a radius of infinity, the table shows a radius of 20,000.

Table 6. Site characteristics summary statistics.

Site Characteristic	Range of Values in Data for Treatment Sites	Range of Values in Data for Reference Sites
Curve radius (ft) before realignment	Range: 110 to 1,780	Range: 75 to 2,900
Curve radius (ft) before realignment	Average: 430	Average: 600
Curve radius (ft) after realignment	Range: 350 to 4,500 (and essentially straight tangent for four sites with radii over 10,000)	N/A
Curve radius (ft) after realignment	Average (including radii over 10,000): 2,700	N/A
Curve radius (ft) after realignment	Average (excluding radii over 10,000): 1,000	N/A
Number of lanes	Range: 2 to 3	Range: 2 to 3
Shoulder width	Range: 1 to 8	Range: 1 to 9
Shoulder width	Average: 3.9	Average: 3.7
AADT	Range: 440 to 12,000	Range: 400 to 12,000
AADT	Average: 3,480	Average: 2,600

N/A = not applicable.

CRASH DATA

The project team obtained crash data from HSIS for each year of the study period. HSIS provided individual crash records; the team aggregated these into counts by year for each curve. Table 7 provides a list of the types of crashes collected for this study.

The project team assigned crashes to each segment according to the start and end mileposts of the curve (i.e., the point of curvature and point of tangency). In relying on mileposts, the authors recognize the potential for data error, specifically crash locating, when working with sections/curves of small length. In addition, crash positions in rural areas especially can vary in accuracy because of fewer landmarks and intersections. Appendix B provides a further discussion of this issue.

For treatment sites, the realignment of the curve from a sharp curve to a flatter curve resulted in a longer length. The team used mileposts from the after period for crash data. This means that crashes from the before period for the treatment site would include some amount of tangent section on either end of the curve. Another option would be to limit crashes in the before period to only those crashes occurring on the curve. However, that would mean a comparison from before to after periods of two different lengths—a shorter length in the before period and a longer length in the after period. The team felt this approach would have an inherent bias because of the length difference. Table 8 provides the summary statistics regarding the crash data.

Table 7. Crash types and descriptions.

Crash Type	Description	Coding Notes
Total	Total crashes occurring within the curve.	Availability of certain years of crashes depended on the State data in HSIS.
Fatal and injury	Fatal or injury crashes occurring within the curve.	Any injury level (A, B, and C) were included.[1]
Run-off-road and fixed-object	Run-off-road and fixed-object crashes occurring in the curve.	This crash count combined crashes coded as run-off-road, fixed-object, or hit object into one total.
Head-on	Head-on crashes occurring in the curve.	N/A
Dark	Dark crashes occurring in the curve.	Included any dark time crashes, lighted or unlighted roads.
Sideswipe	Sideswipe crashes occurring in the curve.	Included sideswipes in the same or opposing directions.
Wet	Wet crashes occurring in the curve.	Included rain, sleet, snow, or ice.

[1]Measured on the KABCO scale, which is used to represent injury severity in crash reporting: K is fatal injury, A is serious injury, B is minor injury, C is possible injury, and O is property damage only.
N/A = not applicable.

Table 8. Crash data summary statistics.

Variables	Treatment Sites Before	Treatment Sites After	Reference Sites
Number of sites	39	39	56
Years of data	220	130	610
Mi-yr	33.2	18.8	55.8
Total crashes per year	198	29	214
Injury and fatal per year	109	10	86
Run-off-road plus fixed-per-year	132	11	104
Head-on per year	10	0	5
Sideswipe per year	11	2	17
Dark per year	61	13	53
Wet per year	88	7	78

CHAPTER 6. DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

This section presents the single SPF developed. The project team used the SPF in the EB methodology to estimate the safety effectiveness of this strategy. The team used generalized linear modeling to estimate model coefficients, assuming a negative binomial error distribution. This is consistent with the state of research in developing these models. In specifying a negative binomial error structure, the team iteratively estimated the dispersion parameter, *k*, from the model and the data. For a given dataset, smaller values of *k* indicate relatively better models.

The project team combined all States together to estimate the SPF with a separate intercept term estimated for each State. The team only calibrated the SPF for total crashes because the other crash type sample sizes were small. For other crash types, they applied the SPF for total crashes with a multiplier equal to the number of crashes of the type of interest divided by the number of total crashes at the reference sites. The project team developed the following multipliers for each crash type:

- Injury and fatal: 0.40.
- Run-off-road and fixed-object: 0.49.
- Head-on: 0.02.
- Sideswipe: 0.08.
- Dark: 0.25.
- Wet: 0.36.

Ideally, the project team would calibrate the SPF for each year to reflect time trends in crashes not related to the treatment of interest. However, the reference site data comprise only 214 crashes in total, ranging from 2 to 28 in a single year. With such low yearly crash totals, it was not feasible to calibrate the SPF each year to reflect potential time trends.

To assess the entire impact on safety of curve realignment to a larger radius curve, it is necessary to consider a study area that extends beyond the limits of the smaller radii curve. When changing from a smaller to a larger radius, the reconstruction removes tangents on either side of the curve. The study area therefore needs to include the entire roadway travelled to get from the beginning to the ending of the largest curve radius under consideration.

Because the reference group consisted of only curved segments, the project team adjusted the SPF predictions in order to consider the expected crash frequencies on the tangent segments associated with the smaller radius curve in the before period that were subsequently removed.

For this adjustment, the project team first applied the SPF calibrated from the reference group to the tangent segments as if the tangent segments removed had the same curvature as the curved segment to which they were adjacent. Then, they adjusted this estimate by an estimated ratio of expected crashes on a tangent to expected crashes on a curve.

The adjustment made use of the model developed by Zegeer et al., which is the basis of the CMF for horizontal curvature on two-lane roads in the HSM.[8,9] Figure 9 shows the model prediction for the number of crashes per year.

$$A = (1.55L + 0.014D - 0.012S) \times C \times 0.978^{w-30}$$

Figure 9. Equation. Zegeer et al. model for crash prediction.[9]

Where:

A = expected crash frequency per year.
L = length of the curve in mi.
D = degree of curvature.
S = one if spirals exist and zero otherwise.
V = AADT.
W = roadway width in ft.

The project team did not know if spiral transitions existed at the treated curves, so they assumed that spiral transitions are not present. Recognizing that the traffic volume and road width remain unchanged and the degree of curvature for a tangent is 0, they estimated the adjustment as shown in figure 10.

$$\frac{A_{tangent}}{A_{curve}} = \frac{1.552L}{1.552L + 0.014D}$$

Figure 10. Equation. Adjustment for tangent and curve difference.

Where:

L = total tangent length.
D = degree of curve of the curved segment adjacent to the tangents.

The estimate of crashes for the before-period conditions, which include both the curved and tangent segments removed, is then shown in figure 11.

$$Crashes\ per\ year = (SPF\ applied\ to\ curved\ segment) + \left(\frac{A_{tangent}}{A_{curve}}\right)(SPF\ applied\ to\ tangent\ segments\ removed)$$

Figure 11. Equation. Estimate of crashes for before-period conditions.

The form of the SPF developed using the reference group sites, which is presented in table 9, is shown in figure 12.

$$Crashes\ per\ year = exp^{(a+b)} AADT^{c} Length^{d} exp^{(e \times RAD)}$$

Figure 12. Equation. Form of SPF.

Where:

AADT = annual average daily traffic volume.
Length = length of horizontal curve in miles.
RAD = radius of horizontal curve in miles.
a, b, c, d, e = parameters estimated in the SPF calibration process (*a* is the intercept; *b* represents a set of coefficients for each State).

Table 9. SPF parameter estimates with standard errors.

State	Parameter	Value	Standard Error
All	*a*	–0.8951	1.6329
California	*b*	–1.2198	0.3352
North Carolina	*b*	–0.7103	0.3881
Ohio	*b*	0.0000	N/A
All	*c*	0.4424	0.1509
All	*d*	0.9659	0.2943
All	*e*	–3.7331	1.6331
All	*k*	0.4527	0.1555

N/A = not applicable.

CHAPTER 7. BEFORE–AFTER EVALUATION RESULTS

AGGREGATE ANALYSIS

Table 10 provides the estimates of expected crashes in the after period without treatment, the observed crashes in the after period, and the estimated CMF and its standard error for all crash types considered. Although all crash categories have low sample sizes of crashes, the project team did not analyze head-on and sideswipe crashes because of the very low number of crashes of these types at the study sites. The team based the CMFs reported in table 10 on all 39 locations that the States realigned. The project team also estimated the CMFs after removing the three locations that the States realigned to straight segments, and the resulting CMFs were almost identical to the ones reported in table 10.

Table 10. Aggregate CMF results.

Metric	Total	Injury and Fatal	Run-Off-Road Plus Fixed-Object	Dark	Wet-Road
EB estimate of crashes expected in after period without strategy	91.43	38.11	50.29	21.90	33.88
Count of crashes observed in after period	29	10	11	13	7
Estimate of CMF	**0.315**	**0.259**	**0.216**	**0.584**	**0.204**
Standard error of estimate of CMF	0.064	0.086	0.068	0.176	0.079

Note: Bold text indicates that CMFs are statistically significant at the 95-percent confidence level.

The results indicate large reductions that are statistically significant at the 95-percent confidence level for all crash types analyzed. It is important to note, however, that the sample size of after-period crashes is small.

The results pertain to a range of site characteristics, the most important of which is the range of before and after curve radii. The average degrees of curve in the before and after periods were 18.1 and 6.9, respectively (the degree of curve is mentioned here instead of radius because three of the curves were realigned to straight segments, which have undefined radius values but have a degree of 0.0). The average central angle of the curves was approximately 42 degrees. As indicated earlier, the average AADT at these sites was about 3,500. The average length of the segments the States realigned was 0.1455 mi.

One of the intents of this evaluation was to compare the results of the before–after evaluations with published results from cross-sectional studies. The project team used two approaches to do this comparison. The team only did a comparison for the total crash CMF. The first approach involved entering the average radii in the before and after periods along with the average segment length of the study sites to estimate the CMFs based on the equations given in Zegeer et al. (for total crashes) and Bauer and Harwood (for injury and fatal crashes).[4,8] Based on the equation given in Zegeer et al., and assuming no spiral transition curves, the ratio of the CMF for a curve with a degree 6.9 to a curve with degree 18.1 is 0.672 for total crashes.[8] For the same conditions, the CMFunction in Bauer and Harwood estimate a CMF of 0.784 for injury and fatal crashes.(4)

The first approach is simplistic in that it does not specifically account for the fact that the relationship between the CMF and curve radius and segment length is non-linear in both Zegeer et al. and Bauer and Harwood.(4,8) To address this limitation, the project team identified a second approach. The second approach involved the following steps:

1. For each treated site, calculate the CMF based on Zegeer et al. and Bauer and Harwood.(4,8)

2. Multiply the EB expected crashes in the after period for each site (this is the expected crashes had the treatment not been implemented) with the CMFs from Zegeer et al., (1992) and Bauer and Harwood (2014). This product gives the expected crashes with the treatment for each site based on the CMFs from these two studies.

3. Calculate the sum of the expected crashes with the treatment for all sites based on the two studies.

4. The ratio of the expected crashes with the treatment to the EB expected crashes without the treatment provides an approximate CMF associated with the equations from the two studies.

Based on the second approach, the CMF from Zegeer et al. was 0.699 (for total crashes), and the CMF from the Bauer and Harwood was 0.736 (for injury and fatal crashes).(4,8)

The CMFs from the previous studies are higher than the CMFs of 0.315 and 0.259 that were estimated using the before and after EB evaluation for total and injury and fatal crashes, respectively. However, as mentioned earlier, the project team based this before–after evaluation on a limited sample, and readers should consider it with caution.

DISAGGREGATE ANALYSIS

The expected CMF value for a specific site could vary significantly based on its characteristics. This is the object of the disaggregate analysis. The focus of the disaggregate analysis was on total crashes due to the small number of after-period crashes. Since the CMF could be a function of the site characteristics (e.g., change in the radius or degree of curvature due to realignment), an attempt was made to further analyze the data to develop a CMFunction for the purposes of estimating a site-specific CMF.

The traditional approach for estimating CMFunctions includes the use of the CMF value as the dependent variable and site/treatment characteristics as independent variables. Figure 13 presents one way to express this.

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

Figure 13. Equation. General form for CMFunction.

Where *f* represents a generic function.

This CMFunction could then be estimated as a regression equation. Elvik recommended that the variance of the CMF needs to be considered in this estimation.(17) The inverse of the variance is typically introduced as a weight in a weighted regression model. In other words, for an observation (or site) whose CMF is CMF_i with a variance of $Var(CMF_i)$, the weight will be $1/Var(CMF_i)$. For linear regression, this would be appropriate.

Some recent studies have recommended the use of a different model form such as a lognormal model that would ensure the predicted CMF from a CMFunction would always be greater than zero. In the case of the log-normal model, Bonneson showed that the appropriate weight for a weighted log-normal regression model would instead be $[CMF_i/Var(CMF_i)]$.(18) This is because, based on figure 7, the $Var(CMF_i)$ is not independent of CMF_i, i.e., lower CMFs values would tend to have lower variances as well.

For either the normal regression or lognormal regression models with weights, reliable estimates of CMFs and their variances are necessary. In order to have reliable estimates of these parameters, researchers often combine sites with similar characteristics, especially if there are sites where the reported crashes in the after period are zero. However, this aggregation can lead to loss of useful information. In this study, the project team proposed a different approach to overcome the disadvantage of losing information due to aggregation. This approach involves rewriting figure 13 as follows in figure 14.

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

Figure 14. Equation. Rewritten form of CMFunction.

Where:

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

Figure 14 can again be rewritten as follows in figure 15.

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

Figure 15. Equation. Another rewritten form of CMFunction.

Written in this form, it is possible to estimate this equation as a count data model (such as Poisson or negative binomial model) with π as the dependent variable and λ as the offset. This approach is similar to estimating an SPF with the goal of predicting the number of crashes per mile, where crash frequency is included as the dependent variable and section length is included as the offset. One limitation with this approach is that the offset is an estimated value from the EB procedure with a variance. There has been some limited research in traffic safety on the implications of errors/variance in the independent variables, but further research is necessary, possibly using simulation.

The independent variables for the CMFunction included the following:

- AADT.
- Difference/ratio between the after and before radius/degree of curvature.
- Central angle of the curve.

Figure 16 is the functional form for the CMFunction that was estimated using negative binomial regression.

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

Figure 16. Equation. Functional form for CMFunction.

Where a_0 represents the intercept, and a_1 through a_n represent the coefficients for independent variables X_1 through X_n.

In three locations, States aligned the curved sections to be a straight segment, indicating a radius of infinity in the after period. However, expressing the curvature as a degree of the curve (5,730/radius in ft) instead of radius would allow this study to include these sites the States realigned to a straight segment, since the degree of curvature for a straight segment is 0. To address this issue, the project team explored the following two options:

- Option 1: Include all 39 sites.
- Option 2: Exclude the three sections that the States realigned to a straight segment (i.e., include data from 36 sites).

Multiple CMFunctions were considered, including the consideration of the ratio of degree of curvature instead of the difference in degree of curvature from the before to the after periods (in Option 1), and the ratio the radius (and/or curvature) instead of the difference in radius (and/or curvature) from the before and after periods (in Option 2). The best CMFunction was from Option 2, which is presented in table 11.

Table 11. Option 2 CMFunction for total crashes.

Variable	Estimate (Standard Error)
Intercept	–3.4775 (3.7253)
ln(AADT)	0.5299 (0.4219)
Central Angle	–0.0342 (0.0162)
Radius after – radius before (mi)	–1.6628 (1.5026)
Overdispersion parameter (*k*)	0.3951 (0.5239)

The estimated parameters indicate that the CMF increases as AADT increases but decreases as the difference between the radii of the two curves increases and as the central angle increases. Many of the parameters have a high standard error including the overdispersion parameter. If the true value of the overdispersion parameter were zero, then a Poisson model would be appropriate. The project team calibrated the same model with a Poisson error distribution but showed little change in the parameter estimates.

Readers should not consider the CMFunction robust because the project team based it on a small sample of sites. In checking the predicted CMFs for individual sites, some illogical predictions do result, such as predicting a large increase in crashes at high AADT sites. For these reasons, the project team does not recommend applying the CMFunction developed. However, the general indications of the CMFunction may be useful in a contemplated curve realignment, in particular that safety benefits may be greater for curves with a larger central angle and where the difference in radius between the before- and after-period conditions is larger. This is consistent with previous cross-sectional studies (e.g., Zegeer et al., Bauer and Harwood) that indicate that the safety benefits due to realignment would be greater with a larger increase in radius from the before to the after periods.[4,8]

CHAPTER 8. ECONOMIC ANALYSIS

The project team undertook the following steps for the economic analysis:

1. The research team estimated the change in property-damage-only (PDO) crashes using the EB predicted crashes in the after period and the actual crashes in the after period for total and injury and fatal crashes.

2. Using the number of mi-yr in the after period, the research team determined the change in PDO crashes per mi-yr and the change in injury and fatal crashes per mi-yr. The team estimated the expected benefit due to the realignment as 1.495 injury and fatal crashes per mi per yr and 1.826 PDO crashes per mi per yr.

3. For the benefit calculations, the project team used the most recent FHWA mean comprehensive crash costs disaggregated by crash severity and location type as a base.(19) They developed these costs based on 2001 crash costs and the unit cost (in 2001 U.S. dollars) for injury and fatal crashes and PDO crashes in rural areas was $206,015 and $7,800, respectively. The team updated this to 2015 dollars by applying the ratio of the U.S. Department of Transportation (USDOT) 2015 value of a statistical life of $9.4 million to the 2001 value of $3.8 million (USDOT 2015).(20) Applying this factor of 2.48 to the unit costs resulted in an aggregate 2015 unit cost of $510,446 for injury and fatal crashes and $19,326 for PDO crashes. The expected annual benefit due to the fewer crashes after realignment was $510,446 * 1.495 + $19,326 * 1.826, which totals approximately $798,507. Based on the suggestions from USDOT, the team conducted sensitivity analyses to obtain a low and high value for the benefits, and consequently a low and high value for the B/C ratios.

4. The research team estimated the annualized cost of the treatment, as shown in figure 17.

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

Figure 17. Equation. Determining annual cost.

Where:
C = treatment cost; based on information from North Carolina, the average realignment cost per mi was $3,121,599.
R = discount rate (as a decimal) and assumed to be 0.07.
N = expected service life (years) of 30 yr.

The annualized cost per year for realignment was $251,558.

5. The project team calculated the B/C ratio of the annual crash savings to the annualized treatment cost. The B/C ratio was 3.17:1, with a low of 1.75:1 to a high of 4.38:1.

CHAPTER 9. SUMMARY AND CONCLUSIONS

This evaluation used the EB before–after method in order to evaluate the safety aspects of curve realignment on rural, two-lane roads. Not surprisingly, the sample size in this evaluation was limited because realignments are expensive. However, previous studies used cross-sectional regression methods that may not always provide reliable CMFs.

Table 12 presents the recommended CMFs for curve realignment on rural, two-lane roads. The results pertain to a range of site characteristics, the most important of which is the range of before and after degree of curve. The average degrees of curve in the before and after periods were 18.1 (with a minimum of 3.2 and a maximum of 52.1) and 6.9 (with a minimum of 0.0 and a maximum of 16.3), respectively. The average central angle of the curves was approximately 42 degrees (with a minimum of 1 and a maximum of 117). The average AADT at the treated sites was about 3,500 (with a minimum of 465 and a maximum of 11,917). The average length of the realigned segments was 0.15 mi (with a minimum of 0.03 and a maximum of 0.60).

Table 12. Recommended CMFs.

Metric	Total	Injury and Fatal	Run-Off-Road Plus Fixed-Object	Dark	Wet-Road
Estimate of CMF	**0.315**	**0.259**	**0.216**	**0.584**	**0.204**
Standard error of estimate of CMF	0.064	0.086	0.068	0.176	0.079

Note: Bold text indicates that CMF is statistically significant at the 95-percent confidence level.

Estimated CMFunctions showed that safety benefits may be greater for curves with a larger central angle and where the difference in radius between the before- and after-period conditions is larger.

In addition to developing the CMFs using before–after evaluation, this study also compared the total crash CMF with the results from previous cross-sectional studies. The CMFs from this before–after evaluation are much lower than CMFs estimated by two previous cross-sectional studies. The CMFs from the cross-sectional studies were between 0.600 and 0.750 compared to the CMF of 0.315 derived from this before–after evaluation. The economic analysis revealed a B/C ratio of 3.17:1 with a range of 1.75:1 to 4.38:1.

LIMITATIONS

There are several recognized limitations to these findings, which are as follows:

- The sample size is limited. The project team recommends further studies with a larger set of sites.
- Typically, before–after evaluations using the EB method include annual calibration factors to account for time trends. However, the limited sample of sites and crashes in the reference group did not allow for the use of annual calibration factors. Given the substantial effects estimated for all crash types, it is unlikely that accounting for time trends would have materially affected the conclusions.

- This evaluation did not explicitly consider other changes that may have occurred at the same time that the States realigned the curves (e.g., changes to the roadside, including the clear zone). It is important to note that at least one of the previous cross-sectional studies did not account for changes to roadside or the shoulder.[4]

- The project team did not collect grade and vertical curvature of the subject segments. The team recognizes that, as shown in the work by Bauer and Harwood, the presence of a grade or vertical curve can affect the CMF of the change in horizontal curve radius.[4]

- The project team did not explicitly know of the presence of a spiral transition for each curve, though the total curve length and crash data would have included any spiral portion of road. The work by Zegeer et al. and presented in the HSM includes a factor for spiral presence.[8]

- This evaluation did not include information about chevrons or other types of delineation at the horizontal curves that States realigned. However, other previous cross-sectional studies also did not account for delineation of the curves.[4]

- The authors recognize the potential for data error, specifically crash locating, when working with sections/curves of small length. In addition, crash positions in rural areas especially can vary in accuracy. Appendix B provides a further discussion of this issue.

APPENDIX A. SITE DATA

The tables in this appendix provide the full characteristics and volume data on the sites used in the study. Table 13 provides a description of each data field and notes on how the project team coded each field. Table 14 provides the data for the treatment sites, and table 15 provides the data for the reference sites.

Table 13. Descriptions and coding of data fields.

Data Field	Description	Coding Notes
DCMF StudyID	Unique ID for each curve.	Concluding letter R mostly indicates reference site, but not always. Trust the "Treatment or Reference" column.
Segment length (mi)	Length of curve.	Distances are in miles.
State	State of origin.	There were three States—CA, NC, and OH.
Treatment or reference	Indicator of treatment or reference site.	
Curve radius before (ft)	Radius of curve before realignment.	Measurement was taken from estimated point of curve (PC) to estimated point of tangent (PT).
Curve radius after (ft)	Radius of curve after realignment.	Measurement was taken from estimated PC to estimated PT.
Last year of before period	Use all years up to and including this year for the before period (treatment sites).	This was determined based on the project construction start date.
First year of after period	Use all years after and including this year for the after period (treatment sites).	This was determined based on the project construction end date.
Distance to end milepost of previous curve (mi)	Distance in miles to previous curve (upstream according to mileposting).	This can be used to categorize curves as isolated or grouped. If the distance was over 0.5 mi, the exact distance was not always measured but listed as “>0.5.”
Distance to begin milepost of next curve (mi)	Distance in mi to next curve (downstream according to mileposting).	This can be used to categorize curves as isolated or grouped.
At or near intersection	Indicates whether an intersection occurred in or near the ends of the curve.	Unknown means the data was not collected for that site.
Speed limit	Speed limit in mph.	Only available for NC.
Right shoulder width	Right shoulder width in feet.	Only available for NC and CA.
Left shoulder width	Left shoulder width in feet.	Only available for NC and CA.
Number of lanes	Number of though lanes in curve.	Note that CA had some sections that were 3-lane.
AADT	AADT in vehicles per day (vpd) for the curve. Provided annually.	Availability of certain years of AADT depended on the State data in HSIS.

Table 14. Treatment site data by segment.

DCMF StudyID	Length (mi)	Curve Radius Before (ft)	Curve Radius After (ft)	Last Year of Before Period	First Year of After Period	Distance to End Milepost of Previous Curve (mi)	Distance to Begin Milepost of Next Curve (mi)	At or Near Intersection	Speed Limit	Right Shoulder Width (ft)	Left Shoulder Width (ft)	Lanes	Average AADT
NC002-A	0.1710	470	20,000	2004	2007	0.384	0.261	N	55	4	3	2	4,167
NC002-C	0.1430	398	698	2004	2007	0	0.667	N	55	4	4	2	2,608
NC003	0.1950	445	842	2009	2012	0.05	0.268	N	55	4	4	2	4,500
NC004-A	0.0600	337	433	2011	2013	0.064	0.147	N	45	3	3	2	11,917
NC004-B	0.0830	380	415	2011	2013	0.392	0.064	N	45	3	3	2	11,917
NC005	0.3150	554	818	2011	2014	0.55	0.363	N	55	6	6	2	3,042
NC006	0.1700	307	512	2011	2014	0.009	0.016	Y	55	4	4	2	1,942
NC008	0.0830	206	351	2007	2010	0.199	0.072	N	55	4	4	2	445
NC009	0.1090	570	1,023	2010	2013	0.063	0.258	Y	55	2	2	2	6,008
NC010	0.0800	579	1,146	2011	2013	>0.5	0.34	N	45	5	5	2	4,150
CA002A	0.0668	110	362	2009	2012	0.000	0.000	Unknown	–	2	2	2	2,720
CA002B	0.0250	158	445.5	2009	2012	0.000	0.041	Unknown	–	2	2	2	2,720
CA003-A	0.1095	335	500	2008	2012	0.054	0.000	N	–	2	2	2	2,246
CA003-D	0.3189	1,781	10,000	2008	2012	0.000	0.068	N	–	2	2	2	2,246
CA005	0.1290	545	872	2006	2010	0.372	0.074	Unknown	–	6	6	2	988
CA011	0.1303	229	1,640	2003	2006	0.345	0.577	N	–	6	2	2	3,400
CA013-2	0.1223	419	684	2004	2007	0.063	0.022	Unknown	–	4	4	3	6,004
CA013-A	0.0867	440	742	2005	2009	0.163	0.061	Unknown	–	4	4	3	6,145
CA013-C	0.1077	429	601.5	2005	2009	0.000	0.135	Unknown	–	4	4	3	6,145
CA013-D	0.1200	390	809	2005	2009	0.000	0.052	Unknown	–	4	4	3	6,145
CA015-A	0.1095	566	1,102	2005	2008	0.206	0.000	N	–	2	2	2	466
CA018-A	0.0600	157	1,588	2008	2012	0.040	0.000	Unknown	–	8	4	2	3,800
CA018-B	0.0700	190	1,079	2008	2012	0.017	0.000	Unknown	–	8	4	3	3,800
CA018-C	0.0700	190	1,657	2008	2012	0.000	0.000	Unknown	–	8	4	3	3,800

DCMF StudyID	Length (mi)	Curve Radius Before (ft)	Curve Radius After (ft)	Last Year of Before Period	First Year of After Period	Distance to End Milepost of Previous Curve (mi)	Distance to Begin Milepost of Next Curve (mi)	At or Near Intersection	Speed Limit	Right Shoulder Width (ft)	Left Shoulder Width (ft)	Lanes	Average AADT
CA018-D	0.0700	200	441	2008	2012	0.000	0.000	Unknown	–	8	4	3	3,800
CA022	0.0752	227.5	446	2008	2011	0.000	0.000	Unknown	–	4	2	2	3,975
CA025-A	0.1754	902.5	1,312	2005	2009	0.517	0.124	N	–	8	8	2	1,669
CA025-B	0.3341	850.5	4,495	2005	2009	0.124	0.092	Y	–	8	8	2	1,669
CA026-D	0.1100	405	1,902	2006	2010	0.000	0.000	Y	–	6	6	2	753
CA027	0.1246	500	1,200	2004	2008	0.100	0.150	N	–	2	2	2	1,055
CA028-C	0.0455	500	1,312	2006	2010	0.000	0.180	Unknown	–	1	1	2	2,535
CA030-A	0.0432	187	20,000	2005	2010	0.000	0.000	Unknown	–	2	2	2	466
CA030-B	0.0703	475	875	2005	2010	0.000	0.000	Unknown	–	2	2	2	466
CA034-A	0.6000	964	20,000	2008	2011	0.030	0.000	N	–	2	2	2	1,181
CA034-B	0.4500	532.5	1,409	2008	2011	0.000	0.265	N	–	8	2	3	1,181
OH001	0.2080	177.12	954.93	2004	2006	1.329	0.347	Y	–	–	–	2	6,143
OH004	0.1540	387.04	1,069.28	2009	2012	2.69	0.357	N	–	–	–	2	3,396
OH011	0.1080	259.12	700	2003	2005	0.32	>.5	Y	–	–	–	2	3,579
OH012	0.1700	282.08	800	2007	2009	0.695	0.52	N	–	–	–	2	2,368

–No data.

Table 15. Reference site data by segment.

DCMF StudyID	Length (mi)	Curve Radius (ft)	Distance to End Milepost of Previous Curve (mi)	Distance to Begin Milepost of Next Curve (mi)	At or Near Intersection	Speed Limit	Right Shoulder Width (ft)	Left Shoulder Width (ft)	Lanes	Average AADT
NC002-R	0.0650	304	0.458	0.31	Y	55	4	4	2	2,608
NC004-R	0.0940	538	0.496	0.392	N	45	8	8	2	11,917
NC005-R	0.1300	1,141	0.363	NA	N	55	6	6	2	3,042
NC007-R	0.0870	673	0.088	0.196	N	55	6	6	2	2,142
NC008-R1	0.0610	168	0.05	0.061	N	55	4	4	2	442
NC008-R2	0.0650	170	0.068	0.052	N	55	4	4	2	428
NC009-R	0.1010	967	0.087	0.074	N	55	2	2	2	6,008
NC010-R	0.0450	730	0.405	0.637	N	45	5	5	2	4,150
NC001-R	0.0540	248	0.29	>0.5	N	55	4	4	2	917
NC003-R	0.1890	741	0.332	0.209	Y	55	4	4	2	3,808
NC006-R	0.0590	918	0.059	0.341	N	55	4	4	2	1,121
CA002R1	0.0470	144	0.034	0.034	Unknown	–	2	2	2	2,720
CA002R2	0.0532	75	0.022	0.030	Unknown	–	8	8	2	2,663
CA003R1	0.0598	324	0.075	0.000	Unknown	–	2	2	2	2,246
CA003R2	0.0744	516	0.053	0.100	Unknown	–	4	2	2	1,808
CA005R1	0.0824	503	0.097	0.384	Unknown	–	6	6	2	988
CA005R2	0.0496	404	0.102	0.131	Unknown	–	6	6	2	988
CA006	0.1900	2,938	0.542	4.600	Y	–	4	4	2	2,878
CA006R	0.1400	2,181	0.660	0.542	Unknown	–	4	4	2	3,257
CA011R	0.1015	1,341	0.113	0.340	Unknown	–	6	2	2	3,400
CA013R1	0.1000	430	0.000	0.140	Unknown	–	4	4	3	6,209
CA013R3	0.0621	420	0.028	0.108	Unknown	–	4	4	3	6,145
CA015R1	0.0907	940	0.179	0.284	Unknown	–	2	2	2	466
CA015R2	0.0483	427	0.056	0.021	Unknown	–	2	2	2	466
CA018R1	0.0811	234	0.027	0.072	Unknown	–	4	4	2	3,975

DCMF StudyID	Length (mi)	Curve Radius (ft)	Distance to End Milepost of Previous Curve (mi)	Distance to Begin Milepost of Next Curve (mi)	At or Near Intersection	Speed Limit	Right Shoulder Width (ft)	Left Shoulder Width (ft)	Lanes	Average AADT
CA018R2	0.0650	298	0.010	0.009	Unknown	–	4	4	2	3,975
CA018R3	0.0981	210	0.000	0.000	Unknown	–	4	4	2	3,975
CA018R4	0.0697	137	0.000	0.000	Unknown	–	4	4	3	3,975
CA022R	0.0360	309	0.000	0.026	Unknown	–	4	2	2	3,975
CA025R2	0.2000	1,443.5	0.070	0.180	Unknown	–	9	9	2	1,669
CA026R1	0.0636	332	0.052	0.000	Unknown	–	2	2	2	401
CA026R2	0.0508	179	0.000	0.020	Unknown	–	2	2	2	401
CA026R3	0.0754	345	0.000	0.086	Unknown	–	2	2	2	401
CA027R	0.4379	1,993	0.100	0.192	Unknown	–	2	2	2	1,037
CA028R1	0.0811	592	0.087	0.000	Unknown	–	2	2	2	3,200
CA028R2	0.0900	1,270	0.302	0.036	Unknown	–	1	1	2	2,618
CA028R3	0.0498	580	0.170	0.150	Unknown	–	3	3	2	1,871
CA029	0.2155	340	3.083	1.467	N	–	4	4	2	7,068
CA029R1	0.0854	336	0.082	0.032	Unknown	–	4	4	2	4,938
CA029R2	0.1076	441	0.000	0.000	Unknown	–	2	2	2	4,938
CA030R1	0.0473	197	0.000	0.000	Unknown	–	2	2	2	466
CA030R2	0.0960	335	0.152	0.000	Unknown	–	2	2	2	466
CA032R1	0.0445	253	0.000	0.000	Unknown	–	3	3	2	719
CA032R2	0.0300	241	0.022	0.009	Unknown	–	6	6	2	719
CA034R1	0.1300	480	0.050	0.120	Unknown	–	2	2	2	1,181
CA034R2	0.1200	467	0.080	0.000	Unknown	–	2	2	2	1,181
CA034R3	0.2000	925	0.060	0.400	Unknown	–	2	2	2	1,181
CA035R1	0.1028	350	0.028	0.099	Unknown	–	4	4	2	589
CA035R2	0.0769	292	0.100	0.033	Unknown	–	4	4	2	589
OH002R	0.0350	331.28	0.084	0.915	Y	–	–	–	2	4,055
OH002R1	0.0520	764.24	0.186	0.177	N	–	–	–	2	4,055

DCMF StudyID	Length (mi)	Curve Radius (ft)	Distance to End Milepost of Previous Curve (mi)	Distance to Begin Milepost of Next Curve (mi)	At or Near Intersection	Speed Limit	Right Shoulder Width (ft)	Left Shoulder Width (ft)	Lanes	Average AADT
OH002R2	0.0620	295.2	0.919	0.806	Y	–	–	–	2	4,055
OH003R	0.0860	541.2	0.145	0.272	Y	–	–	–	2	1,733
OH003R1	0.1090	596.96	0.157	0.189	N	–	–	–	2	2,396
OH012R	0.0510	403.44	0.268	0.695	N	–	–	–	2	2,368
OH013R1	0.0920	583.84	0.168	0.633	N	–	–	–	2	1,879

–No data.

APPENDIX B. INVESTIGATION OF CRASH LOCATION ACCURACY ISSUES USING NORTH CAROLINA DATA

One of the issues with crash studies involving horizontal curves, particularly in rural areas, is the potential error in locating crashes on short sections. In order to investigate the potential impact of crash location errors, North Carolina Department of Transportation (NCDOT) conducted a detailed manual review of each crash that occurred at and/or near the treated sections in North Carolina. NCDOT staff assigned a crash to the treated sections based on a manual review of each crash report, including the crash diagram and the narrative, even if the crash was not originally assigned to the section based on the milepost. The authors conducted a naïve before–after evaluation of the treatment using both the NCDOT results and the results based on the crashes assigned to the sections solely based on the mileposts. The results of the naïve before–after evaluation for total crashes are available in table 16.

Table 16. Naïve before–after evaluation for total crashes—North Carolina.

Source of Crash Data	Crashes in the Before Period	Crashes in the After Period	Expected Crashes in the After Period Without Treatment	CMF (S.E.) Based on Naïve Before–After Evaluation
Mileposted crashes only	68	12	32.6	0.34 (0.13)
NCDOT manual review of individual crashes	184	18	80.2	0.22 (0.06)

As evidenced in the table, the number of crashes in the before period is about three times higher for NCDOT's manual review of individual crash reports compared to crashes that were assigned solely based on milepost information. A large portion of this difference is from one site where there were 7 crashes assigned to that section based on the milepost, but NCDOT determined that there were 65 crashes in that section. However, even after excluding this potential outlier, the number of crashes in the before period was about two times higher based on NCDOT's review.

This led to the question of whether the accuracy of crash counts on short sections affected the CMF results. The results from this investigation by NCDOT show that the curve realignment may be more effective than originally thought (i.e., calculated from mileposted crashes). However, a homogeneity test conducted using the CMFs from these two methods revealed that the difference between the CMFs was not statistically significant at the 0.05 level.

This analysis presents considerations for future research efforts. Most studies solely rely on mileposts to assign a crash to a section. This limited study by NCDOT has revealed that relying solely on mileposts could potentially lead to significant errors, as the crashes may be largely undercounted. For this study, the effect of this undercounting on the CMF result was not significant. Further research is needed to investigate this issue.

ACKNOWLEDGMENTS

This report was prepared for the FHWA Office of Safety Research and Development under Contract DTFH61-13-D-0001. The FHWA Program and Task Manager for this project was Roya Amjadi.

The team gratefully acknowledges that this research would not have been possible without the assistance provided by the following agencies:

- Caltrans.
- NCDOT.
- Ohio DOT.

The authors would like to especially thank NCDOT staff for their detailed review of the crash data from North Carolina and for educating the research team about the importance of crash location errors in short sections. The authors would also like to thank HSIS staff for providing data for this research.

REFERENCES

1. Bureau of Transportation Statistics. (2010). *BTS Technical Report: Factors Involved in Fatal Vehicle Crashes*, U.S. Department of Transportation's Research and Innovative Technology Administration, Washington, DC. Available online: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/bts_technical_report/september_2010/index.html, last accessed May 2016.

2. Srinivasan, R., et al. (2009). *Safety Evaluation of Improved Curve Delineation*, Report No. FHWA-HRT-09-045, Federal Highway Administration, Washington, DC.

3. Torbic, D., et al. (2004). *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan Volume 7: A Guide for Reducing Collisions on Horizontal Curves*, National Cooperative Highway Research Program, Report 500, Transportation Research Board, Washington, DC.

4. Bauer, K.M. and Harwood, D.W. (2014). *Safety Effects of Horizontal Curve and Grade Combinations on Rural Two-Lane Highways*, Report FHWA-HRT-13-077, Federal Highway Administration, Washington, DC.

5. Saleem, T. and Persaud, B. (2016). *Another Look at the Safety Effects of Horizontal Curvature on Rural Two-Lane Highways*, Paper No. 16-6347, Transportation Research Board Annual Meeting Paper Compendium, National Academies of Science, Washington, DC.

6. Gross, F., Persaud, B., and Lyon, C. (2010). *A Guide to Developing Quality Crash Modification Factors*, Report No. FHWA-SA-10-032, Federal Highway Administration, Washington, DC.

7. AASHTO. (2010). *Highway Safety Manual*, First Edition, American Association of State Highway and Transportation Officials, Washington DC.

8. Zegeer, C., Stewart, J., Council, F., Reinfurt, D., and Hamilton E. (1992). "Safety Effects of Geometric Improvements on Horizontal Curves," *Transportation Research Record*, *1356*, Transportation Research Board, Washington, DC.

9. Schneider, W.H., Zimmerman, K., Van Boxel, D., and S. Vavilikolanu. (2009). "*A Bayesian Analysis of the Effect of Horizontal Curvature on Truck Crashes Using Training and Validation Data Sets*," Presented at the 88th Annual Meeting of the Transportation Research Board Compendium of Papers, Transportation Research Board, Washington, DC.

10. Banihashemi, M. (2015). "*Is Horizontal Curvature a Significant Factor of Safety in Rural Multilane Highways?*" Presented at the 94th Annual Meeting of the Transportation Research Board, Transportation Research Board, Washington, DC.

11. Fitzpatrick, K., Lord, D., and Park, B. (2009). "*Horizontal Curve Accident Modification Factor with Consideration of Driveway Density on Rural, Four-Lane Highways in Texas*." Presented at the 88th Annual Meeting of the Transportation Research Board Compendium of

Papers, Transportation Research Board, Washington, DC.

12. Graham, J., Harwood, D., Richard, K., O'Laughlin, M., Donnell, E., and Brennan, S. (2014). *Median Cross-Section Design for Rural Divided Highways*, NCHRP Report 794, Transportation Research Board of the National Academies, Washington, DC.

13. Pratt, M. Geedipally, S., Pike, A., Carlson, P., Celoza, A., and Lord, D. (2014). *Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves*, Report No. FHWA/TX-14/0-6714-1, Texas Department of Transportation, Austin, TX.

14. Choi, Y., Kho, S., Lee, C., and Kim, D. (2015). "*Development of Crash Modification Factors of Alignment Elements and Safety Countermeasures for Korean Freeways*," Paper No. 05-0503. Presented at the 94th Annual Meeting of the Transportation Research Board, Transportation Research Board, Washington, DC.

15. Hauer, E. (1997). *Observational Before-After Studies in Road Safety*, Pergamon Press, Oxford, UK.

16. Bahar, G. (2010). "Methodology for the Development and Inclusion of Crash Modification Factors in the Highway Safety Manual," *Transportation Research Circular E-C142*, Transportation Research Board of the National Academies, Washington, DC.

17. Elvik, R. (2015). "Methodological guidelines for developing accident modification functions," *Accident Analysis and Prevention, 80*, pp. 26–36, Elsevier, Amsterdam, Netherlands.

18. Bonneson, J. (2015). *Local adjustment of CMFs based on crash distribution*, Working Paper 3, NCHRP Project 17–63, Transportation Research Board, Washington, DC.

19. Council, F., Zaloshnja, E., Miller, T., and Persaud, B. (2005). *Crash Cost Estimates by Maximum Police-Reported Injury Severity Within Selected Crash Geometries*, FHWA-HRT05-051, Federal Highway Administration, Washington, DC.

20. USDOT. (2015). *Guidance on Treatment of the Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses—2015Adjustment*, U.S. Department of Transportaion. Available online: https://cms.dot.gov/sites/dot.gov/files/docs /VSL2015_0.pdf, last accessed on May 10, 2016.

HRDS-20/04-18(200)E