Safety Effects of Full-Length Retroreflective Posts for In-Curve Horizontal Alignment Signs

October 2026

Publication No. FHWA-HRT-26-066

250
U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
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Turner-Fairbank
Highway Research Center

FOREWORD

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

More than 25 percent of fatal crashes are associated with a horizontal curve, and most of these crashes involve a roadway departure. Curve safety improvements, such as curve enhanced delineation (CED) and horizontal alignment signs, provide additional emphasis and guidance for drivers negotiating curves. CED treatments can be used to reduce the frequency and severity of horizontal curve crashes by emphasizing the direction and severity of the curve. The project objective was to determine the safety effectiveness of full-length yellow retroreflective posts for in-curve horizontal alignment signs. The analysis results indicate that these treatments are effective at reducing total, fatal-and-injury, and nighttime crashes. The economic evaluation of the treatments showed that the average benefit–cost ratio of installing these CED treatments is 10.1.

This report may interest transportation practitioners, State departments of transportation, transportation safety researchers, transportation industries, and those working to improve transportation safety.

John Harding
Director, Office of Safety and Operations
Research and Development

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Recommended citation: Federal Highway Administration, *Safety Effects of Full-Length Retroreflective Posts for In-Curve Horizontal Alignment Signs* (Washington, DC: 2026) https://doi.org/10.21949/3mm1-hh58

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-26-066	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Safety Effects of Full-Length Retroreflective Posts for In-Curve Horizontal Alignment Signs		5. Report Date October 2026	
		6. Performing Organization Code:	
7. Author(s) Michael P. Pratt and Srinivas R. Geedipally (ORCID: 0000-0002-6842-8172)		8. Performing Organization Report No.	
9. Performing Organization Name and Address Texas A&M Transportation Institute The Texas A&M University System TAMU 3135 College Station, TX 77843-3135		10. Work Unit No.	
		11. Contract or Grant No. DTFH61-16-D-00039	
12. Sponsoring Agency Name and Address Office of Safety Research and Development Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101		13. Type of Report and Period Covered Final Report; August 2022—June 2026	
		14. Sponsoring Agency Code HRSO-20	
15. Supplementary Notes The contracting officer's representatives were Woon Kim (HRSO-20; ORCID: 0000-0001-9806-1204) and Carol Tan (HRSO-20; ORCID: 0000-0002-0549-9782).			
16. Abstract Curve enhanced delineation (CED) includes treatments such as full-post delineators, full-length retroreflective posts for horizontal alignment signs, warning beacons on signs, wider edge lines, profiled pavement markings, speed reduction markings (also known as optical speed bars), and other treatments that provide more effective curve delineation than typical delineators, Chevron Alignment signs, and pavement markings. Several types of CED treatments have been studied in the past and found to be effective at reducing crash frequency on horizontal curves. The objective of this study is to analyze the safety effectiveness and cost effectiveness of full-length yellow retroreflective posts for Chevron Alignment signs and the One-Direction Large Arrow sign.(1) This analysis focuses on total crashes, fatal and injury crashes, and nighttime crashes on curves. The results of the study show that the analyzed CED treatments are effective at reducing the frequency of these crash types, with an average benefit–cost ratio of 10.1. The treatments can be used to address curve safety issues when needed.			
17. Key Words Safety, rural two-lane roads, roadway departures, countermeasures		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. https://www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 52	22. Price N/A

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1,000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 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 (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS

AADT	annual average daily traffic
CED	curve enhanced delineation
CI	confidence interval
CMF	crash modification factor
DOT	department of transportation
EB	Empirical Bayes
FHWA	Federal Highway Administration
FI	fatal and injury
GIS	geographic information system
KABCO	K = fatal; A = incapacitating injury; B = nonincapacitating injury; C = possible injury; O = property damage only (crash severity scale)
LED	light-emitting diode
MUTCD	*Manual on Uniform Traffic Control Devices for Streets and Highways*
NA	not applicable
NCHRP	National Cooperative Highway Research Program
NB	negative binomial
PC	point of curvature
PDO	property damage only
PennDOT	Pennsylvania Department of Transportation
PMD	post-mounted delineator
PT	point of tangency
SPF	safety performance function
TxDOT	Texas Department of Transportation
Unk.	unknown
veh	vehicles

CHAPTER 1. INTRODUCTION

Curve enhanced delineation (CED) can include various treatments, such as full-post delineators, full-length retroreflective Chevron Alignment signposts, warning beacons on signs, wider edge lines, profiled pavement markings, speed reduction markings (also known as optical speed bars), and other treatments that provide more effective delineation than typical delineators, Chevron Alignment signs, and pavement markings. Two CED treatment types are shown in figure 1. CED treatments like these and other types are acknowledged in the Federal Highway Administration (FHWA) *Proven Safety Countermeasures in Rural Communities* document to reduce crashes, including roadway departure crashes, on rural two-lane roads.[(2)]



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A. Chevron Alignment signs with full-length retroreflective posts.



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B. One-Direction Large Arrow sign with full-length retroreflective posts.

Figure 1. Photos. Examples of CED.[(3)]

The objective of this study is to analyze the safety effectiveness and cost effectiveness of the CED treatments shown in figure 1 (i.e., full-length retroreflective posts). This analysis focuses on total crashes, fatal and injury (FI) crashes, and nighttime crashes on curves. The results of the study show that the CED treatments of interest provide benefits similar to other types of CED treatments that have been previously evaluated and hence can be used to address curve safety issues when needed.

CHAPTER 2. LITERATURE REVIEW

The *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) gives provisions for the use of Chevron Alignment signs in chapter 2C (Warning Signs and Object Markers) and delineators in chapter 3G (Delineators).[1] Section 2C.08 of the MUTCD states the following provisions for using Chevron Alignment signs:

- The Chevron Alignment sign is used "to provide additional emphasis and guidance for a change in horizontal alignment."
- Chevron Alignment signs may be used instead of or in addition to delineators.
- The provisions in chart A of table 2C-4 indicate "the need for devices for changes in horizontal alignment" (i.e., standard, guidance, or option) based on roadway type and annual average daily traffic (AADT).
- The provisions in chart B of table 2C-4 specify the use of Chevron Alignment signs if the speed differential, defined as "the difference between the horizontal curve's advisory speed and the roadway's posted speed limit, statutory speed limit, or the 85th-percentile speed on the approach to the curve," is 20 mph or more.
- When used, Chevron Alignment signs shall be installed on the outside of the curve, in line with and at approximately a right angle to traffic, at a minimum height of 4 ft (Section 2C.08, Par.4).

The 11th Edition of the MUTCD (published in 2023) specifies Chevron Alignment signs on fewer curves compared to the 2009 MUTCD.[1,4] Table 2C-5 in the 2009 MUTCD stated that Chevron Alignment signs or the One-Direction Large Arrow sign may be used if the difference between the regulatory and advisory speeds is 5 mph, should be used if the difference is 10 mph, and shall be used if the difference is 15 mph or greater, without consideration of roadway type or AADT.

The MUTCD states the following provisions for using delineators:[1]

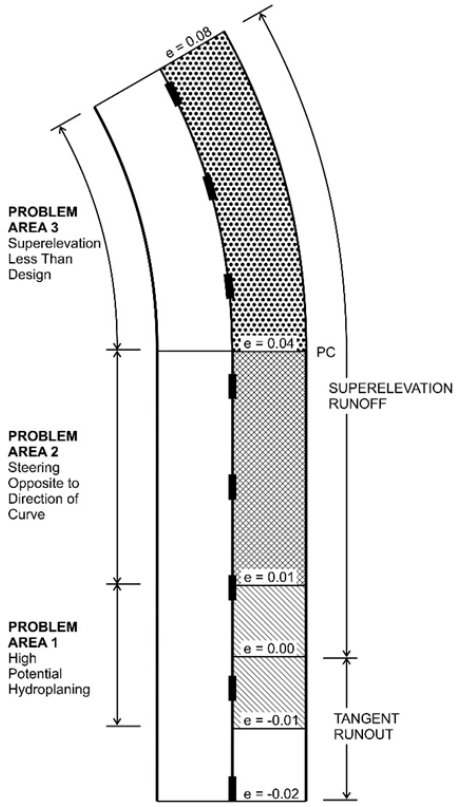
- "Delineators are particularly beneficial at locations where the alignment might be confusing or unexpected, such as at lane-reduction transitions and curves." (Section 3G.01, Par.1)
- Delineators are considered guidance devices rather than warning devices.
- The color of delineators must match the corresponding edge line. On the outside of a curve on a two-way roadway, the delineators shall be white. (Section 3G.03, Par.1; Section 3G.03, Par.6; Section 3A.03, Par.4, B)
- The retroreflective element of a delineator should be mounted approximately 4 ft above the roadway edge.

The MUTCD provisions acknowledge that Chevron Alignment signs and delineators both serve to indicate the presence and sharpness of a horizontal curve.[1] The provisions are more prescriptive for Chevron Alignment signs than for delineators, in that Chevron Alignment signs are included in table 2C-4 based on a quantitative criterion (the speed differential) for the curve.

The purpose of adding retroreflective sheeting to these two treatments (i.e., either on the Chevron post or along the entire height of the delineator) is to increase the visibility of the treatments in nighttime and inclement weather conditions. The following two sections discuss studies that have focused on the operational and safety effects of curve delineation treatments.

OPERATIONAL EFFECTS OF CURVE DELINEATION

Horizontal curves represent a challenge because motorists need to detect the curve, assess the severity of the curve, and reduce speed accordingly. Numerous studies have examined the relationship between vehicle speed and the key geometric variables of radius, superelevation rate, and deflection angle, as well as approach tangent speed. (See references 5, 6, 7, and 8.) Glennon observed that the curve's point of curvature (PC) and its immediate vicinity represent points of particular concern for several reasons.[9] First, motorists are often still braking when they pass the PC and begin to negotiate the curve, which forces the tire-pavement interface to provide braking friction in addition to side friction. Second, the superelevation is not yet fully developed in the early portions of the curve length. Third, there is a zone upstream of the PC where the pavement cross slope is less than 2 percent, making it susceptible to water buildup and hydroplaning. Figure 2 illustrates these concerns.



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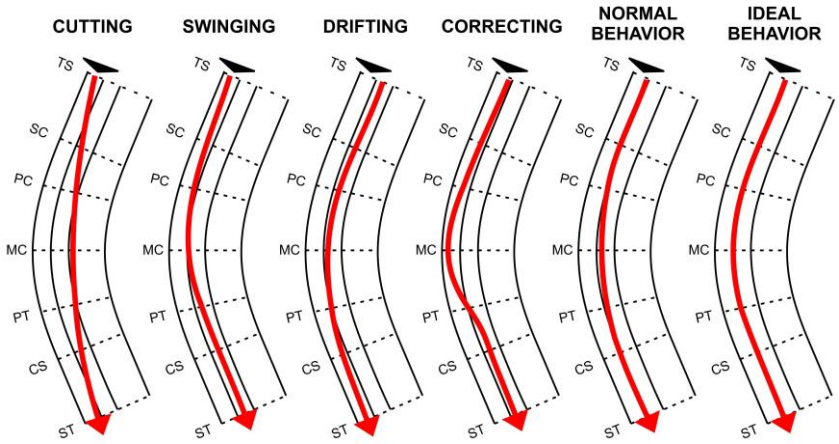
e = superelevation rate.

Figure 2. Illustration. Problem areas near curve PC.[9]

Additionally, Glennon and Weaver observed that the side friction demand estimate provided by the point-mass model used in design practice assumes that drivers traverse the curve "with geometric exactness."[10] Spacek tracked approximately 2,000 vehicles across a set of 10 curves and identified 5 typical types of travel paths commonly adopted by motorists in curves.[11] Figure 3 illustrates these travel paths. Spacek observed that when motorists make course corrections in a curve, they briefly drive a path with a radius that is significantly smaller than the geometric radius of the curve, and that a sliding failure at that moment can lead to a crash if the motorist fails to recover.



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CS = circle to spiral; MC = middle of curve; PT = point of tangency; SC = spiral to circle; ST = spiral to tangent; TS = tangent to spiral.

Figure 3. Illustration. Curve travel paths.[11]

Because of the aforementioned concerns, curve delineation treatments are likely to improve safety performance if they encourage motorists to reduce speed ahead of the curve and reduce the amount of braking and course correction that occurs within the curve. Various studies have been conducted using simulators to examine speed, acceleration, and lane placement trends before and after delineation treatments were added to horizontal curves.

Molino et al. conducted a simulator evaluation of curve delineation treatments, including edge line markings, standard delineators on one or both sides of the road, and delineators enhanced with LEDs (light-emitting diodes) that flashed in a streaming pattern in the direction of curvature, in nighttime conditions.[12] Their simulated course included 8 curves on a rural highway with a 55-mph regulatory speed limit, and involved 36 participants who drove through the course 3 times. The curves did not have Horizontal Alignment signs or Advisory Speed plaques, but the advisory speeds on the curves would have been 20 mph or 30 mph if posted. The curves had radii of 100 ft or 300 ft. The participants tended to reduce their speed more both ahead of curves and within them (table 1) when post-mounted delineators (PMDs) were provided. Similarly, the participants tended to brake farther ahead of the curve and less within the curve (table 2) when PMDs were provided. In all cases, the baseline condition included a marked center line but no marked edge lines or delineators. The numbers in table 1 are derived from figures 16 and 17 of Molino et al., and the numbers in table 2 are derived from figures 18 and 19 of Molino et al.[12]

Table 1. Speed trends.

Distance From PC	Average Speed (mph), Center Line Only	Average Speed (mph), Edge Lines Added	Average Speed (mph), Edge Lines and Single Side PMDs Added	Average Speed (mph), Edge Lines and Both Sides PMDs Added	Average Speed (mph), Edge Lines and Streaming PMDs Added
1,000 ft upstream	56.2	57.0	56.8	56.4	55.3
600 ft upstream	57.5	58.1	57.5	56.6	56.0
300 ft upstream	57.5	58.3	56.0	54.5	53.2
200 ft upstream	57.0	56.8	51.5	50.1	47.9
100 ft upstream	51.1	49.0	40.1	38.6	36.5
At PC	37.0	35.1	30.1	29.0	28.3
100 ft downstream	34.6	33.8	31.0	30.3	29.8
200 ft downstream	35.7	35.7	33.8	33.5	32.9

Table 2. Acceleration rate trends.

Distance From PC	Average Acceleration Rate (ft/s^2), Center Line Only	Average Acceleration Rate (ft/s^2), Edge Lines Added	Average Acceleration Rate (ft/s^2), Edge Lines and Single Side PMDs Added	Average Acceleration Rate (ft/s^2), Edge Lines and Both Sides PMDs Added	Average Acceleration Rate (ft/s^2), Edge Lines and Streaming PMDs Added
800 ft upstream	0.3	0.4	0.2	0.0	0.1
450 ft upstream	0.1	0.0	−0.6	−0.7	−1.0
250 ft upstream	−0.8	−1.8	−5.4	−5.1	−5.6
150 ft upstream	−6.3	−8.4	−10.7	−10.4	−10.2
50 ft upstream	−12.0	−11.4	−6.9	−6.3	−5.2
50 ft downstream	−2.9	−1.8	0.2	0.6	0.7
150 ft downstream	0.6	1.2	2.0	2.2	2.3

The participants were instructed to tell the researchers when the participants could detect the direction of an upcoming curve (left or right) and its severity (sharp or gentle, corresponding to the radius values of 100 or 300 ft). The participants tended to detect both the direction and severity farther in advance of the curve if PMDs were provided (table 3). Participants also tended to detect the curves sooner as they conducted more drives through the course, suggesting that they were becoming somewhat more familiar with the curves in the course.

Table 3. Average direction and severity detection distances.

Treatment	Average Direction Detection Distance (ft)	Average Severity Detection Distance (ft)
Center line only	225	53.4
Edge lines added	249	71.6
Edge lines and single side PMDs added	426	116
Edge lines and both sides PMDs added	355	97.4
Edge lines and streaming PMDs added	1,288	612

Several other studies have focused on the effect of curve delineation on vehicle speeds and have generally found that the magnitudes of observed speed reductions were small. For example, Hallmark, Hawkins, and Smadi observed that when reflectorized treatments were added to Chevron posts at two curve sites in the field, mean speeds decreased by 1.6 mph at one curve in one direction of travel at night, but increased by 1.0 mph at another curve in one direction of travel at night.[13] Ré, Hawkins, and Chrysler conducted a field study at two curves that were evaluated without Chevrons (baseline), with conventional Chevrons, and with Chevrons with full-length retroreflective posts.[14] The authors found that mean speeds decreased by approximately 1.3 mph compared to baseline when conventional Chevrons were installed, and approximately 2.2 mph compared to baseline when Chevrons with full-length retroreflective posts were installed. Ré et al. described these changes as statistically significant (based on multivariate analysis of variance and Tukey's honestly significant difference tests) but inconsequential.

SAFETY EFFECTS OF CURVE DELINEATION

Relatively few studies have been conducted to quantify the expected crash reduction following the installation of curve delineation treatments. The crash modification factor (CMF) Clearinghouse lists two studies, which the following paragraphs summarize.[15]

Srinivasan et al. conducted an Empirical Bayes (EB) before–after analysis of crash data from the States of Connecticut and Washington following the installation of enhanced curve delineation treatments.[16] The Connecticut data included 334 reference curves and 89 treated curves that were treated with Horizontal Alignment, Chevron Alignment, or One-Direction Large Arrow signs that had fluorescent yellow sheeting. In some cases, existing signs were replaced with new signs that had the upgraded sheeting, and in other cases, new signs were installed. The Washington data included thousands of reference curves and 139 treated curves where Chevrons were added or the number of Chevrons was increased. Srinivasan et al. derived the following CMF values:

- FI nonintersection crashes: 0.820.
- Nighttime nonintersection crashes: 0.725.
- Nighttime lane-departure nonintersection crashes: 0.746.

Montella conducted an EB before–after analysis of crash data from 312 reference curves and 15 treated curves on a four-lane motorway in southern Italy.[17] The curves were treated with one or more of the following treatments: warning signs, Chevrons, or sequential flashing beacons along the length of the curve. Montella derived various CMFs for different combinations of treatments, light and weather conditions, and curve geometry. He found the following statistically significant CMF values for installing Chevrons alone or installing curve warning signs and Chevrons:

- Chevrons, rainy weather: 0.41.
- Curve warning signs and Chevrons:
  - All light and weather conditions: 0.59.
  - Daytime: 0.56.
  - Rainy weather: 0.49.
  - Run-off-road crashes: 0.56.
  - Property-damage-only crashes: 0.46.

Montella found that treatments generally resulted in a statistically significant reduction in crash frequency if the curve radius was less than 985 ft but not if the curve radius was greater than or equal to 985 ft.[17] He additionally found that the reduction in crash frequency was statistically significant in all conditions if all three treatments (curve warning signs, Chevrons, and sequential flashing beacons) were installed at the same time, regardless of curve radius. Table 4 provides the CMF values for these conditions.

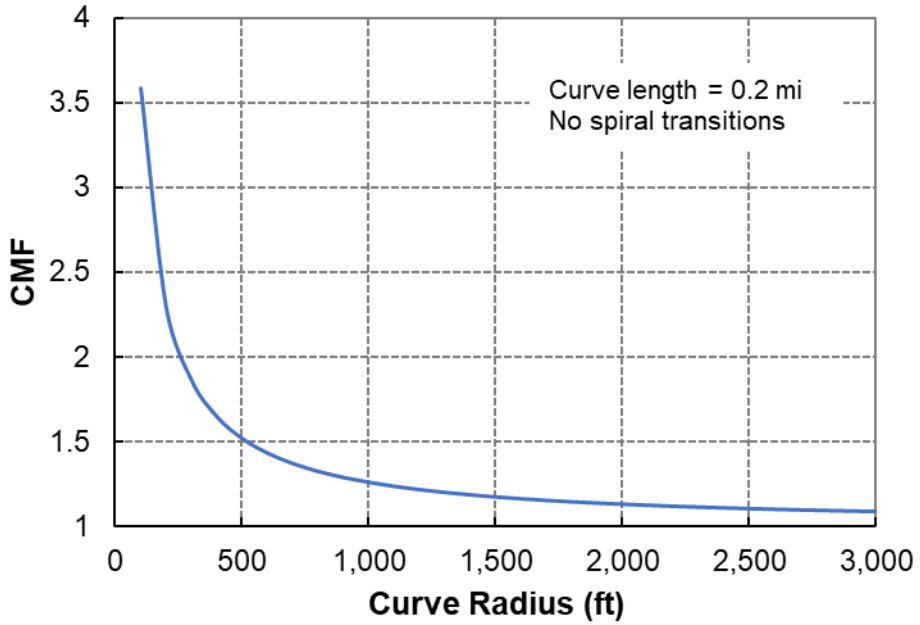
Table 4. CMFs for delineation treatments on motorway curves.

Condition	CMF Value (Treated Curves With Radius ≤985 ft)	CMF Value (Treated Curves With All Three Treatments Installed Simultaneously, Any Radius)
Total	0.48	0.52
Nighttime	0.21	0.23
Daytime	0.58	0.63
Rainy weather	0.53	0.56
Nonrainy weather	0.42	0.48
Run-off-road crashes	0.45	0.52
Non-run-off-road crashes	0.62	0.53
FI crashes	0.61	0.62
Property-damage-only crashes	0.38	0.44

FI = fatal and injury.

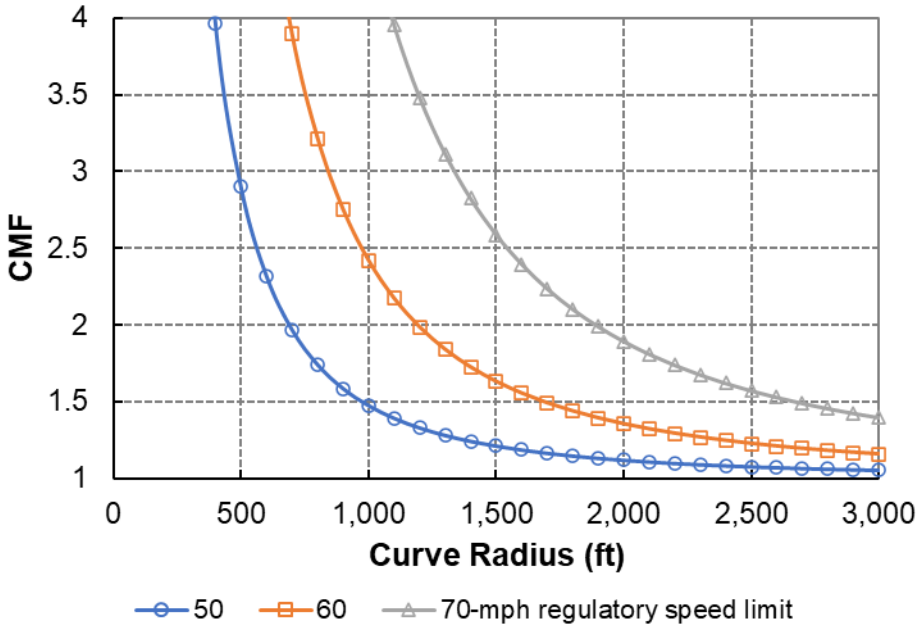
Montella found no statistically significant CMF values for curves with radii greater than 985 ft, likely because such curves are sufficiently gradual that they are less likely to benefit from enhanced delineation.[17]

Figure 4 shows the curve radius CMF for rural two-lane highways from chapter 10 of the *Highway Safety Manual*.[18] The plot shows that crash frequency tends to increase notably when curve radius decreases less than approximately 500 ft. Curves with radii in that range are more likely to need enhanced delineation. Figure 5 shows a curve radius CMF for rural highways (two-lane or four-lane) that accounts for both radius and regulatory speed limit.[19]



Source: FHWA.

Figure 4. Graph. Curve radius CMF for rural two-lane highways (based on the *Highway Safety Manual*).[18]



Source: FHWA.

Figure 5. Graph. Curve radius CMF for rural highways (based on Bonneson and Pratt).[19]

Chakraborty and Gates conducted a detailed analysis of single-vehicle crash frequency on rural secondary highway curves, accounting for variables like curve type (simple, compound, or reverse), approach tangent length, curve design speed, and curve deflection direction (left or right).[20] The analysis found that simple curves have lower crash frequencies than other curve types, crash frequency on the first curve in a series increases with increasing approach tangent length, crash frequencies on successive curves increased with decreasing approach tangent lengths between the curves, and more crashes occurred in the left-deflecting direction of a curve than the right-deflecting direction. Chakraborty and Gates recommended that when highway alignments are designed, compound or reverse curvature should be avoided as much as possible, or compound or reverse curves should be treated with enhanced delineation if their use cannot be avoided.

Hamilton et al. examined rural two-lane highway curves in the States of Indiana and Pennsylvania to evaluate the relationship between design consistency measures and crash frequency.[21] The analysis included the ratio of tangent length (i.e., average of the approach tangents in both travel directions) to subject curve radius and the ratio of adjacent curve radius (i.e., average radii of the next upstream and downstream curves) to subject curve radius. Hamilton et al. found that the roadway departure crash frequency on the subject curve will be lower if the adjacent curve radii are sharper or if the approach tangent lengths are shorter. They found the effect of adjacent curve radii to be statistically significant in both States, but the effect of approach tangent lengths to be statistically significant only in Pennsylvania.

In addition to the curve and tangent variables, the model by Hamilton et al. also included an indicator variable for the State of Pennsylvania, which had a statistically significant value greater than zero for KABC crashes on the KABCO crash scale (K = killed; A = major injury;

B = moderate injury; C = minor injury, O = property damage only).[21,18] Hamilton et al. suggested that this finding is intuitive "due to central Pennsylvania's dynamic topography compared with Indiana's flatter topography"."[21] Lee, Aizpuru, and Neely conducted an analysis of crashes involving curves and guardrails in Vermont.[22] They accounted for vertical curvature by calibrating separate models for straight grades, crest vertical curves with approach and departure grades having opposite signs, crest vertical curves with approach and departure grades having the same sign, sag vertical curves with approach and departure grades having opposite signs, and sag vertical curves with approach and departure grades having the same sign.

Radius is one of several variables that affect curve safety performance. Pratt et al. synthesized several literature sources and described a framework to analyze curves based on margin of safety, which is summarized by the following equations:[23]

$$M.S. = f_s - f_D \tag{1}$$

$$f_s = f(SK) \tag{2}$$

$$f_D = \frac{v^2}{gR}\cos\left(\frac{e}{100}\right) - \sin\left(\frac{e}{100}\right)\cos G \tag{3}$$

Where:

M.S. = margin of safety.
f_s = side friction supply.
f_D = side friction demand.
SK = skid number.
v = vehicle speed, ft/s.
g = gravitational constant (= 32.2 ft/s^2).
R = curve radius, ft.
e = superelevation rate, percent.
G = vertical grade, ft/ft.

The margin of safety concept accounts for the key variables of radius, superelevation rate, grade, vehicle speed (which is in turn affected by curve geometry and approach tangent speed), and pavement skid resistance. Curve safety performance is affected by all these variables in addition to the presence of curve delineation treatments. Pratt et al. suggested the margin of safety analysis framework for assessing the adequacy of pavement skid resistance; however, margin of safety has not been directly linked to crash frequency.[23]

CHAPTER 3. SITE IDENTIFICATION

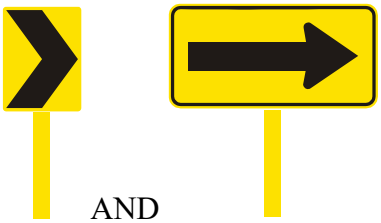
TREATED SITES

The research team conducted an electronic survey of State department of transportation (DOT) practitioners who are part of the Evaluation of Low-Cost Improvements Pooled Fund Study.[24] Part of the survey included questions about the use of CED treatments in the practitioners' jurisdictions. A respondent from the Pennsylvania DOT (PennDOT) stated that his agency uses Chevron Alignment signs with full-length retroreflective posts. He provided data in the form of a State inventory of Chevron Alignment signs and full-length retroreflective posts (not necessarily paired with each other). The inventory data include device description, roadlog segment numbers and offsets, and latitude and longitude coordinates. The research team used these data and street-level photography sources available online, including Google® Earth™ and the PennDOT video log web interface, to locate and verify the presence of full-length retroreflective posts on curve signs.[25,3] Some of the located installations were on posts for Horizontal Alignment warning signs (W1-1, W1-2, W1-3, W1-4, or W1-5), curve delineation signs such as Chevron Alignment signs (W1-8) or the One-Direction Large Arrow sign (W1-6), or other types of warning signs unrelated to curves.

The research team contacted 20 practitioners who work in various Texas DOT (TxDOT) districts or who have assisted district personnel in collecting curve data in the field. Efforts to check and update curve advisory speeds within the State of Texas have been ongoing for the past several years as a result of the December 31, 2019, compliance date for table 2C-5 in Section 2C.06 of the *Texas Manual on Uniform Traffic Control Devices*, which requires Chevrons if the difference between the regulatory speed limit and the advisory speed is 15 mph or greater.[26] Based on responses received, the research team identified a set of sites in Texas that have Chevron Alignment signs with full-length retroreflective posts.

Table 5 provides a count of located sites by State and CED treatment type. A total of 248 sites are included in the count. The geographic distribution of the treated sites in Pennsylvania and Texas are shown as yellow pins in figure 6 and figure 7, respectively.

Table 5. Count of identified sites with curve enhanced delineation.

Treatment	Diagram	Site Count in PA	Site Count in TX	Site Count in Both States
Chevron Alignment signs with full-length retroreflective posts		137	85	222
BOTH Chevron Alignment signs with full-length retroreflective posts AND One-Direction Large Arrow signs with full-length retroreflective posts	 AND	6	0	6
One-Direction Large Arrow signs with full-length retroreflective posts		20	0	20
All treatments	Any combination of the diagrams in the preceding rows	163	85	248

All images source: FHWA.
PA = Pennsylvania; TX = Texas.

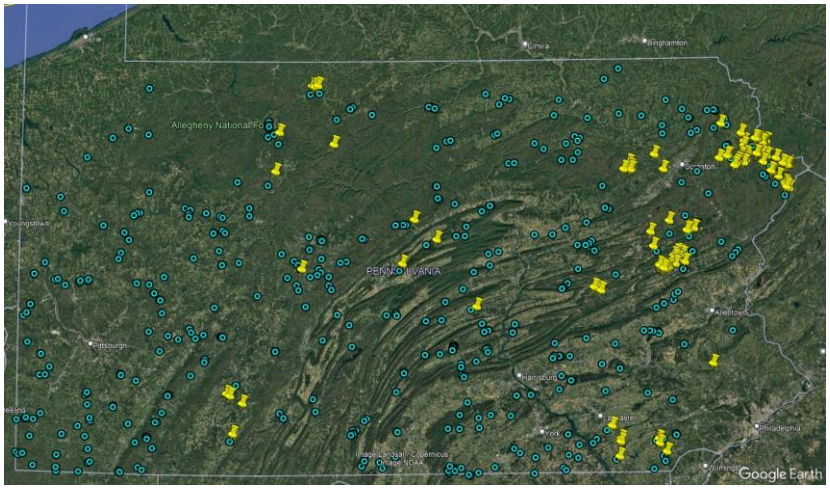


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Figure 6. Map. Geographic distribution of identified sites in Pennsylvania.[(25)]

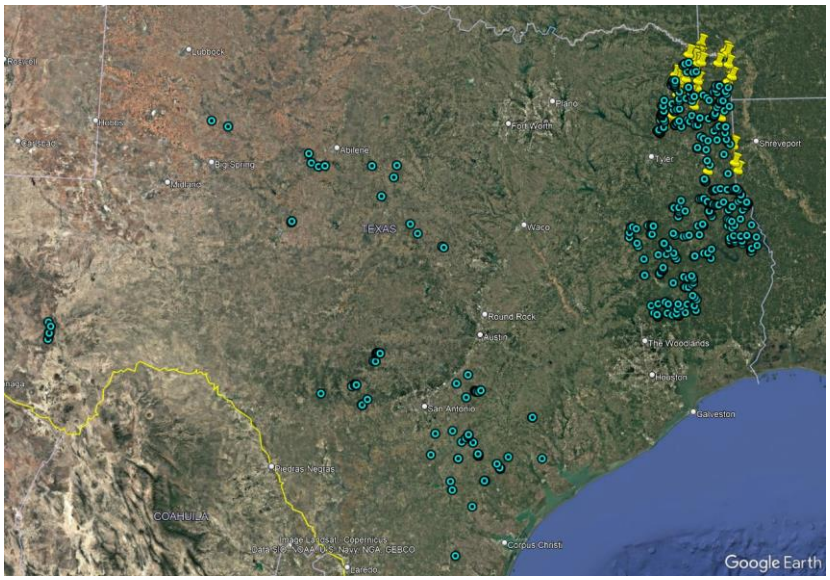

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Figure 7. Map. Geographic distribution of identified sites in Texas.[(25)]

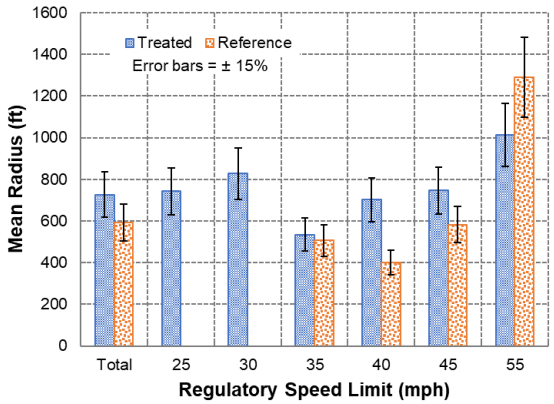
REFERENCE SITES

To conduct a before–after safety analysis, using reference sites is necessary. The reference sites to be used in the analysis are shown as blue dots in figure 6 and figure 7. Reference sites were identified from a query of State DOT curve geometry files using the following criteria:

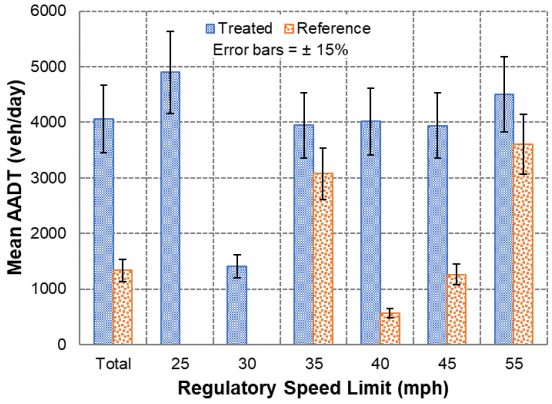
- The treated site and the reference sites have the same area type (urban or rural), functional classification, number of lanes, and regulatory speed limit.
- The pavement width of the sites differs by no more than 10 ft.
- The curve radius of the sites differs by no more than 200 ft.

- The deflection angle of the sites differs by no more than 10 degrees.
- The AADT of the sites differs by no more than 200 vehicles (veh)/d.

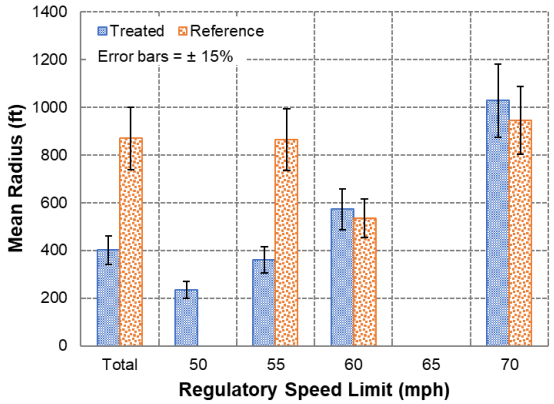
Figure 8 provides a graphical comparison of the mean radius and AADT values for the treated and reference sites by regulatory speed limit. The error bars on the graphs represent a 15-percent range. The mean radius values for the two sets of sites were within 15 percent in most categories for which reference sites were available. Similarly, the mean AADT values compared well for the Texas sites as well as for the Pennsylvania sites that had regulatory speed limits of 35 or 55 mph.



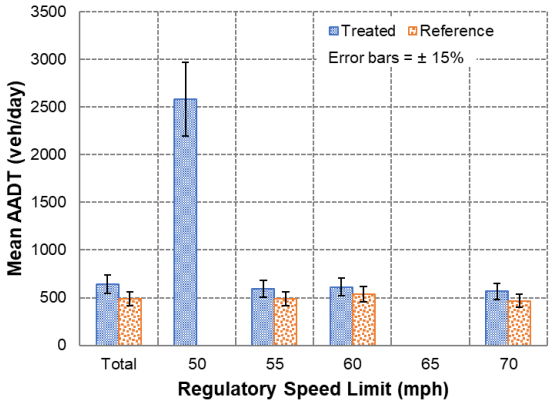
A. Radius (Pennsylvania).



B. AADT (Pennsylvania).



C. Radius (Texas).



D. AADT (Texas).

All images source: FHWA.

Figure 8. Graphs. Comparison of treated and reference site variables.

Table 6 provides a comparison of AADT and curve radius statistics for the treated and reference sites. Generally, the radius statistics compare favorably, but the treated sites have higher AADTs, especially for regulatory speed limits of 40–45 mph. This difference likely reflects the State DOT's practices for selecting sites to treat. That is, sites with higher traffic volumes are deemed higher priority for treatment. The total site count in table 6 differs slightly from that in table 5 due to a small number of sites having missing values for some of the variables.

Table 6. Comparison of treated and reference sites.

State	Regulatory Speed Limit (mph)	Site Set	Count	Mean AADT (veh/day)	AADT Range (veh/day)	Mean Radius (ft)	Radius Range (ft)
PA	25	Treated	2	4,898	4,883–4,912	742	226–1,257
PA	25	Reference	0	NA	NA	NA	NA
PA	30	Treated	1	1,411	1,411–1,411	827	827–827
PA	30	Reference	0	NA	NA	NA	NA
PA	35	Treated	46	3,944	481–9,529	535	49–1,362
PA	35	Reference	17	3,075	2,208–7,326	507	33–939
PA	40	Treated	28	4,016	378–9,885	702	309–1,493
PA	40	Reference	162	566	180–5,308	400	131–1,214
PA	45	Treated	53	3,943	431–14,212	747	141–1,671
PA	45	Reference	219	1,264	234–4,341	583	167–1,595
PA	55	Treated	29	4,506	2,166–9,529	1014	223–2,143
PA	55	Reference	49	3,605	2,345–6,115	1290	299–2,222
PA	Total	Treated	159	4,055	378–14,212	727	49–2,143
PA	Total	Reference	447	1,336	180–7,326	591	33–2,222
TX	50	Treated	2	2,580	2,580–2,580	234	232–237
TX	50	Reference	0	NA	NA	NA	NA
TX	55	Treated	70	594	40–1,993	361	75–1,169
TX	55	Reference	478	488	40–1,784	864	188–3,501
TX	60	Treated	11	612	318–1,662	572	349–960
TX	60	Reference	9	535	252–1,439	535	403–4,316
TX	70	Treated	2	568	225–911	1,027	948–1,106
TX	70	Reference	17	466	60–798	944	357–1,502
TX	Total	Treated	85	642	40–2,580	401	75–1,169
TX	Total	Reference	504	488	40–1,784	869	188–4,316

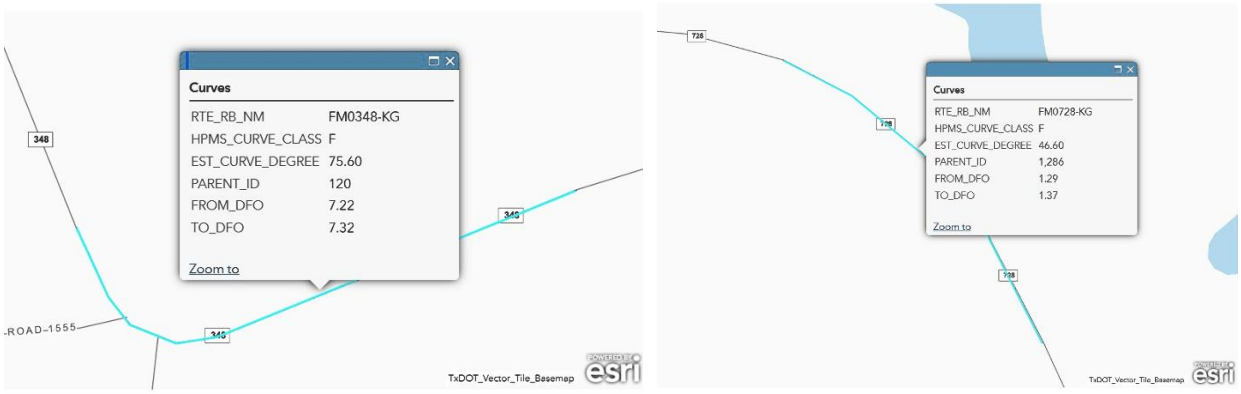
NA = not applicable.

CHAPTER 4. DATA COLLECTION

To conduct the safety analysis, the research team collected detailed data to describe the treated and reference sites and their safety performance. The collected variables have been identified as relevant to safety performance in published studies and were typically available either in State-maintained databases or online photography sources.

SITE DESCRIPTION DATA

The research team obtained as many variables as possible from State data files (either roadlog files or crash files) and supplemented them with variables obtained from aerial and street-level photos as needed. The most notable variables included sign presence and type, treatment type and installation date, and curve geometry. The research team first obtained curve geometry data (i.e., radius and deflection angle) from State DOT curve geometry files, which were built on a geographic information system (GIS) platform.[27] The research team used the curve data overlay shapes from these files to build a list of curves and identify the approximate midpoint of each curve. However, data validation efforts revealed that while the GIS-based files provided an excellent list of curves for easy location on maps, the radius and deflection angle values were often incorrect. Inspection revealed that the curve data overlay shapes often do not overlay the entire length of the curve or track the curve precisely. Figure 9 shows examples of curve overlay shapes that either exclude part of the curve length or extend past the curve's PC or point of tangency (PT). The research team observed similar issues in both States. In these cases, the curve length computed from the overlay shape will be an underestimate or overestimate of the true curve length, which means that the curve radius value computed from length and deflection angle will be incorrect.



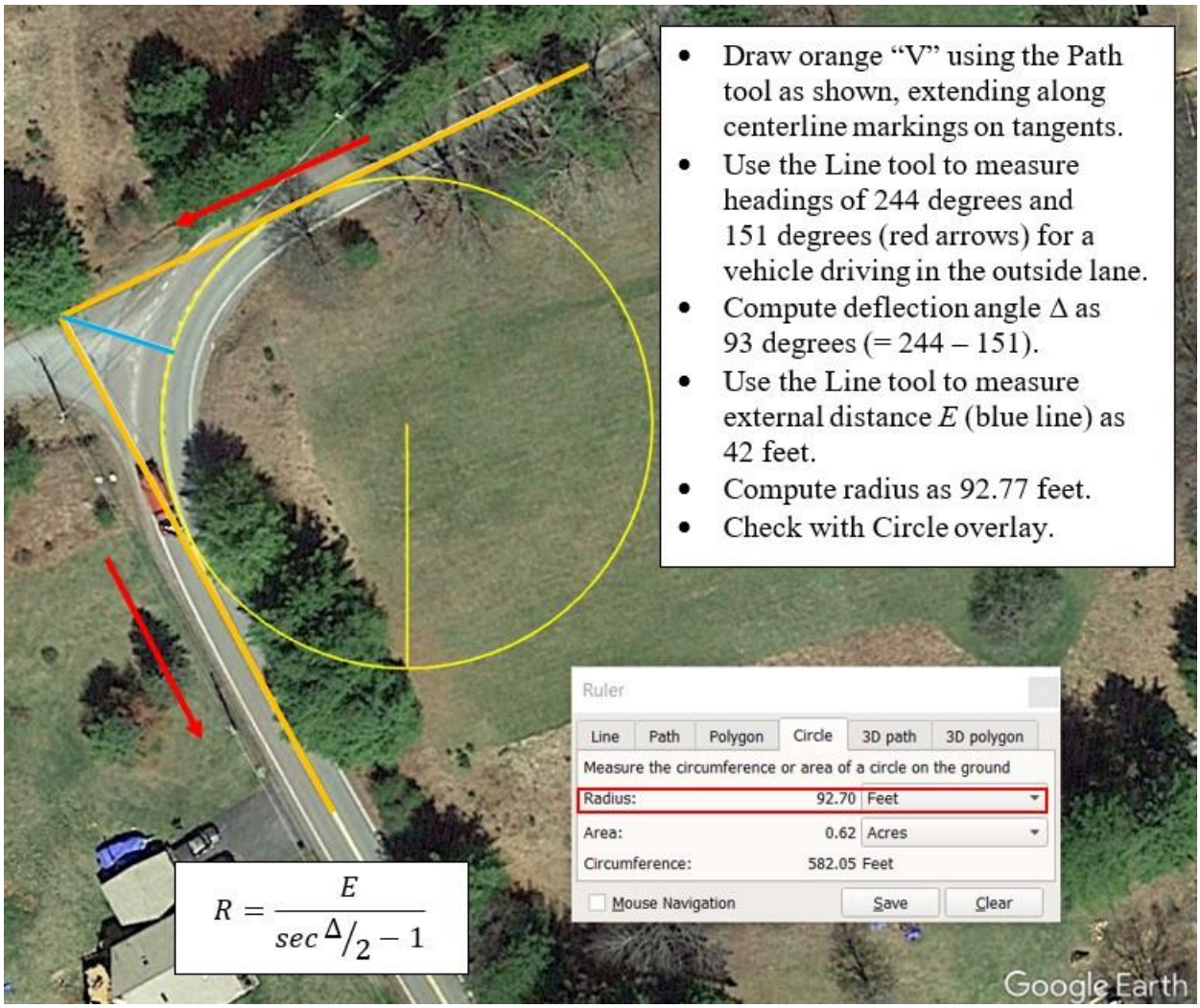
A. Curve overlay extending beyond curve endpoint.

B. Incomplete curve overlay.

All images original map: © 2025 Esri® ArcGIS®. Data source: TxDOT.

Figure 9. Maps. Examples of GIS data curve overlay shapes.[27,28]

The research team used aerial photography sources to measure precise curve radius and deflection angle values using the method shown in figure 10. Various methods are available for measuring curve geometry from aerial photos or scale diagrams; the research team chose the method shown because it does not need precise identification of the PC and PT, which can be difficult using aerial photos.

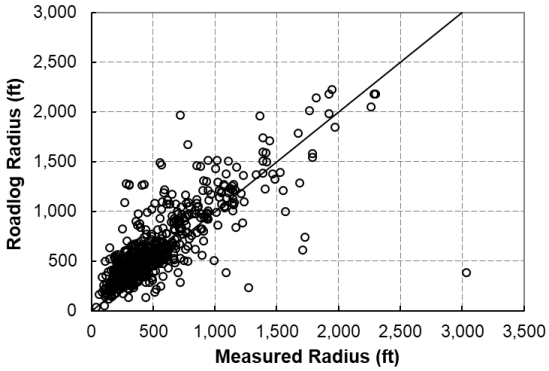


Original photo: © 2023 Google® Earth™. Modified by FHWA. (See Acknowledgments section.)

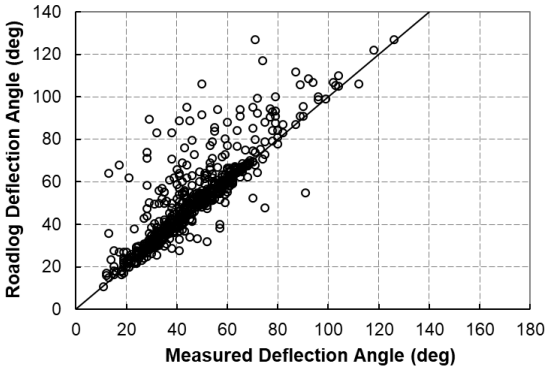
Figure 10. Map. Curve radius measurements from aerial photo.[25]

Figure 11 shows a comparison of the roadlog-extracted and photograph-measured radius and deflection angle values for the sites (including treated and reference) in both States. For the Pennsylvania sites, most of the deflection angle values are close to the $y = x$ line, but many of the points plot above the line. Most of the radius values for the Pennsylvania sites plot above the line. These observations suggest a tendency for many of the GIS curve overlay shapes to extend past the curve endpoints in the Pennsylvania data file, as shown in figure 9-A. Conversely, for the Texas sites, most of the deflection angle values are below the line, while the radius values are mostly centered on the line but with more points notably above the line than below. These

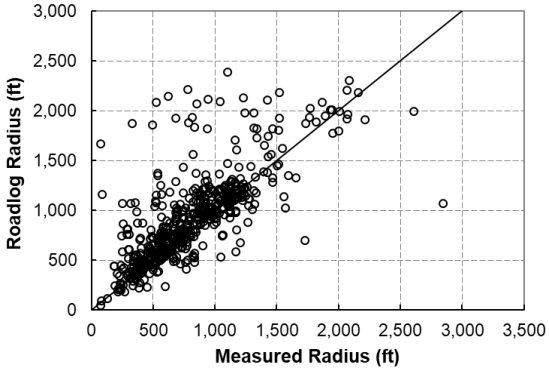
observations suggest a tendency of many of the GIS curve overlay shapes to include less than the entire curve length in the Texas data file, as shown in figure 9-B.[28]



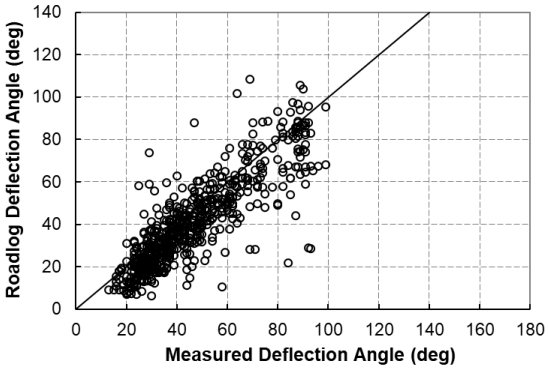
A. Radius (Pennsylvania).



B. Deflection angle (Pennsylvania).



C. Radius (Texas).



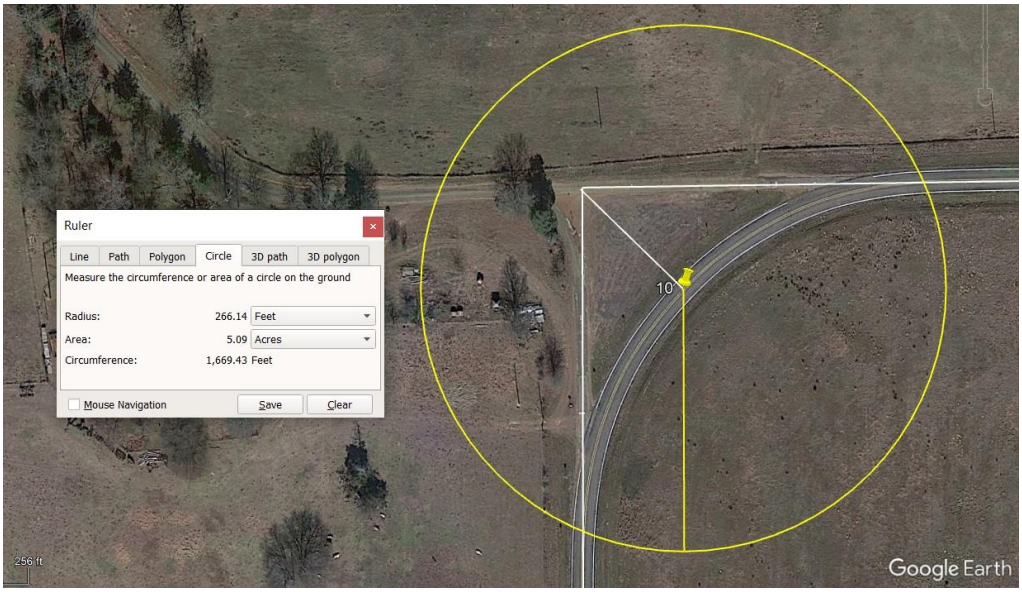
D. Deflection Angle (Texas).

All images source: FHWA.
deg = degree.

Figure 11. Graphs. Comparison of roadlog and measured curve radius values.

CRASH DATA

The research team considered using spatial joining methods to merge the crash data files with the curve roadlog data, using the curve segments that are defined in the GIS files. However, using imprecise overlay shapes would lead to crashes on approach tangents being included or crashes on missed portions of the curve being excluded. Instead, the research team conducted a different type of spatial joining using curve midpoints that are plotted on aerial photos. With this method, any crash that occurred on the same roadway as the curve (i.e., not on adjacent roadways or driveways) within a distance of half of the curve length would be assigned to the curve. This method would include crashes within the circle shown in figure 12 that are coded as occurring on the highway but not crashes on the driveway or county road on the outside of the curve.



Original photo: © 2023 Google® Earth™. Modified by FHWA. (See Acknowledgments section.)

Figure 12. Map. Defining the spatial join area surrounding a curve midpoint.[25]

Table 7 provides the typical treatment installation years and crash data query years for the treated sites. A small number of sites had installation dates outside the years specified for the typical range.

Table 7. Timeframes for treatment installation and crash data query.

State	Treatment	Typical Installation Year Range	Crash Data Query Year Range
PA	All	2008–2022	2010–2023
TX	Chevron Alignment signs with full-length retroreflective posts	2007	2003–2006, 2009–2012

STATISTICAL ANALYSIS NEEDS

The research team used an EB before–after analysis to estimate the safety effects of the identified CED treatments. To conduct a well-designed EB before–after analysis, it is important to consider the following factors:

- Accurate records on when the treatment was implemented.
- Availability of at least 24 mo of after-period crash data.
- Availability of a sufficient number of treatment sites.

The research team used an EB before–after analysis using reference sites. With this approach, the reference sites are used to calibrate a safety performance function (SPF) to predict crash frequency at untreated curves. The calibrated SPF is then used with EB adjustment to derive a CMF for the safety effect of the CED treatments of interest. The research team calibrated a single CMF for all included CED treatments, not separate CMFs for each treatment, to make best use of the sample size available in the dataset. The approach of combining CED treatments into a

single analysis was previously applied by Srinivasan et al. for a variety of treatments, including Horizontal Alignment, Chevron Alignment, or One-Direction Large Arrow signs that had fluorescent yellow sheeting (either adding new signs or replacing existing signs with new signs that had the upgraded sheeting); adding Chevrons to a curve; or increasing the number of Chevrons at a curve that already had some Chevrons.[16]

The research team applied statistical calculations to estimate the number of curve sites needed to calibrate a CMF for CED. The method is documented by Lord, Qin, and Geedipally and is based on an earlier method developed by Hauer.[29,30] This method is described as follows:

$$k = \frac{x_1 - (y_1/y_2)x_2}{\sqrt{x_1 + (y_1/y_2)^2 x_2}} \quad (4)$$

With:

$$x_n = NC_n y_n \quad (5)$$

Where:

k = critical value (= 1.96 for a 95-percent confidence level or 1.645 for a 90-percent confidence level).
x_n = total crashes in period n (n = 1 for before or 2 for after).
y_n = duration of period n, years.
N = number of treated sites.
C_n = average crash frequency in period n, crashes per site per year.

The research team identified the following input values for the variables based on a preliminary analysis of the assembled dataset:

- Duration of before period: 4 yr.
- Duration of after period: 3 yr.
- Average crash frequency in the before period: 0.283 crashes per site per year.
- Approximate CMF value: 0.764. This is an average of the CMF values of 0.820, 0.725, and 0.746 derived by Srinivasan et al. for CED treatments.[16]
- Average crash frequency in the after period: 0.216 crashes per site per year (= 0.283 × 0.764).

Based on these inputs, the research team estimated that with the assembled dataset of 248 treated sites, the analysis would yield a critical value of 2.272, which is greater than needed for a 95-percent confidence level. If the duration of the after period decreases to 1.5 yr, the critical value decreases to 2.336, which is still adequate for a 95-percent confidence level.

FINAL DATABASE STRUCTURE

The numbers in table 5 represent a preliminary count of treated and reference sites. The research team conducted a detailed site review to vet the sites and verify that sufficient detail was available to describe each site for analysis. This review resulted in the discarding of 13 treated sites and 64 reference sites, in most cases because street-level photography was not available for the site. A few sites were discarded because State roadlog or crash data were not available for the site, or because of unusual geometric configurations. Table 8 provides the count of included sites after detailed vetting.

Table 8. Count of vetted sites.

Treatment	Site Count in PA	Site Count in TX	Site Count in Both States
Chevron Alignment signs with full-length retroreflective posts	135	78	213
Chevron Alignment signs with full-length retroreflective posts and One-Direction Large Arrow signs with full-length retroreflective posts	6	0	6
One-Direction Large Arrow signs with full-length retroreflective posts	18	0	18
All treated sites	159	78	237
Reference sites	454	440	894
All sites	613	518	1,131

To successfully complete the safety analysis, the research team collected data to describe the treated and reference sites and the sites' safety performance. Table 9 lists the variables needed for the analysis. The variables have been identified as relevant to safety performance in published studies and are typically available either in State-maintained databases or online photography sources.

The research team obtained most of the variables from State data files (either roadlog files or crash files). Variables obtained from aerial and street-level photos needed the largest amount of staff time for collection. The most notable variables included sign presence and type, treatment type and installation date, and curve geometry. The research team used street-level photos to account for the presence of the following treatments in the before and after periods at each site:

- Horizontal Alignment signs (W1-1, W1-2, W1-3, W1-4, W1-5, W1-10, W1-11, or W1-15).
- Advisory Speed plaques (W13-1P).

- Chevron Alignment signs (W1-8).
- One-Direction Large Arrow signs (W1-6).
- Combination Horizontal Alignment / Advisory Speed sign (W1-1a or W1-2a in the 2009 MUTCD).[4]
- Full-length retroreflective posts for Chevron Alignment signs, One-Direction Large Arrow signs, or both.
- Delineators (conventional).
- Object Markers (OM1-3).
- Guardrail.

Table 9. Data for CMF calibration.

Category	Variable	Source
Location	State	Map
Location	Region (State DOT district)	Map, State records
Traffic	Traffic volume (AADT)	State roadlog
Traffic	Regulatory speed limit	State roadlog, photos
Traffic	Curve advisory speed (if present)	State roadlog, photos
Traffic	Location and type of Horizontal Alignment sign	State roadlog, photos
Traffic	Presence of supplemental traffic control devices	Photos
Geometry	Number of lanes	State roadlog, photos
Geometry	Curve radius	State roadlog, photos
Geometry	Curve length	State roadlog, photos
Geometry	Curve deflection angle	State roadlog, photos
Geometry	Lane width	State roadlog, photos
Geometry	Shoulder width	State roadlog, photos
Geometry	Presence of roadside longitudinal barrier	Photos
Geometry	Presence of center line rumble strips	Photos
Weather	Annual precipitation rate from weather stations (30-yr normal, 1981–2010)	Literature,[31] State agency[32]
Treatment	Type of CED	Photos
Treatment	Installation date for CED	State records, photos

Category	Variable	Source
Treatment	Presence of other treatments before installation	State records, photos
Crash	Crash timestamp (date and time)	State crash database
Crash	Crash location (latitude and longitude coordinates)	State crash database
Crash	Crash severity (KABCO scale)[18]	State crash database
Crash	Crash type (rear-end, sideswipe, run-off-road, etc.)	State crash database

Table 10 provides the distribution of Chevron Alignment and One-Direction Large Arrow signs at the treated and reference sites. Some sites had both Chevron Alignment and One-Direction Large Arrow signs, and are counted in both of the rightmost columns of the table. The research team identified a small set of sites (24 sites in one PennDOT district) where Object Markers were used in a manner similar to the full-length retroreflective posts. Over time, these sites were first treated with only Chevron Alignment signs, then Chevron Alignment signs and Object markers, and then Chevron Alignment signs and full-length retroreflective posts. For these sites, the research team defined the before period as the period when only Chevron Alignment signs were present and the after period as the period when Chevron Alignment signs and full-length retroreflective posts were present.

Table 10. Distribution of Chevron Alignment and One-Direction Large Arrow signs.

State	Site Type	Site Count (All Sites)	Site Count (Sites With Chevron Alignment Signs)	Site Count (Sites With One-Direction Large Arrow)
PA	Treated—before	159	90	23
PA	Treated—after	159	138	27
PA	Reference	454	63	64
TX	Treated—before	78	78	0
TX	Treated—after	78	78	0
TX	Reference	440	169	8

The research team identified a total of 1,246 crashes across the Pennsylvania sites and 282 crashes across the Texas sites. Table 11 provides the distribution of crashes by severity using the KABCO crash severity scale plus unknown (Unk.) for crashes of unknown severity.[18] The trends are generally intuitive when viewed in light of the AADT distributions.

Table 11. Crash frequency and severity distribution.

State	Site Category	AADT Range (veh/day)	Total Crash Count	K Crash Count	A Crash Count	B Crash Count	C Crash Count	PDO Crash Count	Unk. Crash Count
PA	Treated	360–13,179	634	19	21	117	115	283	79
PA	Reference	134–7,225	612	19	27	103	95	311	57
TX	Treated	40–2,580	53	1	4	10	9	27	2
TX	Reference	29–1,831	229	11	25	45	33	105	10

PDO = property damage only.

CHAPTER 5. ANALYSIS RESULTS

STATISTICAL ANALYSIS METHODOLOGY

Independent of the method used, before–after studies are usually accomplished using two tasks:[33]

- *Task 1*: Predict what would have been the safety performance of a site in the after period, had the treatment not been implemented.
- *Task 2*: Estimate the safety effect of the treatment at the site after implementation.

These tasks are accomplished as follows:

- The variable π is defined as the expected number of crashes at a specific site in the after period if the treatment has not been implemented. This variable only applies to the crash type of interest (e.g., angle crashes or rear-end crashes) and those crash types' severity (i.e., fatal, incapacitating injury, or property damage only). π is referred to as the predicted value.
- The variable λ is used to define the expected number of crashes in the after period (after the implementation of the treatment). λ is referred to as the estimated value.

The effects of a treatment are estimated by comparing both of the preceding variables in the following manner:

- The reduction (or increase) in the expected number of crashes is given as equation 6. A positive number indicates a decrease in the expected number of crashes.
- The ratio or the Index of Safety Effectiveness is defined as shown in equation 7. A value less than 1.0 indicates a reduction in the number of crashes.

$$\delta = \pi - \lambda \tag{6}$$

$$\theta = \frac{\lambda / \pi}{\left[1 + Var\{\pi\} / \pi^2\right]} \tag{7}$$

The before–after study with EB method incorporates the before–after study with the EB method to minimize regression-to-the-mean bias.[33,34] This method allows the estimation of safety benefits at treated sites using information from reference sites. The expected crash frequency ($E[k \mid K]$) at a treated site is a result of the combination of the predicted crash count ($E[k]$) based on the reference sites with similar traits and the crash history (K) of that site. The terms k and

$E[k]$ are technically the same, but the latter is usually used for statistical models. The following EB method uses $E[k]$ rather than k.

The parameter $E[k]$ is estimated from SPFs developed using a negative binomial (NB) regression (also known as Poisson-gamma) model under the assumption that the covariates in the SPFs represent the main safety traits of the reference sites.[35] The procedure for using the before–after study with EB method is described in the following steps.

Step 1: Estimate the predicted number of crashes in the before period.

Develop a new SPF or use an existing and reliable SPF. In this study, the research team developed new SPFs for horizontal curves using Pennsylvania and Texas data.

Using the SPFs, estimate the number of crashes for the before period at each treatment site. Obtain an EB estimate of the expected number of crashes before implementation of the countermeasure at each treatment site and an estimate of variance of the expected number of crashes.

The estimate of the expected number of crashes is obtained by combining the SPF predictions for the before period with the total count of crashes during the before period while accounting for the weight and overdispersion of the SPF.

Step 2: Calculate the proportion of the after-period crash estimate to the before-period estimate.

Using the SPFs developed in step 1, estimate the number of crashes in the after period at each treatment site. Compute the proportion of the after-period crash estimate to the before-period estimate.

Step 3: Obtain the expected crashes and the estimated variance.

Calculate the expected crashes during the after period that would have occurred without implementing the countermeasure (i.e., curve delineation treatments) and the variance of this estimate.

Step 4: Compute the sum of the predicted and observed crashes over all sites in the treatment group.

Compute the after-period crashes and the variances for a group of sites had the treatment not been implemented at the treated sites as the sum of the expected after-period crashes at all treated sites had there been no treatment.

Step 5:Compute the sum of the observed crashes over all treated sites.

For a treated site, crashes in the after period are influenced by the implementation of the treatment. To obtain the safety effectiveness of a treatment, compare the observed crashes with the treatment to the expected crashes without the treatment. Compute the observed number of after-period crashes for a group of treated sites as the sum of the observed crashes across all treated sites during the after period.

Step 6: Estimate the variances of the predicted and observed crash frequencies over all sites in the treatment group.

Conduct these calculations assuming a Poisson distribution (i.e., the estimate of variance of crash frequency is assumed to be equal to the mean crash frequency).

Step 7. Compute the safety effect of the treatment.

The index of effectiveness (θ) (also referred to as a CMF) is defined as the ratio of crash frequency with the treatment to crash frequency without the treatment, also accounting for variance. If θ is less than 1, then the treatment has a positive safety effect. The approximate 95-percent confidence interval (CI) for θ is given by adding and subtracting 1.96 times the standard error from θ. If the CI contains the value 1, then no significant effect has been observed.

Previous studies have indicated that before–after studies with EB method are the most robust approach in terms of developing CMFs and hotspot identification. (See references 36, 37, 38, and 39.) A large portion of CMFs in the CMF Clearinghouse were developed using this approach.[15] The safety effects of many treatments are being estimated with this method. (See references 40, 41, and 42.)

However, the EB method is not free of limitations. This method suffers from mixed safety effects and possibly low sample size issues. Recently, Lord and Kuo documented the limitations of the EB method.[43] One of the limitations is the presence of the site selection bias. This type of bias is similar to regression-to-the-mean bias, but its effects differ in that the sites are selected based on a known or unknown entry criterion (e.g., 5 crashes per year).

MODELING RESULTS

The research team developed separate SPFs for Pennsylvania and Texas. The research team considered various functional forms and interactions before finalizing the model form. All variables from table 9 and table 10 were first included, and the ones that were significant and intuitive were retained in the final models. Indicator variables for different periods were introduced in the models to capture the safety trends over time. In Texas, the sites were treated in 2007 for region 1 (Atlanta and Lufkin districts), so the before period included crashes from 2003 to 2006 and the after period included crashes from 2009 to 2012. For the sites in region 2 (Abilene, Brownwood, Corpus Christi, El Paso, San Angelo, San Antonio, and Yoakum districts), the treatment year was 2018, so the before period included crashes from 2014 to 2017, and the after period included crashes from 2020 to 2022. In Pennsylvania, sites were treated in different periods from 2010 to 2022, so the before and after periods varied among the sites.

For Texas, the predicted annual crash frequency is calculated as follows:

$$N_j = (N_{r1}I_{r1} + N_{r2}I_{r2})CMF_R \quad (8)$$

With:

$$N_{r1} = L \times n \times e^{b_{r1} + b_{adt}\ln(AADT) + b_{aft,r1}I_{aft}} \quad (9)$$

$$N_{r2} = L \times n \times e^{b_{r2} + b_{adt}\ln(AADT) + b_{aft,r2}I_{aft}} \quad (10)$$

$$CMF_R = 1 + b_R(0.147V)^4 \frac{(1.47V)^2}{32.2R^2} \quad (11)$$

Where:

N_{r1} = base predicted annual crash frequency for region 1, crashes per year.
N_{r2} = base predicted annual crash frequency for region 2, crashes per year.
CMF_R = horizontal curve radius CMF.
L = horizontal curve length, mi.
n = number of years of crash data, yr.
$AADT$ = annual average daily traffic on the horizontal curve, veh/day.
I_{r1} = indicator variable for region 1 (= 1 if in region 1; = 0 otherwise).
I_{r2} = indicator variable for region 2 (= 1 if in region 2; = 0 otherwise).
I_{aft} = indicator variable for the after period (= 1 if it is after period; = 0 otherwise).
V = regulatory speed limit, mph.
b_i = calibration coefficient for variable i.

For Pennsylvania, the predicted annual crash frequency is calculated as follows:

$$N = L \times n \times e^{b_0 + b_{adt}\ln(AADT) + b_t I_t} CMF_R \quad (12)$$

Where I_t is the indicator variable for different years between 2010 and 2023.

Table 12 and table 13 contain the calibrated coefficients for total crashes on horizontal curves in Texas and Pennsylvania, respectively. The research team considered a confidence level of 95 percent for retaining the variables in the models. A few variables that were not significant at a 95-percent confidence level were also retained if those variables were important to the model (even if the specific value was not known with a great deal of certainty). These variables

included the time period indicator variables and horizontal curve radius. The time period indicator variables are essential to account for temporal variations in crash frequency, and radius is well-documented in the literature as a key variable affecting the safety performance of horizontal curves.

Table 12. Calibrated coefficients for Texas—total crashes.

Coefficient	Variable	Value	Std. Dev.	*t*-Statistic	*p*-Value
$b_{bef,r1}$	Intercept for before period (2003–2006), region 1	−6.373	0.862	−7.40	<0.0001
$b_{aft,r1}$	Intercept for after period (2009–2012), region 1	−6.101	0.859	−7.10	<0.0001
$b_{bef,r2}$	Intercept for before period (2014–2017), region 2	−6.547	0.871	−7.52	<0.0001
$b_{aft,r2}$	Intercept for after period (2020–2022), region 2	−7.008	0.921	−7.61	<0.0001
b_{adt}	AADT	0.795	0.125	6.37	<0.0001
b_R	Horizontal curve radius	0.691	0.292	2.37	0.018
ϕ	Inverse dispersion parameter	2.383	1.235	1.93	0.054

Std. Dev. = standard deviation.

Table 13. Calibrated coefficients for Pennsylvania—total crashes.

Coefficient	Variable	Value	Std. Dev.	*t*-Statistic	*p*-Value
b_0	Intercept	−6.163	0.463	−13.29	<0.0001
b_{adt}	AADT	0.805	0.055	14.65	<0.0001
b_R	Horizontal curve radius	0.844	0.179	4.70	<0.0001
b_t	Indicator for period 2014–2016	0.135	0.133	1.02	0.308
b_t	Indicator for period 2017–2018	−0.165	0.158	−1.05	0.294
b_t	Indicator for period 2019–2020	−0.298	0.165	−1.80	0.071
b_t	Indicator for period 2021–2023	−0.221	0.142	−1.55	0.121
ϕ	Inverse dispersion parameter	1.681	0.375	4.48	<0.0001

Table 14 and table 15 contain the calibrated coefficients for FI crashes on horizontal curves in Texas and Pennsylvania, respectively.

Table 14. Calibrated coefficients for Texas—FI crashes.

Coefficient	Variable	Value	Std. Dev.	*t*-Statistic	*p*-Value
$b_{bef,r1}$	Intercept for before period (2003–2006), region 1	−7.678	1.208	−6.35	<0.0001
$b_{aft,r1}$	Intercept for after period (2009–2012), region 1	−7.555	1.208	−6.25	<0.0001
$b_{bef,r2}$	Intercept for before period (2014–2017), region 2	−8.295	1.234	−6.72	<0.0001
$b_{aft,r2}$	Intercept for after period (2020–2022), region 2	−8.446	1.284	−6.58	<0.0001
b_{adt}	AADT	0.844	0.171	4.93	<0.0001
b_R	Horizontal curve radius	1.269	0.716	1.77	0.077
ϕ	Inverse dispersion parameter	8.584	24.667	0.35	0.728

Table 15. Calibrated coefficients for Pennsylvania—FI crashes.

Coefficient	Variable	Value	Std. Dev.	*t*-Statistic	*p*-Value
b_0	Intercept	−6.820	0.639	−10.67	<0.0001
b_{adt}	AADT	0.774	0.076	10.19	<0.0001
b_R	Horizontal curve radius	0.890	0.262	3.40	0.001
b_t	Indicator for period 2017–2019	−0.175	0.176	−1.00	0.319
b_t	Indicator for period 2020–2021	−0.348	0.220	−1.59	0.113
b_t	Indicator for period 2022–2023	−0.469	0.227	−2.07	0.039
ϕ	Inverse dispersion parameter	3.329	3.183	1.05	0.296

Table 16 and table 17 contain the calibrated coefficients for nighttime crashes on horizontal curves in Texas and Pennsylvania, respectively. The inverse dispersion parameter for the Texas model is too high, meaning that the NB model converged to a Poisson model. In this situation, the EB-estimated expected crashes will be highly dependent on the predicted crashes only and little weight will be given to the observed crashes.

Table 16. Calibrated coefficients for Texas—nighttime crashes.

Coefficient	Variable	Value	Std. Dev.	*t*-Statistic	*p*-Value
$b_{bef,r1}$	Intercept for before period (2003–2006), region 1	−8.052	1.259	−6.40	<0.0001
$b_{aft,r1}$	Intercept for after period (2009–2012), region 1	−7.625	1.254	−6.08	<0.0001
$b_{bef,r2}$	Intercept for before period (2014–2017), region 2	−8.583	1.302	−6.59	<0.0001
$b_{aft,r2}$	Intercept for after period (2020–2022), region 2	−8.274	1.320	−6.27	<0.0001
b_{adt}	AADT	0.928	0.185	5.02	<0.0001
b_R	Horizontal curve radius	0.466	0.271	1.72	0.086
ϕ	Inverse dispersion parameter	154.06	9169.25	0.02	0.987

Table 17. Calibrated coefficients for Pennsylvania—nighttime crashes.

Coefficient	Variable	Value	Std. Dev.	*t*-Statistic	*p*-Value
b_0	Intercept	−6.946	0.646	−10.75	<0.0001
b_{adt}	AADT	0.805	0.078	10.27	<0.0001
b_R	Horizontal curve radius	0.713	0.205	3.48	0.001
b_t	Indicator for period 2012–2013	−0.493	0.228	−2.16	0.031
b_t	Indicator for period 2017–2019	−0.321	0.188	−1.70	0.089
b_t	Indicator for period 2020–2021	−0.252	0.212	−1.19	0.234
ϕ	Inverse dispersion parameter	2.594	1.885	1.38	0.169

The first three rows of table 18 present the average safety effect of installing CED treatments on total crashes based on the EB method. The first row provides the analysis results for the combined Texas and Pennsylvania database. The analysis results indicate that if the treatment had not been installed, the expected number of crashes would have been 155.1 during the after-study period. The actual number of reported crashes is 127. It is estimated that the CED treatments decreased total crashes by 18 percent, which corresponds to a CMF value of 0.82. The standard deviation of the estimate is 8 percent, which makes the estimate statistically significant at a 95-percent confidence level. The research team conducted an additional analysis by State to determine if the treatment had different effects in the two States. The Texas result is marginally significant, but the Pennsylvania result is not.

Table 18. EB analysis results.

Crash Type	State	Expected Crashes (After)	Observed Crashes (After)	Reduction in Crashes	Safety Index (θ)	95-Percent CI of Reduction in Crashes
Total crashes	Both	155.1 (7.0)	127 (11.3)	28.1 (14.3)	***0.82*** (0.08)	2 to 34 percent
Total crashes	TX	53.1 (4.3)	30 (5.5)	23.1 (8.4)	*0.56* (0.11)	22 to 66 percent
Total crashes	PA	102.0 (5.5)	97 (9.8)	5.0 (11.5)	0.95 (0.11)	−16 to 27 percent
FI crashes	Both	63.9 (2.4)	47 (6.9)	16.9 (8.3)	***0.73*** (0.11)	5 to 48 percent
FI crashes	TX	30.7 (2.5)	14 (3.7)	16.7 (5.8)	*0.45* (0.12)	30 to 79 percent
FI crashes	PA	33.2 (1.8)	33 (5.7)	0.2 (6.0)	0.99 (0.18)	−34 to 36 percent
Nighttime crashes	Both	65.4 (2.5)	43 (6.6)	22.4 (8.5)	***0.66*** (0.10)	14 to 55 percent
Nighttime crashes	TX	26.8 (0.3)	17 (4.1)	9.8 (5.1)	*0.63* (0.15)	6 to 67 percent
Nighttime crashes	PA	41.2 (2.5)	30 (5.5)	11.2 (6.9)	0.73 (0.14)	0 to 55 percent

Note: Bold values are the derived CMFs for the combined-State database. Italic values are statistically significant at a 95-percent confidence level. Values in parentheses are the standard errors of the estimates.

The next three rows of table 18 present the average safety effect of installing CED treatments on FI crashes based on the EB method. The combined-State analysis results indicate that if the treatment had not been installed, the expected number of crashes would have been 63.9 during the after-study period. The actual number of reported crashes is 47. It is estimated that the CED treatments decreased FI crashes by 27 percent, which corresponds to a CMF value of 0.73. The standard deviation of the estimate is 11 percent, which makes the estimate statistically significant at a 95-percent confidence level. The research team conducted an additional analysis by State to determine if the treatment had different effects in the two States. The Texas result is highly statistically significant, but the Pennsylvania result is not.

The final three rows of table 18 present the average safety effect of installing CED treatments on nighttime crashes based on the EB method. The combined-State analysis results indicate that if the treatment had not been installed, the expected number of crashes would have been 65.4 during the after-study period. The actual number of reported crashes is 43. It is estimated that the CED treatments decreased nighttime crashes by 34 percent, which corresponds to a CMF value of 0.66. The standard deviation of the estimate is 10 percent, which makes the estimate statistically significant at a 95-percent confidence level. The research team conducted an additional analysis by State to determine if the treatment had different effects in the two States. The results were similar in both States, although the effect was statistically significant only for the Texas sites.

In addition to the preceding analyses, the research team also considered developing a CMF for wet-weather crashes. However, the research team was unable to conduct this analysis because of limitations in sample size (particularly after-period crashes) and the observed range of annual precipitation rates across the sites.

BENEFIT–COST ANALYSIS

The research team conducted a benefit–cost analysis of the analyzed CED treatments using the methodology described by Lawrence et al.[44] This methodology needs input data to describe treatment cost, crash frequency and severity distribution, crash costs, treatment effectiveness, and discount rate. The research team used the following input values for the benefit–cost analysis:

- Analysis period: 15 yr.
- Cost for CED treatment installation, including labor and materials: $566.86 per site (high), $457.07 per site (average), $347.28 per site (low):
    - For the high estimate, assume 6 person-hours of labor at $45.14/h, 60 vehicle-miles at $2.00/mile, 14 ft^2 of fluorescent sheeting (8 poles, 7-ft height, 3-inch width) at $4.00/$ft^2$, and 24 mounting brackets at $5.00/bracket.
    - For the low estimate, assume 4 person-hours of labor at $37.62/h, 30 vehicle-miles at $2.00/mile, 14 ft^2 of conventional sheeting (8 poles, 7-ft height, 3-inch width) at $1.20/$ft^2$, and 24 mounting brackets at $5.00/bracket.
- Crash costs (table 35):[44]
    - K crash: $11,637,947.00.
    - ABC crash (average): $335,832.33.
    - Property damage-only (PDO) crash: $12,108.00.
- CMF value: 0.82 (from table 18).
- Discount rate: 3 percent (to account for inflation and the changing value of resources over the life span of the treatment).
- Annual crash frequency: 0.41 crashes per year per site (based on table 8 and table 11).
- Crash proportions:
    - K crashes: 0.03 (computed from table 11).
    - KABC and unknown-severity crashes: 0.55 (computed from table 11).
    - PDO crashes: 0.45 (from table 11).

Using these parameters, the research team obtained benefit–cost ratios of 13.29 (low-cost range), 10.10 (average-cost range), and 8.14 (high-cost range).

CHAPTER 6. FINDINGS AND CONSIDERATIONS

The research team derived a CMF value of 0.82 for the effect of the studied CED treatments on total crashes. This value indicates a positive safety effect that compares well with other CMFs for CED treatments in the literature (table 19). For example, the study by Srinivasan et al. included a variety of treatments, such as Horizontal Alignment, Chevron Alignment, or One-Direction Large Arrow signs that had fluorescent yellow sheeting (either adding new signs or replacing existing signs with new signs that had the upgraded sheeting); adding Chevrons to a curve; or increasing the number of Chevrons at a curve that already had some Chevrons. Some of these treatments were upgrades to pre-existing treatments, not new treatments at the site.[16] The CMF value from the study was 0.82 for FI nonintersection crashes, compared to a value of 0.73 derived by the research team. The CMF values obtained by the research team are similar in magnitude to the CMF values reported by Srinivasan et al., showing that the CED treatments analyzed in this study provide a safety benefit similar to those in the Srinivasan et al. study. The study by Montella yielded an overall CMF value of 0.59 for adding Horizontal Alignment and Chevron Alignment signs to sites that were previously untreated.[17] The CMF value reported by Montella shows a larger magnitude of safety benefit, which is expected because the treatments analyzed in the Montella study were more notable than those analyzed in this study (i.e., treating previously untreated curves versus improving treatments on curves that are already treated).

Table 19. Comparison of CMF values.

Source	Treatments	CMF Values
Research team	Add full-length retroreflective posts to existing Chevron Alignment signs	0.82 (total crashes), 0.73 (FI crashes), 0.66 (nighttime crashes)
Srinivasan et al.[16]	Add Horizontal Alignment signs, add Chevron Alignment signs, add One-Direction Large Arrow signs (add new or replace existing with new that have upgraded sheeting), decrease Chevron Alignment sign spacing by adding signs	0.91 (nonintersection crashes), 0.82 (FI nonintersection crashes), 0.73 (nighttime nonintersection crashes)
Montella[17]	Add Horizontal Alignment and Chevron Alignment signs	0.59 (total crashes)

When the data for Pennsylvania and Texas are analyzed separately, the resulting CMFs for the two States are notably different. This finding is likely due to the differences in the key site variables between the States (figure 8). In particular, the Texas sites generally had higher regulatory speed limits than the Pennsylvania sites, and the analyzed CED treatments showed more of a safety benefit at the Texas sites than the Pennsylvania sites, suggesting a greater need for enhanced delineation for curves on higher speed roadways (consistent with the trend shown in figure 5). The distribution of key site variables between the two States confounds efforts to determine if the differences between the States are attributable to measured variables or other variables not measured. For example, the research team was able to obtain precipitation rates

(which were found not to be statistically significant) but not vertical curvature, grade, or terrain type. These variables were addressed in previous research involving horizontal curves.[21,22]

The CED treatments studied are low cost, with installation labor representing the largest cost component. The research team found a positive benefit–cost ratio (10.10) for the treatments, so the decision to install them should be based on a prioritization of the various needs of the jurisdiction, in particular the frequency and severity of crashes on rural highway curves versus crashes at other sites.

The main limitation of this study is sample size, in terms of both site characteristics and crash count. Though the research team was able to identify over 1,100 sites, the total sample in terms of roadway mileage, traffic volume, and crash count (particularly in the after period) was meager, and the ranges of several key variables (e.g., AADT and radius) varied between the reference sites and the treated sites. Additionally, the timeframes for treatment installation differed between the States where the treated sites are located. The research team applied a study design intended to overcome these constraints, but a larger dataset with fewer constraints and a longer after period would likely yield more robust results and provide insights into treatment effect on more crash types (e.g., wet-weather crashes). Including additional site variables, particularly those describing vertical curvature, grade, and terrain, could also yield models that are more transferable.

ACKNOWLEDGMENTS

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Recommended citation: Federal Highway Administration,
*Safety Effects of Full-Length Retroreflective Posts
for In-Curve Horizontal Alignment Signs*
(Washington, DC: 2026) https://doi.org/10.21949/3mm1-hh58

HRSO-20/10-26(WEB)E