Developing Crash Modification Factors for Guardrails, Utility Poles, and Side-Slope Improvements

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

FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA's) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS in 2005 to research the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program's Report 500 Series as part of the implementation of the American Association of State Highway and Transportation Officials' *Strategic Highway Safety Plan* (NCHRP 2009; AASHTO 1998). The ELCSI-PFS research studies provide crash modification factors (CMFs) and a benefit–cost economic analysis for each safety strategy identified as a priority by the PFS's 41 member States.

Through the study in this report, researchers evaluated the safety effectiveness of three fixed roadside objects—guardrails, utility poles, and side slopes—using safety data from Indiana and Pennsylvania. The estimated CMFs for protecting utility poles with guardrails were statistically significant for reducing fatal-and-injury crashes but not for reducing total and roadway-departure crashes. For utility pole removal, the CMFs were statistically significant for reducing fatal, injury, and total crashes. The estimated CMFs for side-slope flattening indicated reductions in total and roadway-departure crashes and were statistically significant for roadway-departure crashes. The guardrail economic evaluation indicated guardrails are economically viable when protecting roadside utility poles. The economic evaluation of utility-pole removal or relocation indicated that this strategy is economically viable when not considering the acquisition of new right-of-way.

These study results may be of interest to State and local engineers and planners responsible for the design, operation, and maintenance of fixed roadside objects. Highway safety practitioners also may find the results useful in making decisions regarding the safety effectiveness of guardrails, utility poles, and side-slope improvements.

Brian P. Cronin, P.E.
Director, Office of Safety and Operations Research and Development

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Raul Avelar (ORCID: 0000-0002-3962-1758), Karen Dixon (ORCID: 0000-0002-8431-9304), Sruthi Ashraf (ORCID: 0000-0002-3304-9682), Ankit Jhamb (ORCID: 0000-0002-6123-9352)</td><td colspan="2">8. Performing Organization Report No.</td></tr>
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Through this project, researchers evaluated the safety effects of guardrails, utility poles, and side slopes using safety data from Indiana and Pennsylvania. Safety evaluations in this project focused on total, fatal-and-injury, and roadway-departure crash risk. Crash modification factors (CMFs) and benefit–cost (B/C) ratios were developed for the safety improvements (guardrails, utility poles, and side slopes) of interest. The CMFs for protecting utility poles with guardrails were not statistically significant for total and roadway-departure crashes (CMF values were 0.89 and 1.52, depending on how close the utility poles were to the roadway). The CMFs for fatal-and-injury crashes were statistically significant (CMFs of 0.524 and 0.433, depending on pole proximity to the roadway). Results for CMFs developed for pole removal in terms of fatal-and-injury crashes indicated a statistically significant CMF of 0.656. For pole relocation, this evaluation found a statistically significant CMF of 0.866 on total crashes. Finally, estimated CMFs for side-slope flattening indicated reductions in total and roadway-departure crashes. The statistically significant CMFs varied between 0.923 and 0.936 for total crashes and between 0.784 and 0.951 for roadway-departure crashes, depending on the initial and final flattened-slope values.

The economic evaluation of guardrails indicated that guardrail implementations are economically viable when protecting roadside utility poles (a B/C ratio of 1.28 or 1.48). The economic evaluation of pole removal or relocation indicated that this strategy is economically viable when not considering the acquisition of new right-of-way (a B/C ratio of 6.73).</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
B/C	benefit–cost
CMF	crash modification factor
DCMF	development of crash modification factors
DOT	department of transportation
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FHWA	Federal Highway Administration
GIS	geographic information system
GLM	generalized linear model
GLMM	generalized linear mixed model
H	horizontal
INDOT	Indiana Department of Transportation
PDO	property-damage only
PS	propensity score
PSM	propensity-score matching
PSW	propensity-score weighting
RID	Roadway Inventory Database
ROR	run-off-the-road
ROW	right-of-way
SHRP2	Second Strategic Highway Research Program
SPF	safety performance function
TxDOT	Texas Department of Transportation
USDA	U.S. Department of Agriculture
USDOT	U.S. Department of Transportation
V	vertical
VSL	value of a statistical life

EXECUTIVE SUMMARY

The Federal Highway Administration's (FHWA's) Development of Crash Modification Factors (DCMF) program was established in 2012 to address highway-safety research needs and evaluate new and innovative safety strategies (improvements) by developing reliable quantitative estimates of their effectiveness in reducing crashes.

The ultimate goal of the FHWA DCMF program "is to save lives by identifying new safety strategies that effectively reduce crashes and promote them for nationwide installation by providing measures of their safety effectiveness" (crash modification factors (CMFs)) and benefit–cost (B/C) ratios through research (FHWA 2019). State departments of transportation (DOTs) and other transportation agencies need to have objective measures to evaluate safety effectiveness and B/C ratios before investing in new strategies for statewide safety improvements.

Forty-one State DOTs provide technical feedback on safety improvements to the DCMF program and implement new safety improvements to facilitate evaluations. These States are the members of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS), which functions under the DCMF program.

The ELCSI-PFS Technical Advisory Committee selected evaluating the effects of fixed roadside objects as one of ELCSI-PFS's priorities. This report documents the evaluation of the safety effects of fixed roadside objects, such as utility poles and guardrail faces, to reduce crashes in terms of risks of total, fatal-and-injury, and roadway-departure crashes. CMFs and B/C ratios were developed for the safety improvement strategies of interest: addition of guardrails, removal or relocation of utility poles, and changes to fore slope and back slope. Practitioners can use these CMFs and B/C ratios for decisionmaking in their project-development and safety-planning processes.

The estimated CMFs for guardrail implementations were consistently smaller than 1.0 for fatal-and-injury crashes but were only statistically significant for implementations that were intended to protect poles on the roadside. Results were inconclusive for implementations intended to protect side slopes (all CMFs not statistically different from 1.0).

The estimated CMFs for pole removal or relocation were consistently smaller than 1.0 for fatal-and-injury crashes. The CMF for total crashes was smaller than 1.0 and statistically significant only for the case of removing poles from the roadside; for the case of relocating poles farther from the paved surface, the CMF was not statistically different from 1.0.

The estimated CMFs for side-slope flattening were consistently smaller than 1.0 and statistically significant for roadway-departure crashes. In the case of total crashes, the CMFs tended to be smaller than 1.0 but were only statistically significant for the following two treatments:

- Reducing the side slope from 1:4 to 1:6 or flatter.
- Reducing the side slope from 1:2 or 1:3 to 1:6 or flatter.

The economic evaluation of guardrails indicated that guardrail implementations are economically viable when protecting roadside poles (B/C ratio of 1.28 or 1.48, depending on the distance of the pole from the paved surface). Results were inconclusive for protecting side slopes with guardrails (because the safety analysis yielded no statistically significant estimate of the crash-reduction benefit).

The economic evaluation of pole removal indicated that this strategy is economically viable (B/C ratio of 1.41 or 17.1, depending on the cost of right-of-way acquisition), as is pole relocation to 20 ft or farther from the paved shoulder (a B/C ratio of 6.73).

The economic evaluation of side-slope flattening indicated that this strategy is not economically viable. The research team surmises that the reason for low B/C ratios for this method is the relatively low crash frequency per mile on the roads used in the evaluation, and the team anticipates that flattening the side slope may be economically viable in locations where annual average daily traffic tends to be higher and roadway-departure crashes are more numerous.

CHAPTER 1. INTRODUCTION TO SAFETY EVALUATION OF FIXED ROADSIDE OBJECTS

Fixed roadside objects, such as trees, signs, utility poles, signals, and guardrails, play a significant role in roadway-departure crashes. According to Neuman et al. (2003), 40 percent of roadway-departure crashes involve a fixed roadside object; 63 percent of these objects are trees or utility poles.

A large proportion of roadway departures occur in rural environments, particularly on two-lane highways. According to the Federal Highway Administration (FHWA), over 25,000 people were killed on all U.S. road networks combined in 2005 because drivers left their lane and impacted an oncoming vehicle, rolled over, or hit an object located along the highway. Of all these fatalities, about 17,000 were the result of single-vehicle, run-off-the-road (ROR) crashes; this type of crash accounts for about 60 percent of all fatalities on the U.S. highway network. Examining these characteristics more closely reveals that about 80 percent of ROR fatalities occurred on rural roadways, with about 90 percent of those rural crashes occurring on two-lane highways alone (FHWA 2006).

Lord et al. (2011) identified factors that influence the number and severity of roadway-departure crashes on rural two-lane highways in Texas. The researchers analyzed crash, traffic-flow, and geometric data between 2003 and 2008 and visited the 20 sites (across 4 Texas Department of Transportation (TxDOT) districts) with the highest crash rates. The study showed that the proportion of roadway departures varied from 25 to 52 percent of all crashes occurring on Texas's rural two-lane highway network (Lord et al. 2011). From 2013 to 2015, an average of 18,275 fatalities, which is 54 percent of all traffic fatalities in the United States, resulted from roadway departures (FHWA 2017).

The *Green Book* by the American Association of State Highway and Transportation Officials (AASHTO) stipulates the minimal horizontal clearance required for normal roadway operations, but the AASHTO *Roadside Design Guide* recommends an additional clear zone to accommodate errant vehicles (AASHTO 2002, 2011).

LITERATURE REVIEW ON FIXED ROADSIDE OBJECTS AND CRASH MODIFICATION FACTORS

Despite the environmental, social, and economic benefits of trees in communities, municipalities, and regions, nearly 25 percent of all roadway-departure crashes with fixed objects in the United States each year are single-vehicle collisions with trees (AASHTO 2002). In a study conducted on 4,951 mi of rural two-lane roads in seven States, Zeeger et al. (1988) identified the following obstacles as having the most involvement with severe crashes: trees, utility poles, culverts, light poles, bridges, rocks, and earth embankments. This research found that roadside improvements seem to be associated with crash reductions ranging from 19 to 52 percent. The presence of a side slope was an important factor in roadside crashes, and flatter side slopes provided greater safety benefits (Zeeger et al. 1988).

Stigson et al. (2009) identified the severity of frontal two-vehicle and single-vehicle crashes with deformable objects and single-vehicle crashes with rigid roadside objects as statistically higher than other conditions. Among these collision types, these researchers found that single-vehicle crashes with deformable objects are the least harmful type (Stigson et al. 2009).

A study by Lee and Mannering (2002) combined databases on roadside features and several other factors to analyze ROR crashes on a 96.6-km section of highway in Washington State. The researchers developed zero-inflated count models and nested logit models to estimate accident frequency. The authors found significant differences in the factors that determined ROR-accident frequencies (crashes per month on roadway sections) in urban and rural areas. The results showed that ROR-accident frequencies can be reduced by avoiding cut side slopes, decreasing the distance from the outside shoulder edge to the guardrail, decreasing the number of isolated trees along roadway sections, and increasing the distance from the outside shoulder edge to light poles (Lee and Mannering 2002).

Ray (1999) studied the effects of vehicle mass in roadway-departure collisions and the energy-dissipation characteristics of various roadside features. The author used estimates of velocity change to simulate energy-dissipation distributions. The vehicle mass did not appear to be a good predictor of the risk to occupants in side impacts with fixed roadside objects. The author argued that a lateral impact velocity of 50 km/h probably represents the 90th-percentile speed of fixed-object side impacts. The author estimated the average orientation of impact to be approximately 60°. However, the mode of such an angle (i.e., the most common value) was a full-broadside collision (90°). The analyzed accident data revealed that, regarding fixed-object collisions, the most probable location of a side impact on a vehicle is the area next to the front-seat occupant's space (Ray 1999).

Crashes with fixed roadside objects accounted for 20 percent of crashes in South Carolina. Ogle et al. (2009) evaluated more than 60,000 crashes involving fixed roadside objects (trees, utility poles, culverts, bridge piers, etc.) on South Carolina roadsides over a 3-yr period (2004 through 2006). The researchers developed a crash modification factor (CMF) based on nonregression cross-sectional analysis. Removal or replacement of fixed roadside objects outside the clear zone was the evaluated improvement. Out of 287 sites surveyed, 58 were selected as reference sites, and 47 met the clear-zone requirements. The odds of a site having a fixed-object crash were 42 times higher if the minimum clear zone was not met (Ogle et al. 2009).

Daniello and Gabler (2011) found that roadside objects, such as guardrails, concrete barriers, signs, utility poles, and trees, seem to increase the fatality rate of motorcycle crashes. These results were based on an analysis of motorcycle-crash data in the Fatality Analysis Reporting System database for the years 2004 through 2008. Compared to collisions with the ground, collisions with guardrails were 7 times more likely to result in fatalities, and collisions with trees were nearly 15 times more likely to result in fatalities (Daniello and Gabler 2011).

Holdridge et al. (2005) evaluated crash-severity impacts with roadside objects to assess the in-service performance of roadside hardware on the urban State route system in Washington State using multivariate nested logit models. This research suggested that leading ends of guardrails, bridge rails, and large wooden poles (trees and utility poles) were associated with an increased probability of fatal injury, whereas the faces of guardrails seemed to reduce the probability of evident injury (Holdridge et al. 2005).

Wolf and Bratton (2006) analyzed national traffic-collision data to address safety concerns regarding urban trees and crash incidence and severity. Rural and urban conditions were distinctly evaluated using descriptive-, comparative-, and predictive-analysis methods. The analysis considered crashes under a wide range of conditions. The researchers concluded that implementation of roadside hardware might eliminate crash risk (Wolf and Bratton 2006).

Rajamäki (2013) found that the most common primary collision object for fatal collisions was trees, which accounted for 27 percent of the crashes in Finland. Electricity and light poles accounted for 14 percent and guardrails accounted for 10 percent of crashes. Because distances between roadsides and trees were not available, the safety effect was estimated based on road age; trees are closer to the edge of the road on older roads than on newer roads. The researcher found that crashes per driven kilometer were equal for both types of roads because the number of cars colliding with objects other than trees balanced out the safety improvement of removing trees (Rajamäki 2013).

Ewan et al. (2016) collected and analyzed a large sample of data from low-volume roads in Oregon to quantify the effects of geometric and roadside features on crash occurrence and severity. The researchers used crash-rate multivariate regression and correlation analysis. The study found that the roads with narrow or no shoulders had higher crash rates than roads with 4- or 5-ft shoulders. Fifty-five percent of the total number of collisions were with fixed roadside objects, but the number of these objects near the roadway had no obvious relationship with the crash rate because of a small sample size (Ewan et al. 2016).

Corben et al. (1997) evaluated 254 engineering treatments implemented to address crashes with fixed roadside objects in Victoria, Australia. The researchers estimated that road and roadside geometry improvements may reduce casualty-crash frequencies by 23 percent, with a benefit–cost (B/C) ratio of 4.1 (Corben et al. 1997).

Because landscaping may reduce travel-related stress or improve drivers' attention, Mok et al. (2006) attempted to quantify the benefits of landscape improvements. This study was based on 61 road sections in Texas with landscapes designed as either urban arterials or State highways. A significant reduction in crash rate was observed using 3- to 5-yr before–after crash data (5,874 crashes from 1984 through 1999) at 10 urban arterial test sites. The researchers also noted a decrease in the number of tree collisions based on before–after crash data comparisons. The calculated reduction factor of tree collisions was about 70.8 percent (Mok et al. 2006).

B/C STUDIES

A reduction in the severity of ROR crashes is a benefit of roadside improvements. Some crash countermeasures reduce ROR crashes, but the installation of guardrails or other barriers might increase total crashes while reducing the severity of those crashes. Costs related to roadside safety improvements could include the following:

- Cost to purchase right-of-way (ROW) and cost of earthwork for widening the clear zone, flattening side slopes, redesigning ditches, and so forth.
- Installation costs of guardrails or barriers.

- Maintenance costs of guardrails or barriers.
- Cost to repair damages when vehicles hit the guardrails or barriers.
- Cost to improve shoulders to support installation of guardrails or barriers (e.g., widening narrow shoulders and repairing, stabilizing, or reinforcing shoulders).
- Cost to relocate utility poles.
- Cost to replace non-breakaway poles with breakaway poles.
- Cost to remove or relocate trees.

The Roadside Safety Analysis Program version 3 software is often used to perform roadside-safety economic analyses (Transportation Research Board 2013). Because 75 percent of roadway-departure crashes occurred in a rural setting, the Kansas Department of Transportation (DOT) developed a road program to mitigate roadway-departure crashes with fixed roadside objects so the department could get the greatest return on investment (FHWA 2014). Van Schalkwyk and Washington (2008) proposed a decision matrix for countermeasure selection on rural two-lane highways in Washington. The assessment identified that roadside features are likely to affect the outcome and severity of ROR collisions, particularly on two-lane rural highways, given the high frequency of ROR collisions on these roads. The suggested countermeasures included increasing clear zone; shielding, removal, or relocation of fixed features; and flattening of side slopes.

CHAPTER SUMMARY

This chapter introduces the background of this report and outlines the characteristics of past safety evaluations for deploying guardrails, removing and relocating poles from the roadside, or flattening side slopes of rural highways. A brief literature review describes past research on the topic and similar evaluations regarding safety tradeoffs. The chapter presents cost elements found in the literature that will be used in chapter 5. Chapter 2 outlines the study design and analytical methods implemented for the safety-effectiveness evaluation of this project.

CHAPTER 2. STUDY DESIGN AND STATISTICAL METHODOLOGY

The study design needed to account for multiple characteristics of the roadside safety evaluations and the anticipated features of the data. Because a strong study design can significantly boost the quality of the results, it is critical to closely examine all potential data sources, their characteristics, and available data elements. Ideally, this step should precede any data acquisition or collection and consider the needs of the analysis stage.

Safety studies are often limited to evaluations of observational data because randomization is not possible and true experiments, such as randomized control-group experiments, are not feasible. Good observational studies rely on data from both treated and nontreated sites in a manner consistent with control-group experiments. A cross-sectional data analysis without any matching or reference group is sometimes called a static-group comparison (Campbell and Stanley 1966). Likewise, a before–after design without any control group is called a one-group pretest-posttest design. These types of pre-experimental designs have a higher potential for biased results. Therefore, this study initially targeted a quasi-experimental design to the extent possible, such as a nonequivalent control group (or comparison group) design or a control series design (e.g., Campbell and Stanley 1966; Campbell and Russo 1999). However, in the case of evaluating the tradeoff of one roadside condition versus another, obtaining before–after data from multiple jurisdictions was deemed infeasible after reviewing potential data sources. Therefore, a cross-sectional analysis was proposed, and the research team developed a database for such analysis. In addition to incorporating comparison sites, the research team used propensity score (PS)–weighting (PSW) methods to control for imbalances in the values of the covariates between treatment and reference groups.

STATISTICAL METHODS IN THE DATA-MANAGEMENT PROCESS

The data-management stage of the process involves collecting and revising data from multiple sources, supplementing the data where appropriate, concatenating variables across their sources, and preparing the data for statistical analyses. In response to actual data availability, the research team refined datasets through data integration and data balancing.

The research team examined a variety of data sources identified in the feasibility study stage. One goal of this effort was to select candidate sites for study while balancing the features of treated and reference sites. This database-development approach is consistent with the selected study-design methods.

Data Extraction and Integration

The research team used geographic information systems (GIS) tools to prepare, filter, and combine data containing multiple-source geolocations (typically in shapefile format). GIS tools allow the manipulation, combination, and display of data for different types of attributes, including crashes, road infrastructure, traffic volume, census tract, land use, and other types.

Data Balancing

Data-matching and data-balancing methods are used to assist causal inference, which quantifies the impact of a treatment variable on a given response variable. Data matching is essentially a way to achieve data balancing through which each treated site is matched with at least one nontreated site. The result is a robust comparison of the mean response between the group of treated sites and the group of nontreated sites while factors other than the one under evaluation are equally represented at all levels of the variable of interest. In this context, nontreated sites are also referred to as reference sites. The principle behind this effort is to identify untreated locations that are similar on their covariates to the treated locations so that the contrast by the response variable implicitly controls for the levels in other covariates that could have an impact on the response variable. For cases in which treated data are scarce, it is common to use all identified treated sites and then match reference sites using sampling techniques on a wider sampling frame of candidate reference sites. The matching of treated and reference sites is based on the covariates identified to covary with the treatment variable.

An important step in data matching is the validation of the matched data, also referred to as the quality-control step. The matched data are validated by examining the mean of the covariates across the treatment and reference groups. A good balanced dataset is one where the means are almost identical, carrying the implication that any observed difference between the treatment and reference groups in the response variable is most likely due to the effect of treatment.

PS Methods

More analytical approaches to guide the data-collection stage are based on PSs. Under this framework, the PSs of the treatment cases and their corresponding reference cases are estimated and compared. A PS is a metric of similarity between covariates from the cases and can be estimated using parametric or nonparametric tools, such as logistic regression or random forest analysis (Jovanis and Gross 2007; Sasidharan and Donnell 2013, 2014; Guo and Fraser 2015).

In the case of binary logistic regression as a basis for PS estimation, figure 1 shows the definition of the conditional probability of a site receiving a specified treatment ($T=1$).

$$P(T_i = 1|\boldsymbol{X}_i) = \frac{e^{\alpha_i \cdot X_i'}}{1 + e^{\alpha_i \cdot X_i'}}$$

Figure 1. Equation. Conditional probability of a site receiving treatment ($\boldsymbol{T}$ = 1).

Where:

$P(T_i = 1|\boldsymbol{X}_i)$ = PS denoting the probability of the site (i) receiving the treatment (i.e., $T = 1$).
T_i = treatment status, which takes binary values {0 if no treatment, 1 if treatment}, of site i.
$\boldsymbol{X}_i$ = vector of covariates that vary with T.
$\boldsymbol{\alpha}_i$ = vector of coefficients through the binary logistic regression.

In a balanced sample, the distribution of PSs is expected to be similar for treated ($P(T = 1|\boldsymbol{X})$) and reference sites ($P(T = 0|\boldsymbol{X})$). An examination of these differences at various stages of data collection can be used to direct collection of data at additional reference sites to improve the balance in the dataset.

An alternative to PS matching (PSM) is PSW. In this approach, the PS is used to balance two or more partitions of the data by the variable of interest (i.e., treatment or reference). In contrast with PSM, balance is achieved by defining appropriate weights for each unit of analysis so that they are representative of an underlying target population of sites with and without the treatment under evaluation. The data are weighted based on the probabilities of being in either the reference or the treatment group, and the selection of the weights defines the target population (Olmos and Govindasamy 2015). If all weights are equal, then the database is implied to be a simple random sample from the larger pool of sites from which the data were collected. However, through the use of appropriate weights, more flexible definitions of the target population can be assigned, as described in the statistical literature (Olmos and Govindasamy 2015). The definition of the weights also determines quantities that can be estimated, including the average treatment effect, average treatment effect among the treated cases, average treatment effect among the control cases, and average treatment effect among the evenly matched cases.

STUDY DESIGN

Based on the findings of the feasibility study, the research team collected and assembled data for a cross-sectional estimation of the CMFs of interest (installing a guardrail, removing/relocating utility poles, and flattening side slopes). Reference sites were also added to strengthen the design. Data collection required direct estimation of the roadside conditions. The research team also decided to implement strategies to balance the covariates accordingly.

Initially, the research team used matching methods (e.g., Stuart 2010) based on the PS to obtain reference sites comparable to the guardrail-treated sites to ensure similar covariate distributions to the extent possible. A variety of conditions pertaining to pole presence and side slope were also sought in the initial stages of data collection. For the analysis, the research team adopted the framework of PSW. The target population was set as the overlap between the guardrail-treated and reference (no-guardrail) populations, as proposed by Li et al. (2018). Under this scheme, the target population was the set of all sites that have comparable chances to be in either the treatment group or the reference group. This approach effectively curbed the undue influence of the following two subsets of sites when the average treatment effect of the countermeasure was estimated:

- Reference sites with characteristics such that they are unlikely candidates for the treatment.
- Treated sites with characteristics for which no comparable reference sites are represented in the data.

An additional advantage of this choice of target population is a desirable small-sample exact balance property, as demonstrated by Li et al (2018). Additionally, the corresponding weights minimize the asymptotic variance of the weighted average treatment effect within their class of weights (Li et al. 2018).

DATA-ANALYSIS METHODS

The empirical analyses were conducted using the statistical methods appropriate to the characteristics of the assembled datasets. The research team used appropriate generalized-linear-mixed-model (GLMM) variants (binomial mixed) to obtain the safety-effectiveness estimates of interest.

Generalized Linear Regression Analysis With PSM or PSW

The predictive methods described in the *Highway Safety Manual* provide crash-frequency estimates for a site through the use of a safety performance function (SPF) based on the site's key characteristics (AASHTO 2010). SPFs are crash-prediction models commonly estimated from regression analyses. Because of the characteristics of crashes—the response variable in such models—most SPFs currently in use are derived from generalized linear models (GLMs) that relate the mean of the response (crashes in this case) to the levels of predictor (i.e., independent) variables linearly through some link function. The model includes an error term that describes the variability between the mean response and the observations. The most common error distribution in current SPFs is the negative binomial. Alternatively, other suitable Poisson mixture distributions can be specified to better account for data characteristics.

In the context of predictive methods, the safety effect of a countermeasure is estimated by comparing the expected crash frequency at treated sites to the expected crash frequency when the treatment is absent. In general, a potential problem exists when comparing sites (with and without the countermeasure) because the measured difference in crash frequency may be due to other safety-influential covariates. For example, if sites with the countermeasure carry more traffic, then those sites would tend to experience more crashes merely because of exposure to crash risk despite the presence of the countermeasure. Such potential differences in key covariates must be accounted for while developing CMFs. In the case of before–after designs (e.g., the empirical Bayes method), an SPF or a reference group is used to adjust crash expectations to the different levels of key covariates before estimating the CMF.

In the context of cross-sectional designs, controlling for the effects of other covariates is achieved by including those covariates among the explanatory variables so that their safety association is estimated simultaneously with that of the variable of interest (i.e., the one linked to the CMF being estimated). Despite explicitly accounting for key covariates, the estimated CMF could still exhibit bias if the database does not support a balanced comparison between the treated and reference sites represented. Such bias is removed in the ideal case that all key safety-influential covariates are equally represented in the treated and reference groups at all levels of the variable of interest. In such circumstances, the difference in safety between the treated and reference groups is most likely due to the treatment of interest. Achieving such an ideal case is difficult, and it is common to observe uneven distributions of key covariates at the different levels of the variable of interest.

One way to reduce the risk of bias is to select study sites in a way that achieves balance in the covariates during database development. By using PS-based methods (PSM or PSW), the bias due to imbalances in the distributions of covariates can be mitigated. When performing PSM, a balanced database can be constructed by identifying treated sites and systematically matching them to untreated sites so that selection probabilities are comparable to a randomized sample for the two site types (Rosenbaum and Rubin 1984). When performing PSW, the influence of each data point is either increased or decreased so that it is representative of a balanced distribution of covariates. Under the PSW framework, weights are developed based on a PS analysis. Essentially, PS methods help to balance covariates at treated and reference subsets of sites, which should result in a nearly unbiased estimate of the effect of interest.

GLMs for Safety Evaluations

GLMs are widely used to perform safety statistical evaluations. A discussion of the types used in this research is presented next.

Types of GLMs

Within the frame of GLM methods, a distinction can be made between models with fixed effects, random effects, and mixed effects. Commonly, the coefficients obtained from GLMs can be thought of as fixed effects. The variables corresponding to fixed effects are implied to have time-invariant safety associations (e.g., roadway-design elements). The model coefficients are measured and interpreted as estimates of underlying parameters in a latent data-generating process.

In contrast, random-effects models estimate the effects of factors that are observed realizations of a random variable. Therefore, quantifying how the response variable shifts with the observed realizations in the dataset is typically not of interest; rather, accounting for the impact of such variation in the model is necessary. The simplest analogy for random effects in a GLM is the use of blocking in analyses of variance designs: typically, the effect of each block is not the focus of the analysis, but it is of interest to account for the blocking variability to quantify the variability explained by the independent variable of interest.

Mixed-effects models are models that include both fixed and random effects (Pinheiro and Bates 2000). Generalized linear mixed models (GLMMs) approach the analysis of repeated-measures cross-sectional data by including a random effect per every unit of data aggregation (i.e., the blocking units in the data, such as individual study locations with more than one datum in the analysis). Orthogonal to the random effects, the model estimates fixed effects for the variable of interest and any additional fixed-effects covariates. Similar to GLMs, an appropriate link function can be specified to model count-data distributions, such as Poisson and negative binomial, that are applicable to crash data.

As described previously, the use of PSM in the data-collection stage can produce a more robust dataset in general. A PS model from the final dataset can also be incorporated through PSW in the analysis stage.

Binomial Mixed Models for Crash Risk

The research team initially used logistic mixed models on data that were aggregated by year, site, and roadside to assess the safety effectiveness of various roadside conditions in terms of their link to total, fatal-and-injury, and roadway-departure crashes. Yearly variation was explicitly accounted for in this initial analysis; outcomes (yearly crash counts) were found to be mostly

0 crashes or 1 crash per year (more than 90 percent of the dataset had either 0 or 1 total crashes), thus the appeal of using logistic regression. However, the account of yearly variation came at the cost of slower convergence in the estimation algorithm. The research team decided to use binomial mixed models on data aggregated only by roadside and site. In this instance, the distribution of a given variable *Y*, conditional to a vector of independent variables ***X***, is modeled as a binomial variable, conditional to a set of predictors and a site-specific adjustment (figure 2).

$$P(Y = y|X, Site_i) = \binom{n}{y} \cdot p^n \cdot (1-p)^{n-p} \cdot k(Site_i)$$

Figure 2. Equation. Conditional probability of *y* value, given explanatory variables and site characteristics.

Where:

P = probability of *Y* taking value *y*, given a vector of explanatory variables and a site random effect.
y = a particular value in the domain of random variable *Y*.
$Site_i$ = random effect for the *i*th site in the analysis.
n = number of subperiods in the analysis (i.e., number of trials).
p = probability of a crash in the period of study.
k = multiplicative random function of site meant to capture binomial overdispersion in the data through site-by-site variability.

Crash counts larger than 1 were handled by applying proportional prior weights to the *p* estimate for each study location. Then, at site *i*, the logit of p_i can be expressed as in figure 3.

$$g(p_i) = \ln\left(\frac{p_i}{1-p_i}\right) = \boldsymbol{\beta}' \cdot \boldsymbol{X} + Site_i$$

Figure 3. Equation. Binomial-lognormal mixed-model parameterization.

Where:

$g(p_i)$ = logit function of p_i.
p_i = probability of crash at *i*th site.
X = vector of independent variables (including key variables and safety-influential covariates).
$\boldsymbol{\beta}$ = vector of regression coefficients.

The research team applied the mixed-model approach to account for possible correlation of the outcome variable (i.e., number of crashes) obtained for the two roadsides of the same segment. From each model, the research team estimated rate parameters, which were used to estimate odds ratios (when combined with the different levels of the independent variables). An odds ratio is a direct estimate of a CMF and is expressed as the expected increase or decrease in crash risk due to the change in a roadside condition. An odds ratio greater than 1.0 indicates that the change in roadside condition increases risk, and a ratio less than 1.0 indicates a decrease in risk.

CMF Estimation

In most cases, the process of using regression models to characterize the relationship of a single independent variable and dependent variables comprises extracting a single parameter estimate and its standard error from the model output. This single parameter estimate quantifies the relationship of interest after accounting for additional variability in the data due to independent covariates and under an appropriately modeled error distribution. However, some research questions may require combining multiple parameter estimates and their standard errors. For instance, the questions of interest in this report—safety effectiveness and tradeoffs between roadside conditions—involve multiple roadside elements and their characteristics, each needing to be accounted for through coding different independent variables in the model. Estimating the CMFs of interest then involves multiple model-parameter estimates. The uncertainty of the compound CMF is then a function of the uncertainties of the constituent coefficients.

The methods outlined in the following subsections were used to estimate the required CMF uncertainty. These methods leverage the asymptotically multivariate normal distribution of multiple regression-model estimates from maximum-likelihood estimation (Morrell et al. 1997; Booth and Hobert 1998; Wackerly et al. 2008).

CMF Estimates for Conditions Implying Changes in Multiple Independent Variables

In general, a combination of multiple coefficient estimates is needed to answer the research questions at hand. The answer to the research questions (i.e., the safety implications of installing guardrails, removing poles, or flattening side slopes) is a function of the values of the independent variables coding the characteristics under study. A key challenge is the broad range of potential baseline conditions for each evaluation, given the largely heterogeneous roadside features in the data. For example, the safety effectiveness of installing a guardrail significantly depends on the side slope and presence of fixed roadside objects before installation.

CMF Estimates From Linear Combinations of Regression Estimates

Appropriate linear combinations of coefficient estimates can be developed to estimate the combined safety shifts from changes in multiple predictor variables from a fitted model. These linear combinations can be used, for example, to produce estimates of the crash risk for a treatment condition (e.g., guardrail presence) and a select base condition (e.g., no guardrail on a down-sloped roadside without poles). In the link scale, the contrast is carried over the arithmetic contrast of risk, which is equivalent to a ratio of risk estimates in the response scale. Such contrast, therefore, yields an odds ratio for the treatment condition with respect to the base condition. To produce the corresponding standard error, the contrast coefficients need to be combined with the model's inverse-information matrix. If variable vectors $\boldsymbol{X_B}$ and $\boldsymbol{X_T}$ represent the base and treatment conditions and $\boldsymbol{\Sigma}$ the maximum likelihood model-inverse-information matrix, the standard error (*SE*) for the contrast in the link scale (i.e., the logarithm-CMF estimate) is given in figure 4.

$$\mathrm{SE}(\ln CMF) = \sqrt{(\boldsymbol{X}_T' - \boldsymbol{X}_B') \cdot \boldsymbol{\Sigma} \cdot (\boldsymbol{X}_T - \boldsymbol{X}_B)}$$

Figure 4. Equation. *SE* of natural logarithm of *CMF* (scenario based).

Where:

$\boldsymbol{X'}_T$ = transpose vector of treatment conditions.
$\boldsymbol{X'}_B$ = transpose vector of base conditions.

In the contrasts just defined, the levels of safety-influential covariates (e.g., annual average daily traffic (AADT), lane width, and speed limit) are fixed equally at the dataset average for both contrasting subsets.

This approach can be generalized and applied over ranges of values in the dataset for the multiple variables of interest so that the contrasts can be calculated to reflect comparisons of physically observed conditions, as represented in the dataset. Under this approach, a model-based estimate for the safety effectiveness is constructed for each unit of analysis and then averaged within each subgroup (i.e., either treated sites or base-condition sites). The CMF (odds ratio) is then estimated as the contrast between the two group averages while explicitly accounting for the correlation of multiple estimates from a common model.

The approach described here compares the average safety expectations of two groups, normalizing other covariates at that average and correcting for covariate imbalances via PSW. As a result, the contrast should reflect only a shift in crash risk (either an increase or a decrease) due to the treatment. For a treatment design matrix (***A***), comparison-group design matrix (***B***), maximum likelihood model-inverse-information matrix (**$\boldsymbol{\Sigma}$**), and vector of PS weights (***w***), the standard error of the average effect of the treatment condition (i.e., the standard error of the CMF estimate) in the link scale is given in figure 5.

$$\mathrm{SE}(\ln CMF) = \sqrt{\boldsymbol{w}' \cdot \{(\boldsymbol{A} - \boldsymbol{B}) \cdot \boldsymbol{\Sigma} \cdot (\boldsymbol{A}' - \boldsymbol{B}') \cdot \boldsymbol{w}\}}$$

Figure 5. Equation. *SE* of natural logarithm of *CMF* (PSW).

Where:

$\boldsymbol{w'}$ = transpose vector of PS weights.
$\boldsymbol{A'}$ = transpose of treatment design matrix.
$\boldsymbol{B'}$ = transpose of comparison-group design matrix.

The weights in figure 5 are defined as the overlap weights from the PS analysis. The statistical literature provides more details on these formulations (Johnson and Wichern 2007; Wackerly et al. 2008).

CHAPTER SUMMARY

This chapter describes the statistical methodology, analysis methods, and tools that the research team used in performing the statistical analyses. The chapter presents the challenges associated with the evaluation and the critical step to develop a database with a range of roadside conditions to be evaluated. Then, the rationale for a cross-sectional study design is presented, and a discussion is provided about why and how PS methods are appropriate to reduce the risk of biased estimates in cross-sectional designs. This chapter also outlines how PS methods were used to guide the database development so that the resulting databases are naturally balanced in key safety-influential covariates. Finally, this chapter outlines statistical analysis methods to develop statistical models of crashes (binomial mixed-effects regression models, as specified in figure 2 and figure 3) to support developing the CMFs of interest. The chapter ends with a discussion of additional techniques based on mathematical statistics that can be applied to the model results to provide average CMF estimates for the treatments of interest. The next chapter outlines the data collection effort for Indiana and Pennsylvania in more detail.

CHAPTER 3. DATA COLLECTION AND INTEGRATION

The research team constructed a database for the safety analysis of the following roadside objects:

- Barriers and guardrails.
- Utility poles.

The site information for these objects—barriers, guardrails, and utility poles—was obtained from the Barrier and Signs layers of the Second Strategic Highway Research Program (SHRP2) Roadway Inventory Database (RID). The Barrier layer is a polyline shapefile, whereas Signs is a point shapefile. The research team used other RID layers to complete the database. The following are the other layers used:

- Alignment (lane and shoulder).
- Rumble Strips.
- Highway Performance Monitoring System.
- AADT.
- Crash Records.

The Rumble Strips layer was initially considered to identify locations that have this treatment present to account for it in the analysis. Ultimately, the presence or absence of rumble strips was confirmed during data collection, so this layer did not feed directly into the database for analysis.

The research team conducted the cross-sectional data analysis using PS models on preliminary data to help develop a suitable, balanced database. A first level of filtering is classifying each potential site as either a tangent or a curve segment. Therefore, researchers used the RID Alignment layer as the reference segmentation layer. The research team selected the sites from two States based on the roadway characteristics, targeting tangents (rather than curve segments) 1,500 to 5,000 ft in length.

JURISDICTIONS AND DATA SOURCES

This section outlines the sources identified to collect data for this safety evaluation. The following two types of data are discussed:

- Relational databases (either geolocated or not).
- Imagery databases.

Relational Databases

The research team obtained data from various sources for this evaluation, including the RID and various State DOT databases. The RID roadside data are collected from six States. The research team collected preliminary data on four SHRP2 States: Indiana, North Carolina, Pennsylvania, and Washington. Detailed data were initially collected for these States from relational databases.

Data Collection

Given the availability of details of geographical variety and directional assignment of crashes to the road segments, relational databases were excellent sources for the new database creation. Ultimately, the effort required to supplement these data with variables from processed imagery reduced the initial scope of States and facility types, as described in the "Collected Data Elements" section later in this report.

Segmentation

Linear segmentation was implemented to break down the road segments that were longer than 1 mi. Additionally, roadside features (e.g., guardrails and utility poles) on either side of the roadway were used to define the segment lengths where appropriate.

In addition to data available in the RID tables, the research team obtained data elements on geometric design and traffic from other relational databases available online. For example, complete vehicle-level tables for Pennsylvania and AADT values were obtained from the Pennsylvania DOT website (PennDOT 2019a, 2019b).

Imagery Databases

Imagery data are a key type of data to characterize roadsides. The image analysis methods previously developed by members of the research team were adapted in combination with a calibration procedure to use RID imagery data.

Initial data-collection efforts leveraged the unpublished TxDOT's imagery database, which was available from a past project, to take advantage of the seamless calibration of the image analysis tools on the original database used in their development (Avelar et al. 2017). Unfortunately, this database yielded few uniform suitable segments for analysis, considering that the database has a wide range of road types and heterogeneous segments in general. However, data-collection protocols and modified calibration procedures were developed from this effort so that RID imagery data could be used to collect roadside data.

RID Mobile Data Imagery Database

RID mobile data (collected by instrumented vans) are accompanied by images taken by a camera (a front view looking at the road and covering the roadside to some extent) (Smadi et al. 2015). The camera faces forward, assumingly completely in the direction of travel. The images are in JPG format with a 1,920-pixel width and 1,080-pixel height. The images have latitude and longitude information, and the location information is accessible through the RID iVision utility, which can be used online. This utility provides access to the images and has the capability of exporting batches along stretches of highways.

Google Earth Imagery Database

Google® Earth™ is a vast platform for imagery data collection (Google, Inc. 2019). The Street View™ option facilitates the firsthand viewing experience rather than the usual bird's-eye view.

The locations of interest can be saved as JPGs with a resolution of 1,570 by 943 pixels. Figure 6 shows a sample image from this source.

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Figure 6. Screenshot. Google Earth sample image.

Although Google Street View imagery is available online for most of the routes in the United States, the research team only considered this database as a last alternative to collect roadside data because the images are rendered from multiple cameras. Calibrating the image analysis tools to these images, therefore, adds uncertainty to the estimated equivalent optical parameters. Additionally, the lens, camera types, and heights of camera mount can vary from site to site. Additional effort is required to run the calibration procedure multiple times for small batches of images before analysis.

Image-Analysis Procedure

Core Methodology

By analyzing a database of imagery and roadside information, it is possible to estimate the available roadside objects along certain stretches of highway. To identify the fixed roadside objects, the research team adapted image-processing analytical methods previously developed for a recently completed project (TxDOT Project 0-6860). (The details about this methodology can be found in Avelar et al. [2017], chapter 4.) The core of the methodology is a set of analytical methods that yield geometric measurements from close-range perspective images, such as those in the databases discussed previously. These analytical methods are calibrated to sample images with known object sizes and locations in space using a nonconvex optimization algorithm. The calibrated methods can then be applied to process a stream of images from where distances and dimensions of interest can be estimated with acceptable precision. In this research, the objective was to estimate the size and location of a range of roadside conditions.

Image Calibration and Estimation of Lateral Distances

The research team modified the calibration procedure originally developed to process the Texas imagery database. This modified calibration was necessary to apply the analysis tools to other imagery databases. Applying the analytical methods to different imagery databases requires estimating additional unknown parameters and, thus, a larger set of ground-truth objects in the calibration images. This approach allowed for the estimation of the lateral distances to roadside objects and side slopes using imagery databases.

The research team validated the calibration procedure using the original imagery database previously used to develop the analysis tools. Because critical metadata parameters are already known for these images, the validation exercise consisted of applying the calibration procedure to re-estimate the metadata parameters and then comparing them with the true values. Additionally, the research team performed a comparison of estimated distances from both calibration procedures with satisfactory results. The validated calibration procedure was then applied to images from the RID and Google Street View. The research team verified that critical roadside features could be acceptably measured from street-level imagery, as shown in figure 7 and figure 8.

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Figure 7. Screenshot. Roadside features measured from street-level imagery.

Figure 8. Screenshot. Side slope measured from street-level imagery.

COLLECTED DATA ELEMENTS

The focus of this safety evaluation was on rural two-lane highways. The research team collected the following data elements to construct the database for the analysis of fixed-roadside-object crashes:

- Safety characteristics.
- Roadway characteristics.
- Roadside characteristics.
- Traffic-operation characteristics.

Table 1 lists the data elements for each category within the database. The research team identified available fields in the databases mentioned in the "Jurisdictions and Data Sources" section to determine single-vehicle non-intersection head-on crashes; non-intersection sideswipe crashes; and fixed-object crashes as indicators to define roadway-departure crashes for analysis (based on the FHWA definition of roadway-departure crashes).

Table 1. Data elements for fixed-roadside-object evaluation.

Category	Element
Safety	State, county, city, and milepost (measure)
Safety	Latitude and longitude (degrees)
Safety	Date (day, month, and year)
Safety	Time (nighttime and daytime)
Safety	Crash contributing factor (fixed roadside object and speed)
Safety	Crash type (single vehicle and multivehicle)
Safety	Crash severity (fatal and severe injury)
Safety	Driver impairment and distraction (presence)
Safety	Vehicle type (passenger and truck)
Roadway	Facility type (highway)
Roadway	Area type (rural and urban)
Roadway	Number of lanes
Roadway	Segment length (feet)
Roadway	Lane width (feet)
Roadway	Alignment (tangent and curve)
Roadside	Utility poles (presence)
Roadside	Trees and shrubs (presence)
Roadside	Signs and signals (presence)
Roadside	Barriers and guardrails (presence)
Roadside	Rumble strips and stripes (presence)
Roadside	Shoulder width (feet)
Roadside	Shoulder type (paved, gravel, sod)
Traffic operations	Traffic volume (AADT)
Traffic operations	Speed limit (miles per hour)

FIXED ROADSIDE OBJECTS AND RELATED DATA

The image inventory of SHRP2 RID was mined to collect roadside characteristics from multiple routes in Indiana and Pennsylvania. The final list of variables considered for analysis were broadly classified in the following four categories:

- Roadway features: road-related variables to characterize the road segments.
- Roadside features: information about fixed roadside objects and other relevant details.
- AADT: traffic volume.
- Crash data: variables to show the severity and number of crashes.

Table 2 lists the variable names and descriptions for these four variable categories.

Table 2. List of variables collected for each site.

Variable Category	Type of Data	Variable Name	Variable Description
Roadway features	RID and GE imagery	*Site ID*	Unique site number
Roadway features	RID and GE imagery	*Road Type*	Site setting (rural or urban)
Roadway features	RID and GE imagery	*Lane_W*	Lane width (ft)
Roadway features	RID and GE imagery	*PS_W*	Paved-shoulder width (ft)
Roadway features	RID and GE imagery	*L*	Length of a segment (ft)
Roadway features	RID and GE imagery	*Median*	Type of median present
Roadway features	RID and GE imagery	*N_Lanes*	Number of lanes
Roadway features	RID and GE imagery	*n_points*	Number of images analyzed per segment
Roadside features	RID and GE imagery	*D_PS*	Lateral offset from shoulder (ft)
Roadside features	RID and GE imagery	*G_Height*	Guardrail height (ft)
Roadside features	RID and GE imagery	*ET_Wid*	End-terminal width (ft)
Roadside features	RID and GE imagery	*ET_Height*	End-terminal height (ft)
Roadside features	RID and GE imagery	*RS_wid*	Rumble-strip width (ft)
Roadside features	RID and GE imagery	*G_len*	Guardrail length (ft)
Roadside features	RID and GE imagery	*Pole_Width*	Pole width (ft)
Roadside features	RID and GE imagery	*Fore_Slope*	Fore slope (V-H ratio)
Roadside features	RID and GE imagery	*Back_Slope*	Back slope (V-H ratio)
Roadside features	RID and GE imagery	*AADT_year*	AADT for the segment; the year represents the year when traffic volume data were collected
AADT	RID geodatabase	*Total Crashes*	Total number of crashes per year per mile
Crash data	RID geodatabase	*Fatal and Injury Crashes*	Number of fatal-and-injury crashes per year per mile
Crash data	RID geodatabase	*Roadway Departure Crashes*	Number of roadway-departure crashes per year per mile
Crash data	RID geodatabase	*Fatal and Injury Roadway Departure Crashes*	Number of fatal-and-injury roadway-departure crashes per year per mile

GE = Google Earth; V-H = vertical–horizontal.

A decision to focus the database development on two States was made because the data collection, data integration, quality control, and quality assurance of the data obtained from imagery databases required intensive efforts. Indiana and Pennsylvania were selected because the sites from these States that were used to adapt and test the calibration procedures showed cross-sectional uniformity, and the crash databases offered enough detail to reliably assign crashes directionally. The following two sections describe the characteristics of the data collected from these two States.

Indiana

Data were initially collected from freeway and highway corridors in Indiana. Ultimately, comprehensive data collection, reduction, and analysis focused on only rural highways. Figure 9 and table 3 show the sites and collected details of fixed roadside objects. Initial data were collected from 464 segments.

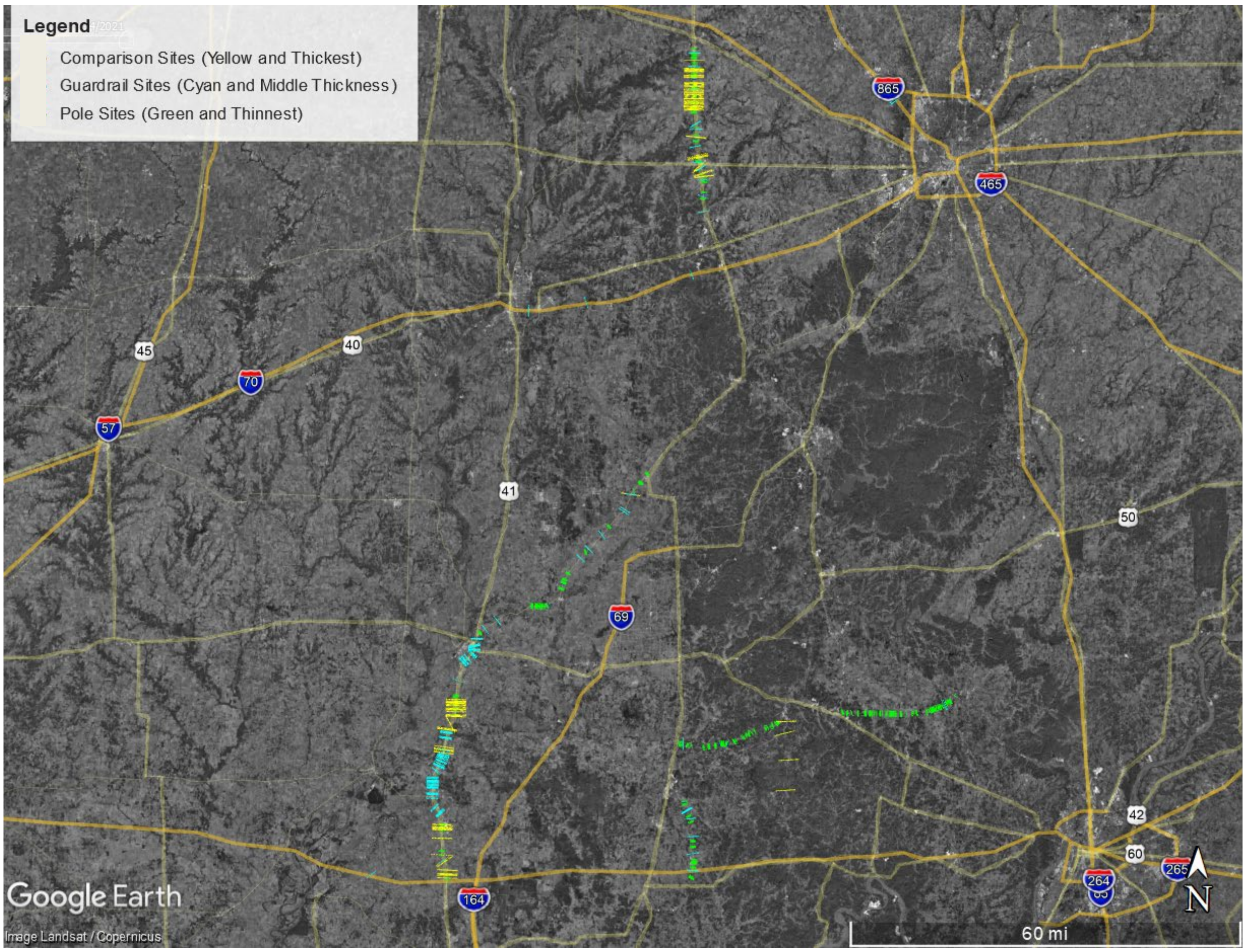

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Figure 9. Map. Location of Indiana corridors.

Table 3. Data collection for corridors in Indiana.

Fixed Roadside Objects	Study Site Corridors
Guardrails	SR 29, SR 56, SR 67, SR 162, US 41, US 231
Guardrails and utility poles	SR 56, SR 67, SR 162, US 231
Utility poles	SR 13, SR 56, SR 67, SR 145, SR 162, US 41, US 231
None	US 41, US 231, SR 145, SR 67, SR 56, SR 162

SR = State route.

The locations were marked in Google Earth, and the research team collected data on roadway design elements from Google Earth satellite imagery. The research team obtained crash and AADT data (2008–2013) from the RID repository to be used in combination with the roadside and geometric data and merged the data to each site based on location. AADT values were not available for all analyzed segments. In such cases, locally averaged AADT values were imputed from linear random-effects models based on partially available AADT values on the same routes or ones in proximity.

A set of 12 highway segments were excluded from the dataset because they considered the utility poles that existed behind guardrails. Table 4 and table 5 show the summary statistics for the final dataset of highway segments from Indiana.

Table 4. Summary statistics for data collected from Indiana RID photographic record (*n* = 273).

Variable	Description	Mean	Std. Dev.	Range	Min.	Max.
n_points	Number of images analyzed per segment	2.40	1.23	4	1	5
Lane_W	Lane width (ft)	11.57	0.55	5.38	9.32	14.7
PS_W	Paved-shoulder width (ft)	6.33	3.62	13.34	0.6	13.94
D_PS	Lateral offset from shoulder (ft)	1.80	0.97	4.51	0.61	5.12
G_Height	Guardrail height (ft)	3.39	0.25	1.34	2.76	4.10
ET_Wid	End-terminal width (ft)	1.60	0.40	1.44	1.03	2.47
ET_Height	End-terminal height (ft)	3.43	0.43	1.63	2.55	4.19
RS_wid	Rumble-strip width (ft)	1.73	0.630	0	1.73	1.73
L	Length (ft)	1,032.47	538.78	2,174	291	2465
G_len	Guardrail length (ft)	915.77	461.40	1,531	427	1958
N_Lanes	Number of lanes	2.62	0.94	3	2	5
Pole_Width	Pole width (ft)	1.32	0.6155	5.08	0.53	5.61
Fore_Slope	Fore slope (V-H ratio)	−0.03	0.13	1.29	−0.41	0.88
Back_Slope	Back slope (V-H ratio)	0.15	0.13	0.70	0.01	0.71

Max. = maximum; Min. = minimum; Std. Dev. = standard deviation; V-H = vertical–horizontal.

Table 5. Summary statistics for crash and AADT in Indiana in years 2008 to 2013 (*n* = 273).

Variable	Description	Mean	Std. Dev.	Min.	Max.	Total
AADT	AADT values	4,546.8	1,804.8	299	12,530	—
Total Crashes	Total number of crashes per year per mile	0.758	1.663	0	17	207
Fatal and Injury Crashes	Number of fatal-and-injury crashes per year per mile	0.194	0.565	0	5	53
Roadway Departure Crashes	Number of roadway-departure crashes per year per mile	0.436	0.938	0	9	119
Fatal and Injury Roadway Departure Crashes	Number of fatal-and-injury roadway-departure crashes per year per mile	0.09	0.34	0	3.02	27

—Not applicable.
Max. = maximum; Min. = minimum; Std. Dev. = standard deviation.

Pennsylvania

The data collection and merging procedure for Pennsylvania was similar to that used for the Indiana data. Locations with the required fixed roadside objects (guardrails and utility poles) were identified via the Google Street View option and marked in Google Earth. The geometric properties of segments (roadways) that include the required objects were collected from Google Earth imageries. Consistent with the data collection effort in Indiana, comprehensive data collection, reduction, and analysis focused on rural highways only.

From this database, speed limit data, traffic data (2011 to 2013), and crash data (2006 to 2013) were merged with the marked segments by creating a buffer of 100 ft around the locations and using the location proximity function in ArcGIS. The roadside characteristics were obtained using Google Earth images, and the image analysis tool was used to process roadside imagery. Table 6 and figure 10 show the sites and collected details of fixed roadside objects.

Table 6. Data collection for corridors in Pennsylvania.

Fixed Roadside Objects	Study Site Corridors
Guardrails	SR 07, SR 36, US 22, US 522, US 30, SR 164
Guardrails and utility poles	SR 36, SR 164, US 26, US 30, US 522
Utility poles	SR 36, SR 45, SR 164, US 26, US 30, US 522
None	SR 36, SR 45, SR 283, US 15, US 22, US 522, US 30, SR 164

SR = State route.

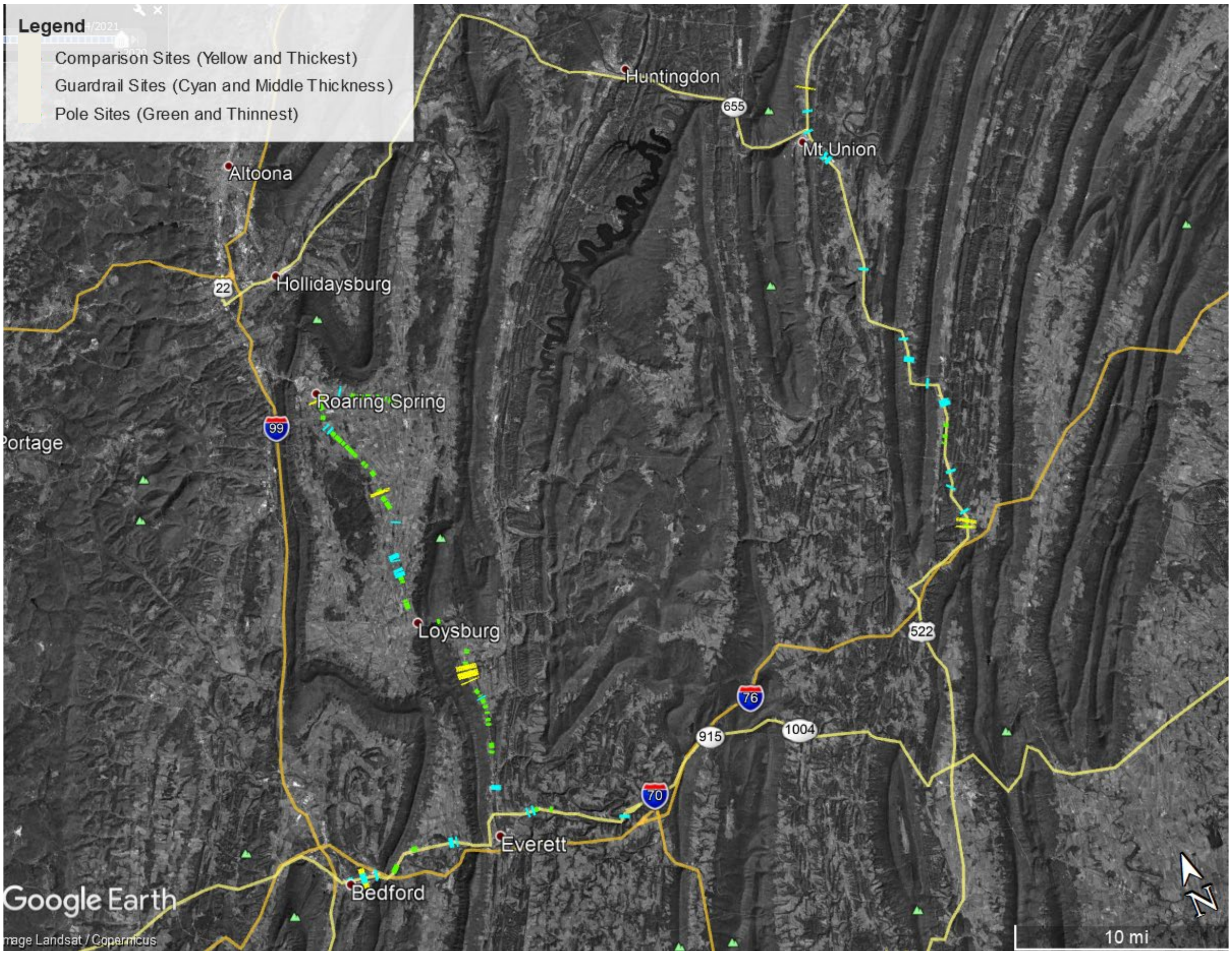


Figure 10. Map. Location of Pennsylvania corridors.

Table 7 and table 8 summarize the roadside data, crash data, and AADT data evaluated. The number of images analyzed was not the same for different segments. The research team determined how many images would be necessary to characterize the roadside conditions depending on the complexity of the roadside features measured and the segment length. If, for example, the segment had no fixed roadside objects uniformly distributed and was relatively short (shorter than 0.25 mi), then only the side slope was estimated from one or two photographs. Longer segments required additional photos to be acquired and analyzed to confirm uniformity of roadside conditions along the segment. To correctly characterize a location with utility poles required processing additional photos to reflect the location and dimensions of multiple poles along the segment length.

Table 7. Summary statistics for data collected from Pennsylvania RID photographic record (n = 75).

Variable	Description	Mean	Std. Dev.	Range	Min.	Max.
n_points	Number of images analyzed per segment	2.72	0.98	7	1	8
Lane_W	Lane width (ft)	11.98	0.62	2.53	10.73	13.26
PS_W	Paved-shoulder width (ft)	6.49	2.77	11.31	2.09	13.4
D_PS	Lateral offset from shoulder (ft)	1.81	1.92	6.64	0	6.64
G_Height	Guardrail height (ft)	2.49	0.29	1.43	1.61	3.04
ET_Wid	End-terminal width (ft)	1.19	0.57	1.36	0.45	1.81
ET_Height	End-terminal height (ft)	2.61	0.38	1.12	2.11	3.23
RS_wid	Rumble-strip width (ft)	0.22	0.40	1.48	0	1.48
L	Length of segment (ft)	928.34	421.03	2,914	491	3,405
G_len	Guardrail length (ft)	733.20	272.66	912.2	275.8	1,188
N_Lanes	Number of lanes	2.16	0.55	2	2	4
Pole_Width	Pole width (ft)	1.17	0.50	2.470	0.53	3.00
Fore_Slope	Fore slope (V-H ratio)	0.08	0.24	1.28	−0.39	0.89
Back_Slope	Back slope (V-H ratio)	0.31	0.21	0.57	0.02	0.59

Max. = maximum; Min. = minimum; Std. Dev. = standard deviation; V-H = vertical–horizontal.

Table 8. Summary statistics for crash and AADT in Pennsylvania in years 2008 to 2013 (n = 75).

Variable	Description	Mean	Std. Dev.	Min.	Max.	Total
AADT	AADT values	4,295.4	1,545.5	2,267.5	11,339	—
Total Crashes	Total number of crashes per year per mile	0.707	0.969	0	6	53
Fatal and Injury Crashes	Number of fatal-and-injury crashes per year per mile	0.373	0.632	0	3	28
Roadway Departure Crashes	Number of roadway-departure crashes per year per mile	0.373	0.588	0	3	28
Fatal and Injury Roadway Departure Crashes	Number of fatal-and-injury roadway-departure crashes per year per mile	0.227	0.452	0	2	17

—Not applicable.
Max. = maximum; Min. = minimum; Std. Dev. = standard deviation.

CHAPTER SUMMARY

This chapter documents the process of selecting data elements for evaluation and data collection in general for the safety evaluation of roadside conditions. Summary statistics are presented for the two databases developed: one for Indiana sites and one for Pennsylvania sites. Because of the common variable nomenclature under the RID framework, the research team was able to merge the data from both States into a single database for analysis. The next chapter describes the statistical evaluations of these datasets that yielded CMF estimates for the various roadside interventions represented in the database.

CHAPTER 4. SAFETY-EFFECTIVENESS EVALUATIONS

This chapter describes the analysis and presents the results of the safety-effectiveness evaluations, including estimated CMFs of interest.

The research team assembled a multi-State database for analysis. Using variables in the vehicle-level crash tables, the research team assigned crashes directionally to either side of the roadway at each study location.

MODELING PROCESS

Model entropy metrics (Akaike information criterion and Bayesian information criterion) were used to guide model development. In each case, the research team found the best fitting model for each response variable of interest: total, fatal-and-injury, and roadway-departure crashes.

First, the research team fitted PS models for the nested conditions in figure 11.

$$P(T = Guardrail|\boldsymbol{X_{GR}}) = \frac{e^{X'_{GR} \cdot \alpha}}{1 + e^{X'_{GR} \cdot \alpha}}$$

Figure 11. Equation. PS for guardrail presence.

Where:

P = vector of PSs denoting the probabilities of receiving the treatment (in this case, guardrails).
T = variable indicating treatment status.
Guardrail = guardrail treatment.
α = vector of coefficients through the binary logistic regression.
X_{GR} = vector of covariates for which there is imbalance between the two groups (guardrail present and guardrail not present).
X'_{GR} = transpose of vector of covariates for which there is imbalance between the two groups (guardrail present and not present).
e = Euler constant equal to 2.71828.

The condition *T* = *Guardrail* takes binary values: 1 if *T* = *Guardrail* and 0 otherwise.

The PSs obtained from figure 11 were applied when estimating CMFs for guardrails. To assess the safety effectiveness of utility pole configurations, the research team decided to use PSs to correct for covariate imbalances related to the number of poles at the site being evaluated. Because the number of poles is not a dichotomous variable (as the presence of a guardrail is), the research team decided to develop the PS model for two levels of pole density (determined from the observed distribution in the final dataset). This model was fitted using only sites that satisfied the condition $T \neq Guardrail$. This model is described in figure 12.

$$P\left(Pole\ Density > 20\ utility\ poles\ per\ mi \middle| \boldsymbol{X_{Poles}}, T \neq Guardrail\right) = \frac{e^{X'_{Poles} \cdot \alpha}}{1 + e^{X'_{Poles} \cdot \alpha}}$$

Figure 12. Equation. Conditional PS for utility poles, given no guardrail.

Where:

Pole Density = number of utility poles per mile.

T = variable indicating treatment status (either 20 utility poles per mile or not, given no guardrail is present).

X_{Poles} = vector of covariates for which there is imbalance between the two groups (utility poles present and not present).

X'_{Poles} = transpose vector of covariates for which there is imbalance between the two groups (utility poles present and not present).

The condition *T* = *Poles* takes binary values: 1 if utility poles are present and 0 otherwise.

The research team fitted another PS model to balance the comparison of side slopes. Again, this model was fitted only to sites that satisfied the condition $T \neq Guardrail$ and is described in figure 13.

$$P\left(Foreslope > 1V{:}\,6H \middle| \boldsymbol{X_{Sideslope}}, T \neq Guardrail\right) = \frac{e^{X'_{Sideslope} \cdot \alpha}}{1 + e^{X'_{Sideslope} \cdot \alpha}}$$

Figure 13. Equation. Conditional PS for side slope, given no guardrail.

Where:

Foreslope = fore slope vertical–horizontal ratio.

V = degree of verticality.

H = degree of horizontalness.

$X_{Sideslope}$ = vector of covariates for the presence of side slopes.

$X'_{Sideslope}$ = transpose vector of covariates for the presence of side slopes.

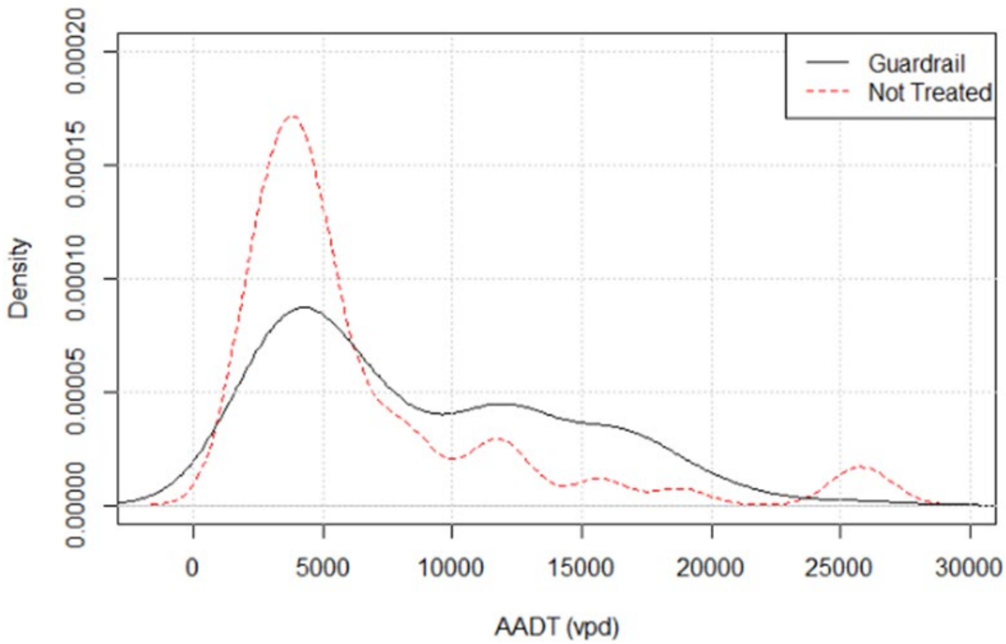
The research team fitted crash-risk models for the three crash types of interest. Because the response variables had similar distributions in the two State datasets and all explanatory variables were collected consistently using the same tools, the research team decided to combine data from both databases and fit overarching models for analysis.

As a last step, CMFs were constructed using the coefficients from the fitted models. The research team developed sensible contrasts for conditions represented in the final dataset.

SAFETY ANALYSIS OF ROADSIDE CONDITIONS AT HIGHWAYS

Initially, the research team prepared for analysis by defining appropriate variables across the subsets of sites. For example, guardrail length was defined as 0 ft for sites without guardrails. The research team then developed overlap weights from the three previously described PS models following the procedures discussed in Li et al. (2018). These weights are defined such that they represent the population of sites in the overlap of the two subsets. The following plots illustrate the balancing effect of this procedure for the evaluation of guardrail effectiveness on AADT and shoulder width, two covariates known to influence safety performance.

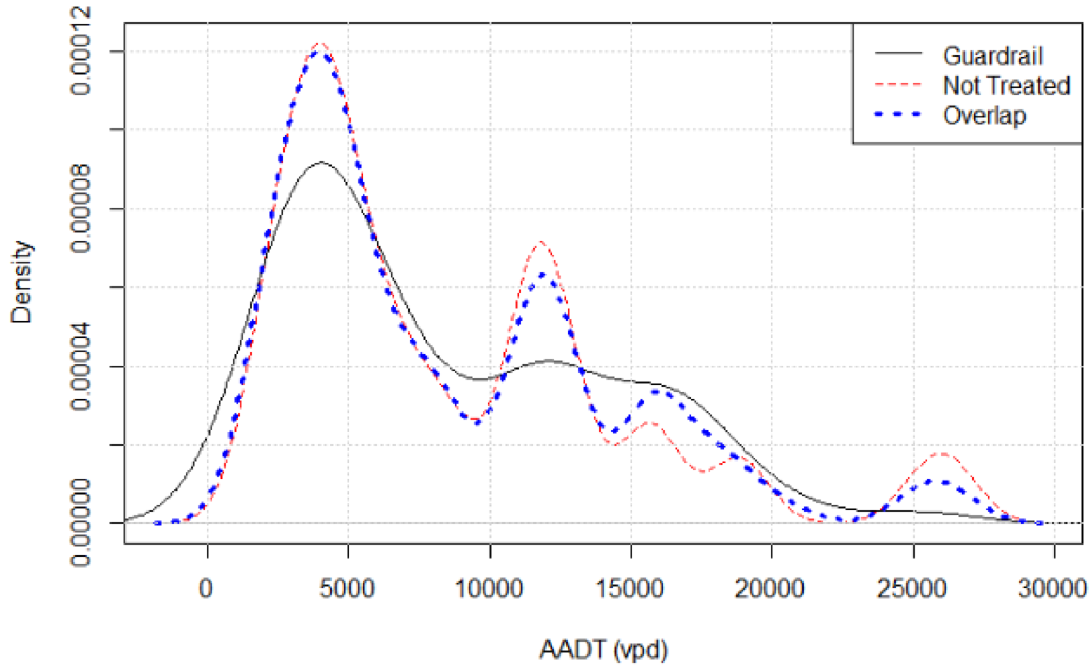
Figure 14 shows a slight imbalance in AADT distributions between the sites with and without guardrails. The ranges are similar, but the subset without guardrails has a smaller proportion of sites with higher AADTs and higher kurtosis (i.e., peakness).



vpd = vehicles per day.

Figure 14. Graph. AADT distributions by presence of guardrail in database.

In contrast, figure 15 shows how the application of PS weights balances the distributions, resulting in a more comparable contrast between the two data subgroups. This figure also shows the overlap distribution (blue, thickly dotted line).



vpd = vehicles per day.

Figure 15. Graph. AADT weighted distributions and overlap distribution.

This distribution of sites is equally likely to be in either the treated or the reference group. Therefore, the overlap distribution is the population of inference when applying the PS weights. Next, figure 16 shows the clearly unbalanced distributions of right shoulders by presence of guardrails. This figure indicates that sites with guardrails tend to also have wider right shoulders.

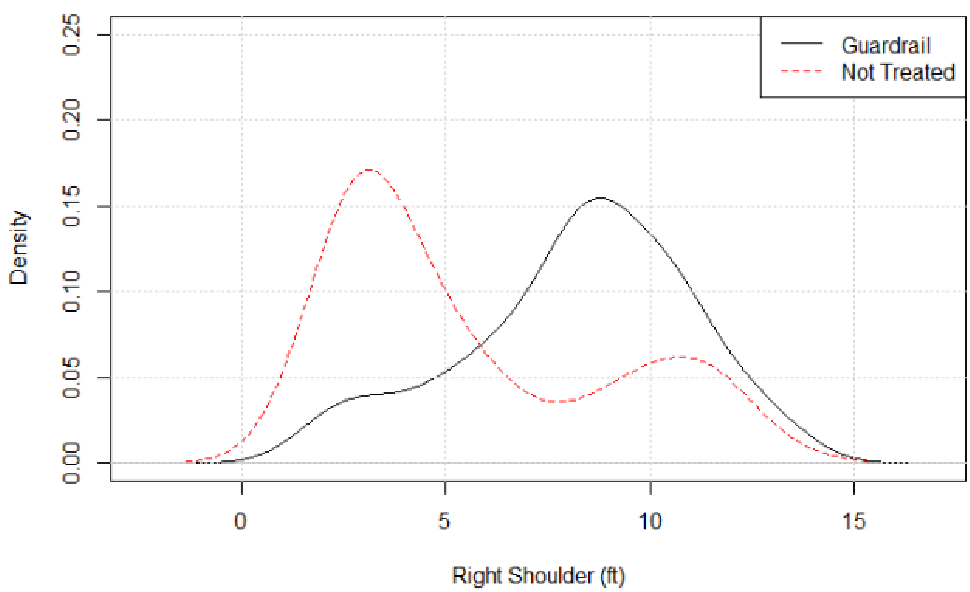


Figure 16. Graph. Right-shoulder distributions by presence of guardrail in database.

In contrast, figure 17 shows how the weighted distributions as well as the overlap distribution represented by the two subsets are clearly more similar than those shown in figure 16.

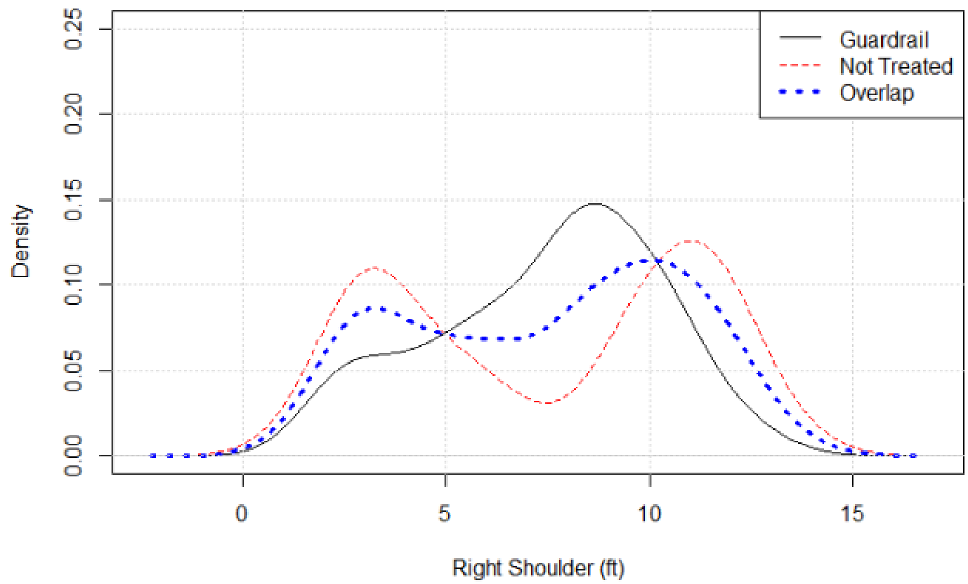


Figure 17. Graph. Right-shoulder weighted distributions and overlap distribution.

The next section describes the analysis process and results for the safety evaluation of roadside conditions.

DATA-ANALYSIS RESULTS

Because of the codependence structure in the data, the research team developed statistical models under the frame of generalized mixed models. To expedite the convergence of the estimating algorithm, model variables were centered at their mean and scaled by their standard deviation. This procedure normalized the range of variation of all covariates and centered the intercept of the model at the mean of the independent-variable distributions.

The CMF estimate derived from the logistic models was the odds ratio corresponding to each condition under evaluation. The research team also accounted for correlation between the two sides of a segment and among segments from the same State through a nested structure of random effects.

Statistical models were fit for three crash types defined in this dataset. The model for this analysis was a GLMM with a binomial-lognormal mixture. This approach models site-to-site variability as a lognormal distribution, whereas the crash risk for a given site is modeled as a binomial variable. Although the magnitude of the coefficient is not directly interpretable from the model output (i.e., models were developed on the scaled variables for efficiency in the estimation algorithm), the results in table 9 show similarities and differences in the sets of variables that are linked to the different crash types and severities. For example, the link of rumble strips to safety appears consistent between total and roadway-departure crashes. Also, unsurprisingly, speed limit was linked to fatal-and-injury-crash risk only. In general, the safety association of roadside conditions is not straightforward. For example, each model shows multiple coefficients for guardrail characteristics that should be taken jointly to derive sensible CMFs for that treatment. The next section, "Safety Effectiveness of Guardrails," documents the CMF development using the model results from table 9.

Table 9. Coefficient estimates for crash-risk models on rural highways.

Parameter[a]	All Crashes Coefficient	All Crashes SE	Roadway-Departure Crashes Coefficient	Roadway-Departure Crashes SE	Fatal-and-Injury-Crashes Coefficient	Fatal-and-Injury-Crashes SE
Intercept	2.7034***	0.8144***	−0.7966*	0.4646*	−1.4054***	0.3602***
VMT ($L \times AADT$)	0.5243***	0.1488***	0.6312***	0.155***	—	—
Posted speed limit (mph)	—	—	—	—	0.0172**	0.0073**
Rumble strip (1 = yes, 0 = no)	−0.7602*	0.3898*	−0.9283**	0.377**	—	—
PS_W	—	—	−0.0414	0.1614	—	—
All-travel-lanes width (*Sur_W*)	3.0149**	0.9221**	—	—	—	—
Number of lanes (*N_Lanes*)	−0.4246	1.0371	—	—	—	—
Presence of concrete median (1 = yes, 0 = no)	—	—	1.9113***	0.6499***	—	—
Presence of two-way left-turn median (1 = yes, 0 = no)	—	—	—	—	−1.3417	0.9148
Lateral offset from shoulder (*D_PS*)	—	—	0.0643	0.1866	—	—
Lateral offset including shoulder (*D_PS* + *PS_W*)	−0.2568*	0.1349*	—	—	—	—
Guardrail present (1 = yes, 0 = no)	—	—	6.2488**	2.647**	—	—
G_Height	—	—	−2.5578**	1.099**	—	—
G_len	—	—	—	—	0.6455***	0.2138***
Proportion of guardrail[b]	0.2326*	0.1378*	—	—	−1.6168**	0.7774**
Fore slope present (1 = yes, 0 = no)	—	—	—	—	−0.5269	0.4271
Abs (*Fore_Slope*)[c]	—	—	—	—	3.0885	2.2106
Pole Density[d]	—	—	—	—	0.3221*	0.1687*
Sur_W × *N_Lanes*	−2.1987**	0.7709**	—	—	—	—

—Not applicable.
*Significant at the 90-percent confidence level.
**Significant at the 95-percent confidence level.
***Significant at the 99-percent confidence level.
Abs = absolute value; SE = standard error; VMT = vehicle-miles traveled.
[a]All coefficients are estimated for scaled variables (i.e., variables centered at their mean and scaled by their standard deviation).
[b]This term is defined as the ratio of guardrail length to total segment length.
[c]Coefficient estimate is conditional to the absence of utility poles.
[d]This term is defined as the ratio between the number of utility poles and the length of the segment.

When analyzing a combined multi-State database, a potential concern is the underlying differences between the States represented. The research team addressed this concern in the following two ways:

- Before model selection, the PS weights were developed using functions that allowed potential State-specific interactions with other imbalanced covariates.
- Post-hoc testing of the final model coefficients by State was conducted.

Table 10 shows the results of these post-hoc likelihood ratio tests on the total crashes model for State-specific coefficient estimates and no statistically significant differences for any of the key variables by State in the final multi-State model.

Table 10. Likelihood-ratio tests for State-specific coefficient estimates in total-crash-risk model on rural highways.

Model	Degrees of Freedom	*p*-Value
FTCM	9	—
FTCM + State-specific intercept	10	0.2315
FTCM + State-specific VMT line	11	0.4867
FTCM + State-specific RS line	11	0.4885
FTCM + State-specific *Sur_W* line	11	0.1518
FTCM + State-specific *N_Lanes* line	11	0.4846
FTCM + State-specific (*D_PS* + *PS_W*) line	11	0.4864
FTCM + State-specific (*proportion of guardrail*) line	11	0.4704
FTCM + State-specific (*Sur_W* + *N_Lanes*) line	11	0.4660

—Not applicable.
FTCM = final total crash model; RS = rumble strip; VMT = vehicle-miles traveled.
Note: FTCM was the reference against which each alternative model was compared. Large *p*-values indicate a lack of improvement in model fit when allowing State-specific parameters in the model.

SAFETY EFFECTIVENESS OF GUARDRAILS

As described in the previous section, the research team defined contrasts from the model coefficients to estimate relative differences in crash expectations. For the contrasts, actual values of the roadside independent variables represented in the database were used while keeping other influential covariates equal at their global average levels in both groups. The corresponding CMF was then estimated as the exponentiated contrast, which is equivalent to the odds ratio between the counterfactuals from both groups.

The following sections summarize the estimated CMFs by treatment and for appropriate sets of base conditions.

Protecting Utility Poles With Guardrails

To develop a CMF for guardrail treatment, defining the base condition is critical. As the data summary and result tables show, multiple roadside conditions could be conceivably compared to guardrails. The research team developed CMFs for a set of sensibly defined base conditions. For a given pair of data subsets to be contrasted, the research team estimated the combined effects of the coefficients of interest—all coefficients involving guardrail and lateral offset from each of the models in table 9. The PS weights for the contrast between guardrail and other roadside conditions were applied when estimating the contrasts. The standard errors of the contrasts were estimated as explained in chapter 2. The research team obtained the results shown in table 11 for protecting roadside utility poles in proximity to the road with guardrails. The base and treatment conditions for these CMFs were defined by applying filters to the corresponding variables and identifying the size of the subsets represented in the comparisons.

Table 11. CMF estimates for guardrail addition at sites with lateral offsets to utility poles smaller than 20 ft and side slope flatter than 1 vertical to 6 horizontal.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	0.892	0.0915	95% CI	0.7306	1.089
Total	0.892	0.0915	90% CI	0.754	1.0552
Fatal and injury	0.5239*	0.1865*	95% CI	0.2753*	0.9968*
Fatal and injury	0.5239*	0.1865*	90% CI	0.3048*	0.9004*
Roadway departure	0.8172	0.2412	95% CI	0.4735	1.4103
Roadway departure	0.8172	0.2412	90% CI	0.5162	1.2937

*Value is statistically significant.
CI = confidence interval; SE = standard error.
Note: The base condition is side slopes flatter than 1 vertical to 6 horizontal and lateral offsets shorter than 20 ft. The contrast evaluation is represented in 59 guardrail sites and 139 non-guardrail sites.

Results from table 11 indicate a statistically significant reduction in fatal-and-injury crashes at sites with guardrails compared with sites that have roadside objects (utility poles) at lateral offsets smaller than 20 ft and side slopes flatter than 1 vertical (V):6 horizontal (H). No significant differences were found for total and roadway-departure crashes. These findings are sensible given that the lateral offsets of guardrails and utility poles are comparable in this scenario.

It is also of interest to estimate CMFs with a wider lateral offset in the base condition. Therefore, the research team developed another set of CMFs comparing the following conditions:

- Sites having guardrails covering the complete roadside.
- The reference group includes only sites with lateral offsets larger than 20 ft.

The resulting CMFs from these conditions are shown in table 12. These estimates differ from those in table 11 in the trends observed for total crashes and roadway-departure crashes: the values in table 12 tend to be larger, which would suggest more crashes of these types when guardrail is present. However, these two CMFs were not statistically significant, providing no clear evidence of changes in total or roadway-departure crashes when installing guardrails at locations with lateral offsets larger than 20 ft and side slopes flatter than 1V:6H. The CMF remained smaller than 1 and statistically significant for fatal-and-injury crashes, clearly indicating fewer severe crashes are expected at locations with guardrails.

Table 12. CMF estimates for guardrail addition at sites with lateral offsets larger than or equal to 20 ft and side slope flatter than 1V:6H.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	1.520	0.513	95% CI	0.8218	2.8095
Total	1.520	0.513	90% CI	0.9057	2.5493
Fatal and injury	0.433*	0.163*	95% CI	0.2201*	0.8515*
Fatal and injury	0.433*	0.163*	90% CI	0.2449*	0.7651*
Roadway departure	1.380	0.706	95% CI	0.5809	3.2795
Roadway departure	1.380	0.706	90% CI	0.6661	2.8600

*Value is statistically significant.
CI = confidence interval; SE = standard error.
Note: The base condition is side slopes flatter than 1V:6H and lateral offset longer than 20 ft. The contrast evaluation is represented in 59 guardrail and 31 non-guardrail sites.

The combined results from table 11 and table 12 are intuitive: CMFs tend to be larger for total and roadway-departure crashes when guardrails are applied at sites with larger lateral offsets, which is expected because the lateral offset is typically reduced after applying guardrails (the range of lateral offset for guardrails in the dataset is from 0 to 6.64 ft).

In any case, the CMF was not found to be statistically significant for total and roadway-departure crashes. In contrast, the CMF for fatal-and-injury crashes remained relatively unchanged for both base conditions (lateral offsets smaller than 20 ft in one case and larger than 20 ft in the other), indicating a statistically significant reduction of approximately 50 percent in fatal-and-injury crashes.

Protecting Side Slopes With Guardrails

Another quantity of interest to this research is the CMF for using guardrails to protect steep side slopes. The following filters were applied to define a common set of conditions for comparison with three ranges of side slopes:

- Safety effectiveness is estimated using only sites with guardrails that cover the complete roadside.
- The base condition includes only sites with lateral offsets smaller than 20 ft (to achieve similarity to the typical lateral offset of guardrails).
- Guardrail CMFs were estimated against different combinations of side slopes in the base conditions, including the following:
    - Between 1V:6H and 1V:4H.
    - Between 1V:4H and 1V:3H.
    - Between 1V:3H and 1V:2H.

The sets of CMFs for these three ranges of side slopes are shown in table 13, table 14, and table 15, respectively.

Table 13. CMF estimates for protecting 1V:6H to 1V:4H side slopes with guardrails.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	1.044	0.089	95% CI	0.8841	1.2334
Total	1.044	0.089	90% CI	0.9077	1.2014
Fatal and injury	0.648	0.313	95% CI	0.2832	1.4826
Fatal and injury	0.648	0.313	90% CI	0.3228	1.3006
Roadway departure	0.933	0.266	95% CI	0.55	1.5835
Roadway departure	0.933	0.266	90% CI	0.5979	1.4565

CI = confidence interval; SE = standard error.
Note: The base condition is 1V:6H to 1V:4H side slopes, 20 utility poles per mile or less, and 20 ft or less of lateral offset. The contrast evaluation is represented in 59 guardrail sites and 51 side-slope sites.

Table 14. CMF estimates for protecting 1V:4H to 1V:3H side slopes with guardrails.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	0.960	0.080	95% CI	0.8167	1.1286
Total	0.960	0.080	90% CI	0.8378	1.1001
Fatal and injury	0.607	0.290	95% CI	0.2671	1.3776
Fatal and injury	0.607	0.290	90% CI	0.3041	1.21
Roadway departure	1.044	0.321	95% CI	0.5928	1.8383
Roadway departure	1.044	0.321	90% CI	0.6483	1.681

CI = confidence interval; SE = standard error.
Note: The base condition is 1V:4H to 1V:3H side slopes, 20 utility poles per mile or less, and 20 ft or less of lateral offset. The contrast evaluation is represented in 59 guardrail sites and 24 side-slope sites.

Table 15. CMF estimates for protecting 1V:3H to 1V:2H side slopes with guardrails.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	0.975	0.063	95% CI	0.8599	1.1057
Total	0.975	0.063	90% CI	0.8772	1.0839
Fatal and injury	0.524	0.262	95% CI	0.2244	1.226
Fatal and injury	0.524	0.262	90% CI	0.2566	1.0719
Roadway departure	1.046	0.327	95% CI	0.5894	1.8575
Roadway departure	1.046	0.327	90% CI	0.6454	1.6963

CI = confidence interval; SE = standard error.
Note: The base condition is 1V:3H to 1V:2H side slopes, 20 utility poles per mile or less, and 20 ft or less of lateral offset. The contrast evaluation is represented in 59 guardrail sites and 22 side-slope sites.

Table 13 shows that the number of total and roadway-departure crashes is expected to remain roughly unchanged when protecting the side slope with guardrails. The trend in fatal-and-injury crashes is a reduction, although this result was not statistically significant.

Similar to the results in table 13, the results in table 14 indicate an unchanged number of total and roadway-departure crashes and a trend of reduction in fatal-and-injury crashes. Again, this result was not statistically significant.

In general, the trends in the results shown by table 13, table 14, and table 15 are intuitive. Jointly, they indicate that protecting side slopes with guardrails may have little to no effect on the risk of total and roadway-departure crashes, regardless of the slope value. This countermeasure was expected to reduce the risk of fatal-and-injury crashes, more so for steeper side slopes. Although the results for fatal-and-injury crashes seem to be consistent with that expectation, the analysis did not provide statistical evidence of a reduction in fatal-and-injury crashes when protecting side slopes of any value.

SAFETY EFFECTIVENESS OF UTILITY POLE REMOVAL OR RELOCATION

For comparisons that do not involve guardrails, the research team developed different sets of PS weights, conditional to no guardrail presence, as explained previously (figure 12), to balance covariates when developing CMFs for utility pole removal or relocation as a countermeasure.

Utility Pole Removal

Table 16 shows the estimated CMFs for removing utility poles completely or placing them beyond the maximum lateral offset considered in this study (a maximum of 50 ft from the paved shoulder).

Table 16. CMF estimates for utility pole removal or relocation beyond 50 ft of the paved shoulder.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	1.0428	0.1555	95% CI	0.7822	1.3903
Total	1.0428	0.1555	90% CI	0.8186	1.3285
Fatal and injury	0.6555*	0.1236*	95% CI	0.4572*	0.9398*
Fatal and injury	0.6555*	0.1236*	90% CI	0.484*	0.8878*
Roadway departure	1.3375	0.2942	95% CI	0.8817	2.0291
Roadway departure	1.3375	0.2942	90% CI	0.9417	1.8997

*Value is statistically significant.
CI = confidence interval; SE = standard error.
Note: The base condition is 20 utility poles per mile or less within 20 ft of the paved shoulder and side slope flatter than or equal to 1V:6H. The contrast evaluation is represented in 64 sites with utility poles within 20 ft and 54 sites without utility poles or with utility poles farther than 50 ft.

This estimation was achieved with respect to the following base condition: 20 utility poles per mile or less within 20 ft of the paved shoulder and side slopes flatter than or equal to 1V:6H. The contrast in safety performance is carried out between sites with the base condition and sites with no utility poles on the roadside and side slopes flatter than or equal to 1V:6H.

The results in this table indicate that no significant effects are expected in total or roadway-departure crashes but that statistically significant reductions of fatal-and-injury crashes are expected when removing utility poles from the proximity of the paved surface.

Utility Pole Relocation

Table 17 shows the CMFs for setting utility poles less than 20 ft back to beyond 20 ft from the paved roadway.

Table 17. CMF estimates for utility pole removal or relocation beyond 20 ft of the paved shoulder.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	0.8656	0.0655	95% CI	0.7467	1.0034
Total	0.8656*	0.0655*	90% CI	0.7644*	0.9803*
Fatal and injury	0.9892*	0.0052*	95% CI	0.9790*	0.9995*
Fatal and injury	0.9892*	0.0052*	90% CI	0.9806*	0.9978*
Roadway departure	0.9007	0.083	95% CI	0.7528	1.0778
Roadway departure	0.9007	0.083	90% CI	0.7745	1.0476

*Value is statistically significant.
CI = confidence interval; SE = standard error.
Note: The base condition is 20 utility poles per mile or less within 20 ft of the paved shoulder and side slope flatter than or equal to 1V:6H. The contrast evaluation is represented in 64 sites with utility poles within 20 ft and 88 sites with utility poles farther than 20 ft from the pavement edge.

The results in table 17 indicate a statistically significant reduction in total crashes (a 13.5-percent total crash reduction at the 90-percent confidence level) when relocating utility poles to a distance longer than 20 ft from the paved surface. Similar to the results in table 16, the results in table 17 indicate a statistically significant reduction of fatal-and-injury crashes (a 1.2-percent reduction in fatal-and-injury crashes at the 95-percent confidence level).

SAFETY EFFECTIVENESS OF FLATTENING SIDE SLOPES

The research team performed a set of evaluations to develop CMFs for flattening side slopes using a third set of PSs developed for this purpose (as defined in figure 13). Table 18 presents the results for flattening side slopes from 1V:4V to 1V:6H or flatter.

Table 18. CMF estimates for flattening side slopes from 1V:4H to 1V:6H or flatter.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	0.9223	0.0396	95% CI	0.848	1.0032
Total	0.9223*	0.0396*	90% CI	0.8593*	0.9899*
Fatal and injury	0.6886	0.2531	95% CI	0.3554	1.3341
Fatal and injury	0.6886	0.2531	90% CI	0.3946	1.2016
Roadway departure	0.7844	0.1134	95% CI	0.5934	1.0369
Roadway departure	0.7844*	0.1134*	90% CI	0.6202*	0.9921*

*Value is statistically significant.
CI = confidence interval; SE = standard error.
Note: The base condition is slope toe at least 5 ft from paved shoulder, less than 20 utility poles per mile, lateral offsets between 10 and 20 ft, and 1V:4H side slope. The contrast evaluation is represented in 50 sites with 1V:6H side slope or flatter and 3 sites with 1V:4H side slopes.

As table 18 shows, only three sites in the database had 1V:4H side slopes meeting the other requirements defined in the base condition. To increase the representativeness of the results, the research team developed a CMF for an expanded base condition including 1V:5H as well. The results in table 19 are similar to the results in table 18.

Table 19. CMF estimates for flattening side slopes from 1V:4H or 1V:5H to 1V:6H or flatter.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	0.9360*	0.0302*	95% CI	0.8787*	0.997*
Total	0.9360*	0.0302*	90% CI	0.8875*	0.9871*
Fatal and injury	0.7216	0.2113	95% CI	0.4197	1.2407
Fatal and injury	0.7216	0.2113	90% CI	0.4572	1.1388
Roadway departure	0.8220	0.0964	95% CI	0.6548	1.032
Roadway departure	0.8220*	0.0964*	90% CI	0.6788*	0.9955*

*Value is statistically significant.
CI = confidence interval; SE = standard error.
Note: The base condition is slope toe at least 5 ft from paved shoulder, less than 20 utility poles per mile, lateral offsets between 10 and 20 ft, and side slope 1V:4H or 1V:5H. The contrast evaluation is represented by 50 sites with 1V:6H side slopes or flatter and 8 sites with 1V:4H or 1V:5H side slopes.

Table 19 includes eight cases in the database that match the base condition. A modest reduction in total crashes and a moderate reduction in roadway-departure crashes is expected when flattening 1V:4H or 1V:5H slopes to 1V:6H or flatter.

Next, the research team estimated the CMFs for reductions to 1V:4H or 1V:5H from 1V:3H. Table 20 shows a small reduction in roadway-departure crashes is expected when flattening 1V:3H side slopes (4.01-percent, statistically significant reduction at the 90-percent confidence level).

Table 20. CMF estimates for flattening side slopes from 1V:3H to 1V:4H or 1V:5H.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	1.0153	0.0142	95% CI	0.9879	1.0434
Total	1.0153	0.0142	90% CI	0.9921	1.0389
Fatal and injury	0.7432	0.1904	95% CI	0.4599	1.2011
Fatal and injury	0.7432	0.1904	90% CI	0.4962	1.1133
Roadway departure	0.9509	0.0283	95% CI	0.8971	1.0079
Roadway departure	0.9509*	0.0283*	90% CI	0.9054*	0.9986*

*Value is statistically significant.
CI = confidence interval; SE = standard error.
Note: The base condition is slope toe at least 5 ft from paved shoulder, less than 20 utility poles per mile, lateral offsets between 10 and 20 ft, and 1V:3H side slope. The contrast evaluation is represented in 10 sites with 1V:4H or 1V:5H side slopes and 3 sites with 1V:3H side slope.

To obtain a CMF with a more representative base condition, the research team repeated the estimation for a broader set of parameters defining a broader base condition. Table 21 shows the results and redefined base condition.

Table 21. CMF estimates for flattening side slopes from 1V:2H or 1V:3H to 1V:4H or 1V:5H.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	0.9788	0.0226	95% CI	0.9355	1.0241
Total	0.9788	0.0226	90% CI	0.9422	1.0168
Fatal and injury	0.7443	0.1927	95% CI	0.4585	1.2084
Fatal and injury	0.7443	0.1927	90% CI	0.495	1.1193
Roadway departure	0.8699	0.0715	95% CI	0.7411	1.0211
Roadway departure	0.8699*	0.0715*	90% CI	0.7601*	0.9955*

*Value is statistically significant.
CI = confidence interval; SE = standard error.
Note: The base condition is slope toe at least 5 ft from paved shoulder, less than 20 utility poles per mile, lateral offsets between 10 and 20 ft, and either 1V:2H or 1V:3H side slope. The contrast evaluation is represented in 9 sites with 1V:4H or 1V:5H side slopes and 12 sites with 1V:2H or 1V:3H side slope.

Similar to the prior evaluation, table 21 indicates only a statistically significant reduction in roadway-departure crashes when flattening slopes from 1V:2H or 1V:3H to either 1V:4H or 1V:5H.

CHAPTER SUMMARY

This chapter documents the statistical evaluations and steps taken to develop CMFs from the two-State database developed for this study. The analysis developed statistical models for the crash risk at the study sites using roadside conditions as well as other influential covariates as explanatory variables. Using the model coefficients, the research team computed CMFs through contrasting subsets of sites in the database. The contrasts reflected the changes in conditions that would occur as a result of the implementation of various safety improvements. The produced CMFs are representative of both States in the database (Indiana and Pennsylvania). Results generally indicate the following:

- Guardrails are expected to result in fewer fatal-and-injury crashes for the two ranges of lateral offsets to utility poles tested.
- Results are inconclusive for guardrails on total and roadway-departure crashes when protecting utility poles of various lateral offsets from the paved road. However, the trends in those evaluations consistently suggest (but not statistically significantly) that total and roadway-departure crashes tend to increase when implementing guardrails. Results indicate statistically significant reductions in fatal-and-injury crashes when protecting roadside utility poles with guardrails.
- Removing or relocating utility poles farther back from the travel lanes is linked to statistically significant reductions in total and fatal-and-injury crashes.

- The safety effectiveness of flattening side slopes in general indicates statistically significant reductions in roadway-departure crashes only. No evidence was found of changes in fatal-and-injury crashes for this evaluation.

CHAPTER 5. ECONOMIC ANALYSIS

The research team conducted an economic analysis to estimate B/C ratios for the evaluated roadway-departure countermeasures on urban arterials, collectors, and city streets. The research team used the CMFs developed from the combined Indiana and Pennsylvania database. Economic analyses were performed for the three countermeasures under evaluation in the cases where a statistically significant change in crashes was found to be linked to the countermeasures.

To perform a B/C ratio analysis, the research team followed the procedures recommended in FHWA's technical document titled *Highway Safety Benefit-Cost Analysis Guide* (Lawrence et al. 2018).

BENEFITS AND COSTS ESTIMATES

The results in the prior chapter determined which benefits were considered in assessing the economic effectiveness of the countermeasures under study. In the case of guardrail applications and utility pole removals, the research team considered benefits due to reductions in fatal-and-injury crashes linked to these countermeasures. For side-slope flattening countermeasures, the research team considered benefits due to reductions in roadway-departure crashes, as found in chapter 4.

Regarding costs, the research team found that the average cost to relocate the electrical services from one point to another is $2,439.86, as reported by TxDOT (2019), whereas the weighted average cost to relocate a steel light pole is $1,650, as reported by the Indiana DOT (INDOT) (2018). The weighted average rate for resetting a guardrail is $20.59 per linear foot (INDOT 2018). Additionally, the average cost in Texas in 2011 for ROW acquisition was reported as $26.6 per square foot (Xiong and Kockelman 2014).

Average per-mile costs for clearing and grubbing with different back slopes were obtained for Idaho from the U.S. Department of Agriculture (USDA) Forest Service (2017). It is assumed in this analysis that the cost of clearing of timber by volume/acre is $0 and the excavation and seeding costs are those obtained from USDA Forest Service.

The value of a statistical life (VSL) was obtained from the most recent memorandum on the U.S. DOT (USDOT) website (Trottenberg and Rivkin 2016). The recommended range for VSL is from $5.2 million to $12.9 million in 2012 dollars. Knowing the applicable range for 2001 dollars as well allows for the computation of the underlying geometric rate of inflation. The range for 2013 (the latest year for crashes available in the database) was between $5.17 million and $13.52 million. A nominal value of $9.35 million was adopted for this evaluation.

The average cost of a crash was computed using all severities, USDOT guidance, and the distribution of severe crashes observed in each State (Trottenberg and Rivkin 2016). Using a VSL of $9.35 million, the research team estimated the average cost of a crash in both States at $530,541.

B/C Ratios for Guardrail Applications

A key assumption in the calculation of the B/C ratio for protecting utility poles far (20 ft or more) from the road with guardrails is an expected increase in total crashes due to the placement of guardrails but a reduction in severe crashes, per the results in chapter 4. Indeed, this increase was observed as a trend in the statistical analyses that involved placing roadside objects farther from the road. However, this trend was not statistically significant in the evaluations of protecting utility poles with guardrails, despite a statistically significant coefficient for lateral offset in the model for total crashes. The research team surmised two reasons for this discordance: the significance of the coefficient is relatively low (0.05 significance level), and the contrast in the evaluation considers jointly the uncertainty of this and other coefficients (both in the treated and base condition groups). Therefore, the significance of a single coefficient is not a guarantee that the contrast will yield a statistically significant result. Regardless, for a more realistic economic evaluation, the research team used the estimated effect from the model for total crashes (shown in table 9) for a reduced lateral offset to estimate the tradeoff in severity due to a shift in lateral offset resulting from installing guardrails to protect utility poles farther than 20 ft from the paved surface.

Economic Effectiveness of Protecting Utility Poles Within 20 ft of the Paved Shoulder With Guardrail

It was estimated that the benefit of protecting utility poles within 20 ft of the paved shoulder is derived from its 48-percent reduction in fatal-and-injury crashes (table 11), which is equivalent to a benefit of $373,849 over the 5 yr of useful life of the guardrail over 1 mi of roadside. On the other side, considering the joint costs of installation and annual maintenance of $292,387 (due to having to repair 50 ft of the guardrail for each fatal-and-injury crash saved), the B/C ratio is estimated to be 1.28 for this treatment.

Economic Effectiveness of Protecting Utility Poles Farther Than 20 ft From the Paved Shoulder With Guardrail

In contrast to the estimation regarding utility poles within 20 ft of the paved shoulder, the economic effectiveness of protecting utility poles that are initially at a relatively safe distance from the pavement (i.e., at least 20 ft from the pavement) considered the tradeoff between fatal-and-injury crashes (estimated to be a reduction) and property-damage-only (PDO) crashes (anticipated to be an increase according to past literature and inconclusive—not statistically significant—from the results shown in table 12). It was estimated that the benefit of protecting utility poles located 20 ft from the paved shoulder or farther is derived from the 57-percent reduction estimated for fatal-and-injury crashes (table 12), which is equivalent to a benefit of $445,227 over the 5 yr of useful life of the guardrail over 1 mi of roadside. On the cost side, a joint cost of $300,877 was estimated for installation and annual maintenance, assuming the need to repair 50 ft of the guardrail for each crash saved and assuming an 89-percent increase in PDO crashes. This estimate assumes that the guardrail repair cost from the reduction in fatal-and-injury crashes is captured in the increase of PDO crashes. The overall B/C ratio was therefore estimated to be 1.48 for this treatment.

B/C Ratios for Utility Pole Removal or Relocation

For the economic effectiveness estimation of utility pole removal or relocation, the research team assumed a useful life of 20 yr. For each of the two treatments, two scenarios were considered: including the cost of new ROW acquisition or not.

Economic Effectiveness of Removing Utility Poles (Considering ROW Acquisition)

It was estimated that the benefit of removing utility poles within 20 ft of the paved shoulder is derived from the 34.6-percent reduction in fatal-and-injury crashes found in the safety evaluation (according to table 16). Over a 20-yr useful life, this benefit is equivalent to $1.08 million per mile. On the cost side, joint costs of installation and annual maintenance amount to $765,671 (considering the cost of ROW acquisition, utility pole relocation, resetting of electric/utilities, and repair of one pole per mile every 2 yr). The B/C ratio is estimated in this case to be 1.41 for this treatment.

Economic Effectiveness of Removing Utility Poles (Not Considering ROW Acquisition)

It was estimated that the benefit of removing utility poles within 20 ft of the paved shoulder is derived from the 34.6-percent reduction in fatal-and-injury crashes found in the safety evaluation (according to table 16). Over a 20-yr useful life, this benefit is equivalent to $1.08 million per mile. On the cost side, joint costs of installation and annual maintenance amount to $63,431 (considering utility pole relocation, resetting of electric/utilities, and repair of one pole per mile every 2 yr). The B/C ratio is estimated in this case to be 17.1 for this treatment.

Economic Effectiveness of Relocating Utility Poles Beyond 20 ft From the Pavement (Considering ROW Acquisition)

It was estimated that the benefit of relocating utility poles farther than 20 ft from the paved shoulder is derived from the 13-percent reduction in total crashes found in the safety evaluation (according to table 17). Over a 20-yr useful life, this benefit is equivalent to $426,886 per mile. On the cost side, joint costs of installation and annual maintenance amount to $765,671 (considering the cost of ROW acquisition, utility pole relocation, resetting of electric/utilities, and repair of one pole per mile every 2 yr). The B/C ratio is estimated in this case to be 0.56 for this treatment.

Economic Effectiveness of Relocating Utility Poles Beyond 20 ft From the Pavement (Not Considering ROW Acquisition)

It was estimated that the benefit of relocating utility poles farther than 20 ft from the paved shoulder is derived from the 13-percent reduction in fatal-and-injury crashes found in the safety evaluation (according to table 17). Over a 20-yr useful life, this benefit is equivalent to $426,886 per mile. On the cost side, joint costs of installation and annual maintenance amount to $63,431 (considering the cost of utility pole relocation, resetting of electric/utilities, and repair of one pole per mile every 2 yr). The B/C ratio is estimated in this case to be 6.73 for this treatment.

B/C Ratios for Side-Slope Flattening

The data obtained from the USDA report *Cost Estimating Guide for Road Construction* were used in this estimation exercise. With no cost of ROW acquisition considered, the cost and benefits associated with crash countermeasures for calculating the B/C ratio are presented in the following sections (USDA Forest Service 2017).

Economic Effectiveness of Flattening Side Slopes From 1V:4H or 1V:5H to 1V:6H or Flatter

It was estimated that the benefit of flattening side slopes is derived from the 18-percent reduction in roadway-departure crashes found in the safety evaluation (according to table 19). Over a 20-yr useful life, this benefit is equivalent to $1.17 million per mile. On the cost side, joint costs of installation and annual maintenance amount to $5.70 million (considering the cost of clearing and grubbing, excavation, and seeding every 4 yr). The B/C ratio is estimated in this case to be 0.21 for this treatment.

Economic Effectiveness of Flattening Side Slopes From 1V:2H or 1V:3H to 1V:4H or 1V:5H

It was estimated that the benefit of flattening side slopes is derived from the 13-percent reduction in roadway-departure crashes found in the safety evaluation (according to table 21). Over a 20-yr useful life, this benefit is equivalent to $856,188 per mile. On the cost side, joint costs of installation and annual maintenance amount to $6.4 million (considering the cost of clearing and grubbing, excavation, and seeding every 4 yr). The B/C ratio is estimated in this case to be 0.13 for this treatment.

CHAPTER SUMMARY

This chapter describes the analysis performed to estimate the economic effectiveness of implementing guardrails, removing or relocating utility poles, and flattening side slopes on rural two-lane highways. The chapter outlines the resources and assumptions involved in developing B/C ratios for the evaluations. For the two cases of implementing guardrails to protect utility poles, both B/C ratios were larger than 1.0, indicating larger benefits than costs for these implementations.

Mixed results were obtained for relocating and removing utility poles and flattening side slopes. If no cost of ROW acquisition is considered, then the B/C ratios are larger than 1.0 for both relocation and removal of utility poles. In contrast, the B/C ratio is smaller than 1.0 for utility pole relocation if the cost of ROW acquisition is considered in the evaluation. B/C ratios were smaller than 1.0 in the two cases evaluated for flattening side slopes (0.21 and 0.13), which indicates that flattening side slopes as a safety countermeasure may not be economically feasible for the range of traffic volumes and rural highway characteristics considered in this study.

The following chapter provides a summary and conclusions of the project.

CHAPTER 6. SUMMARY AND CONCLUSIONS

The objective of this study was to perform rigorous safety-effectiveness evaluations of treating roadside conditions as crash countermeasures at rural highways. Specifically, the study focused on the safety effectiveness of implementing guardrails, removing or relocating utility poles, and flattening side slopes on rural highways. To accomplish the goals of this study, the research team compiled safety data from 463 mi of roadside in Indiana and Pennsylvania. The safety evaluation included total, fatal-and-injury, and roadway-departure crashes.

The elements under study were guardrails, utility poles, and side slopes. The research team obtained geometric, traffic, and crash data at treated locations in Indiana and Pennsylvania. Roadside conditions were obtained directly from road-level imagery and the use of photogrammetry tools. The study had a cross-sectional design, and the analysis was performed by using generalized linear mixed binomial models. When developing the database, PS weights were applied in the estimation of CMFs to achieve a balance between untreated sites (i.e., without any of the studied roadside conditions) and sites with the treatments of interest so that a comparison could be deemed balanced in all key covariates (Li et al. 2013, 2018). This complementary method is expected to contribute to the robustness of the study when the intent is to estimate causal effects (Imai and Ratkovic 2015; Vermeulen and Vansteelandt 2015). Preliminary PSs were also computed throughout the data collection to assess the level of balance in the partial database and to direct further collection of data accordingly.

The CMFs estimated for guardrail implementations were consistently smaller than 1.0 for fatal-and-injury crashes for applications to protect utility poles and roadside slopes. The guardrail CMFs were only statistically significant for applications to protect utility poles on the roadside (CMF of 0.524 and 0.433, depending on pole proximity to the roadway). Results were inconclusive for protecting side slopes with guardrails (all CMFs statistically equivalent to 1.0).

The CMFs estimated for utility pole removal or relocation were also consistently smaller than 1.0 for fatal-and-injury crashes. The CMFs were smaller than 1.0 and statistically significant when removing utility poles or relocating utility poles (CMF of 0.6555 for fatal-and-injury crashes when removing the pole and 0.8656 for total crashes when relocating the pole beyond 20 ft of the paved shoulder).

The CMFs estimated for side-slope flattening were consistently smaller than 1.0 and statistically significant for roadway-departure crashes (CMF of 0.784 for 1V:4H to 1V:6H or flatter, CMF of 0.822 for 1V:4H or 1V:5H to 1V:6H or flatter, CMF of 0.951 for 1V:3H to 1V:4H or 1V:5H, and CMF of 0.870 for 1V:2H or 1V:3H to 1V:4H or 1V:5H). In the case of total crashes, the CMFs tended to be smaller than 1 (in three out of four evaluations) but were only statistically significantly smaller than 1 for the following two treatments: reducing the side slope from 1V:4H to 1V:6H or flatter (CMF of 0.922 for total crashes) and reducing the side slope from 1V:2H or 1V:3H to 1V:6H or flatter (CMF of 0.936 for total crashes).

The economic evaluation of guardrails indicated that guardrail implementations are economically viable when protecting roadside utility poles (B/C ratio of 1.28 or 1.48, depending on the distance of the pole from the paved surface). Results were inconclusive for protecting side slopes with guardrails (because the safety analysis yielded no statistically significant estimate of the crash-reduction benefit).

The economic evaluation of utility pole removal or relocation indicated that this strategy is economically viable when removing roadside utility poles (B/C ratio of 1.41 or 17.1, depending on whether the cost of ROW acquisition is considered). However, in the case of relocating utility poles farther than 20 ft from the paved shoulder, the strategy was found to be economically viable only when not considering the cost of ROW acquisition (B/C ratio of 6.73). If ROW acquisition costs are considered, then the costs of pole relocation nearly double the crash-reduction benefit (B/C ratio of 0.56).

The economic evaluation of side-slope flattening indicated that this strategy is not economically viable (B/C ratios of 0.21 and 0.13, depending on how steep the initial and reduced side slopes are). A relatively low crash frequency per mile at the roads in the evaluation is surmised as the main reason for these low B/C ratios. Flattening the side slope may be economically viable in locations where AADTs tend to be higher and roadway-departure crashes are more prominent. However, potential ROW acquisition was not considered in the economic evaluation of this strategy. The economic viability may be further curtailed if this significant cost is considered, even in cases of higher AADTs and roadway departure–crash frequency.

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