TECHBRIEF

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

FHWA Publication No.: FHWA-HRT-21-076

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INTRODUCTION

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

This project evaluated the safety effectiveness of three roadside modifications that States have implemented as safety treatments: guardrail installation, utility pole relocation or removal, and side-slope flattening. The ELCSI-PFS Technical Advisory Committee selected the safety evaluation of such roadside treatments as one of the priorities of the PFS.

Study Objective

This evaluation assessed the potential of guardrail installation, utility pole relocation or removal, and side-slope flattening to reduce crashes in terms of total, fatal-and-injury, and roadway-departure crashes. The research team's intent was to develop crash modification factors (CMFs) and benefit–cost (B/C) ratios for the safety improvements. Practitioners can use the CMFs and B/C ratios for decision making in the project-development and safety-planning processes.

Background

Fixed roadside objects, such as trees, signs, utility poles, signals, barriers, and guardrails, play a significant role in increasing the severity of roadway-departure crashes.

According to FHWA (2006), 56 percent of all fatal crashes are roadway departures. Of these crashes, 40 percent involve a fixed roadside object, most commonly a tree or utility pole. In 2005, over 25,000 people died across all road networks in the United

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States because drivers left their lane and impacted an oncoming vehicle, rolled over, or hit an object located along the highway. About 17,000 of 25,000 roadway-departure fatalities in 2015 were the result of single-vehicle run-off-the-road crashes. About 80 percent of roadway-departure fatalities occurred on rural roadways, a vast majority of which (9 out of every 10) took place on two-lane highways (FHWA 2006).

From 2013 to 2015, an average of 18,275 fatalities resulted from roadway departures, accounting for 54 percent of all traffic fatalities in the United States during that period (FHWA 2017). 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 from 2003 through 2008 and conducted visits to the 20 sites with the highest crash rates in four Texas Department of Transportation districts. Their study showed that roadway departures accounted for 25 to 52 percent of all crashes occurring on each of the rural two-lane highways studied (Lord et al. 2011). A more recent Texas study on rural two-lane highways found that the risk of roadway-departure crashes that involved guardrails increases with shorter guardrail offsets and the risk of fixed-object crashes increases with reduced clear zones (Avelar et al. 2020).

Despite the environmental, social, and economic benefits of trees in communities, municipalities, and regions, nearly 25 percent of all fixed-object crashes 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) found that roadside improvements seem to be associated with crash reductions ranging from 19 to 52 percent. Side-slope angle was an important factor in roadside crashes, and flatter side slopes provided greater safety benefits by lowering the rates of single-vehicle accidents (Zeeger et al. 1988).

A Policy on Geometric Design of Highways and Streets (2004) (more popularly referred to as 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). An improvement to clear zones is the removal or replacement of fixed roadside objects, such as guardrails and utility poles.

STUDY DESIGN

The research team collected and assembled data for a cross-sectional estimation of the CMFs of interest (e.g., installing a guardrail, removing or relocating utility poles, and flattening side slopes). Reference sites were also added to strengthen the study design. Data collection required estimating roadside conditions using image-analysis methods. The research team also decided to implement propensity score (PS)-based strategies to balance covariates during data collection and analysis. During data collection, covariate balancing was performed based on preliminary PSs using an initial data subset that included some reference sites in order to procure similar covariate distributions, to the extent possible, for the rest of the data collection.

DATA-ANALYSIS METHODS

The empirical analyses were conducted using the statistical methods appropriate to the characteristics of the assembled datasets. The research team used generalized-linear-mixed-model variants (binomial mixed) to obtain the safety-effectiveness estimates of interest. For the analysis, the research team adopted a framework of PS weighting, setting the target population of sites at the overlap population as proposed by Li et al. (2018). This choice of target population is desirable because of its small-sample, exact-balance property, and the required weights minimize the asymptotic variance of the weighted average treatment effect within their class of weights (Li et al. 2018). Under this scheme, the target population is the set of all sites that have comparable chances of being in either the treatment group or the reference group.

This approach effectively curbs the undue influence of the following two subsets of sites when estimating the average treatment effect of the countermeasure:

- Reference sites with characteristics unlikely in candidate sites for the treatment.
- Rare treated sites with no comparable reference sites in the data.

By using PS weighting, the influence of each data point is either increased or decreased so that it represents a balanced covariate distribution, which should result in a nearly unbiased estimate of the effect of interest. Estimating the CMFs of interest required combining multiple parameter estimates and their standard errors through applying appropriate linear combinations.

DATA

The research team constructed a database for the analysis, focusing on road segments with guardrails and utility poles. Other locations without these treatments were also included to provide a baseline for the evaluation. The team considered the side slope of the road as an additional variable because it may affect the type and severity of roadside crashes. Most site information, including the presence of guardrails, lane and shoulder dimensions, facility type, average annual daily traffic (AADT), and crash numbers and types, was obtained from the Second Strategic Highway Research Program (SHRP2) Roadway Inventory Database (RID) (Smadi et al. 2015). The presence of rumble strips was also recorded at certain locations in the analysis.

SHRP2 RID data are from six States. Preliminary data from four SHRP2 States were collected. The research team determined that supplementing these data with additional variables was necessary to better characterize the roadside conditions at the studied sites. The additional variables were to be obtained by processing various imagery databases. This process reduced the initial scope of facility types to rural highways in Indiana and Pennsylvania.

In addition to the data available in the RID tables, the research team obtained data on geometric design and traffic from other relational databases available online. For example, complete vehicle-level crash information and AADTs for additional years were obtained directly from the Pennsylvania Department of Transportation website for Pennsylvania (PennDOT 2020).

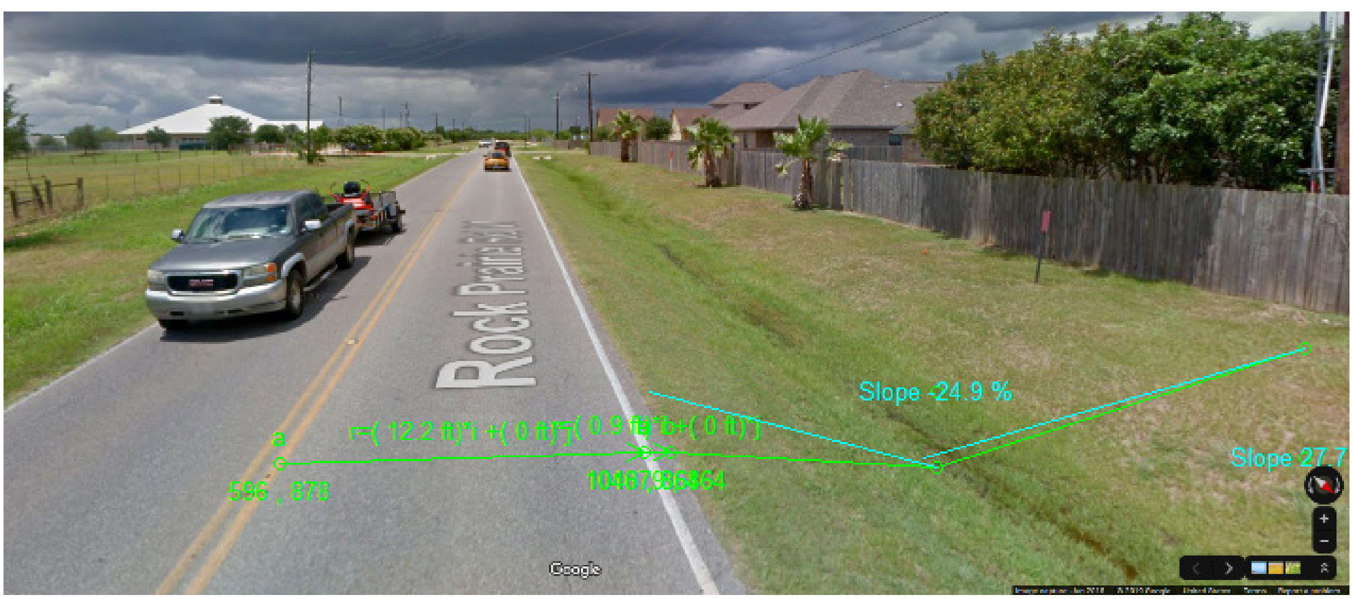
Use of Propensity Scores in Data Collection

During data collection, PS models were fitted on preliminary data to help direct the data-collection efforts toward a suitable, balanced database. The research team used the RID alignment layer as the reference segmentation layer to separate curves from tangent sections. The data collection focused on tangents up to 1 mi long. These segments were further broken down to achieve subsegments with relatively uniform roadside characteristics.

Image-Analysis Procedure

To identify fixed roadside objects on the studied road segments, the research team adapted image-processing analytical methods developed for a recently completed project in Texas (Avelar et al. 2017). The methodology consisted of a set of analytical methods to estimate geometric features from close-range perspective images. The methods were calibrated to sample images with known object sizes and locations in space using a nonconvex optimization algorithm. The calibrated methods were then applied to estimate the lateral distances and dimensions of roadside objects, including side slopes, in other images, as shown in figure 1.

Figure 1. Screenshot. Side slope measured from street-level imagery.



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The research team mined the RID's image inventory to collect roadside characteristics from multiple routes in Indiana and Pennsylvania. After breaking down segments to achieve uniform cross sections and discarding segments with trees and other irregular roadside features, the research team assembled a dataset of 348 highway segments from both States combined with detailed roadside information. Table 1 lists the variables collected, and table 2 summarizes the statistics for select variables in the final dataset.

Table 1. List of variables collected for each site.

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

Table 2. Summary statistics for select variables in final dataset (number of sites = 348).

Variable	Mean	Std. Dev.	Minimum	Maximum	Total
AADT_year	7,223.843	5,781.125	1,531	26,560	—
Lane_W (ft)	11.652	0.583	9.32	14.7	—
PS_W (ft)	6.257	3.444	0.6	13.94	—
L (mi)	0.189	0.098	0.05	0.64	—
Total Crashes	0.747	1.539	0	17	—
KABC Crashes	0.233	0.584	0	5	81
Roadway Departure Crashes	0.422	0.874	0	9	147

—Not applicable.
KABC = fatal (K), severe injury (A), moderate injury (B), minor injury (C); Std. Dev. = standard deviation.

ANALYSIS

Risk models with PS weights were developed for each response variable of interest: total, fatal-and-injury, and roadway-departure crashes. The weights were developed from PS models for decreasing hierarchy levels in the nested structure of the data, namely guardrails versus no guardrails; utility pole presence versus no presence, given no guardrails; and steep side slope versus flat side slope, given no guardrails. CMFs were estimated using the corresponding model coefficients through sensible contrasts representative of the roadside conditions in the final datasets.

Results

Because multiple roadside conditions could be conceived as base conditions, the research team developed CMFs defining base conditions as values represented in the database for each evaluation. For a given comparison, the research team estimated the combined effects of the coefficients of interest for the sites with the treatment in contrast to the set of comparison sites. Treatment-specific PS weights were developed and applied in the CMF estimation. Table 3 and table 4 show the CMFs for protecting roadside utility poles in proximity to the road with guardrails.

Table 3. CMF estimates for guardrail addition at sites with lateral offsets to utility poles smaller than 20 ft and side slopes 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	90% CI	0.754	1.0552
Fatal and injury	0.5239*	0.1865*	90% CI	0.3048*	0.9004*
Roadway departure	0.8172	0.2412	90% CI	0.5162	1.2937

*Statistically significant at 90-percent confidence level.
CI = confidence interval; SE = standard error.
Note: The contrast evaluation is represented in 59 guardrail sites and 139 non-guardrail sites.

Table 4. CMF estimates for guardrail addition at sites with lateral offsets larger than or equal to 20 ft and side slopes flatter than 1 vertical to 6 horizontal.

Crash Type	CMF	SE (CMF)	CI	Lower Limit of CI	Upper Limit of CI
Total	1.520	0.513	90% CI	0.9057	2.5493
Fatal and injury	0.433*	0.163*	90% CI	0.2449*	0.7651*
Roadway departure	1.380	0.706	90% CI	0.6661	2.86

*Statistically significant at 90-percent confidence level.
CI = confidence interval; SE = standard error.
Note: The contrast evaluation is represented in 59 guardrail sites and 31 non-guardrail sites.

Table 5 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 5. 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	90% CI	0.8186	1.3285
Fatal and injury	0.6555*	0.1236*	90% CI	0.484*	0.8878*
Roadway departure	1.3375	0.2942	90% CI	0.9417	1.8997

*Statistically significant at 90-percent confidence level.
CI = confidence interval; SE = standard error.
Note: The base condition is 20 poles per mile or less within 20 ft of the paved shoulder and side slopes flatter than or equal to 1 vertical to 6 horizontal. 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.

Based on the results in table 5, no significant effects are expected in total or roadway-departure crashes, but statistically significant reductions of fatal-and-injury crashes are expected when removing utility poles from the proximity of the paved surface. As table 6 shows, statistically significant CMFs indicate reductions in total and roadway-departure crashes when flattening side slopes.

Table 6. CMF estimates for flattening side slopes from 1 vertical to 4 horizontal or 1 vertical to 5 horizontal through 1 vertical to 6 horizontal or flatter.

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

*Statistically significant at 90-percent confidence level.
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 1 vertical to 6 horizontal side slopes or flatter. The contrast evaluation is represented by 50 sites with 1 vertical to 6 horizontal side slopes or flatter and 8 sites with 1 vertical to 4 horizontal or 1 vertical to 5 horizontal side slopes.

Table 7 suggests a small reduction in roadway-departure crashes can be expected when flattening 1 vertical (V):3 horizontal (H) side slopes to 1V:4H or 1V:5H (4.01-percent statistically significant reduction at the 90-percent confidence level).

Table 7. 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	90% CI	0.9921	1.0389
Fatal and injury	0.7432	0.1904	90% CI	0.4962	1.1133
Roadway departure	0.9509*	0.0283*	90% CI	0.9054*	0.9986*

*Statistically significant at 90-percent confidence level.
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 slopes. The contrast evaluation is represented in 10 sites with 1V:4H or 1V:5H side slopes and 3 sites with 1V:3H side slopes.

Finally, table 8 indicates a statistically significant reduction in roadway-departure crashes on a slightly redefined base condition.

Table 8. 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	90% CI	0.9422	1.0168
Fatal and injury	0.7443	0.1927	90% CI	0.495	1.1193
Roadway departure	0.8699*	0.0715*	90% CI	0.7601*	0.9955*

*Statistically significant at 90-percent confidence level.
CI = confidence interval; SE = standard error.
Note: The base condition is slope toe at least 5 ft from paved shoulder, less than utility 20 poles per mile, lateral offsets between 10 and 20 ft, and either 1V:2H or 1V:3H side slopes. 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 slopes.

Economic Effectiveness

The research team estimated that the benefit of using guardrails to protect utility poles has a B/C ratio of 1.28 or 1.48, depending on how far the pole is from the paved shoulder. For the economic-effectiveness estimation of utility pole removal, the research team estimated a B/C ratio of 1.41 if new right-of-way (ROW) is acquired and 17.1 otherwise (assuming the pole is removed or relocated beyond 50 ft of the paved shoulder). When assuming the utility pole is relocated beyond 20 ft from the paved shoulder, the B/C ratio was estimated as 0.56 if new ROW is acquired and 6.73 otherwise. The B/C ratio was estimated as 0.21 for flattening slopes of 1V:4H or 1V:5H to 1V:6H or flatter and 0.13 for side-slope reduction from 1V:2H or 1V:3H to 1V:4H or 1V:5H.

CONCLUSIONS

This document summarizes the data and steps taken to estimate roadway-departure CMFs from the two-State database. The analysis developed statistical models for crash risk at the study sites using roadside conditions as well as other influential covariates as explanatory variables. The produced CMFs are representative of both States in the database (Indiana and Pennsylvania), generally indicating the following:

- Statistically significant reductions in fatal-and-injury crashes occur when protecting roadside utility poles with guardrails (CMF of 0.524 for fatal-and-injury crashes when protecting poles within 20 ft of the pavement edge).
- Removing or relocating utility poles farther back from the travel lanes was statistically significantly associated with reductions in total and fatal-and-injury crashes (CMF of 0.6555 for fatal-and-injury crashes when removing poles).
- The safety effectiveness of flattening side slopes generally indicates statistically significant reductions in roadway-departure crashes with no evidence of changes in total and fatal-and-injury crashes (CMF of 0.936 for total crashes and 0.822 for roadway-departure crashes when flattening side slopes from 1V:4H or 1V:5H to 1V:6H or flatter and CMF of 0.951 for roadway-departure crashes when flattening side slopes from 1V:3H to 1V:4H or 1V:5H and 0.8699 for flattening side slopes from 1V:2H or 1V:3H to 1V:4H or 1V:5H).

The economic evaluation of guardrails indicated economic viability 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). The economic evaluation of utility pole removal or relocation indicated that this strategy is economically viable when removing roadside 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). 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 ratio values. Flattening the side slope may be economically viable in locations where AADTs tend to be higher and roadway-departure crashes are more prominent.

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Distribution—This TechBrief is being distributed according to a standard distribution. Direct distribution is being made to FHWA division offices and the Resource Center.

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Key Words—Crash modification factor, CMF, roadside, guardrails, poles, side slopes, safety.

AUGUST 2021

Recommended citation: Federal Highway Administration, *Developing Crash Modification Factors for Guardrails, Utility Poles, and Side-Slope Improvements* (Washington, DC: 2021) https://doi.org/10.21949/1521663

FHWA-HRT-21-076
HRDS-20/08-21(300)E