Safety Effects of Horizontal Curve and Grade Combinations on Rural Two-Lane Roads

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by

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ABSTRACT

The safety effects of horizontal curves and grades on highways have been quantified separately, but it is not currently known whether and how the safety performance of horizontal curves and that of grades interact.

While the first edition of the AASHTO *Highway Safety Manual* (HSM) provides crash modification factors (CMFs) for the safety effects of horizontal curvature and percent grade on rural two-lane highways, it does not have any method for accounting for the interactions between these effects. In other words, in the HSM procedures for rural two-lane highways, the safety effect of a horizontal curve is the same whether it is located on a level roadway, a straight grade, or a vertical curve. Similarly, the safety effect of a straight grade is the same whether it is located on a tangent roadway or on a horizontal curve. Researchers have always supposed that there are interactions between the safety effects of horizontal and vertical alignment, but this has not been demonstrated in a form useful for safety prediction.

This paper summarizes the results of research undertaken to quantify the safety effects of five types of horizontal and vertical alignment combinations based on Washington Highway Safety Information System (HSIS) data and crash records from 2003 to 2008. The outcome is a set of safety prediction models for fatal-and-injury and property-damage-only (PDO) crashes. To present the results in a form suitable for incorporation in the AASHTO *Highway Safety Manual*, crash modification factors representing safety performance relative to level tangents were developed from these models for each of the five combinations.

INTRODUCTION

The safety effects of horizontal curves and grades on highways have been quantified separately, but it is not currently known whether and how the safety performance of horizontal curves and grades interact. Furthermore, there are established safety effects for crest and sag vertical curves and it is not known whether and how the safety performance of crest and sag vertical curves interacts with any horizontal curves that may be present.

Design criteria for horizontal and vertical alignment are presented in Chapter 3 of the AASHTO *Policy on Geometric Design of Highways and Streets*, commonly known as the *Green Book*. (*1*) Many state highway agencies have their own design manuals, but in the areas of horizontal and vertical alignment state manuals tend to closely resemble the AASHTO *Green Book*.

The key design criteria for horizontal curves include:

- Radius of curvature;
- Length of curve;
- Superelevation; and
- Transition design.

Straight road sections with no horizontal curvature are generally referred to as tangents, because such straight road sections are generally tangent to any horizontal curves that they adjoin.

The fundamental design criterion for vertical alignment is the percent grade. A road section with constant percent grade, regardless of its horizontal alignment, is generally referred to as a straight grade. Where the grade of the roadway changes, the straight grade sections are normally joined by a parabolic vertical curve. Figure 1 illustrates the four types of vertical curves—two types of crest vertical curves and two types of sag vertical curves—that are used in highway design. Key design criteria for vertical curves include:

- Algebraic difference in grade (A in Figure 1);
- Length of curve (L_{VC} in Figure 1); and
- Alternatively, ratio of algebraic difference in grade and length of curve, ($K=A/L_{VC}$),

which represents the sharpness of the vertical curve.

The assessment of the literature conducted by Harwood et al., (2) as part of the development of the FHWA Interactive Highway Safety Design Model (IHSDM), (*3*) concluded that the model developed by Zegeer et al. was the most useful and accurate model to account for the safety effect of horizontal curves on rural two-lane highways. (*4,5*) Harwood et al. expressed the Zegeer et al. model as a crash modification factor (CMF) in the following form:

$$CMF_{HC} = \frac{1.55L_C + \frac{80.2}{R} - 0.012S}{1.55L_C} \quad \textbf{(1)}$$

where:

CMF_{HC} = crash modification factor for horizontal curvature on a rural two-lane highway

L_C = Length of curve (mi)

R = Radius of curvature (ft)

S = Presence of spiral transition where S=0 if no spirals exist and S=1 if spirals do exist

The base condition for this CMF is a tangent roadway. The first edition of the AASHTO *Highway Safety Manual* (*6*) adopted the CMF shown in Equation (1) to represent the safety effects of horizontal curvature on rural two-lane highways.

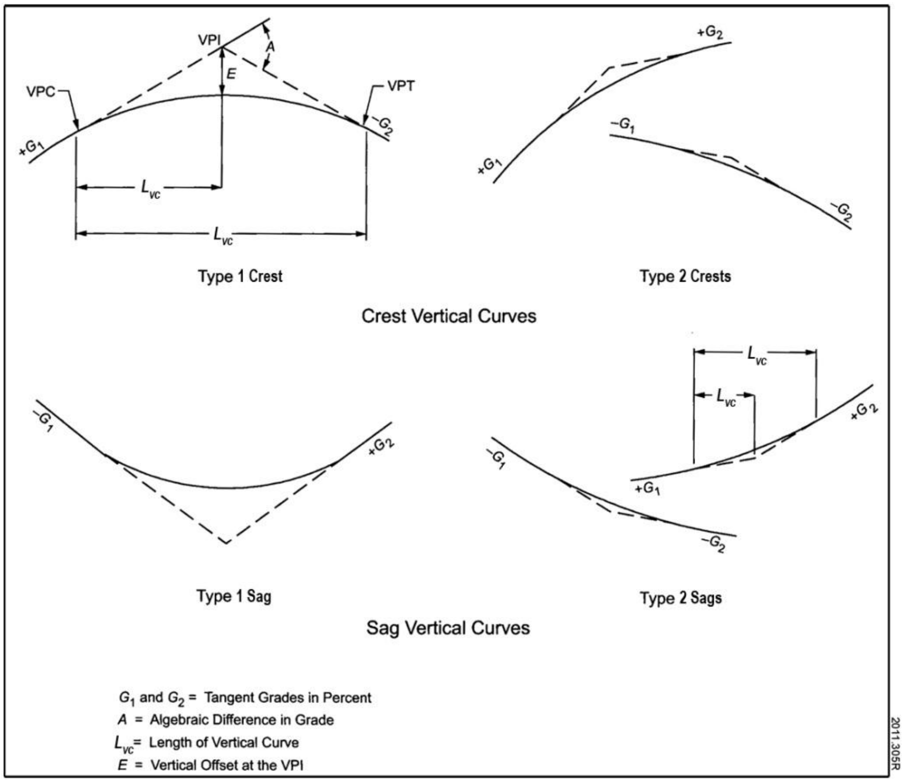

FIGURE 1 Types of vertical curves. (*1*)

The AASHTO *Highway Safety Manual* (HSM) also includes a CMF for the safety effect of superelevation for horizontal curves of rural two-lane highways in the following form:

$$CMF_{SV} = 1.00 \; for \; SV < 0.01 \quad \textbf{(2)}$$

$$CMF_{SV} = 1.00 + 6(SV - 0.01) \; for \; 0.01 \leq SV < 0.02 \quad \textbf{(3)}$$

$$CMF_{SV} = 1.06 + 3(SV - 0.02) \; for \; SV \geq 0.02 \quad \textbf{(4)}$$

where: CMF_{SV} = crash modification factor for superelevation variance on a rural two-lane highway

SV = superelevation variance (ft/ft), which represents the design superelevation rate presented in the AASHTO *Green Book* minus the actual superelevation of the curve

This CMF was also adapted by Harwood et al. (*2*) from the work of Zegeer et al. (*4,5*) The base condition for this CMF is a horizontal curve with superelevation within 0.01 ft/ft of the applicable design superelevation presented in the AASHTO *Green Book*.

No CMFs for horizontal curvature on rural multilane undivided highways, rural multilane divided highways, or urban and suburban arterials are included in the first edition of the HSM.

The first edition of the HSM presents a CMF representing the safety effect of percent grade on rural two-lane highways shown in Table 1.

TABLE 1 Crash Modification Factors (CMF_{5r}) for Grade of Roadway Segments (*6*)

Approximate grade (%)		
Level grade (≤ 3%)	Moderate terrain (3% < grade ≤ 6%)	Steep terrain (> 6%)
1.00	1.10	1.16

This CMF is based on research by Miaou. (*7*) The base condition for this CMF is a level roadway.

The following equation represents the underlying functional form for the CMF shown in Table 1:

$$CMF_G = 1.016^{|G|} \quad \textbf{(5)}$$

where: CMF_G = crash modification factor for percent grade on a rural two-lane highway
$|G|$ = absolute value of percent grade

The CMF in this form, as a continuous function, is a more useful representation of the safety effect of percent grade than the form shown in Table 1, as the stepwise function represented in Table 1 may be misleading.

The CMF for percent grade shown in Table 1 and Equation (5) applies only to straight grades. There are no CMFs in the HSM for crest or sag vertical curves on rural two-lane highways. And, there are no vertical alignment CMFs in the HSM for facility types other than rural two-lane highways.

While the first edition of the HSM provides CMFs for the safety effects of horizontal curvature and percent grade on rural two-lane highways, it does not have any method for accounting for the interactions between these effects. In other words, in the HSM procedures for rural two-lane highways, the safety effect of a horizontal curve is the same whether it is located on a level roadway, a straight grade, or a vertical curve. Similarly, the safety effect of a straight grade is the same whether it is located on a tangent roadway or on a horizontal curve. We have always supposed that there are interactions between the safety effects of horizontal and vertical alignment, but this has not been demonstrated in a form useful for safety prediction. Recent papers by Easa and You (*8*) and You and Easa (*9*) have partially addressed this issue with separate models for horizontal curves and horizontal tangents, but they did not tie their models back to a common base condition (such as a level, tangent roadway) or express the modeling results in a form that could be considered as a CMF.

OBJECTIVE

The objective of this research is to quantify the safety effects of horizontal and vertical alignment combinations and to present the results in a form suitable for incorporation in the AASHTO *Highway Safety Manual* (HSM). (*6*)

The scope of the work initially included horizontal and vertical alignment for the four facility types whose safety performance is addressed in the first edition of the HSM:

- Rural two-lane highways;
- Rural multilane undivided highways;
- Rural multilane divided highways; and
- Urban and suburban arterials.

The research found that only rural two-lane highways had sufficient data for which modeling efforts appeared promising. Therefore, the research efforts were focused on rural two-lane highways.

DATABASE DESCRIPTION

The research was performed with the Highway Safety Information System (HSIS) data for state highways in Washington. This is the only data source of which the authors were aware that includes systemwide data on curve and grade geometry that can be linked to systemwide roadway characteristics, traffic volume, and crash data.

Database Development

The research began with a review of available databases that contained roadway data (including horizontal and vertical alignment), traffic volume data, and crash data, in a format that could be linked together by location, with the primary focus on available HSIS data. The only data set found with sufficient detail concerning horizontal and vertical alignment were the HSIS data for state highways in Washington.

Roadway segments with atypical features such as passing and climbing lanes were eliminated from consideration. Roadway segments with transitions between grades identified as angle points were eliminated from consideration; angle points most likely represent crest or sag vertical curves that were too short or not well enough defined to be measured properly. Finally, a limited set of roadways with obvious data problems, such as successive vertical curves whose lengths appeared to overlap, were also eliminated from consideration.

Next, each roadway segment was classified into categories by its horizontal and vertical alignment. Horizontal alignment was classified as:

- Tangent roadways; and
- Roadways on horizontal curves.

Vertical alignment was classified as:

- Level roadways;
- Straight grades (constant percent grade of 1 percent or more);
- Type 1 crest vertical curves;
- Type 2 crest vertical curves;
- Type 1 sag vertical curves; and
- Type 2 sag vertical curves.

Figure 1 illustrates the distinction between crest and sag vertical curves of Types 1 and 2. Every roadway segment was defined by its horizontal alignment, vertical alignment, and combination of horizontal and vertical alignment. Where horizontal and vertical curves overlap, their beginnings and ends may not coincide; therefore, a new roadway segment was begun at any point where the horizontal or vertical alignment changed. Thus, some segments might include all of a horizontal or vertical curve, while others might include only part of a horizontal or vertical curve. The length of every roadway segment (L) was determined for use in the analysis, as well as the length of any horizontal curve (L_C) that was wholly or partially within the segment and the length of any vertical curve (L_{VC}) that was wholly or partially within the segment. Additionally, each horizontal curve was characterized by its radius (R). No data on the superelevation of horizontal curves were available for analysis. Each straight grade was characterized by its percent grade (G). Each vertical curve was characterized by its approach grade (G_1) and departure grade (G_2), its algebraic difference in grade [$A = |G_1 - G_2|$], and the ratio of its length to its algebraic difference in grade ($K = L_{VC}/A$).

Crash data for a 6-year period (2003 to 2008) were obtained and used in the analysis. Each crash was assigned to a particular roadway segment, with particular horizontal and vertical alignment, based on its assigned milepost location. Since the results of this research are intended for use in the roadway segment procedures of the HSM, only nonintersection crashes were considered. Nonintersection crashes are those that did not occur at an intersection and were not classified by the investigating officer or data coder as related to the operation of an intersection. The traffic volume for each roadway segment was determined from available traffic volume data.

Descriptive Statistics

Of the 3,970 mi of roadway in the Washington HSIS database, 3,457 mi (87 percent) are on rural two-lane highways. Roadway length (miles), exposure (million vehicles of miles traveled in the 6-year period [MVMT]), fatal-and-injury and property-damage-only (PDO) crash frequencies, and crash rates per MVMT are shown in Table 2 for specific horizontal and vertical alignment for rural two-lane highways.

TABLE 2 Roadway Length, Exposure, Crash Frequency, and Crash Rates for Rural Two-Lane Highways in Washington HSIS Database

				Crash frequency[a]		Crash rate per MVMT	
Type of alignment	Roadway alignment	Roadway length (mi)	Exposure (MVMT)[a]	Fatal and Injury	PDO	Fatal and Injury	PDO
Horizontal	Tangent	2,472.1	16,675.2	7,360	10,519	0.441	0.631
	Curve	985.0	6,194.2	3,659	4,758	0.591	0.768
	Total	3,457.1	22,869.5	11,019	15,277	NA	NA
Vertical	Straight grade	2,260.7	14,847.0	7,347	10,222	0.495	0.688
	Type 1 Crest	364.5	2,616.4	1,168	1,498	0.446	0.573
	Type 2 Crest	300.8	1,870.5	826	1,264	0.442	0.676
	Type 1 Sag	252.1	1,772.6	896	1,154	0.505	0.651
	Type 2 Sag	279.1	1,762.9	782	1,139	0.444	0.646
	Total	3,457.1	22,869.5	11,019	15,277	NA	NA

[a] For years 2003 to 2008

Value Range of Roadway Characteristics

Prior to statistical modeling, the variables of interest were assessed for extreme values (both high and low); this was done using a combination of plots of crash rates per MVMT versus selected variables and distributions of the individual variables. The following rules were implemented:

- Roadway segments less than 0.01 mi in length were excluded from analysis;
- For Type 1 crest and Type 1 sag vertical curves and tangents, segments where both initial (G1) and final (G2) grades were, in absolute value, less than 1 percent were excluded;
- For Type 2 crest and Type 2 sag vertical curves and tangents, segments where A [= |G1 – G2|] was less than 1 percent were excluded;
- All records with K exceeding 1,000 were excluded (these are typically long vertical curves with small grade changes and could be classified as straight grades);
- All records with a curve radius exceeding 11,460 ft were excluded (these could be classified as tangents for all practical purposes); and
- Horizontal curves with a radius less than 100 ft were included in the analysis but the radius was set at 100 ft.

STATISTICAL ANALYSIS

The overall statistical approach to estimating the safety effects of horizontal curve and grade combinations on rural two-lane highways is presented along with the results for each type of combination, separately for fatal-and-injury and PDO crashes. Additional details can be found in Bauer and Harwood (2012). (*10*)

Analysis Approach

The safety effects of horizontal curve and grade combinations were estimated based on a cross-sectional analysis using a generalized linear model (GLM) approach with a negative binomial distribution and a log link using the combined crash data from all 6 years and selected roadway geometrics. Fatal-and-injury and PDO crashes were modeled separately and for each type of horizontal curve and grade combination.

The variables considered in each model include, depending on the particular combination:

- AADT (averaged across all 6 years);
- Segment length;
- Horizontal curve radius;
- Absolute value of percent grade;
- Horizontal curve length;
- Vertical curve length;
- A, the algebraic difference between the initial and final grades;
- K, a measure of the sharpness of vertical curvature; and
- Relevant interactions of selected variables.

To explore the functional form of the relationship between crash frequency and horizontal curve and grade variables, the variables were categorized into three groups (typically of equal size, i.e., number of segments). A crash prediction model was developed including AADT and only the interaction of all categorized variables (this is a standard analysis of variance [ANOVA] using a negative binomial distribution and a log link). The safety effect of one variable was then plotted against the cell means of another variable, encoding the data by the levels of the third variable; if a four-way interaction was included, then multiple sets of plots were generated. From these plots, the shape of the relationship between safety effects and a given variable across the levels of another variable was assessed. These trends were assessed for each model to determine whether they were consistent; if not, an assessment was made to determine whether interactions exist. Based on the visual assessment of these relationships, a final model form was selected using all variables and relevant interactions. The variables in these final model forms were continuous variables.

Final crash prediction models were derived for horizontal curves and tangents using the same group of level tangent sections as base condition for all five horizontal curve and grade combinations. A stepwise approach was used where first all variables and interactions were included and the least significant interaction(s) and then the least significant variable(s) were eliminated, one at a time, until all remaining interactions and variables were significant. This is known as backwards stepwise selection. At each step, extreme data points were excluded from the data using leverage estimates, residuals, or Cook's D criterion, all statistical criteria to evaluate the goodness-of-fit of the model to the data. In general, a 5-percent significance level associated with the Type 3 χ^2-statistic was selected. All analyses were performed using PROC GENMOD of SAS Version 9.3. (*11*)

Additional geometric features for roadway segments, such as lane and shoulder widths, were not included in the analysis. The decision to exclude other geometric features was made because (a) they were outside the scope of the current research; (b) experience with the Zegeer et al. results (*2,4,5*) found that the roadway width term dropped out of the final CMF; and (c) it was unlikely that the available data would support inclusion of additional terms.

The next sections present the final modeling results for the five alignment categories for rural two-way highways, including basic description of the database used, final predictive regression equations, and ANOVA tables.

Models for Horizontal Curves and Tangents on Straight Grades

The following three alignment combinations were included in this analysis:

- Horizontal curves on straight grades (including both level and nonlevel alignments);
- Tangents on nonlevel grades (grade ≥ 1 percent); and
- Base condition: level tangents (grade < 1 percent).

Basic descriptive statistics for the roadway segments used are shown in Table 3. The final crash prediction models for fatal-and-injury and PDO crashes are:

$$N_{FI\ or\ PDO} = \exp\left[b_0 + b_1 \ln(AADT) + b_2 G + b_3 \ln\left(2 \times \frac{5730}{R}\right) \times I_{HC} + b_4 \left(\frac{1}{R}\right)\left(\frac{1}{L_C}\right) \times I_{HC}\right] \quad \textbf{(6)}$$

where:

	N_{FI}	=	fatal-and-injury crashes/mi/yr
	N_{PDO}	=	PDO crashes/mi/yr
	AADT	=	veh/day
	G	=	absolute value of percent grade; 0 percent for level tangents; ≥ 1 percent otherwise
	R	=	curve radius (ft); missing for tangents
	I_{HC}	=	horizontal curve indicator: 1 for horizontal curves; 0 otherwise
	L_C	=	horizontal curve length (mi); not applicable for tangents

ln	=	natural logarithm function
$b_0,\ldots,b_4$	=	regression coefficients

TABLE 3 Descriptive Statistics for Horizontal Curves and Tangents on Straight Grades

Variable	Minimum	Maximum	Mean	Median
Horizontal Curves on Straight Grades (N=8,095) Total Roadway Length=595 mi				
AADT (veh/day)	169	26,088	2,695	1,664
Section length (mi)	0.01	0.75	0.07	0.05
Horizontal curve length (mi)	0.01	1.19	0.15	0.11
Curve radius (ft)	100	11,459	2,067	1,433
Grade (%)	0	9.67	2.11	1.53
FI crashes per MVMT	0	39.50	0.75	0
PDO crashes per MVMT	0	46.26	0.91	0
Total crashes per MVMT	0	54.62	1.66	0
Tangents on Nonlevel Grades (N=7,569) Total Roadway Length=727 mi				
AADT (veh/day)	169	26,088	2,700	1,644
Section length (mi)	0.01	0.99	0.10	0.06
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Grade (%)	1.00	10.85	3.10	2.64
FI crashes per MVMT	0	39.33	0.61	0
PDO crashes per MVMT	0	44.14	0.80	0
Total crashes per MVMT	0	53.48	1.42	0
Level Tangents—Base Condition (N=5,701) Total Roadway Length=779 mi				
AADT (veh/day)	169	26,088	3,285	2,153
Section length (mi)	0.01	0.98	0.14	0.09
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Grade (%)	NA	NA	NA	NA
FI crashes per MVMT	0	34.21	0.46	0
PDO crashes per MVMT	0	39.50	0.67	0
Total crashes per MVMT	0	55.38	1.13	0

The regression results, including the coefficient estimate, standard error, confidence limit, χ^2-statistic, and significance level for all statistically significant parameters and interaction, are shown in Table 4.

TABLE 4 Fatal-and-Injury and PDO Crash Modeling Results for Horizontal Curves and Tangents on Straight Grades

Parameter description	Regression coefficient	Coefficient estimate	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	χ^2 statistic	Significance level
Fatal and Injury Crashes per Mile per Year							
Intercept	b_0	–8.76	0.15	–9.05	–8.46		
ln(AADT)	b_1	1.00	0.02	0.96	1.03	3,052.7	<.0001
Grade	b_2	0.044	0.01	0.03	0.06	27.5	<.0001
1/Radius term[a]	b_3	0.19	0.02	0.16	0.22	116.3	<.0001
1/R × 1/L_c interaction	b_4	4.52	0.79	2.97	6.07	26.8	<.0001
Dispersion		0.85	0.04	0.77	0.94		
PDO Crashes per Mile per Year							
Intercept	b_0	–8.63	0.14	–8.89	–8.36		
ln(AADT)	b_1	1.03	0.02	1.00	1.06	4,003.5	<.0001
Grade	b_2	0.040	0.01	0.03	0.05	29.1	<.0001
1/Radius term[a]	b_3	0.13	0.02	0.10	0.16	67.4	<.0001
1/R × I/L_c interaction	b_4	3.80	0.84	2.15	5.45	17.3	<.0001
Dispersion		0.80	0.03	0.73	0.87		

[a] 1/Radius term = ln(2 × 5730/R).

Models for Horizontal Curves and Tangents at Type 1 Crest Vertical Curves

The following three alignment combinations were included in this analysis:

- Horizontal curves at Type 1 crest vertical curves;
- Tangents at Type 1 crest vertical curves; and
- Base condition: level tangents (grade < 1 percent).

Basic descriptive statistics for the roadway segments used are shown in Table 5. The final crash prediction models for fatal-and-injury and PDO crashes are:

$$N_{FI\ or\ PDO} = \exp\left[b_0 + b_1 \ln(AADT) + \ b_2\left(\frac{5730}{R}\right) A \times I_{VC\times HC}\right] \quad \textbf{(7)}$$

where:
- A = $|G_1 - G_2|$ (percent); not applicable for level tangents [in that case, use Equation (6)]
- G_1 = initial grade (percent) (positive for upgrade; negative for downgrade)
- G_2 = final grade (percent) (positive for upgrade; negative for downgrade)
- $I_{VC\times HC}$ = combined vertical and horizontal curve indicator: 1 for combined vertical and horizontal curves; 0 otherwise

The regression results, including the significant interaction, are shown in Table 6.

TABLE 5 Descriptive Statistics for Horizontal Curves and Tangents at Type 1 Crest Vertical Curves

Variable	Minimum	Maximum	Mean	Median
Horizontal Curves at Type 1 Crest Vertical Curves (N = 1,219) Total Roadway Length = 87 mi				
AADT (veh/day)	175	26,088	3,059	1,877
Section length (mi)	0.01	0.72	0.07	0.06
Horizontal curve length (mi)	0.02	1.00	0.16	0.12
Curve radius (ft)	100	11,459	2,102	1,433
Vertical curve length (ft)	100	4,000	824	600
A	1.0	14.7	5.2	4.9
K	11.1	985.2	186.2	147.9
FI crashes per MVMT	0	23.10	0.55	0
PDO crashes per MVMT	0	28.12	0.66	0
Total crashes per MVMT	0	28.12	1.21	0
Tangents at Type 1 Crest Vertical Curves (N = 2,089) Nonlevel Total Roadway Length = 200 mi				
AADT (veh/day)	169	26,088	3,105	1,858
Section length (mi)	0.01	0.59	0.10	0.08
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Vertical curve length (ft)	60	4,000	776	600
A	1.0	14.7	4.7	4.3
K	5.4	985.2	192.4	151.5
FI crashes per MVMT	0	20.85	0.40	0
PDO crashes per MVMT	0	25.43	0.57	0
Total crashes per MVMT	0	33.85	0.98	0
Level Tangents—Base Condition (N = 5,743) Total Roadway Length = 833 mi				
AADT (veh/day)	169	26,088	3,287	2,160
Section length (mi)	0.01	2.10	0.15	0.09
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Vertical curve length (ft)	NA	NA	NA	NA
A	NA	NA	NA	NA
K	NA	NA	NA	NA
FI crashes per MVMT	0	34.21	0.46	0
PDO crashes per MVMT	0	39.50	0.67	0
Total crashes per MVMT	0	39.50	1.13	0

TABLE 6 Fatal-and-Injury and PDO Crash Modeling Results for Horizontal Curves and Tangents at Type 1 Crest Vertical Curves

Parameter description	Regression coefficient	Coefficient estimate	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	χ^2 statistic	Significance level
Fatal and Injury Crashes per Mile per Year							
Intercept	b_0	–9.56	0.23	–10.01	–9.11		
ln(AADT)	b_1	1.09	0.03	1.04	1.15	1,661.0	< .0001
1/R × A interaction[a]	b_2	0.0088	0.003	0.004	0.014	11.1	0.001
Dispersion		0.70	0.05	0.60	0.81		
PDO Crashes per Mile per Year							
Intercept	b_0	–8.46	0.20	–8.85	–8.08		
ln(AADT)	b_1	1.01	0.02	0.96	1.05	1,858.8	< .0001
1/R × A interaction[a]	b_2	0.0046	0.002	0.001	0.008	6.4	0.011
Dispersion		0.72	0.04	0.64	0.82		

[a] 1/R × A interaction = (5730/R)×A.

Models for Horizontal Curves and Tangents at Type 1 Sag Vertical Curves

The following three alignment combinations were included in this analysis:

- Horizontal curves at Type 1 sag vertical curves;
- Tangents at Type 1 sag vertical curves; and
- Base condition: level tangents (grade < 1 percent).

Basic descriptive statistics for the roadway segments used are shown in Table 7. The final crash prediction models for fatal-and-injury and PDO crashes are:

$$N_{FI\ or\ PDO} = \exp\left[b_0 + b_1 \ln(AADT) + \ b_2 \frac{1}{K} \times I_{VC} \ + b_3 \left(\frac{5730}{R}\right) A \times I_{VC \times HC}\right] \qquad \textbf{(8)}$$

where: K = $\frac{L_{VC}}{A}$; not applicable for level tangents [in that case, use Equation (6)]

L_{VC} = vertical curve length (ft)

I_{VC} = vertical curve indicator: 1 for vertical curves; 0 otherwise

The regression results, including all statistically significant parameters and interaction, are shown in Table 8.

TABLE 7 Descriptive Statistics for Horizontal Curves and Tangents at Type 1 Sag Vertical Curves

Variable	Minimum	Maximum	Mean	Median
Horizontal Curves at Type 1 Sag Vertical Curves (N=982) Total Roadway Length=57 mi				
AADT (veh/day)	169	19,373	3,074	1,821
Section length (mi)	0.01	0.31	0.06	0.05
Horizontal curve length (mi)	0.01	1.00	0.15	0.12
Curve radius (ft)	100	11,459	2,085	1,433
Vertical curve length (ft)	92	2,200	545	500
A	1.0	13.0	4.4	3.8
K	10.4	966.2	153.2	116.4
FI crashes per MVMT	0	36.61	0.71	0
PDO crashes per MVMT	0	21.35	0.81	0
Total crashes per MVMT	0	52.06	1.53	0
Tangents at Type 1 Sag Vertical Curves (N=1,973) Total Roadway Length=145 mi				
AADT (veh/day)	175	26,088	3,098	1,828
Section length (mi)	0.01	0.51	0.07	0.06
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Vertical curve length (ft)	60	2,800	523	400
A	1.0	15.1	4.2	3.6
K	6.8	969.7	153.0	120.2
FI crashes per MVMT	0	46.26	0.48	0
PDO crashes per MVMT	0	40.11	0.65	0
Total crashes per MVMT	0	70.19	1.12	0
Level Tangents—Base Condition (N=5,744) Total Roadway Length=833 mi				
AADT (veh/day)	169	26,088	3,287	2,160
Section length (mi)	0.01	2.10	0.15	0.09
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Vertical curve length (ft)	NA	NA	NA	NA
A	NA	NA	NA	NA
K	NA	NA	NA	NA
FI crashes per MVMT	0	34.21	0.46	0
PDO crashes per MVMT	0	39.50	0.67	0
Total crashes per MVMT	0	55.38	1.14	0

TABLE 8 Fatal-and-Injury and PDO Crash Modeling Results for Horizontal Curves and Tangents at Type 1 Sag Vertical Curves

Parameter Description	Regression coefficient	Coefficient estimate	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	χ^2 statistic	Significance level
Fatal and Injury Crashes per Mile per Year							
Intercept	b_0	–9.55	0.24	–10.02	–9.08		
ln(AADT)	b_1	1.10	0.03	1.04	1.15	1,516.6	< .0001
1/K	b_2	10.51	5.18	0.36	20.66	3.9	0.048
1/R × A interaction[a]	b_3	0.011	0.003	0.005	0.017	12.3	0.0005
Dispersion		0.86	0.06	0.75	0.99		
PDO Crashes per Mile per Year							
Intercept	b_0	–8.63	0.20	–9.03	–8.24		
ln(AADT)	b_1	1.03	0.03	0.98	1.08	1,776.9	< .0001
1/K	b_2	8.62	4.41	–0.02	17.26	3.7	0.055
1/R × A interaction[a]	b_3	0.010	0.002	0.005	0.014	16.7	< .0001
Dispersion		0.79	0.05	0.70	0.89		

[a] 1/R × A interaction = (5730/R)×A.

Models for Horizontal Curves and Tangents at Type 2 Crest Vertical Curves

The following three alignment combinations were included in this analysis:

- Horizontal curves at Type 2 crest vertical curves;
- Tangents at Type 2 crest vertical curves; and
- Base condition: level tangents (grade < 1 percent).

Basic descriptive statistics for the roadway segments used are shown in Table 9. The final crash prediction models for fatal-and-injury and PDO crashes are:

$$N_{FI\ or\ PDO} = \exp\left[b_0 + b_1 \ln(AADT) + b_2 \ln\left(2 \times \frac{5730}{R}\right) \times I_{HC}\right] \qquad \textbf{(9)}$$

The regression results, including all statistically significant parameters, are shown in Table 10. There were no statistically significant interactions for Type 2 crest vertical curves.

TABLE 9 Descriptive Statistics for Horizontal Curves and Tangents at Type 2 Crest Vertical Curves

Variable	Minimum	Maximum	Mean	Median
Horizontal Curves at Type 2 Crest Vertical Curves (N=1,071) Total Roadway Length=62 mi				
AADT (veh/day)	202	20,931	2,603	1,607
Section length (mi)	0.01	0.34	0.06	0.05
Horizontal curve length (mi)	0.01	1.09	0.16	0.12
Curve radius (ft)	100	11,459	1,960	1,433
Vertical curve length (ft)	75	2,400	543	400
A	1.0	8.3	2.8	2.4
K	15.9	952.4	227.0	178.8
FI crashes per MVMT	0	28.16	0.63	0
PDO crashes per MVMT	0	30.02	0.87	0
Total crashes per MVMT	0	30.02	1.50	0
Tangents at Type 2 Crest Vertical Curves (N=1,922) Total Roadway Length=132 mi				
AADT (veh/day)	175	21,825	2,741	1,652
Section length (mi)	0.01	0.38	0.07	0.06
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Vertical curve length (ft)	60	2,400	498	400
A	1.0	8.0	2.6	2.2
K	16.2	985.9	222.4	176.3
FI crashes per MVMT	0	36.12	0.42	0
PDO crashes per MVMT	0	27.05	0.61	0
Total crashes per MVMT	0	36.12	1.03	0
Level Tangents—Base Condition (N=5,742) Total Roadway Length=833 mi				
AADT (veh/day)	169	26,088	3,287	2,160
Section length (mi)	0.01	2.10	0.15	0.09
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Vertical curve length (ft)	NA	NA	NA	NA
A	NA	NA	NA	NA
K	NA	NA	NA	NA
FI crashes per MVMT	0	34.21	0.46	0
PDO crashes per MVMT	0	31.60	0.66	0
Total crashes per MVMT	0	36.34	1.12	0

TABLE 10 Fatal-and-Injury and PDO Crash Modeling Results for Horizontal Curves and Tangents at Type 2 Crest Vertical Curves

Parameter description	Regression coefficient	Coefficient estimate	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	χ^2 statistic	Significance level
Fatal and Injury Crashes per Mile per Year							
Intercept	b_0	–9.52	0.24	–9.99	–9.05		
ln(AADT)	b_1	1.09	0.03	1.03	1.14	1,470.5	< .0001
1/Radius term[a]	b_2	0.20	0.04	0.12	0.28	20.4	< .0001
Dispersion		0.67	0.06	0.57	0.79		
PDO Crashes per Mile per Year							
Intercept	b_0	–8.38	0.20	–8.78	–7.99		
ln(AADT)	b_1	1.00	0.02	0.95	1.05	1,699.0	< .0001
1/Radius term[a]	b_2	0.10	0.04	0.03	0.18	6.6	0.010
Dispersion		0.65	0.05	0.57	0.74		

[a] 1/Radius term = ln(2 × 5730/R).

Models for Horizontal Curves and Tangents at Type 2 Sag Vertical Curves

The following three alignment combinations were included in this analysis:

- Horizontal curves at Type 2 sag vertical curves;
- Tangents at Type 2 sag vertical curves; and
- Base condition: level tangents (grade < 1 percent).

Basic descriptive statistics for the roadway segments used are shown in Table 11. The final crash prediction models for fatal-and-injury and PDO crashes are:

$$N_{FI} = \exp\left[b_0 + b_1 \ln(AADT) + \ b_2 \ln\left(2 \times \frac{5730}{R}\right) \times I_{HC}\right] \quad \textbf{(10)}$$

$$N_{PDO} = \exp\left[b_0 + b_1 \ln(AADT) + \ b_2 \left(\frac{5730}{R}\right) A \times I_{VC \times HC}\right] \quad \textbf{(11)}$$

The regression results, including all statistically significant parameters and interaction, are shown in Table 12.

TABLE 11 Descriptive Statistics for Horizontal Curves and Tangents at Type 2 Sag Vertical Curves

Variable	Minimum	Maximum	Mean	Median
Horizontal Curves at Type 2 Sag Vertical Curves (N=1,217) Total Roadway Length=63 mi				
AADT (veh/day)	175	21,825	2,691	1,742
Section length (mi)	0.01	0.30	0.05	0.04
Horizontal curve length (mi)	0.01	1.09	0.17	0.13
Curve radius (ft)	100	11,459	1,964	1,433
Vertical curve length (ft)	60	1,600	424	400
A	1.0	7.7	2.7	2.5
K	9.7	917.4	185.6	149.3
FI crashes per MVMT	0	26.06	0.60	0
PDO crashes per MVMT	0	27.82	0.95	0
Total crashes per MVMT	0	27.82	1.54	0
Tangents at Type 2 Sag Vertical Curves (N=2,174) Total Roadway Length=129 mi				
AADT (veh/day)	169	23,334	2,909	1,776
Section length (mi)	0.01	0.38	0.06	0.05
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Vertical curve length (ft)	60	2,000	400	400
A	1.0	7.6	2.6	2.2
K	16.2	970.9	184.3	148.1
FI crashes per MVMT	0	27.82	0.44	0
PDO crashes per MVMT	0	28.27	0.61	0
Total crashes per MVMT	0	38.20	1.05	0
Level Tangents—Base Condition (N=5,741) Total Roadway Length=833 mi				
AADT (veh/day)	169	26,088	3,288	2,160
Section length (mi)	0.01	2.10	0.15	0.09
Horizontal curve length (mi)	NA	NA	NA	NA
Curve radius (ft)	NA	NA	NA	NA
Vertical curve length (ft)	NA	NA	NA	NA
A	NA	NA	NA	NA
K	NA	NA	NA	NA
FI crashes per MVMT	0	34.21	0.46	0
PDO crashes per MVMT	0	25.79	0.66	0
Total crashes per MVMT	0	36.34	1.12	0

TABLE 12 Fatal-and-Injury and PDO Crash Modeling Results for Horizontal Curves and Tangents at Type 2 Sag Vertical Curves

Parameter description	Regression coefficient	Coefficient Estimate	Standard error	Lower 95% confidence limit	Upper 95% confidence limit	χ^2 statistic	Significance level
Fatal-and-Injury Crashes per Mile per Year							
Intercept	b_0	–9.42	0.24	–9.90	–8.95		
ln(AADT)	b_1	1.08	0.03	1.02	1.13	1,427.2	< .0001
1/Radius term[a]	b_2	0.188	0.04	0.11	0.27	18.2	< .0001
Dispersion		0.76	0.06	0.65	0.88		
PDO Crashes per Mile per Year							
Intercept	b_0	–8.30	0.20	–8.69	–7.90		
ln(AADT)	b_1	0.99	0.02	0.94	1.03	1,648.2	< .0001
1/R × A interaction[b]	b_2	0.022	0.005	0.013	0.031	20.8	< .0001
Dispersion		0.64	0.05	0.56	0.73		

[a] 1/Radius term = ln(2 × 5730/R).
[b] 1/R × A interaction = (5730/R) × A.

CRASH MODIFICATION FACTORS

Crash modification factors (CMFs) for use in the AASHTO *Highway Safety Manual* (HSM) can be derived from the predictive models in the previous sections. A CMF is a factor that represents the effect on crash frequency, for a given crash severity level, of varying a particular geometric design or traffic control feature of interest (or a particular combination of geometric design or traffic control feature). Each CMF has a nominal value of 1.0 for a specified base condition. A CMF with a value greater than 1.0 represents a condition for which more crashes would be expected for the base condition. A CMF with a value less than 1.0 represents a condition for which fewer crashes would be expected than for the base condition. The base condition for all CMFs developed in this research is a level, tangent roadway.

The CMFs developed here are appropriate for consideration for the next edition of the HSM because they are based on: a substantial dataset; an analysis that considered horizontal and vertical alignment together, rather than separately; an analysis using a generalized linear model approach with a negative binomial distribution; and results that were statistically significant.

For each combination of alignment type (and separately for fatal-and-injury crashes and PDO crashes), CMFs were calculated as the ratio of the predicted crash frequency for a given horizontal curve and grade combination to the predicted crash frequency for the level, tangent base condition. Remember that level tangents are defined as tangent roadways with G < 1 percent. The following sections provide the equations for each CMF in each of the five alignment categories for rural two-way highways.

CMFs Horizontal Curves and Tangents on Straight Grades

The CMFs for horizontal curves and tangents on straight grades can be derived from Equation (6) and the regression coefficients in Table 4 as follows:

$$CMF_{SG,FI} = \begin{cases} \exp\left[0.044\,G + 0.19\,\ln\left(2 \times \frac{5730}{R}\right) + 4.52\left(\frac{1}{R}\right)\left(\frac{1}{L_C}\right)\right] & for\ horizontal\ curves \\ \exp[0.044\,G] & for\ tangents\ on\ nonlevel\ grades \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \mathbf{(12)}$$

$$CMF_{SG,PDO} = \begin{cases} \exp\left[0.040\,G + 0.13\,\ln\left(2 \times \frac{5730}{R}\right) + 3.80\left(\frac{1}{R}\right)\left(\frac{1}{L_C}\right)\right] & for\ horizontal\ curves \\ \exp[0.040\,G] & for\ tangents\ on\ nonlevel\ grades \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \mathbf{(13)}$$

CMFs for Horizontal Curves and Tangents at Type 1 Crest Vertical Curves

The CMFs for horizontal curves and tangents at Type 1 crest vertical curves can be derived from Equation (7) and the regression coefficients in Table 6 as follows:

$$CMF_{C1,FI} = \begin{cases} \exp\left[0.0088\left(\frac{5730}{R}\right)\frac{L_{VC}}{K}\right] & for\ horizontal\ curves \\ 1.0 & for\ tangents\ at\ Type\ 1\ crests \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \mathbf{(14)}$$

$$CMF_{C1,PDO} = \begin{cases} \exp\left[0.0046 \left(\frac{5730}{R}\right) \frac{L_{VC}}{K}\right] & for\ horizontal\ curves \\ 1.0 & for\ tangents\ at\ Type\ 1\ crests \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \textbf{(15)}$$

CMFs for Horizontal Curves and Tangents at Type 1 Sag Vertical Curves

The CMFs for horizontal curves and tangents at Type 1 sag vertical curves can be derived from Equation (8) and the regression coefficients in Table 8 as follows:

$$CMF_{S1,FI} = \begin{cases} \exp\left[10.51\ \frac{1}{K} + 0.011 \left(\frac{5730}{R}\right) \frac{L_{VC}}{K}\right] & for\ horizontal\ curves \\ \exp\left[10.51\ \frac{1}{K}\right] & for\ tangents\ at\ Type\ 1\ sags \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \textbf{(16)}$$

$$CMF_{S1,PDO} = \begin{cases} \exp\left[8.62\ \frac{1}{K} + 0.010 \left(\frac{5730}{R}\right) \frac{L_{VC}}{K}\right] & for\ horizontal\ curves \\ \exp\left[8.62\ \frac{1}{K}\right] & for\ tangents\ at\ Type\ 1\ sags \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \textbf{(17)}$$

To calculate the CMF for fatal-and-injury or PDO crashes for a given horizontal curve at a Type 1 sag vertical curve, one simply substitutes the actual values of the radius, R (ft), vertical curve length (L_{VC}), and parameter K (ft/percent), in Equations (16) or (17).

CMFs for Horizontal Curves and Tangents at Type 2 Crest Vertical Curves

The CMFs for horizontal curves and tangents at Type 2 crest vertical curves can be derived from Equation (9) and the regression coefficients in Table 10 as follows:

$$CMF_{C2,FI} = \begin{cases} \exp\left[0.20\ \ln\left(2 \times \frac{5730}{R}\right)\right] & for\ horizontal\ curves \\ 1.0 & for\ tangents\ at\ Type\ 2\ crests \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \textbf{(18)}$$

$$CMF_{C2,PDO} = \begin{cases} \exp\left[0.10\ \ln\left(2 \times \frac{5730}{R}\right)\right] & for\ horizontal\ curves \\ 1.0 & for\ tangents\ at\ Type\ 2\ crests \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \textbf{(19)}$$

CMFs for Horizontal Curves and Tangents at Type 2 Sag Vertical Curves

The CMFs for horizontal curves and tangents at Type 2 sag vertical curves can be derived from Equations (10) and (11) and the regression coefficients in Table 12 as follows:

$$CMF_{S2,FI} = \begin{cases} \exp\left[0.188\ \ln\left(2 \times \frac{5730}{R}\right)\right] & for\ horizontal\ curves \\ 1.0 & for\ tangents\ at\ Type\ 2\ sags \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \textbf{(20)}$$

$$CMF_{S2,PDO} = \begin{cases} \exp\left[0.022\left(\frac{5730}{R}\right)A\right] & for\ horizontal\ curves \\ 1.0 & for\ tangents\ at\ Type\ 2\ sags \\ 1.0 & for\ level\ tangents\ (base\ condition) \end{cases} \quad \textbf{(21)}$$

CONCLUSIONS

1. For tangents and horizontal curves on straight grades, prediction models for crash frequency by severity level are presented in Equation (6) with parameter estimates presented in Table 4. These models include a main effect for AADT, a main effect for horizontal curve radius, a main effect for percent grade, and an interaction between horizontal curve radius and length of curve. The models indicate that crash frequency increases with decreasing horizontal curve radius, increases with decreasing horizontal curve length, and increases with increasing percent grade. The interaction term shows that short, sharp horizontal curves are associated with higher crash frequencies. CMFs corresponding to the crash prediction models are presented in Equations (12) and (13).
2. For tangents and horizontal curves at Type 1 crest vertical curves, prediction models for crash frequency by severity level are presented in Equation (7) with parameter estimates presented in Table 6. These models include a main effect for AADT and an interaction between horizontal curve radius and the difference between initial and final grade. The models indicate that crash frequency increases with decreasing horizontal curve radius and increases with increasing grade difference. The interaction term shows that short horizontal curves at sharp crest vertical curves are associated with higher crash frequencies. CMFs corresponding to the crash prediction models are presented in Equations (14) and (15).
3. For tangents and horizontal curves at Type 1 sag vertical curves, prediction models for crash frequency by severity level are presented in Equation (8) with parameter estimates presented in Table 8. These models include a main effect for AADT, a main effect for K, and an interaction between horizontal curve radius and the difference between initial and final grade. The models indicate that crash frequency increases with decreasing K and decreasing horizontal curve radius, and increases with increasing grade difference. The interaction term shows that short horizontal curves at sharp sag vertical curves are associated with higher crash frequencies. CMFs corresponding to the crash prediction models are presented in Equations (16) and (17).
4. For tangents and horizontal curves at Type 2 crest vertical curves, prediction models for crash frequency by severity level are presented in Equation (9) with parameter estimates presented in Table 10. These models include only two main effects: a main effect for AADT and a main effect for horizontal curve radius. The models indicate that crash frequency increases

with decreasing horizontal curve radius. CMFs corresponding to the crash prediction models are presented in Equations (18) and (19).

5. For tangents and horizontal curves at Type 2 sag vertical curves, prediction models for crash frequency by severity level are presented in Equations (10) and (11) with parameter estimates presented in Table 12. The fatal-and-injury crash prediction model includes only two main effects: a main effect for AADT and a main effect for horizontal curve radius. This model indicates that fatal-and-injury crash frequency increases with decreasing horizontal curve radius. The PDO crash prediction model includes a main effect for AADT and an interaction between horizontal curve radius and the difference between initial and final grade. The PDO model indicates that crash frequency increases with decreasing horizontal curve radius and increases with increasing grade difference. The interaction term shows that short horizontal curves at sharp sag vertical curves are associated with higher crash frequencies. CMFs corresponding to the crash prediction models are presented in Equations (20) and (21).

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