Transportation Research Center Research Reports

1-31-2015

Statewide Analysis of Guardrails, Curves and Crashes

Brian Lee
University of Vermont, bhylee@uvm.edu

Paola Aizpuru
University of Vermont

Sean Neely
University of Vermont

A Report from the University of Vermont Transportation Research Center

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TRC Report 15-004

June 2016

Lee, Rekalde Aizpuru, Neely

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UVM TRC Report # 15-004

31 January 2015

Prepared by:

Brian H. Y. Lee, Ph.D. (Principal Investigator)
Paola Rekalde Aizpuru
Sean Neely

The UVM Transportation Research Center
Farrell Hall, 210 Colchester Avenue
Burlington, VT 05405

Phone: (802) 656-1312
Website: www.uvm.edu/trc

i. Acknowledgements

This work was funded in part by the Vermont Agency of Transportation (VAOT) through the Research Advisory Council Program (Project Number SPR 736), and the United States Department of Transportation through the University Transportation Center Program at the University of Vermont (UVM) Transportation Research Center (TRC).

The research team would like to thank the Technical Advisory Committee (Amy Gamble, Bill Ahearn, Bruce Nyquist, Evan Brasseur, George Colgrove, Jonathan Croft, Mario Dupigny-Giroux, Wendy Kipp) for their guidance; other VAOT staff members (Jennifer Royer, Mandy White, Mary Spicer, Reid Kiniry, Sarah Kepchar, Susan Clark) for their assistance in our data collection and processing efforts; and other UVM researchers (Donna Rizzo, Kristine Harootunian, Lisa Aultman-Hall, Saghar Sadeghpour) for their technical assistance.

ii. Disclaimer

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1. Introduction

The presence of guardrails and the locations of horizontal and vertical curves, all with respect to crash incidents, are important road safety topics that have been examined separately. Since guardrails and curves, horizontal ones in particular, are often co-located (i.e., many guardrails are placed along curves and many curves have guardrails), it is highly likely that these road features are correlated in space and confound each other's relationship with crashes. Both guardrails and curves may vary in their attributes by location (e.g., guardrails in coverage, size, offset; curves in radii, grades, length) and may relate to crashes in positive and negative ways. Statistical models of crash incidents with a focus on one of these features will, therefore, need to account for the others, while also controlling for many of the same relevant factors (e.g., seasons, times of day, traffic volumes, and other road characteristics). As such, guardrails and curves are examined together with crashes in this statewide study using a single, holistic approach.

The primary goals of this work is to assess the impacts of guardrails, and horizontal and vertical curves on crash incident outcomes in the state of Vermont and to help guide the Vermont Agency of Transportation (VAOT) in developing policies regarding the use and co-locations of these road features.

1.1 Guardrails and Curves

There are many reasons to use guardrails (e.g., protecting motorists from steep drop-offs, separating opposing movements of traffic, guarding roadside structures from vehicles running off the road) but their influences on driving behavior and crash outcomes are not straightforward. On one hand, the existence of guardrails may create a false sense of safety for some drivers and motivate them to drive faster or be less attentive. On the other hand, these barriers may make roadways appear narrower than they actually are and, therefore, act as traffic calming devices that cause drivers to move more slowly and carefully. Studies have shown that the presence or absence of guardrails can affect driver behavior, crash rate, and crash severity (Elvik, 1995), but it is unknown how these impacts interact with horizontal and vertical curves.

Roadway geometries depend on different factors. At the most basic level, the fundamental determinants include topography, physical constraints, right-of-ways, traffic demands, and design speeds. For many roads, particularly in Vermont, horizontal and vertical curves are a necessary component but engineers often do have options in their designs. Curves may vary in length, radius, and grade, and there is a solid literature on the impacts of horizontal and vertical curves on motor vehicle traffic safety. For instance, on highways, the average crash rate for horizontal curves is about three times higher than the average for tangents (Gårder, 2006). The influence of curves on driver behavior, however, may vary depending on the road alignment because it has been shown that drivers pay more attention to road segments with extreme design characteristic values and less to gentler changes in direction (Charlton, 2007). Further, it is unclear what relationships, if any, curve characteristics have with crash incidents when guardrails are also considered.

1.2 **Project Objectives**

This research project focuses on the interactions between guardrails and curves, and their confounding relationships with crash incidents. As such, the goals of this work is to assess the impacts of the presence of guardrails and the locations of horizontal and vertical curves on crash outcomes and to help determine the contexts in which safety interventions may be warranted. Specifically, there are two project objectives:

Objective 1: Provide guidance on the contexts in which the use of guardrails is appropriate. This includes taking into account of the road geometries, the traffic characteristics, road conditions, and other relevant factors.

Objective 2: Determine horizontal and vertical curve characteristics that are correlated with crashes to help identify locations where safety interventions may be warranted. Similar to Objective 1, this would include taking into account of the traffic characteristics, road conditions, and the presence of guardrails.

2. Literature Review

2.1 Crash Rates and Frequencies

Crash incidents are considered rare events. In order to study risk and safety, many researchers have focused on crash rates as the outcome (i.e., dependent) variable in statistical models (Bauer and Harwood, 2013, 2014; Harwood et al., 2000; Khan et al., 2013; C. V. Zegeer et al., 1992). The crash rate can be calculated by dividing the number of crashes in a road segment by the segment length, but it can also be normalized by the traffic volume. For instance, Gibreel et al. (1999) used the number of crashes per million vehicle kilometers travelled as their model output. In some studies, however, the absolute number of crashes (i.e., crash frequencies) has been used as the model outcome variable. Combining the number of crashes with the segment length or the traffic volume in the dependent variable inherently assumes a linear relationship between crash incidents and traffic exposure. Since crashes may not be doubled whenever traffic volume or segment length are doubled, some researchers have argued that the use of “crash per mile” or “crash per volume” as a dependent variable may lead to biased models (Labi, 2006). The need to account for exposure, nevertheless, may outweigh potentials for biased models and justify the use of crash rates.

2.2 Road Characteristics

There is a robust literature on the relationships between various road characteristics and crash incident outcomes. Some analyzed factors include the use of guardrails, horizontal curvature, vertical grade, length of curve, traffic volume, speed limit, and other geometric measures such as lane and shoulder widths.

2.2.1 Guardrails

In a meta-analysis of 32 studies, Elvik (1995) assessed the safety impacts of guardrails as well as median barriers and crash cushions. Guardrails were found to reduce crash rate and crash severity but the impacts on crash rate were less extensively examined than the effects on severity. It was determined that the estimates of the impacts on crash rate are highly uncertain because of methodology shortcomings of the limited studies. On the other hand, it was found that the impacts of guardrails on crash severity are robust. Given that a crash has occurred, Elvik (1995) estimated that guardrails reduce the probability of a fatal injury by approximately 45% and the chance of a non-fatal injury by half.

In a more recent study, Ben-Bassat and Shinar (2011) examined the effect of guardrails as well as shoulder width and horizontal curvature on driver behavior (i.e., speed and lane position) and perception (i.e., perceived speed and estimated road safety) using a driving simulator. Results from twenty-two research subjects revealed the role of guardrails in defining the perceived safety margins of various shoulder width. When a guardrail is absent, the shoulder width loses much of its impact on speed and lane position behavior. This study also showed that horizontal curvature can be used reduce driving speeds but at the expense of maintaining stable lane position in sharper curves. Ben-Bassat and Shinar (2011) concluded that guardrails in combination with should widths are safer interventions for controlling speed and lane positions.

2.2.2 Horizontal Curves, Vertical Grades, and Vertical Curves

Different measures of horizontal and vertical alignment geometries have been tested for statistical relationships with crash outcomes; the statistically significant measures include average radius, ratio of maximum radius to minimum radius, and average rate of vertical curvature (Anderson et al., 1999). Studies have consistently found that crash rates are higher for horizontal curves than tangent sections of similar lengths and traffic compositions, and these rates increase with decreasing curve radius (Anderson et al., 1999; Aram, 2010; Bauer and Harwood, 2013, 2014; Harwood et al., 2000; Labi, 2006; Khan et al., 2013). When other road design characteristics are controlled, shorter curves tend to have higher crash rates (Bauer and Harwood, 2013, 2014). In terms of reducing crashes, increase in horizontal curve radius is most effective on rural minor arterials and lease effective on rural major collectors (Labi, 2006). Further, sharper curves are particularly problematic for trucks (Zegeer et al., 1992) and they have also been found to be less safe for all vehicles on two-lane roads than on freeways, and multilane and urban roads (Khan et al. 2012). As for vertical alignments, many studies have considered straight vertical grades but few have examined vertical curves (i.e., crest and sag curves). In general, studies have found a positive relationship between crash rates and vertical grades (Bauer and Harwood, 2013, 2014; Harwood et al., 2000; Labi, 2006).

Until recently, the safety impacts of horizontal and vertical alignments have been examined separately. In an assessment of the safety performance of rural two-lane highways, Harwood et al. (2000) used crash data from the FHWA Highway Safety Information System (HSIS) for road segments in several states to develop prediction algorithms and crash modification factors. They accounted for the effects on safety of horizontal curves, vertical grades (not curves), plus several other road geometry measures, but presented the outcomes of each feature separately. In their models, Harwood et al. (2000) estimated that the safety performance of flat horizontal curves with large radii to be only marginally worse than a flat tangent road but short sharp curves can have much higher crash rates. As for vertical grades, they found that steeper straight grades can increase crashes by 1.6 percent per 1-percent increase in grade. In a similar study, Labi (2006) examined the safety effects of geometries and other roadway characteristics for rural two-lane roads in Indiana. He found that horizontal curve radius is indirectly related to crashes while vertical grade and crashes have a direct relationship.

In a statewide analysis of crashes and road geometries in Washington state, Bauer and Harwood (2013, 2014) examined the safety performance interactions of five combinations of horizontal and vertical alignments for rural two-lane highways; they include horizontal curves and tangents on straight grades, horizontal curves and tangents at type 1 crest vertical curves, horizontal curves and tangents at type 1 safe vertical curves, horizontal curves and tangents at type 2 crest vertical curves, and horizontal curves and tangents at type 2 safe vertical curves. The results of this work were presented as crash modification factors to represent safety performance of these five combinations relative to level tangents. The various models developed in this study revealed that different factors were related to the safety performance of the different horizontal and vertical curve combinations and confirmed complex interactions between the horizontal and vertical alignments. In general, Bauer and Harwood (2013, 2014) found that crash rates increases with decreasing horizontal curve radius and increasing grade difference.

2.3 Modeling Approach

Due to the high random variability in crash data, spatial correlation analysis is commonly performed in the safety literature (Aguero-Valverde and Jovanis, 2006; Levine et al., 1995; Quddus, 2008). Accounting for spatial relationships enables model improvements and, therefore, more accurate results (Aguero-Valverde and Jovanis, 2010). In addition to spatial analysis, temporal correlation has also been found to have effects in crash analyses. Plug et al. (2011) showed the importance of spatio-temporal interaction effects on vehicle crashes, and their potential to improve road safety. Unfortunately, considerably less research has been dedicated to temporal patterns compared to spatial ones (Plug et al., 2011). Since the current research study is focused on crashes in the State of Vermont where there are distinct seasons, environmental variables (e.g., weather, road surface conditions) may change significantly over the year. Accounting for seasonal differences in crash analyses can potentially increase model accuracy.

In terms of statistical methods, generalized linear models have been found to be more accurate than linear regression analysis for crash prediction (Miaou and Lum, 1993). Conventional linear regression models lack the distributional properties to describe random, discrete, non-negative, and typically sporadic events such as crashes (Anderson et al., 1999; Khan et al., 2013; Miaou and Lum, 1993).

The best results in crash prediction models are typically calculated based on Poisson or negative binomial distributions (Miaou and Lum, 1993). Since the number of crashes in a given space-time region can be considered as random variables with Poisson distributions, the Poisson regression model is an attractive option for modeling crash outcomes. One important restriction for the Poisson distribution is that the mean and variance are equal; this condition, however, does not apply to most crash data where the variance is greater than the mean. For this reason, the negative binomial model has more often been applied for crash prediction models. The negative binomial distribution allows for additional variance representing the effect of omitted variables (Labi, 2006).

3. Data

3.1 Data Collection

Data was collected from various sources for crash incidents, guardrails, horizontal and vertical alignments, cross slopes, signage, traffic volumes, and speed limits. Each dataset was assessed for completeness, accuracy, and usability in this study. Most data was provided in geospatial format for use in a Geographic Information System (GIS). The coordinate system used for all GIS data is the North American Datum of 1983, Vermont State Plane Zone, in meters. The subsections below summarize each dataset with information about its source and format.

3.1.1 Crashes

Crash data was provided by the Vermont Agency of Transportation (VAOT) in Microsoft Excel format for years 2007-2012. The spreadsheet tables were assessed and compared for formatting, number of records, field names, field descriptions, and field completeness. Fields were reformatted for text or number formats where necessary. Coordinate values were cleaned and standardized if they contained extra characters. The crash data included all person records (i.e., one record for each person involved in a crash incident). Each crash incident was identified by a Report Number. The records were aggregated from all person records to driver records only and a unique identifier ("Driver_ID") was assigned.

Crash data tables were imported to a GIS database. Coordinates recorded in "Northing" and "Easting" format (NAD83 State Plane Vermont) were used to create a GIS point feature for each driver record. These point features were clipped to a 500-ft buffer around Vermont road features ("Trans_RDS_line" from the Vermont Center for Geographic Information (VCGI) data center). Driver crash points that fell outside of the state of Vermont were selected; the coordinate values of these points were checked to see if "Northing" and "Easting" had been switched. If so, then the coordinate values were corrected and the revised records were also clipped to the 500-ft buffer around Vermont road features.

All driver crash points from each year (2007-2012) were combined into one GIS dataset. These feature points were then spatially joined to Vermont Towns GIS polygon features ("Boundary_BNDHASH_region_towns" from the VCGI). Points were selected where the town recorded in the crash record was inconsistent with where the point was spatially located. For these records, if the spatial location was within ½ mile of the recorded town, the record was kept. Otherwise, the record was filtered out of the dataset.

Driver crash points were only included if they had a valid value for Linear Reference System (LRS) identifier. Feature points were flagged if they were located on state system routes and not local or interstate roads for inclusion in this study. Of the 53,728 driver records that were included in the raw dataset, 38,372 remained after data cleaning and filtering.

3.1.2 Guardrails

Guardrail data was provided by the VAOT in GIS format. The data was compiled from video logs collected by the VAOT Asset Management Unit. This dataset was one of the best quality datasets available for this study, in terms of the number of features and completeness of the attributes.

3.1.3 Horizontal Alignment

Horizontal alignment data was provided by the VAOT in two versions. Both versions had their drawbacks and discrepancies in terms of the attributes available and data quality. After extensive reviews, the research team coordinated with staff from the VAOT to acquire a third-party dataset from Fugro (an international data vendor) that includes all horizontal alignment features and attributes of interest for all state highways in Vermont.

The Fugro data was delivered, assessed, and redelivered with formatting updates as requested by the VAOT and the research team. The data contained attributes required for analysis in this study, including centerline curvature length and radius.

3.1.4 Vertical Alignment

Vertical alignment data was also provided by the VAOT in two versions. One version was determined to be better suited for this study because of the greater number of features available (n = 160,470) as well as the number and completeness of attributes. This dataset was compiled from data collected by the VAOT Automatic Road Analyzer (ARAN) van. Upon further review, a significant number of overlapping and/or duplicate features were found in the dataset with conflicting values of roadway grade.

The Fugro data also included vertical alignment. This data initially appeared to be more complete than the VAOT dataset but it was not available in plan view with true curvature; it was only available in straight-line segments connected as splines. Despite this limitation, the Fugro dataset was chosen over the VAOT vertical alignment data for use in this study because of the overlapping and duplicate features found in the VAOT dataset.

3.1.5 Cross Slope

The Fugro data included cross slope information, with super-elevation values for roadway segments at about 8-meter increments. While horizontal curvature features from Fugro contain an attribute with the average cross slope value of each curve, this separate cross slope data is more refined and applicable for analysis of the smaller segments that make up each curve.

3.1.6 Signage

Statewide signage data was provided by the VAOT in LRS format. This data was converted to a GIS feature class for analysis. Each sign was coded to indicate alignment and position on roadway relative to vehicle operators. Further, each sign was given a unique identifier for adjacent curves and guardrails, and all sign features relevant to this study were flagged. However, since each sign record is associated with a directionality parameter, it was not possible to relate signs to crash incidents with high confidence due to uncertainties regarding each vehicle's direction of travel. Due to this complication, the sign dataset was not been used for analysis in this study.

3.1.7 Traffic Volumes

Data for the Average Annual Daily Traffic (AADT) was collected from various sources and assessed for use in the study. The Vermont Model Road Network, assembled by the University of Vermont Transportation Research Center for use in the Network Robustness Index, was initially considered. It was later determined that the 2010 AADT dataset prepared by the VAOT and obtained from VCGI was more suitable because of temporal alignment of this data with the crash dataset.

3.1.8 Speed Limits

Speed limit data for the state was provided by the VAOT. The data, however, only covered 30% of the segments within the combined horizontal and vertical curvature dataset. Due to this limited coverage, speed limit was not included in the analysis.

3.2 Data Integration

The crash data (point features) and road geometric data (line features) were received as two different databases. Both sets of data, however, are related in space and their integration is essential for this study. The following subsections describe the steps used to spatially integrate all datasets collected for analysis.

3.2.1 Horizontal Alignment

Horizontal alignment features were each assigned a unique identifier. Crash records were spatially joined in GIS with these features using a buffer of 500 feet (Figure 1); each crash record was associated with the identifier and attribute values from the nearest horizontal segment. This process was followed by verifications based on law enforcement descriptions of alignment features in the crash database. The verification checked for cases where the crash record indicates a curve but no curve feature data is nearby, or vice versa. Crashes that were not successfully verified were flagged. Although the horizontal alignment features include many attributes, the ones of interest for this study are curvature radius and length.

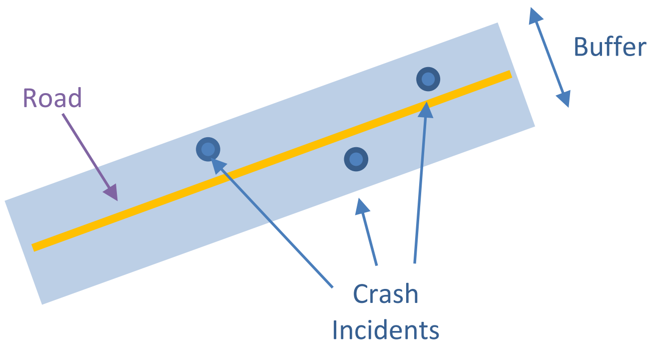

Figure 1 Integration of crash data with alignment data

3.2.2 Vertical Alignment

Vertical alignment features were also each assigned a unique identifier. Similar to above, crash records were spatially joined in GIS with the vertical alignment features using a buffer of 500 feet; each crash record was associated with the identifier and attribute values from the nearest vertical segment. Although the vertical alignment features include many attributes, the one of particular interest for this study is grade.

3.2.3 Guardrails

Guardrail features were each assigned a unique identifier. Each guardrail segment was spatially joined in GIS with the horizontal alignment features using a buffer of 75 feet (Figure 2). The identifier and attributes of each guardrail segment were, therefore, associated with the nearest horizontal alignment feature record(s). Horizontal segments with full guardrail coverage and those with partial guardrail coverage were flagged for analysis.

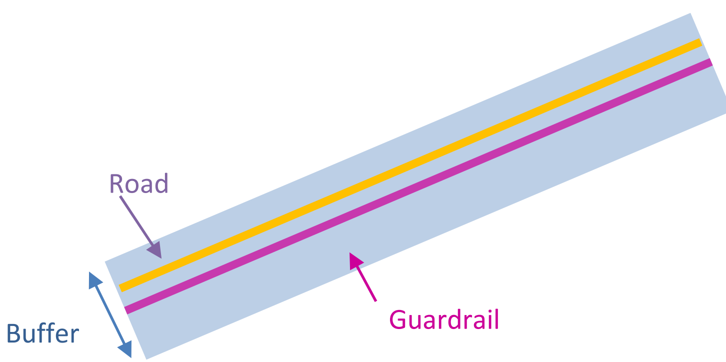

Figure 2 Integration of guardrail data with alignment data

3.2.4 Traffic Volumes

AADT features were each assigned a unique identifier. Similar to the process for the guardrail data above, each AADT segment was spatially joined in GIS with the horizontal alignment features using a buffer of 30 feet. The identifier and attributes of each AADT segment were, therefore, associated with the nearest horizontal alignment feature record(s).

3.3 Data Processing

This section details the development of the basic road segment, defined as a section with both constant horizontal radius and vertical grade throughout, used for analysis in this study. The basic road segment defines the dependent variable in the crash models (i.e., number of crashes per length of segment) and other characteristics of these segments (e.g., presence or absence of guardrails, horizontal and vertical alignments, traffic volume, etc.) are used as the explanatory variables.

3.3.1 Development of the Basic Road Segment for Analysis

Both horizontal and vertical alignment datasets were provided in line feature classes and each of the line features had specific values for each attribute. Each tangent or curve was formed by a line and two nodes, defining two ends of constant line attributes within that length. These nodes, however, were not the same for the horizontal and vertical data.

The horizontal alignment data was segmented based on the vertical alignment nodes. This resulted in smaller segments, where two consecutive segments could share the same horizontal alignment information but were divided by a vertical alignment node (Figure 3). In order to assign vertical grade information to each segment, the midpoint of each segment was assigned to its corresponding vertical grade data using a spatial join of 500-feet buffer in GIS (Figure 3). The resulting segment data contains the following information: the horizontal alignment unique identifier (H_ID), the vertical alignment unique identifier (V_ID), and segment length in feet.

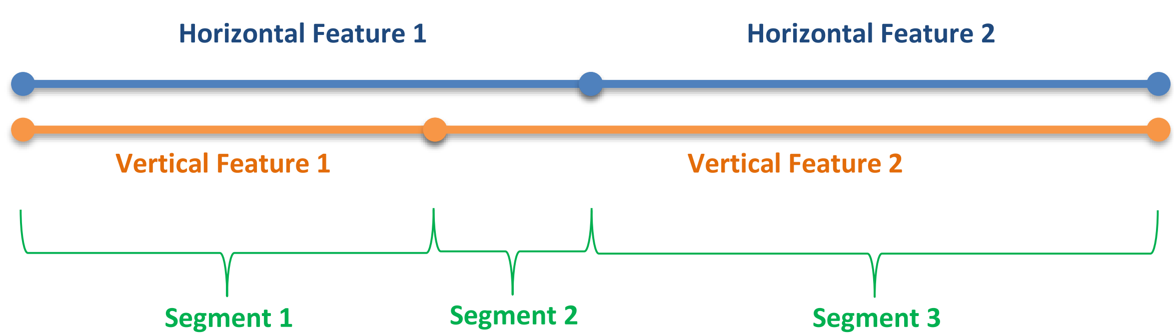

Figure 3 The basic road segment with uniform horizontal and vertical alignment attributes

3.3.2 Geometric Data Simplification

A large variety of horizontal curve radius values are in the dataset. Some of these values are zero, which represent tangents. Since very large radius values also represent negligible change in road direction, they were considered tangents as well. All radius values larger than the 97.5 percentile of the horizontal alignment data were coded as tangent segments. Similarly, all vertical grade change values (A) smaller than 1% were changed to zero and considered flat.

3.3.3 Data Classification

There are different approaches to classify alignment types based on horizontal curvature radii and vertical grade. With respect to the horizontal alignment, a segment can be considered a tangent (i.e., straight) or a curve with a defined radius. Similarly, with respect to the vertical alignment, a segment can be classified as level (i.e., flat), sloped with a straight grade (i.e., constant slope), a crest curve, or a sag curve. The following table (Table 1) shows the classification approach followed in this study.

Table 1 Alignment classification for analysis

Segment Type		**Characteristics**
Horizontal	Tangent	Radius (R) < 100ft; R ≥ 12,778ft
	Curve	100 ≤ R < 12,778ft
Vertical	Level	Approach grade (G_1) = Departure grade (G_2) = 0 (< 1%)
	Non-level	$G_1 = G_2 \geq 1\%$
	Crest Type 1	$G_1 \neq G_2$; G_1 and G_2 have opposite signs; Change in G (A) < 0
	Crest Type 2	$G_1 \neq G_2$; G_1 and G_2 have same signs; Change in G (A) < 0
	Sag Type 1	$G_1 \neq G_2$; G_1 and G_2 have opposite signs; Change in G (A) > 0
	Sag Type 2	$G_1 \neq G_2$; G_1 and G_2 have same signs; Change in G (A) > 0

Cross-classification analyses were performed to verify that sufficient segment and crash incident records were in each combination of horizontal and vertical alignment types. The resulting sample sizes and proportions of the total dataset are shown below in Tables 2 and 3.

Table 2 Summary statistics of road segments by alignment types

Horizontal Alignment	**Vertical Alignment**											
	Straight Grade				**Curve**							
	Level G < 1%		**Non-level G ≥ 1%**		**Crest Type 1**		**Crest Type 2**		**Sag Type 1**		**Sag Type 1**	
	N	**%***	**N**	**%***	**N**	**%***	**N**	**%***	**N**	**%***	**N**	**%***
Tangent	2955	6.82	1232	2.84	3379	7.79	3802	8.77	2892	6.67	3249	7.49
Curve	3935	9.08	1763	4.07	5312	12.3	5571	12.9	4407	10.2	4855	11.2
Total	3890	15.9	2995	6.91	8691	20.0	9373	21.6	7299	16.8	8104	18.7

* % = proportion of total across all horizontal and vertical alignment types

Table 3 Summary statistics of crash incidents per segment by alignment types

Horizontal Alignment	Vertical Alignment											
	Straight Grade				Curve							
	Level G < 1%		Non-level G ≥ 1%		Crest Type 1		Crest Type 2		Sag Type 1		Sag Type 1	
	N	%*	N	%*	N	%*	N	%*	N	%*	N	%*
Tangent	663	8.00	222	2.68	621	7.49	752	9.07	566	6.83	542	6.54
Curve	817	9.86	317	3.83	1003	12.1	1066	12.9	782	9.44	936	11.3
Total	1480	17.9	539	6.51	1624	19.6	1818	21.9	1348	16.3	1478	17.8

* % = proportion of total across all horizontal and vertical alignment types

As shown in Tables 2 and 3, the numbers and proportions of road segments and crash incidents in each combination of horizontal and vertical alignment types are all sufficiently large for statistical analyses. This means that the data classification used is appropriate for the study. As such, five different statistical models will be developed, one for each major combination of horizontal and vertical alignment types with respect to the base condition of tangent segments with straight grades (see Table 4).

Table 4 Base condition and models by combinations of alignment types

<table>
<tr><th rowspan="3">Horizontal Alignment</th><th colspan="6">Vertical Alignment</th></tr>
<tr><th colspan="2">Straight Grade</th><th colspan="4">Curve</th></tr>
<tr><th>Level G < 1%</th><th>Non-level G ≥ 1%</th><th>Type 1 Crest</th><th>Type 1 Sag</th><th>Type 2 Crest</th><th>Type 2 Sag</th></tr>
<tr><td>Tangent</td><td>Base</td><td rowspan="2">Model 1</td><td rowspan="2">Model 2</td><td rowspan="2">Model 3</td><td rowspan="2">Model 4</td><td rowspan="2">Model 5</td></tr>
<tr><td>Curve</td><td>Model 1</td></tr>
</table>

3.3.4 Data Selection

All road characteristic data (guardrails, horizontal alignment, vertical alignment, and traffic volumes) were joined based on their horizontal and vertical identifiers (i.e., H_ID and V_ID). A total of 43,483 road segments were created, each of which had a constant horizontal radius and vertical grade. Of all road segments, 17 had V_ID = 0 because of a lack of vertical curvature information or the distance between the horizontal and vertical alignments was greater than 500ft. Those 17 segments were excluded from analysis. In addition, 133 unique segment IDs were found to be duplicated, having different segment length values for the same H_ID and V_ID. In total, 150 segments were removed from analysis.

The focus of this study is on state highways and the vast majority consists of two-lane roads. There are some cases, especially near urban areas, where the number of lanes increases but the total number of these segments is small. They are, therefore, excluded from the study.

Very short segments likely represent small overlaps in horizontal and vertical features, and are unlikely to be useful analysis sections (Bauer and Harwood, 2013). For this reason, segments less than 0.0125mi (or 66ft) in length were excluded from the analysis. After this step, a total of 4,156 segments (including 150 from the previous step) and 41 crash incidents were excluded.

Crash incident data was joined to road segment data based on both H_ID and V_ID. The final dataset, therefore, includes information about each road segment, the number of crash incidents, and the associated environmental factors recorded in the crash database. The total number of segments analyzed in the study is 39,327.

4. Methodology

4.1 Spatio-Temporal Analysis

Various explanatory variables such as environmental and driver characteristics, as well as roadway geometric attributes (e.g., horizontal and vertical alignment values) were used to study spatio-temporal correlation within the data. The use of semivariograms showed the spatial and temporal correlation in observations of each crash location. The definition of the semivariogram is shown in Equation 1 below; it represents the variance calculation between two points separated in space or time:

$$2\gamma(h) = \frac{1}{n} \sum_{i}^{n} [g_i(x) - g_i(x + h)]^2, \quad (1)$$

where:

h = unit of increase in space/time;
g = value of variable considered; and
n = total number of observations.

As Aguero-Valverde and Jovanis (2010) found, spatial correlation is more important in distances of 1 mile or less. Since the study area of this project is the entire state of Vermont and the majority of the crash incidents are more than one mile away from each other, the spatial analysis results showed that spatial correlation is not significant. However, temporal analysis showed correlation of number of crashes and weather conditions. Two different temporal analyses were developed. One examined the number of crashes per day and the other considered the average weather condition of the crashes per day. The total number of observations analyzed in the semivariogram was the total number of days in each year between 2007 and 2010 that was analyzed (n) and the sample frequency (g) was 7 days.

The temporal analyses were developed for each year separately. A clear pattern could be observed in both cases. The number of crashes and the value for the weather condition follow a clear temporal pattern, as shown with the 2009 example in Figure 4 below. The two distinct periods identified are both six months in length: May through October (i.e., summer) and November through April (i.e., winter).

Similar temporal patterns were found for each year in the 2007-2012 study period, which allowed the six years of data to be analyzed together. The entire dataset was then divided into two groups, summer and winter, and the models were applied to these groups separately.

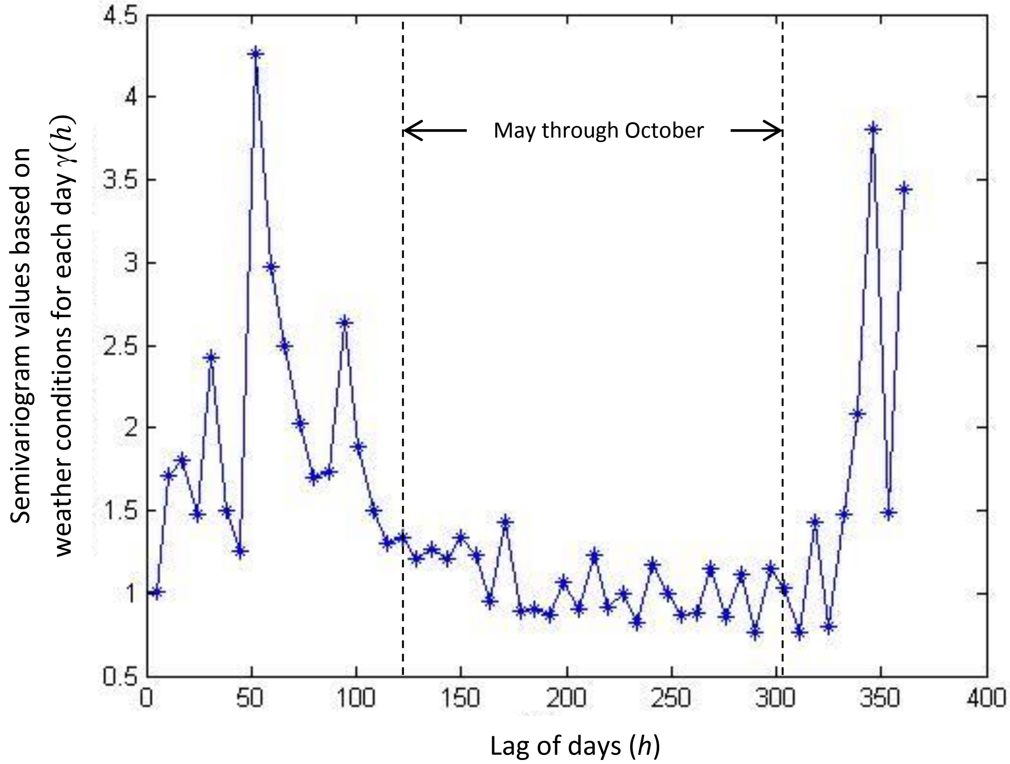

Figure 4 Temporal semivariogram of weather condition data for 2009

4.2 Crash Analysis Model

The negative binomial distribution has been shown to appropriately model dispersed count data such as crash incidents (Bauer and Harwood, 2013, 2014; Khan et al., 2013; Labi, 2006). A generalized linear model approach was chosen for this study, assuming a negative binomial distribution of crash counts and an exponential model using the combined crash data from all six years. As explained above, the summer and winter periods were modeled separately.

Following recent crash modeling studies (Bauer and Harwood, 2013, 2014; Khan et al., 2012, 2013; Labi, 2006), this study identified the outcome variable as the number of crashes per mile per year. In the model development, the effect of each road segment variable – length (L), AADT, curvature radius (R), change in grade (A), ratio of length to the change in grade (K = L/A) – on the number of crashes was examined. Based on visual assessment of these relationships, some variables were transformed or combined, and those that showed relevant interactions were identified. For instance, following the approach taken by Bauer and Harwood (2013), the horizontal curvature radius was recoded as $\ln\left(2\,\frac{6{,}389}{R}\right)$. The minimum value of $\frac{6{,}389}{R}$ for the horizontal curves in the study database is 0.5 (i.e., the maximum value for R is twice 6,389ft). In order for the ratio to become zero as the smallest value, it was multiplied by 2. This term was then set equal to zero for all tangents. Significant explanatory variables were calculated for each of the models.

Before analyzing crashes on horizontal curves, tangents on non-level grades, and level tangents, the effect of vertical alignment characteristics was assessed using tangents alone. This was done by comparing the effects of vertical alignment characteristics on crashes per mile per year between level tangents and tangents on non-level grades for each type of vertical alignment. If a vertical alignment parameter showed a statistically significant effect for tangents on non-level grades, then that parameter was included in the model using all three types of roadway (horizontal curves, tangents on non-level grades, and level tangents).

In addition to applying each model for the summer and winter periods, the model outcomes were also divided by fatal and injury (FI) as well as property damage only (PDO) crash rates.

5. Analysis Results

The safety effects of horizontal curvature and vertical grade combinations are estimated using a cross-sectional analysis and a generalized linear model approach. A negative binomial distribution of crash incidents was assumed and exponential models using the combined crash data from all six years and other associated variables were applied. Fatal and injury (FI) as well as property damage only (PDO) crashes were modeled separately for each of the five combinations of horizontal and vertical alignments. Tangent and level segments (i.e., no horizontal curvature and grade less than 1%) served as the base condition for modelling the alignment combinations. The following subsections detail the summary statistics of the segments in each models as well as the model estimate results.

5.1 Horizontal Curves and Tangents on Non-level Straight Grades (Model 1)

Table 5 below highlights the alignment combinations considered in Model 1.

Table 5 Model 1: Horizontal curves and tangents on non-level straight grades

	Vertical Alignment					
	Straight Grade		Curve			
Horizontal Alignment	Level G < 1%	Non-level G ≥ 1%	Type 1 Crest	Type 1 Sag	Type 2 Crest	Type 2 Sag
Tangent	Base		Model 2	Model 3	Model 4	Model 5
Curve	Model 1					

Basic descriptive statistics such as sample size (i.e., number of roadway segments); total road length; and minimum, maximum, mean, and median values for other variables are shown in Table 6 for this alignment combination.

Table 6 Summary statistics for Model 1: Horizontal curves and tangents on non-level straight grades

Model 1	N = 7,054 segments; Total road length = 498.22mi			
Variable	**Min**	**Max**	**Mean**	**Median**
AADT	0	53900	3627.9	2600
Segment length (mi)	0.0088	0.68	0.071	0.057
Horizontal curve length (L) (mi)	1.74	2376.9	247.8	214.1
Horizontal curve radius (R) (ft)	0	32336.7	2518.2	1513.9
Vertical grade (G) (%)	-15. 5	17.1	0.56	0.44

Equation 2 shows the general form for Model 1. The regression results, including the coefficient estimate, dispersion parameter, standard error, t-value, and significance level for all statistically significant parameters and interactions are shown in the Tables 7 and 8 below.

$$N = \exp\left[\beta_0 + \beta_1 \ln(AADT) + \beta_2 \ln\left(2\frac{6{,}389}{R}\right) + \beta_3 \frac{1}{RL} + \beta_4|G| + \beta_5(FG) + \beta_6(PG)\right], \quad (2)$$

where:

N = crashes per mile per year;

$AADT$ = average annual daily traffic in vehicles per day;

R = horizontal curve in feet (0 for tangents);

L = horizontal curve length in miles;

$|G|$ = absolute value of percent grade (0% for level segments);

FG = full guardrail coverage (1 = yes, 0 = no); and

PG = partial guardrail coverage (1 = yes, 0 = no).

Table 7 Model 1 (FI): Results for fatal and injury crashes on horizontal curves and tangents on non-level straight grades in summer and winter

Parameter Description	Regression Coefficient	Coefficient Estimate	Standard Error	Chi-Squared Statistic	Significance Level
Fatal and injury (FI) crashes/mile/year in SUMMER					
Intercept	β_0	-1.25	0.09	N/A	N/A
ln(AADT)	β_1	0.28	7.0E-03	2536.2	<0.001
R	β_2	0.010	0.001	56.3	<0.001
RL	β_3	0.020	0.001	22.1	<0.001
|G|	β_4	0.0030	0.01	13.5	<0.001
FG	β_5	-0.10	0.03	27.0	<0.001
PG	β_6	-0.14	0.05	42.1	<0.001
Fatal and injury (FI) crashes/mile/year in WINTER					
Intercept	β_0	-3.26	0.13	N/A	N/A
ln(AADT)	β_1	0.84	2.0E-03	2136.2	<0.001
R	β_2	0.020	0.001	43.3	<0.001
RL	β_3	0.12	0.02	19.6	<0.001
|G|	β_4	0.030	0.001	21.4	<0.001
FG	β_5	-0.39	0.06	31.3	<0.001
PG	β_6	-0.050	0.002	45.6	<0.001

Table 8 Model 1 (PDO): Results for property damage only crashes on horizontal curves and tangents on non-level straight grades in summer and winter

Parameter Description	Regression Coefficient	Coefficient Estimate	Standard Error	Chi-Squared Statistic	Significance Level
Property damage only (PDO) crashes/mile/year in SUMMER					
Intercept	β_0	-1.95	0.09	N/A	N/A
ln(AADT)	β_1	0.10	7.0E-04	2013.6	<0.001
R	β_2	0.080	0.001	55.2	<0.001
RL	β_3	0.020	0.001	21.5	<0.001
|G|	β_4	0.050	0.01	19.0	<0.001
FG	β_5	-0.080	0.03	30.0	<0.001
PG	β_6	-0.15	0.05	44.8	<0.001
Property damage only (PDO) crashes/mile/year in WINTER					
Intercept	β_0	-1.58	0.09	N/A	N/A
ln(AADT)	β_1	0.14	7.0E-04	1698.4	<0.001
R	β_2	0.030	0.001	59.0	<0.001
RL	β_3	0.0090	0.001	26.3	<0.001
|G|	β_4	0.0050	0.01	14.5	<0.001
FG	β_5	-0.33	0.03	32.1	<0.001
PG	β_6	-0.090	0.05	43.6	<0.001

5.2 Horizontal Curves and Tangents with Type 1 Crest Vertical Curves (Model 2)

Table 9 below highlights the alignment combinations considered in Model 2.

Table 9 Model 2: Horizontal curves and tangents with type 1 crest vertical curves

<table>
<tr><th rowspan="3">Horizontal Alignment</th><th colspan="6">Vertical Alignment</th></tr>
<tr><th colspan="2">Straight Grade</th><th colspan="4">Curve</th></tr>
<tr><th>Level
G < 1%</th><th>Non-level
G ≥ 1%</th><th>Type 1 Crest</th><th>Type 1 Sag</th><th>Type 2 Crest</th><th>Type 2 Sag</th></tr>
<tr><td>Tangent</td><td>Base</td><td rowspan="2">Model 1</td><td rowspan="2">Model 2</td><td rowspan="2">Model 3</td><td rowspan="2">Model 4</td><td rowspan="2">Model 5</td></tr>
<tr><td>Curve</td><td>Model 1</td></tr>
</table>

Basic descriptive statistics such as sample size (i.e., number of roadway segments); total road length; and minimum, maximum, mean, and median values for other variables are shown in Table 10 for this alignment combination.

Table 10 Summary statistics for Model 2: Horizontal curves and tangents with type 1 crest vertical curves

Model 2	N = 8,702 segments; Total road length = 585.25mi			
Variable	**Min**	**Max**	**Mean**	**Median**
AADT	0	39800	3584.4	2600
Segment length (mi)	0.0088	0.47	0.067	0.055
Horizontal curve length (L) (mi)	2.22	2376.9	254.0	208.7
Horizontal curve radius (R) (ft)	0	32726.6	2174.8	1012.7
Change in grade (A) (%)	-60.1	-0.090	-5.4	-4.9
ratio of length to change in grade (K = L/A)	1.6	3266.2	263.2	104.3

Equation 3 shows the general form for Model 2. The regression results, including the coefficient estimate, dispersion parameter, standard error, t-value, and significance level for all statistically significant parameters and interactions are shown in the Tables 11 and 12 below.

$$N = \exp\left[\beta_0 + \beta_1 \ln(AADT) + \beta_2 \ln\left(2\frac{6{,}389}{R}\right)|A| + \beta_3(FG) + \beta_4(PG)\right], \qquad (3)$$

where:

N = crashes per mile per year;
$AADT$ = average annual daily traffic in vehicles per day;
R = horizontal curve in feet (0 for tangents);
$|A|$ = absolute value of change in grade between approach and departure slopes (%);
FG = full guardrail coverage (1 = yes, 0 = no); and
PG = partial guardrail coverage (1 = yes, 0 = no).

Table 11 Model 2 (FI): Results for fatal and injury crashes on horizontal curves and tangents with type 1 crest vertical curves in summer and winter

Parameter Description	**Regression Coefficient**	**Coefficient Estimate**	**Standard Error**	**Chi-Squared Statistic**	**Significance Level**
Fatal and injury (FI) crashes/mile/year in SUMMER					
Intercept	β_0	-1.98	0.12	N/A	N/A
ln(AADT)	β_1	0.18	5.0E-03	2145.4	<0.001
|A|/R	β_2	0.0030	0.001	11.2	<0.001
FG	β_3	-0.17	0.09	20.1	<0.001
PG	β_4	-0.15	0.06	12.7	<0.001
Fatal and injury (FI) crashes/mile/year in WINTER					
Intercept	β_0	-3.44	0.08	N/A	N/A
ln(AADT)	β_1	0.12	7.0E-03	2351.2	<0.001
|A|/R	β_2	0.0022	0.001	11.0	<0.001
FG	β_3	-0.15	0.02	21.6	<0.001
PG	β_4	-0.14	0.01	11.6	<0.001

Table 12 Model 2 (PDO): Results for property damage only crashes on horizontal curves and tangents with type 1 crest vertical curves in summer and winter

Parameter Description	Regression Coefficient	Coefficient Estimate	Standard Error	Chi-Squared Statistic	Significance Level
Property damage only (PDO) crashes/mile/year in SUMMER					
Intercept	β_0	-2.19	0.09	N/A	N/A
ln(AADT)	β_1	0.165	7.0E-04	1857.0	<0.001
|A|/R	β_2	0.0020	0.001	11.2	<0.001
FG	β_3	-0.39	0.01	22.3	<0.001
PG	β_4	-0.031	0.001	11.1	<0.001
Property damage only (PDO) crashes/mile/year in WINTER					
Intercept	β_0	-1.63	0.09	N/A	N/A
ln(AADT)	β_1	0.15	7.0E-04	1965.5	<0.001
|A|/R	β_2	0.00060	0.001	12.0	<0.001
FG	β_3	-0.51	0.001	20.9	<0.001
PG	β_4	-0.090	0.01	13.2	<0.001

5.3 Horizontal Curves and Tangents with Type 1 Sag Vertical Curves (Model 3)

Table 13 below highlights the alignment combinations considered in Model 3.

Table 13 Model 3: Horizontal curves and tangents with type 1 sag vertical curves

Horizontal Alignment	Vertical Alignment					
	Straight Grade		Curve			
	Level G < 1%	Non-level G ≥ 1%	Type 1 Crest	Type 1 Sag	Type 2 Crest	Type 2 Sag
Tangent	Base	Model 1	Model 2	**Model 3**	Model 4	Model 5
Curve	Model 1					

Basic descriptive statistics such as sample size (i.e., number of roadway segments); total road length; and minimum, maximum, mean, and median values for other variables are shown in Table 14 for this alignment combination.

Table 14 Summary statistics for Model 3: Horizontal curves and tangents with type 1 sag vertical curves

Model 3	N =9,302 segments; Total road length = 614.88mi			
Variable	**Min**	**Max**	**Mean**	**Median**
AADT	0	53900	3581.5	2600
Segment length (mi)	0.0088	0.42	0.066	0.056
Horizontal curve length (L) (mi)	9.54	1994.2	246.4	206.89
Horizontal curve radius (R) (ft)	0	32726.6	2116.7	935.32
Change in grade (A) (%)	0.070	40.4	5.24	4.5
ratio of length to change in grade (K = L/A)	0.070	3270.9	270.6	119.3

Equation 4 shows the general form for Model 3. The regression results, including the coefficient estimate, dispersion parameter, standard error, t-value, and significance level for all statistically significant parameters and interactions are shown in the Tables 15 and 16 below.

$$N = \exp\left[\beta_0 + \beta_1 \ln(AADT) + \beta_2\left(\frac{1}{K}\right) + \beta_3\left(\frac{6{,}389}{R}\right)|A| + \beta_4(FG) + \beta_5(PG)\right], \quad (4)$$

where:

- N = crashes per mile per year;
- $AADT$ = average annual daily traffic in vehicles per day;
- K = ratio of vertical curve length to change in grade (not applicable for straight grades);
- R = horizontal curve in feet (0 for tangents);
- $|A|$ = absolute value of change in grade between approach and departure slopes (%);
- FG = full guardrail coverage (1 = yes, 0 = no); and
- PG = partial guardrail coverage (1 = yes, 0 = no).

Table 15 Model 3 (FI): Results for fatal and injury crashes on horizontal curves and tangents with type 1 sag vertical curves in summer and winter

Parameter Description	**Regression Coefficient**	**Coefficient Estimate**	**Standard Error**	**Chi-Squared Statistic**	**Significance Level**
Fatal and injury (FI) crashes/mile/year in SUMMER					
Intercept	β_0	-1.29	0.07	N/A	N/A
ln(AADT)	β_1	0.61	2.0E-02	2457.8	<0.001
1/K	β_2	24.2	13.2	3.9	<0.001
|A|/R	β_3	0.0033	0.001	10.5	<0.001
FG	β_4	-0.070	0.01	20.7	<0.001
PG	β_5	-0.19	0.05	13.0	<0.001
Fatal and injury (FI) crashes/mile/year in WINTER					
Intercept	β_0	-3.3	0.09	N/A	N/A
ln(AADT)	β_1	0.13	7.0E-03	2189.6	<0.001
1/K	β_2	26.6	12.6	4.5	<0.001
|A|/R	β_3	0.0010	0.0002	13.2	<0.001
FG	β_4	-0.060	0.01	21.4	<0.001
PG	β_5	-0.10	0.03	12.0	<0.001

Table 16 Model 3 (PDO): Results for property damage only crashes on horizontal curves and tangents with type 1 sag vertical curves in summer and winter

Parameter Description	Regression Coefficient	Coefficient Estimate	Standard Error	Chi-Squared Statistic	Significance Level
Property damage only (PDO) crashes/mile/year in SUMMER					
Intercept	β_0	-2.08	0.07	N/A	N/A
ln(AADT)	β_1	0.18	7.0E-04	1854.8	<0.001
1/K	β_2	19.9	7.2	4.2	<0.001
|A|/R	β_3	0.0050	0.001	12.8	<0.001
FG	β_4	-0.011	0.01	22.9	<0.001
PG	β_5	-0.16	0.03	10.7	<0.001
Property damage only (PDO) crashes/mile/year in WINTER					
Intercept	β_0	-1.58	0.09	N/A	N/A
ln(AADT)	β_1	0.153	7.00E-04	1794.3	<0.001
1/K	β_2	15.97	4.56	2.5	<0.001
|A|/R	β_3	0.005	0.001	22.1	<0.001
FG	β_4	-0.19	0.01	13.5	<0.001
PG	β_5	-0.079	0.03	9.9	<0.001

5.4 Horizontal Curves and Tangents with Type 2 Crest Vertical Curves (Model 4)

Table 17 below highlights the alignment combinations considered in Model 4.

Table 17 Model 4: Horizontal curves and tangents with type 2 crest vertical curves

<table>
<tr><th rowspan="3">Horizontal Alignment</th><th colspan="6">Vertical Alignment</th></tr>
<tr><th colspan="2">Straight Grade</th><th colspan="4">Curve</th></tr>
<tr><th>Level
G < 1%</th><th>Non-level
G ≥ 1%</th><th>Type 1 Crest</th><th>Type 1 Sag</th><th>Type 2 Crest</th><th>Type 2 Sag</th></tr>
<tr><td>Tangent</td><td>Base</td><td></td><td rowspan="2">Model 2</td><td rowspan="2">Model 3</td><td rowspan="2">Model 4</td><td rowspan="2">Model 5</td></tr>
<tr><td>Curve</td><td colspan="2">Model 1</td></tr>
</table>

Basic descriptive statistics such as sample size (i.e., number of roadway segments); total road length; and minimum, maximum, mean, and median values for other variables are shown in Table 18 for this alignment combination.

Table 18 Summary statistics for Model 4: Horizontal curves and tangents with type 2 crest vertical curves

Model 4	N =7,101 segments; Total road length = 433.10mi			
Variable	**Min**	**Max**	**Mean**	**Median**
AADT	0	53900	3560.2	2500
Segment length (mi)	0.0088	0.53	0.062	0.050
Horizontal curve length (L) (mi)	1.47	2376.9	252.4	207.1
Horizontal curve radius (R) (ft)	0	32336.7	2132.1	945.9
Change in grade (A) (%)	-13.7	-0.030	-3.33	-2.6
ratio of length to change in grade (K = L/A)	0.070	3275.4	508.3	192.6

Equation 5 shows the general form for Model 4. The regression results, including the coefficient estimate, dispersion parameter, standard error, t-value, and significance level for all statistically significant parameters and interactions are shown in the Tables 19 and 20 below.

$$N = \exp\left[\beta_0 + \beta_1 \ln(AADT) + \beta_2 \ln\left(2\left(\frac{6{,}389}{R}\right)\right) + \beta_3(FG) + \beta_4(PG)\right], \quad (5)$$

where:

N = crashes per mile per year;
$AADT$ = average annual daily traffic in vehicles per day;
R = horizontal curve in feet (0 for tangents);
FG = full guardrail coverage (1 = yes, 0 = no); and
PG = partial guardrail coverage (1 = yes, 0 = no).

Table 19 Model 4 (FI): Results for fatal and injury crashes on horizontal curves and tangents with type 2 crest vertical curves in summer and winter

Parameter Description	**Regression Coefficient**	**Coefficient Estimate**	**Standard Error**	**Chi-Squared Statistic**	**Significance Level**
Fatal and injury (FI) crashes/mile/year in SUMMER					
Intercept	β_0	-1.3	0.08	N/A	N/A
ln(AADT)	β_1	0.53	4.0E-03	2108.9	<0.001
R	β_2	0.11	0.03	55.2	<0.001
FG	β_3	-0.21	0.9	21.2	<0.001
PG	β_4	-0.32	0.12	11.7	<0.001
Fatal and injury (FI) crashes/mile/year in WINTER					
Intercept	β_0	-3.4	0.09	N/A	N/A
ln(AADT)	β_1	0.88	7.0E-03	2065.9	<0.001
R	β_2	0.040	0.001	47.9	<0.001
FG	β_3	-0.47	0.1	22.1	<0.001
PG	β_4	-0.27	0.01	12.2	<0.001

Table 20 Model 4 (PDO): Results for property damage only crashes on horizontal curves and tangents with type 2 crest vertical curves in summer and winter

Parameter Description	Regression Coefficient	Coefficient Estimate	Standard Error	Chi-Squared Statistic	Significance Level
Fatal and injury (FI) crashes/mile/year in SUMMER					
Intercept	β_0	-2.05	0.09	N/A	N/A
ln(AADT)	β_1	0.14	7.0E-04	1424.0	<0.001
R	β_2	0.012	0.001	51.9	<0.001
FG	β_3	-0.69	0.001	19.6	<0.001
PG	β_4	-0.097	0.01	13.0	<0.001
Fatal and injury (FI) crashes/mile/year in WINTER					
Intercept	β_0	-1.74	0.09	N/A	N/A
ln(AADT)	β_1	0.13	7.0E-04	1560.0	<0.001
R	β_2	0.11	0.02	52.0	<0.001
FG	β_3	-0.24	0.06	18.5	<0.001
PG	β_4	-0.11	0.01	12.6	<0.001

5.5 Horizontal Curves and Tangents with Type 2 Sag Vertical Curves (Model 5)

Table 21 below highlights the alignment combinations considered in Model 5.

Table 21 Model 5: Horizontal curves and tangents with type 2 sag vertical curves

	Vertical Alignment					
	Straight Grade		**Curve**			
Horizontal Alignment	**Level G < 1%**	**Non-level G ≥ 1%**	**Type 1 Crest**	**Type 1 Sag**	**Type 2 Crest**	**Type 2 Sag**
Tangent	Base		Model 2	Model 3	Model 4	**Model 5**
Curve	Model 1					

Basic descriptive statistics such as sample size (i.e., number of roadway segments); total road length; and minimum, maximum, mean, and median values for other variables are shown in Table 22 for this alignment combination.

Table 22 Summary statistics for Model 5: Horizontal curves and tangents with type 2 sag vertical curves

Model 5	N =7,890 segments; Total road length = 489.87mi			
Variable	**Min**	**Max**	**Mean**	**Median**
AADT	0	39100	3453.1	2400
Segment length (mi)	0.0088	0.47	0.062	0.049
Horizontal curve length (L) (mi)	1.4	2376.9	249.1	204.4
Horizontal curve radius (R) (ft)	0	32336.7	2076.7	921.2
Change in grade (A) (%)	0.020	14.7	3.32	2.8
ratio of length to change in grade (K = L/A)	0.070	3278.8	477.2	172.8

Equation 6 shows the general form for Model 5. The regression results, including the coefficient estimate, dispersion parameter, standard error, t-value, and significance level for all statistically significant parameters and interactions are shown in the Tables 23 and 24 below.

$$N = \exp\left[\beta_0 + \beta_1 \ln(AADT) + \beta_2 \left(\frac{6{,}389}{R}\right)|A| + \beta_3(FG) + \beta_4(PG)\right], \quad (6)$$

where:

N = crashes per mile per year;
$AADT$ = average annual daily traffic in vehicles per day;
R = horizontal curve in feet (0 for tangents);
$|A|$ = absolute value of change in grade between approach and departure slopes (%);
FG = full guardrail coverage (1 = yes, 0 = no); and
PG = partial guardrail coverage (1 = yes, 0 = no).

Table 23 Model 5 (FI): Results for fatal and injury crashes on horizontal curves and tangents with type 2 sag vertical curves in summer and winter

Parameter Description	**Regression Coefficient**	**Coefficient Estimate**	**Standard Error**	**Chi-Squared Statistic**	**Significance Level**
Fatal and injury (FI) crashes/mile/year in SUMMER					
Intercept	β_0	-1.07	0.05	N/A	N/A
ln(AADT)	β_1	0.083	1.0E-02	1987.0	<0.001
|A|/R	β_2	0.12	0.02	11.3	<0.001
FG	β_3	-0.050	0.001	21.1	<0.001
PG	β_4	-0.12	0.01	12.3	<0.001
Fatal and injury (FI) crashes/mile/year in WINTER					
Intercept	β_0	-3.25		N/A	N/A
ln(AADT)	β_1	0.11	7.0E-04	1998.9	<0.001
|A|/R	β_2	0.060	0.001	9.9	<0.001
FG	β_3	-0.22	0.001	18.3	<0.001
PG	β_4	-0.18	0.01	10.0	<0.001

Table 24 Model 5 (PDO): Results for property damage only crashes on horizontal curves and tangents with type 2 sag vertical curves in summer and winter

Parameter Description	Regression Coefficient	Coefficient Estimate	Standard Error	Chi-Squared Statistic	Significance Level
Property damage only (PDO) crashes/mile/year in SUMMER					
Intercept	β_0	-2.07	0.09	N/A	N/A
ln(AADT)	β_1	0.017	7.0E-04	1546.3	<0.001
|A|/R	β_2	0.020	0.001	10.1	<0.001
FG	β_3	-0.76	0.001	19.8	<0.001
PG	β_4	-0.21	0.01	11.5	<0.001
Property damage only (PDO) crashes/mile/year in WINTER					
Intercept	β_0	-1.76	0.08	N/A	N/A
ln(AADT)	β_1	0.16	7.0E-04	1632.2	<0.001
|A|/R	β_2	0.063	0.001	11.5	<0.001
FG	β_3	-0.16	0.02	22.7	<0.001
PG	β_4	-0.13	0.01	11.4	<0.001

6. Crash Modification Factors

Crash Modification Factors (CMFs) were calculated from the models developed in the previous sections. A CMF in this study represents the impact on crash rates for a given severity level (i.e., fatal and injury or property damage only), a combination of horizontal and vertical alignments, and the presence or absence of guardrails in either the summer or winter period. The CMFs have a nominal value of 1 for the reference base condition. A CMF value of more than 1 indicates a set of conditions in which more crashes are expected than the base condition. On the other hand, a CMF value of less than 1 indicates a set of conditions in which less crashes are expected than the base condition. The following subsections present the CMFs for each combination of horizontal and vertical alignments modeled in this study.

6.1 **Horizontal Curves and Tangents on Non-level Straight Grades (Model 1)**

Tables 25-28 below shows the CMFs for the alignment combinations considered in Model 1. Four horizontal curve lengths (L = 0.01mi, 0.04mi, 0.08mi, 0.12mi), two horizontal curve radii (R = 1,500ft, 5,000ft), and seven grades (G = level, 1%, 2%, 3%, 4%, 5%, 6%) were considered. Note that the base condition is the level tangent segment with no guardrail coverage. Also, note that the CMFs do not vary across the curve lengths examined because the impact of this variable is very small compared to the others.

Table 25 Model 1 (FI): CMFs for fatal and injury crashes on horizontal curves and tangents on non-level straight grades in SUMMER

	Grade (%)	Tangent on non-level grade	Horizontal curve radius, R = 1,500ft				Horizontal curve radius, R = 5,000ft			
			Horizontal curve length (mi)				Horizontal curve length (mi)			
			0.01	**0.04**	**0.08**	**0.12**	**0.01**	**0.01**	**0.01**	**0.01**
NO guardrail	**Level**	1	1.02	1.02	1.02	1.02	1.01	1.01	1.01	1.01
	1	1.00	1.03	1.03	1.03	1.03	1.01	1.01	1.01	1.01
	2	1.01	1.03	1.03	1.03	1.03	1.02	1.02	1.02	1.02
	3	1.01	1.03	1.03	1.03	1.03	1.02	1.02	1.02	1.02
	4	1.01	1.04	1.04	1.04	1.04	1.02	1.02	1.02	1.02
	5	1.02	1.04	1.04	1.04	1.04	1.03	1.03	1.03	1.03
	6	1.02	1.04	1.04	1.04	1.04	1.03	1.03	1.03	1.03
FULL guardrail	**Level**	0.90	0.93	0.93	0.93	0.93	0.91	0.91	0.91	0.91
	1	0.91	0.93	0.93	0.93	0.93	0.92	0.92	0.92	0.92
	2	0.91	0.93	0.93	0.93	0.93	0.92	0.92	0.92	0.92
	3	0.91	0.93	0.93	0.93	0.93	0.92	0.92	0.92	0.92
	4	0.92	0.94	0.94	0.94	0.94	0.92	0.92	0.92	0.92
	5	0.92	0.94	0.94	0.94	0.94	0.93	0.93	0.93	0.93
	6	0.92	0.94	0.94	0.94	0.94	0.93	0.93	0.93	0.93

Table 26 Model 1 (FI): CMFs for fatal and injury crashes on horizontal curves and tangents on non-level straight grades in WINTER

	Grade (%)	Tangent on non-level grade	Horizontal curve radius, R = 1,500ft				Horizontal curve radius, R = 5,000ft			
			Horizontal curve length (mi)				Horizontal curve length (mi)			
			0.01	**0.04**	**0.08**	**0.12**	**0.01**	**0.01**	**0.01**	**0.01**
NO guardrail	**Level**	1	1.05	1.05	1.05	1.05	1.02	1.02	1.02	1.02
	1	1.03	1.08	1.08	1.08	1.08	1.05	1.05	1.05	1.05
	2	1.06	1.12	1.12	1.12	1.12	1.08	1.08	1.08	1.08
	3	1.09	1.15	1.15	1.15	1.15	1.12	1.12	1.12	1.12
	4	1.13	1.19	1.19	1.19	1.19	1.15	1.15	1.15	1.15
	5	1.16	1.22	1.22	1.22	1.22	1.19	1.19	1.19	1.19
	6	1.20	1.26	1.26	1.26	1.26	1.22	1.22	1.22	1.22
FULL guardrail	**Level**	0.68	0.71	0.71	0.71	0.71	0.69	0.69	0.69	0.69
	1	0.70	0.73	0.73	0.73	0.73	0.71	0.71	0.71	0.71
	2	0.72	0.76	0.76	0.76	0.76	0.73	0.73	0.73	0.73
	3	0.74	0.78	0.78	0.78	0.78	0.76	0.76	0.76	0.76
	4	0.76	0.80	0.80	0.80	0.80	0.78	0.78	0.78	0.78
	5	0.79	0.83	0.83	0.83	0.83	0.80	0.80	0.80	0.80
	6	0.81	0.85	0.85	0.85	0.85	0.83	0.83	0.83	0.83

Table 27 Model 1 (PDO): CMFs for property damage only crashes on horizontal curves and tangents on non-level straight grades in SUMMER

	Grade (%)	Tangent on non-level grade	Horizontal curve radius, R = 1,500ft				Horizontal curve radius, R = 5,000ft			
			Horizontal curve length (mi)				Horizontal curve length (mi)			
			0.01	0.04	0.08	0.12	0.01	0.01	0.01	0.01
NO guardrail	Level	1	1.14	1.14	1.14	1.14	1.06	1.06	1.06	1.06
	1	1.09	1.24	1.24	1.24	1.24	1.15	1.15	1.15	1.15
	2	1.18	1.35	1.35	1.35	1.35	1.25	1.25	1.25	1.25
	3	1.29	1.47	1.47	1.47	1.47	1.36	1.36	1.36	1.36
	4	1.40	1.60	1.60	1.60	1.60	1.48	1.48	1.48	1.48
	5	1.52	1.74	1.74	1.74	1.74	1.61	1.61	1.61	1.61
	6	1.66	1.89	1.89	1.89	1.89	1.75	1.75	1.75	1.75
FULL guardrail	Level	0.92	1.00	1.00	1.00	1.00	0.97	0.99	0.98	0.98
	1	1.00	1.05	1.05	1.05	1.05	1.06	1.06	1.06	1.06
	2	1.09	1.07	1.07	1.07	1.07	1.15	1.15	1.15	1.15
	3	1.18	1.14	1.14	1.14	1.14	1.25	1.25	1.25	1.25
	4	1.29	1.22	1.22	1.22	1.22	1.36	1.36	1.36	1.36
	5	1.40	1.06	1.31	1.31	1.31	1.48	1.48	1.48	1.48
	6	1.52	1.72	1.72	1.72	1.72	1.61	1.61	1.61	1.61

Table 28 Model 1 (PDO): CMFs for property damage only crashes on horizontal curves and tangents on non-level straight grades in WINTER

	Grade (%)	Tangent on non-level grade	Horizontal curve radius, R = 1,500ft				Horizontal curve radius, R = 5,000ft			
			Horizontal curve length (mi)				Horizontal curve length (mi)			
			0.01	0.04	0.08	0.12	0.01	0.01	0.01	0.01
NO guardrail	Level	1	1.09	1.09	1.09	1.09	1.03	1.03	1.03	1.03
	1	1.01	1.10	1.10	1.10	1.10	1.05	1.05	1.05	1.05
	2	1.02	1.11	1.11	1.11	1.11	1.06	1.06	1.06	1.06
	3	1.03	1.13	1.12	1.12	1.12	1.07	1.07	1.07	1.07
	4	1.04	1.14	1.14	1.14	1.14	1.08	1.08	1.08	1.08
	5	1.05	1.15	1.15	1.15	1.15	1.09	1.09	1.09	1.09
	6	1.06	1.16	1.16	1.16	1.16	1.11	1.11	1.11	1.11
FULL guardrail	Level	0.70	0.78	0.78	0.78	0.78	0.74	0.74	0.74	0.74
	1	0.72	0.79	0.79	0.79	0.79	0.75	0.75	0.75	0.75
	2	0.73	0.79	0.79	0.79	0.79	0.76	0.76	0.76	0.76
	3	0.74	0.80	0.80	0.80	0.80	0.76	0.76	0.76	0.76
	4	0.74	0.81	0.81	0.81	0.81	0.77	0.77	0.77	0.77
	5	0.75	0.82	0.82	0.82	0.82	0.78	0.78	0.78	0.78
	6	0.76	0.83	0.83	0.83	0.83	0.79	0.79	0.79	0.79

6.2 Horizontal Curves and Tangents with Type 1 Crest Vertical Curves (Model 2)

Tables 29 and 30 below shows the CMFs for the alignment combinations considered in Model 2. Two horizontal curve radii (R = 1,500ft, 5,000ft) and five change in grade between the approach and departure slopes (A = 0%, 5%, 10%, 15%, 20%) were considered. Note that the base condition in this model is where A = 0 with no guardrail coverage.

Table 29 Model 2 (FI): CMFs for fatality and injury crashes on horizontal curves and tangents with type 1 crest vertical curves in SUMMER and WINTER

	Change in grade (A)	SUMMER		WINTER	
		Horizontal curve radius, R = 1,500ft	Horizontal curve radius, R = 5,000ft	Horizontal curve radius, R = 1,500ft	Horizontal curve radius, R = 5,000ft
NO guardrail	0	**1**	**1**	**1**	**1**
	5	1.07	1.02	1.05	1.01
	10	1.14	1.04	1.10	1.03
	15	1.21	1.06	1.15	1.04
	20	1.29	1.08	1.21	1.06
FULL guardrail	0	0.84	0.84	0.86	0.86
	5	0.90	0.94	0.90	0.87
	10	0.96	0.96	0.95	0.89
	15	1.02	0.97	0.99	0.90
	20	1.09	0.99	1.04	0.91

Table 30 Model 2 (PDO): CMFs for property damage only on horizontal curves and tangents with type 1 crest vertical curves in SUMMER and WINTER

	Change in grade (A)	SUMMER		WINTER	
		Horizontal curve radius, R = 1,500ft	Horizontal curve radius, R = 5,000ft	Horizontal curve radius, R = 1,500ft	Horizontal curve radius, R = 5,000ft
NO guardrail	0	**1**	**1**	**1**	**1**
	5	1.04	1.01	1.14	1.04
	10	1.09	1.03	1.29	1.08
	15	1.14	1.04	1.47	1.12
	20	1.19	1.05	1.67	1.17
FULL guardrail	0	0.68	0.68	0.60	0.60
	5	0.71	0.93	0.68	0.62
	10	0.74	0.94	0.78	0.65
	15	0.77	0.96	0.88	0.67
	20	0.80	0.97	1.00	0.70

6.3 Horizontal Curves and Tangents with Type 1 Sag Vertical Curves (Model 3)

Tables 31-34 below shows the CMFs for the alignment combinations considered in Model 3. Six horizontal curve radii (R = 1,000ft, 2,000ft, 3,000ft, 4,000ft, 5,000ft, 13,000ft) and four ratioes of vertical curve length to change in grade (K = 50, 100, 150, 250) were considered. Note that the base condition in this model would be a very large value of K for a tangent but the largest value examined was K = 250.

Table 31 Model 3 (FI): CMFs for fatality and injury crashes on horizontal curves and tangents with type 1 sag vertical curves in SUMMER

	Vertical curve length/change in grade (K)	Tangent with sag curve	Horizontal curve radius (ft)					
			1,000	2,000	3,000	4,000	5,000	13,000
NO guardrail	250	1.11	1.15	1.13	1.12	1.11	1.11	1.11
	150	1.18	1.26	1.22	1.20	1.20	1.19	1.18
	100	1.28	1.42	1.34	1.32	1.31	1.30	1.28
	50	1.65	2.00	1.80	1.74	1.71	1.69	1.65
FULL guardrail	250	1.03	1.07	1.05	1.04	1.04	1.04	1.03
	150	1.10	1.18	1.13	1.12	1.11	1.11	1.10
	100	1.20	1.32	1.25	1.23	1.22	1.21	1.20
	50	1.54	1.87	1.68	1.62	1.59	1.58	1.54

Table 32 Model 3 (FI): CMFs for fatality and injury crashes on horizontal curves and tangents with type 1 sag vertical curves in WINTER

	Vertical curve length/change in grade (K)	Tangent with sag curve	Horizontal curve radius (ft)					
			1,000	2,000	3,000	4,000	5,000	13,000
NO guardrail	250	1.11	1.13	1.12	1.12	1.12	1.11	1.11
	150	1.20	1.22	1.21	1.20	1.20	1.20	1.20
	100	1.31	1.35	1.33	1.32	1.31	1.31	1.31
	50	1.71	1.81	1.76	1.74	1.73	1.72	1.71
FULL guardrail	250	1.05	1.06	1.05	1.05	1.05	1.05	1.05
	150	1.32	1.15	1.14	1.13	1.13	1.13	1.13
	100	1.31	1.27	1.25	1.24	1.24	1.24	1.23
	50	1.71	1.71	1.65	1.64	1.63	1.62	1.61

Table 33 Model 3 (PDO): CMFs for property damage only crashes on horizontal curves and tangents with type 1 sag vertical curves in SUMMER

	Vertical curve length/change in grade (K)	Tangent with sag curve	Horizontal curve radius (ft)					
			1,000	**2,000**	**3,000**	**4,000**	**5,000**	**13,000**
NO guardrail	250	1.09	1.15	1.12	1.11	1.10	1.10	1.09
	150	1.15	1.27	1.20	1.18	1.17	1.17	1.15
	100	1.24	1.43	1.32	1.29	1.27	1.26	1.24
	50	1.53	2.05	1.75	1.66	1.61	1.59	1.53
FULL guardrail	250	0.74	0.78	0.76	0.75	0.74	0.74	0.74
	150	0.78	0.86	0.82	0.80	0.79	0.79	0.78
	100	0.84	0.97	0.89	0.87	0.86	0.85	0.84
	50	1.03	1.39	1.18	1.12	1.09	1.07	1.03

Table 34 Model 3 (PDO): CMFs for property damage only crashes on horizontal curves and tangents with type 1 sag vertical curves in WINTER

	Vertical curve length/change in grade (K)	Tangent with sag curve	Horizontal curve radius (ft)					
			1,000	**2,000**	**3,000**	**4,000**	**5,000**	**13,000**
NO guardrail	250	1.07	1.14	1.10	1.09	1.08	1.08	1.07
	150	1.12	1.24	1.17	1.15	1.14	1.14	1.12
	100	1.19	1.38	1.27	1.24	1.22	1.21	1.19
	50	1.41	1.89	1.61	1.53	1.49	1.47	1.41
FULL guardrail	250	0.64	0.68	0.66	0.65	0.65	0.65	0.64
	150	1.02	0.74	0.70	0.69	0.69	0.68	0.67
	100	1.19	0.83	0.76	0.74	0.73	0.73	0.71
	50	1.41	1.14	0.97	0.92	0.90	0.88	0.85

6.4 Horizontal Curves and Tangents with Type 2 Crest Vertical Curves (Model 4)

Tables 35 and 36 below shows the CMFs for the alignment combinations considered in Model 4. Thirteen horizontal curve radii (R = 100ft, 1,000ft, 2,000ft, 3,000ft, 4,000ft, 5,000ft, 6,000ft, 7,000ft, 8,000ft, 9,000ft, 10,000ft, 11,000ft, 12,000ft) were considered. Note that the base condition in this model is where R = at the maximum (i.e., when the segment is basically a tangent) with no guardrail coverage.

Table 35 Model 4 (FI): CMFs for fatality and injury crashes on horizontal curves and tangents with type 2 crest vertical curves in SUMMER and WINTER

	Horizontal curve radius (ft)	SUMMER	WINTER
NO guardrail	100	1.74	1.21
	1,000	1.34	1.11
	2,000	1.24	1.08
	3,000	1.18	1.06
	4,000	1.14	1.05
	5,000	1.11	1.04
	6,000	1.09	1.03
	7,000	1.07	1.02
	8,000	1.05	1.02
	9,000	1.04	1.01
	10,000	1.03	1.01
	11,000	1.02	1.01
	12,000	**1**	**1**
FULL guardrail	100	1.41	0.76
	1,000	1.08	0.69
	2,000	1.00	0.67
	3,000	0.96	0.66
	4,000	0.93	0.65
	5,000	0.90	0.65
	6,000	0.88	0.64
	7,000	0.87	0.64
	8,000	0.86	0.64
	9,000	0.84	0.63
	10,000	0.83	0.63
	11,000	0.82	0.63
	12,000	0.82	0.63

Table 36 Model 4 (PDO): CMFs for property damage only crashes on horizontal curves and tangents with type 2 crest vertical curves in SUMMER and WINTER

	Horizontal curve radius (ft)	SUMMER	WINTER
NO guardrail	100	1.06	1.67
	1,000	1.03	1.31
	2,000	1.02	1.22
	3,000	1.02	1.17
	4,000	1.01	1.13
	5,000	1.01	1.10
	6,000	1.01	1.08
	7,000	1.01	1.07
	8,000	1.01	1.05
	9,000	1.00	1.04
	10,000	1.00	1.03
	11,000	1.00	1.02
	12,000	**1**	**1**
FULL guardrail	100	0.53	1.32
	1,000	0.52	1.03
	2,000	0.51	0.96
	3,000	0.51	0.92
	4,000	0.51	0.89
	5,000	0.51	0.87
	6,000	0.50	0.85
	7,000	0.50	0.84
	8,000	0.50	0.83
	9,000	0.50	0.82
	10,000	0.50	0.81
	11,000	0.50	0.80
	12,000	0.50	0.79

6.5 Horizontal Curves and Tangents with Type 2 Sag Vertical Curves (Model 5)

Tables 37 and 38 below shows the CMFs for the alignment combinations considered in Model 5. Two horizontal curve radii (R = 1,500ft, 5,000ft) and five change in grade between the approach and departure slopes (A = 0%, 1%, 2%, 3%, 4%) were considered were considered. Note that the base condition in this model is where A = 0% with no guardrail coverage.

Table 37 Model 5 (FI): CMFs for fatality and injury crashes on horizontal curves and tangents with type 2 sag vertical curves in SUMMER and WINTER

	Change in grade (A)	SUMMER		WINTER	
		Horizontal curve radius, R = 1,500ft	Horizontal curve radius, R = 5,000ft	Horizontal curve radius, R = 1,500ft	Horizontal curve radius, R = 5,000ft
NO guardrail	0	**1**	**1**	**1**	**1**
	1	1.66	1.16	1.29	1.08
	2	2.76	1.36	1.67	1.17
	3	4.57	1.58	2.15	1.26
	4	7.59	1.84	2.78	1.36
FULL guardrail	0	0.95	0.95	0.80	0.80
	1	1.58	1.07	1.04	0.87
	2	2.62	1.25	1.34	0.94
	3	4.35	1.45	1.73	1.01
	4	7.22	1.69	2.23	1.09

Table 38 Model 5 (PDO): CMFs for property damage only crashes on horizontal curves and tangents with type 2 sag vertical curves in SUMMER and WINTER

	Change in grade (A)	SUMMER		WINTER	
		Horizontal curve radius, R = 1,500ft	Horizontal curve radius, R = 5,000ft	Horizontal curve radius, R = 1,500ft	Horizontal curve radius, R = 5,000ft
NO guardrail	0	**1**	**1**	**1**	**1**
	1	1.09	1.03	1.31	1.08
	2	1.18	1.05	1.71	1.17
	3	1.28	1.08	2.24	1.27
	4	1.40	1.11	2.93	1.38
FULL guardrail	0	0.47	0.47	0.85	0.85
	1	0.51	0.48	1.11	0.92
	2	0.55	0.49	1.46	1.00
	3	0.60	0.50	1.91	1.08
	4	0.65	0.52	2.49	1.18

7. Conclusions

The following are conclusions based on the analysis results from this study. Tables 39 and 40 below summarize the coefficient estimate results from all models.

Table 39 Models 1-5 (FI): Coefficient estimates for fatal and injury crashes in SUMMER and WINTER

Parameter Description	Model 1: HC & tangents on non-level straight grades	Model 2: HC & tangents with type 1 crest VC	Model 3: HC & tangents with type 1 sag VC	Model 4: HC & tangents with type 2 crest VC	Model 5: HC & tangents with type 2 sag VC
Fatal and injury (FI) crashes/mile/year in SUMMER					
Intercept	-1.25	-1.98	-1.29	-1.3	-1.07
ln(AADT)	0.28	0.18	0.61	0.53	0.083
1/K	N/A	N/A	24.2	N/A	N/A
|A|/R	N/A	0.0030	0.0033	N/A	0.12
R	0.010	N/A	N/A	0.11	N/A
RL	0.020	N/A	N/A	N/A	N/A
|G|	0.0030	N/A	N/A	N/A	N/A
FG	-0.10	-0.17	-0.070	-0.21	-0.050
PG	-0.14	-0.15	-0.19	-0.32	-0.12
Fatal and injury (FI) crashes/mile/year in WINTER					
Intercept	-3.26	-3.44	-3.3	-3.4	-3.25
ln(AADT)	0.84	0.12	0.13	0.88	0.11
1/K	N/A	N/A	26.56	N/A	N/A
|A|/R	N/A	0.0022	0.0010	N/A	0.060
R	0.020	N/A	N/A	0.040	N/A
RL	0.12	N/A	N/A	N/A	N/A
|G|	0.030	N/A	N/A	N/A	N/A
FG	-0.39	-0.15	-0.060	-0.47	-0.22
PG	-0.050	-0.14	-0.10	-0.27	-0.18

Note: All coefficient estimates are at the <0.001 significance level;
HC = horizontal curve;
VC = vertical curve;
$AADT$ = average annual daily traffic in vehicles per day;
K = ratio of vertical curve length to change in grade (not applicable for straight grades);
$|A|$ = absolute value of change in grade between approach and departure slopes (%);
R = horizontal curve in feet (0 for tangents);
L = horizontal curve length in miles;
$|G|$ = absolute value of percent grade (0% for level segments);
FG = full guardrail coverage (1 = yes, 0 = no); and
PG = partial guardrail coverage (1 = yes, 0 = no).

Table 40 Models 1-5 (PDO): Coefficient estimates for property damage only crashes in SUMMER and WINTER

Parameter Description	**Model 1: HC & tangents on non-level straight grades**	**Model 2: HC & tangents with type 1 crest VC**	**Model 3: HC & tangents with type 1 sag VC**	**Model 4: HC & tangents with type 2 crest VC**	**Model 5: HC & tangents with type 2 sag VC**
Property damage only (PDO) crashes/mile/year in SUMMER					
Intercept	-1.95	-2.19	-2.08	-2.05	-2.07
ln(AADT)	0.10	0.17	0.18	0.14	0.017
1/K	N/A	N/A	19.9	N/A	N/A
|A|/R	N/A	0.0020	0.0010	N/A	0.020
R	0.080	N/A	N/A	0.012	N/A
RL	0.020	N/A	N/A	N/A	N/A
G	0.050	N/A	N/A	N/A	N/A
FG	-0.080	-0.39	-0.011	-0.69	-0.76
PG	-0.15	-0.031	-0.16	-0.097	-0.21
Property damage only (PDO) crashes/mile/year in WINTER					
Intercept	-1.58	-1.63	-1.58	-1.74	-1.76
ln(AADT)	0.14	0.15	0.15	0.13	0.16
1/K	N/A	N/A	16.0	N/A	N/A
|A|/R	N/A	0.00060	0.0050	N/A	0.063
R	0.030	N/A	N/A	0.11	N/A
RL	0.0090	N/A	N/A	N/A	N/A
G	0.0050	N/A	N/A	N/A	N/A
FG	-0.33	-0.51	-0.19	-0.24	-0.16
PG	-0.090	-0.090	-0.079	-0.11	-0.13

Note: All coefficient estimates are at the <0.001 significance level;
HC = horizontal curve;
VC = vertical curve;
$AADT$ = average annual daily traffic in vehicles per day;
K = ratio of vertical curve length to change in grade (not applicable for straight grades);
$|A|$ = absolute value of change in grade between approach and departure slopes (%);
R = horizontal curve in feet (0 for tangents);
L = horizontal curve length in miles;
$|G|$ = absolute value of percent grade (0% for level segments);
FG = full guardrail coverage (1 = yes, 0 = no); and
PG = partial guardrail coverage (1 = yes, 0 = no).

- In general, the model results are consistent with the literature. All coefficient estimates for the five sets of models have the expected signs and magnitudes.
  - The presence of full or partial guardrail coverage decreases both fatal and injury (FI) as well as property damage only (PDO) crashes.
  - Horizontal curves with larger radii are generally safer with respect to both types of crashes considered than those with smaller radii.

- The effect of horizontal curve length is almost negligible but is consistently positive (i.e., longer curve segments are indirectly related to both types of crash frequencies).
  - Grades for non-level vertically straight segments (G) and changes in grade between the approach and departure slopes for type 1 crest and sag vertical curves (A) are both positively related to FI and PDO crash frequencies (i.e., steeper grades and bigger grade changes in type 1 crest and sag curves are less safe).
  - Smaller ratios of vertical curve lengths to changes in grade (K) for type 1 sag curves are related to higher crash frequencies for both types of crashes.
  - Lastly, in all cases and as expected, FI and PDO crash frequencies are shown to be directly associated with more heavily used roads in terms of the average annual daily traffic (AADT).
- For model 1 (horizontal curves and tangents on non-level straight grades), the crash modification factors (CMFs) summarized in Tables 25-28 show that increasing horizontal curve radius has minimal positive effects on FI and PDO crash frequencies, while increasing horizontal curve length has virtual no effects. Increasing vertical grade can have relatively bigger negative effects on both types of crashes compared to the horizontal curve measures. The biggest impacts appear to be from the presence or absence of guardrail coverage, particularly during the winter period. In the summer, the presence of guardrails more than fully offset the combined negative effects of steeper vertical grades, smaller horizontal curve radius, and shorter horizontal curve length in association with FI crashes in all cases considered. This positive safety effect of guardrails is even more evident in the winter for both FI and PDO crashes. Interestingly, the presence of guardrail coverage is equivalent to one percent decrease in vertical grade for PDO crash frequencies in the summer.
- For model 2 (horizontal curves and tangents with type 1 crest vertical curves), the CMFs summarized in Tables 29 and 30 show that increasing horizontal curve radius has small positive effects on both FI and PDO crash frequencies. Similar to model 1, the vertical alignment has relatively bigger impacts; greater changes in grade (A) for type 1 crest vertical curves are associated with significant increases in both types of crashes. Further, the effects of guardrail coverage is similarly dramatic; in both summer and winter, the presence of guardrails more than offset the combined negative effects of smaller horizontal curve radius and greater changes in grade for PDO crashes in all cases considered. For FI crash frequencies, the presence of guardrails has slightly smaller effects but does offset all or most of the negative effects of the alignment features in both summer and winter.
- For model 3 (horizontal curves and tangents with type 1 sag vertical curves), the CMFs summarized in Tables 31-34 show that increasing horizontal curve radius has small positive effects on both FI and PDO crash frequencies. The biggest impacts on both types of crashes are from the ratio of the vertical curve length to the change in grade (K); decreasing K is associated with big increases in FI and PDO crash frequencies across all horizontal curve radius (including tangents) considered. The presence of guardrails appears to lessen some of these negative effects for FI crashes and there appear to be little differences between the summer and winter periods. For PDO crashes, however, the presence of guardrails can dramatically offset the negative effects of larger values of K; similar to FI crashes, guardrails is less effective for smaller Ks.

- For model 4 (horizontal curves and tangents with type 2 crest vertical curves), the horizontal curve radius was the only geometric variable that was statistically significant. As such, Tables 35 and 36 only show CMFs for different values of R. In this set of models, increasing the horizontal curve radius is associated with moderate decreases in crash frequencies. The presence of guardrail coverage is particularly impactful for horizontal curves of larger radii, especially for FI crashes in the winter and PDO crashes in the summer. In all cases, guardrails are associated with significant safety gains with respect to both types of crashes in both study periods.
- For model 5 (horizontal curves and tangents with type 2 sag vertical curves), the CMFs summarized in Tables 37 and 38 show significant effects of decreasing horizontal curve radius, particularly for FI crashes in the summer and PDO crashes in the winter. The most dramatic impacts, however, is from the change in grade (A); even small increases in A, there are significant safety impacts for type 2 sag vertical curves, particularly for FI crashes. The presence of guardrails have limited positive effects for FI crash frequencies but is associated with dramatic increases in safety for PDO crashes, especially in the summer.

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