Hindawi
Journal of Advanced Transportation
Volume 2018, Article ID 1492614, 13 pages
https://doi.org/10.1155/2018/1492614

Research Article

Highway Design and Safety Consequences: A Case Study of Interstate Highway Vertical Grades

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Received 7 March 2018; Accepted 6 May 2018; Published 27 June 2018

Academic Editor: Zhi-Chun Li

Vertical alignment, which includes vertical grades and lengths, is a critical aspect of highway design policy that influences safety. A full understanding of the effect of vertical grade and segment length on highway safety can help agencies to evaluate or adjust their design policies regarding vertical alignment design features (grade and length). For this reason, it is useful to assess the current relationships between design policy and safety performance. To address this task, this paper uses data from interstate segments to first establish the relationship between these design features and safety. Safety is expressed in terms of the three different levels of crash severity (fatal, injury, and property damage only). In its analysis, the paper departs from the traditional univariate models (where each crash severity is modeled separately) and instead uses a seemingly unrelated negative binomial (SUNB) technique, a multivariate model that duly accounts for the unobserved shared effects between the different levels of crash severity. In addition, the paper's models duly recognize and account for the holistic nature of the grade and tangent length effects: the effect of the sum (interaction) of the vertical grade and length is different from the sum of their individual effects. The paper investigates the relationships for rural and urban interstate highway segments. Against the background of the developed models, the paper evaluates current design policies (specifications on vertical alignment grade and length) for similar classes of highways at a number of countries and presents a set of nomograms that feature lines representing points of equal safety performance. These charts can be used by the highway agencies to evaluate and compare their current or possible future highway design policies.

1. Introduction

The vertical alignment of a highway segment, which is guided by geometric design policy, is the end result of an evaluation of the benefits and costs associated with alternative route locations with due consideration given to existing terrain, safety, and construction haulage and cost. Grades or straight vertical segments are designed to be steep enough to allow for longitudinal drainage, but not so steep as to pose a danger to vehicles through inadvertent excessive speed at downhill segments (and, conversely, difficulty of climbing steep uphill segments that pose safety risks where there are inadequate passing opportunities).

Therefore, highway vertical alignment design involves a specification of the vertical grade and the length over which such grade occurs. Evidence from the literature suggests that vehicles with relatively high weight-to-power ratio tend to lose speed as they travel uphill at such tangents. Recent studies have assessed the extent to which the operating speed of trucks on highways is sensitive to vertical grade: speeds significantly decrease at upgrade segments and increase at downgrade segments [1–4]. Due to such speed reduction, there can be significant heterogeneity of operating speeds on the vertical grade segment, with resulting adverse effects on safety. Recognizing that the highway vertical alignment plays a pivotal role in highway safety, the design manuals of national highway agencies and organizations, including the AASHTO Green Book-A Policy on Geometric Design of Highways and Streets [5] in the United States, specify that vertical tangent grade and length must be kept within certain limits to promote safety.

Empirical studies that have investigated the relationship between highway vertical grade and safety have been rather sparse compared to the general body of highway safety literature. St. John and Kobett [6] investigated the safety effects of long, steep grades on rural two-lane highways using traffic speed distributions generated with computer simulation and found that where trucks constitute a fifth of the traffic stream, the crash involvement rate increases from 175% of passenger car rates for 4 percent grades, to 250% of passenger cars for 8% grades. They also found that at steep downgrades (greater than 4%) trucks tend to use crawl speeds to maintain control which tends to increase crash rates. At crest curves, steep grades cause inadequate sight distance that could impair safety. Over the past two decades, a number of researchers have established explicit relationships between highway vertical grade and safety, including Easa [7, 8], Hassan and Easa [9], and Labi [10, 11]. Other noteworthy contributors include Hassan et al. [12–14] who discussed the importance of sight distance and operating speed along with combined horizontal and vertical alignments at highway cut and fill sections. Hassan [15] showed that segment grade and length play key roles in the stopping distance, which in turn affects safety. It is not surprising, therefore, that posting a speed indicator at the crest of vertical curves of rural highway segments has been found to have safety benefits [16]. Miaou [17] and Daniel and Chien [18] determined that vertical grades exceeding 2% could cause increased crash rates and recommended that grades be kept as low as 0.005 per 100ft. In addition, a horizontal curve appears to be flatter where it overlaps with a sag vertical curve and sharper where it overlaps with a crest vertical curve; such distortion could impair the ability for drivers to maintain appropriate speeds at such sections, thereby possibly causing unsafe driving conditions [19]. It has been suggested that, in order to minimize the erroneous perception of drivers, the sight distance and the horizontal curve radius should be decreased, and the length of vertical curve per 1% change in grade should be increased [20]. Crash rates on curves with similar tangents are reported to be 1.5 to 4 times higher, compared to other types of curves [21]. This suggests that one way of reducing crash fatalities and injuries is to improve the road alignment consistency.

With regard to modeling technique for highway crash analyses, the literature is replete with a variety of model types and forms. Abbas [22] evaluated traffic safety conditions using a wide variety of functional forms. Hanley and Forkenbrock [23] applied Monte Carlo techniques to analyze two-lane highway safety regarding passing maneuvers. Elvik et al. [24] used power functions to investigate the relationship between operating speed and road safety. Shively et al. [25] used a semiparametric Poisson-gamma model with a Bayesian nonparametric estimation procedure to investigate the number of crashes based on geometric features and operating conditions. Hosseinpour et al. [26], using zero-inflated negative binomial (NB) and Poisson, hurdle NB and Poisson, standard and random-effect NB, and Poisson models, identified terrain type (e.g., flat and rolling terrain) as an influential factor of head-on severe crashes. Mohammadi et al. [27] used a longitudinal NB model that includes autoregressive correlation arrangement to model crash frequency. Bauer and Harwood [28] investigated the effect of combined longitudinal grade and horizontal curve on road safety and generated crash modification factors (CMFs) associated with safety performance at tangent sections. Yan et al. [29] developed a highway alignment comprehensive index (ACI), which includes the grade, to predict highway operating speed which can be used to evaluate highway safety performance. The length of vertical grade, which has been found by Wang et al. [4] to be influential to safety, was not considered in the Yan et al. [29] research. Zeng et al. [30] and Zeng et al. [31] proved that higher grade increased the crash risk on highway segments. Zou and Yue [32] analyzed causation of road accidents by a Bayesian Network approach. Factors, including road geometry and road surface condition, were proved to be influential on road accident frequency.

Crash counts across severity levels (e.g., property damage only, injury, and fatal) are correlated in nature. Such correlations emerge from a variety of sources including data on traffic collisions that involve multiple occupant injuries from the same crash. In addition, unobserved factors (e.g., vehicle speed and weather condition at the time of crash) may influence multiple crash counts of different severity levels simultaneously for each highway segment. Therefore, modeling crashes of each severity level separately and not accounting for these correlations will result in less precise estimations of crash factors associated with different crash severity levels ([33]; Anastasopoulos and Mannering, 2016; [34–36]). Winkelmann [37] introduced a seemingly unrelated negative binomial (SUNB) framework to account for these correlations among count data. It also overcomes drawbacks of other regression models, such as seemingly unrelated Poisson (SUP) model, which are unable to account for overdispersion (a widespread phenomenon in count data analysis). AASHTO's policy on geometric design of highways and streets (also referred to as the "Green Book" [5]) suggests that vertical grade and segment length are influential factors of crashes. The Federal Highway Administration's Highway Safety Manual (HSM) and Porter et al. [38] presented methods for predicting the mean crash frequency under specific conditions of highway operations, geometry, and terrain. The literature lacks studies that specifically investigated the simultaneous effect of vertical grade and segment length on crash frequency and the variation of the nature of this relationship across rural and urban highways. In addition, past work on this topic stopped short of evaluating current geometric design practices vis-à-vis the model outcomes or making any recommendations to guide the former.

In attempting to throw light on this important aspect of highway design policy, this paper assesses the safety impacts of highway vertical alignment by first establishing the relationship between vertical alignment parameters (grade and length) on the safety experience at these highway classes. Another objective is to incorporate the holistic nature of the grade and tangent length effects: the effect of the sum (interaction) of the vertical grade and length is different from the sum of their individual effects. Finally, the paper sets out to evaluate current design policies (regarding vertical alignment grade and length specifications) against the background of the developed models and presents a set of nomograms that feature lines representing points of equal safety performance. These charts can be used by the highway agencies to evaluate and compare their current or future highway design policies. The paper's scope covers highway types of interstate quality or similar class. The analysis was carried out separately for rural and urban segments.

2. Methodology

2.1. Estimate SUNB Models. The paper expresses the safety experience in terms of the three different levels of crash severity (fatal, injury, and property damage only). The paper departs from the traditional univariate models (where each crash severity is modeled separately) and instead uses multivariate models that estimates the models for the different severities simultaneously. In doing so, the paper duly accounts for unobserved yet shared influences across the factors that influence the different levels of crash severity. SUNB can be considered a specific case of multivariate models. The general SUNB framework, which was first introduced by Winkelmann ([37]; 2008), can be tailored to the current problem context as follows.

Let z_i represent a J-dimensional vector which counts each element which is independently Poisson distributed with parameter λ_{ij}, where z_i is a vector of counts (the number) of accidents in the i^{th} level of accident severity, on j^{th} highway segment.

$$z_i = (z_{i1}, z_{i2} \ldots z_{iJ})'. \tag{1}$$

i is fatal, injury, or PDO; and $j = 1, 2, \ldots, J$ is an index referring to a highway segment.

The expected number of accidents of the i^{th} severity level in j^{th} road segment is given by

$$\lambda_{ij} = e^{x_{ij}'\beta_j}. \tag{2}$$

x_{ij} is a vector of independent variables associated with the geometric design (including vertical grade and segment length), traffic volume, and pavement condition.

$\beta_j = [\beta_0, \beta_{vertical\ grade}, \beta_{length}, \beta_{interaction}, \ldots]'$ is a vector of coefficients for the corresponding independent variables.

This paper focuses on the effects of vertical grade ($\beta_{\text{vertical grade}}$), segment length β_{length}, and the interaction $\beta_{interaction}$ between these two factors. Therefore, these coefficients are mentioned specifically in the coefficient vector. To account for the presence of an error term in the model, let $z_{ij} \mid v_{ij}$ a be Poisson distributed random variable with parameter $\lambda_{ij}v_{ij}$. Then (2) becomes

$$\lambda_{ij}v_{ij} = e^{x_{ij}'\beta_j + \varepsilon_{ij}}. \tag{3}$$

v_{ij} is gamma distributed with mean 1 and variance α^{-1}.

The marginal distribution of z_{ij} after integration over v_{ij} is negative binomial with mean $\text{E}(z_{\text{ij}}) = \lambda_{\text{ij}}$ and variance $\text{Var}(z_{\text{ij}}) = \lambda_{\text{ij}} + \alpha^{-1}\lambda_{\text{ij}}^{\,2}$.

In order to develop the probability generating function for the negative binomial distribution, the parameter α is parameterized as follows:

$$\alpha = \frac{\lambda_{\text{ij}}}{\sigma}, \tag{4}$$

where symbols have meanings as explained above.

The parameterization will not affect the mean; however, the variance $\text{Var}(z_{\text{ij}}) = \lambda_{\text{ij}}(1+\sigma)$ becomes a linear function of the mean. After the parameterization, the negative binomial distribution has the following probability generating function:

$$\begin{aligned} P_z(s) &= [1 + \sigma(1 - s)]^{-\lambda_{\text{ij}}/\sigma} \\ P_u(s) &= [1 + \sigma(1 - s)]^{-\gamma/\sigma} \\ P_y(s) &= [1 + \sigma(1 - s)]^{-(\lambda_{\text{ij}}+\gamma)/\sigma} \end{aligned} \tag{5}$$

where u_i represents a scalar random variable with negative binomial distribution and mean γ. $y_{ij} = z_{ij} + u_i$, $s_i = \min(y_{i1}, y_{i2} \ldots y_{iJ})$.

The covariances between y_{ij} and y_{ik} are given by $\text{Cov}(y_{ij}, y_{ik}) = \gamma(1 + \sigma)$.

The framework allows for overdispersion on the condition that $\sigma > 0$. The joint probability function of the multivariate negative binomial framework is expressed as follows:

$$\begin{aligned} &f_{NB}(z_{ij}) \\ &\quad = \frac{\Gamma(\lambda_{ij}/\sigma + z_{ij})}{\Gamma(\lambda_{ij}/\sigma)\Gamma(z_{ij} + 1)} \left(\frac{1}{1+\sigma}\right)^{\lambda_{ij}/\sigma} \left(\frac{\sigma}{1+\sigma}\right)^{Z_{ij}} \end{aligned} \tag{6}$$

where f_{NB} is the negative binomial probability function. Winkelmann ([37]; 2008) provides further details on the framework.

2.2. Nomogram Development. A nomogram is a diagram representing the relationship between at least three variable quantities. This displays two independent variables and shows how they interact to affect a third, dependent variable or outcome. Typical forms include a three-dimensional plot and a contour map. When the dependent variable is placed into distinct levels that have finite boundaries, nomogram can be used to easily compare the effect (on the dependent variable) of different combinations of the independent variables. An example of a contour nomogram is the isopleth (a line on a map connecting points having equal incidence of a specified meteorological feature). Similarly, in this paper, we introduce the term "isodehn" to represent a line drawn on a map through all points having the same safety performance as a function of two variables.

In this paper, after estimating the SUNB models for a certain crash severity level and a highway functional class, isodehns were plotted on a 2-dimensional figure (the dimensions being the segment length and vertical alignment grade) with isodehns along with the current design standards of different countries. In order to provide meaningful and representative information to the practice, we defined three levels of traffic volume based on the quartile values from our data: low traffic volume (corresponds to 25$^{\text{th}}$ percentile value), medium traffic volume (corresponds to 50$^{\text{th}}$ percentile value), and high traffic volume (corresponds to 75$^{\text{th}}$ percentile value). Similarly, the safety level of each isodehn is determined based on the percentiles (e.g., 10%, 20%, 30%) of

Table 1: Descriptive statistics of variables.

	Mean	Std Dev	Minimum	Maximum
Rural Interstate				
Total number of fatal crashes on each segment	0.241	0.501	0	3
Total number of injury crashes on each segment	4.265	3.785	0	19
Total number of PDO crashes on each segment	18.030	15.206	0	79
Segment length (miles)	5.417	2.824	0.560	6.94
Average annual daily traffic (10,000 vehicles)	3.271	1.600	1.181	12.865
Lane width (ft.)	12.030	0.784	8.750	15
Right shoulder width (ft.)	10.335	0.981	2.800	12
Pavement roughness (IRI in in/mile)	80.553	29.482	53	219
Vertical curve grade (%)	1.639	1.950	0	4.084
Road segments with left shoulder or median	100%		0	1
Left shoulder width (ft.)	4.562	1.765	3	11
Median width (ft.)	61.236	14.308	2	60
Urban Interstate				
Total number of fatal crashes on each segment	0.650	1.336	0	7
Total number of injury crashes on each segment	30	60.224	0	228
Total number of PDO crashes on each segment	121.688	261.035	0	953
Segment length (miles)	5.372	2.868	0.400	6.44
Average annual daily traffic (10,000 vehicles)	5.275	3.298	1.140	12.385
Lane width (ft.)	11.986	0.561	10	14.460
Right shoulder width (ft.)	9.953	0.723	6	11
Pavement roughness (IRI in in/mile)	77.329	21.613	48	147
Vertical curve grade (%)	1.540	1.883	0	3.682
Road segments with left shoulder or median	97.50%		0	1
Left shoulder width (ft.)	5.965	4.182	0	15
Median width (ft.)	45.241	21.637	0	60

the crash count for a certain crash severity level on specific road class. By this definition, the area between any two consecutive isodehns is statistically considered to be equally safe (the same level of expected crashes). That is, any combinations (points) of the segment length and vertical curve grade, of which the points locate in the same area, statistically have the same impact in terms of the number of crashes.

In this paper, we develop the isodehn plots for injury and PDO crashes only but not for fatal crashes, because the number of expected fatal crashes is too small to show meaningful comparisons. Nevertheless, in estimating the models, fatal crashes are included in the presented SUNB framework because their occurrences share some of the unobserved effects (including weather condition, speed limit, driver age, and conditions) with other crash severity levels. Therefore, inclusion of the fatal crash model in the system of models helps to improve the estimation performance of the injury and PDO models.

After developing the isodehns, the current design standards/recommendations of different countries are plotted on the same figures. By comparing the combination of segment length and vertical curve grade from the existing design standards/recommendations with the isodehns, the existing practice can be evaluated.

3. Description of the Data

A database of 418 highway segments was used to investigate the safety impacts of highway vertical alignment in this paper. This study database was developed by merging two independent datasets: a road safety dataset and a road inventory dataset. The combined database includes information regarding historical data on vehicle crashes at highways in the state of Indiana over a three-year period. In order to investigate the differences of safety impacts across rural and urban locations, the dataset was further divided into two subdatasets: rural interstate (317 highway segments) and urban interstate (101 highway segments). The vehicle crashes were placed into three levels of crash severity: fatal, injury, and property damage only (PDO). Only segments that did not contain any sag or crest curves were used for the analysis, and the grade along the segment was recorded. In most cases, the grade was uniform but, in a few cases, a segment had one or two grades and the average was recorded. Table 1 presents the summary statistics of the key variables.

4. Model Estimation Results and Interpretation

The estimation results of the SUNB models are presented in Tables 2(a) and 2(b) for rural interstate and urban interstate, respectively. The presented variables were found to be statistically significant at a level of confidence of 10%. The signs of the estimated coefficients were found to be intuitive from an engineering standpoint. Based on the mathematical form of the SUNB model, the coefficients are shown as exponents.

Table 2

(a) Model estimation results for Rural Interstates

Variables	Fatal		Injury		PDO	
	coefficient	*t* value	coefficient	*t* value	coefficient	*t* value
Constant	−12.8386	−4.30	−22.7048	−14.24	−19.8081	−14.11
Segment length (miles)	0.2146	3.98	0.1548	6.24	0.1540	7.05
Natural log of annual average daily traffic	1.4462	5.13	0.8843	6.48	0.8234	6.85
Average vertical grade (%)			0.0963	3.27	0.0636	2.46
Left shoulder width (ft.)	−1.1704	−10.81	−0.6364	−18.50	−0.7372	−24.38
Median width (ft.)			−0.0123	−2.91	−0.0131	−3.52
Number of lanes			3.4596	15.66	3.4045	17.53
Number of observations = 317; *McFadden pseudo* ρ^2 = 0.203						

(b) Model estimation results for Urban Interstates

Variables	Fatal		Injury		PDO	
	coefficient	*t* value	coefficient	*t* value	coefficient	*t* value
Constant	−5.1638	−8.25	−28.7188	−6.34	−24.2710	−5.77
Segment length (miles)	0.2327	9.16				
Natural logarithm of annual average daily traffic			2.8430	8.19	2.2157	8.28
Lane width (ft.)			−0.9093	−3.65	−0.6286	−3.06
Right shoulder width (ft.)			1.2243	5.01	1.1272	6.00
IRI (in/mile)	0.02317	3.25				
Average vertical grade (%)	0.5034	5.12	0.2086	1.96	0.1852	1.86
Left shoulder width (ft.)	−0.2087	−5.01	−0.08187	−1.99	−0.09313	−2.38
Number of lanes	−0.2480	−2.45				
Average vertical curve grade ∗ Lane width (Interaction term)			0.02367	3.19	0.02615	3.72
Number of observations = 101; *McFadden pseudo* ρ^2 = 0.167						

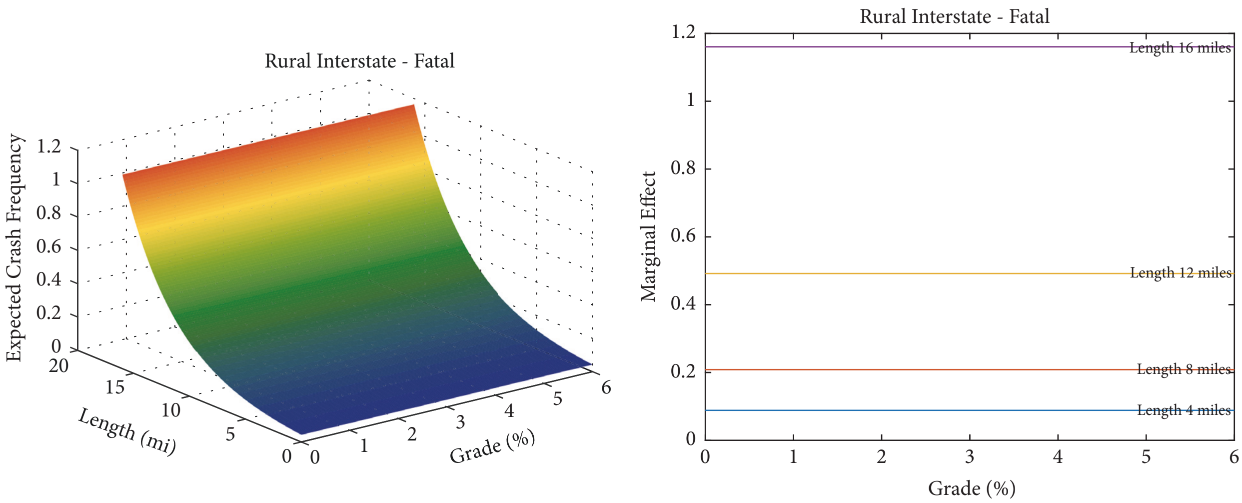
Figures 1–6 present the expected crash frequency of a given crash type across the rural and urban interstate highways and the sensitivity (using marginal effects) of the expected crash frequency to the average grade of the vertical alignment. The marginal effect reflects the impact of a one-unit change in an independent variable on the dependent variable (i.e., the expected frequency of fatal, injury, or PDO crashes). For crash severity level k, the marginal effect of the mth independent variable is calculated as

$$\mathrm{ME}_{X_{mk}}^{\lambda_{mk}} = \frac{\partial \lambda_k}{\partial X_{mk}} = \beta_{mk} EXP\left(X_k' \beta_k\right) \tag{7}$$

where λ_k is the estimated model for crash severity level k; X_{mk} is the mth independent variable; β_{mk} is the corresponding estimated coefficient; X_k' and β_k are the vectors of independent variables and the corresponding estimated coefficients, respectively.

The expected crash frequencies (the vertical axis in 3-dimensional space) are presented in Figures 1, 2, 3, 4, 5, and 6. The interaction between vertical grade and length is presented in Figures 2, 3, 4, 5, and 6. If there is a significant interaction term between segment length and vertical curve grade in the estimated model, the expected crashes will be further elevated as observed in the spike in Figures 5 and 6 (in Figure 4, the "spike-like shape" is due to the large coefficients of the average vertical grade and the segment length variables). Figures 1–3 do not exhibit any spike. The marginal effects (y-axis) and the vertical curve grade (x-axis) are shown in the figures across different road segment lengths. Where there is no interaction between the vertical curve grade and segment length, the lines that represent marginal effects are horizontal. On the contrary, where such interaction exists, the marginal effects are not linear but curves.

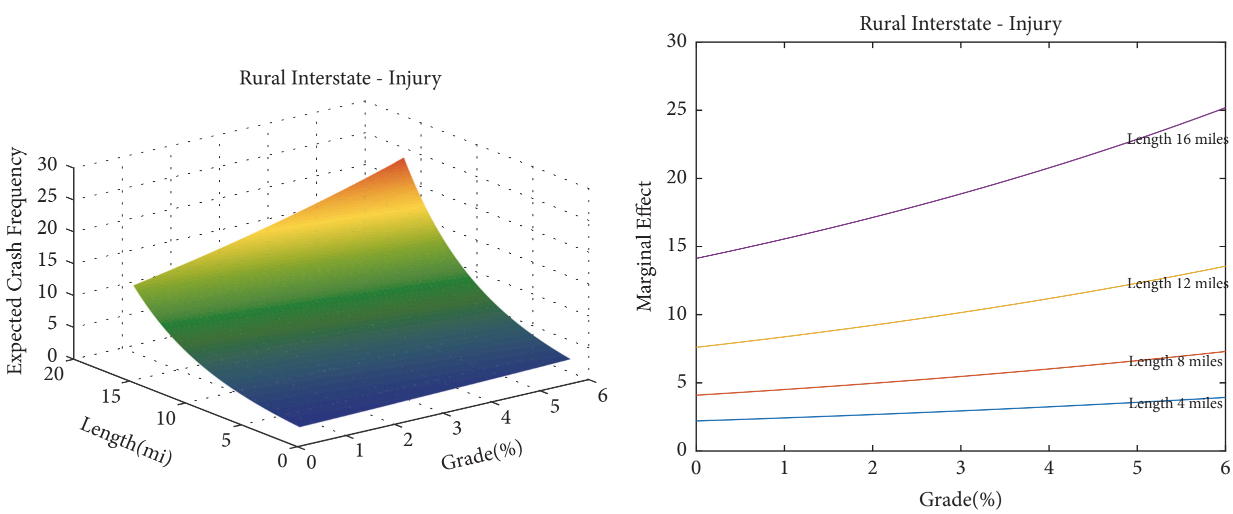
The figures suggest that, compared to their rural counterparts, urban interstate highways generally have higher numbers of expected crashes, and the crashes are more sensitive to changes in the vertical alignment grade (in the marginal effect plots, the change in crashes increases at a faster rate as the grade increases). At the urban interstate highways with relatively steep grades, PDO and injury crashes are very sensitive to the grade length. In other words, at such segments, a small increase in length will lead to a significant increase in the expected PDO and injury crashes. In the case of rural interstate highways, the interaction between the segment length and vertical curve grade is not significant for fatal crashes. However, the interaction is considerable for the injury and PDO crashes (albeit much lower compared to urban interstate highways). Overall, the figures suggest that where there is interaction between the vertical alignment grade and length, the crashes are more sensitive to longer segments at steep segments compared to those at relatively flat segment. In addition, with regard to urban interstate highways with small grades and short lengths, fatal crash



(a) Expected frequency of crashes

(b) Marginal effect (crash sensitivity to grade)

Figure 1: Rural interstate fatal crashes.



(a) Expected frequency of crashes

(b) Marginal effect (crash sensitivity to grade)

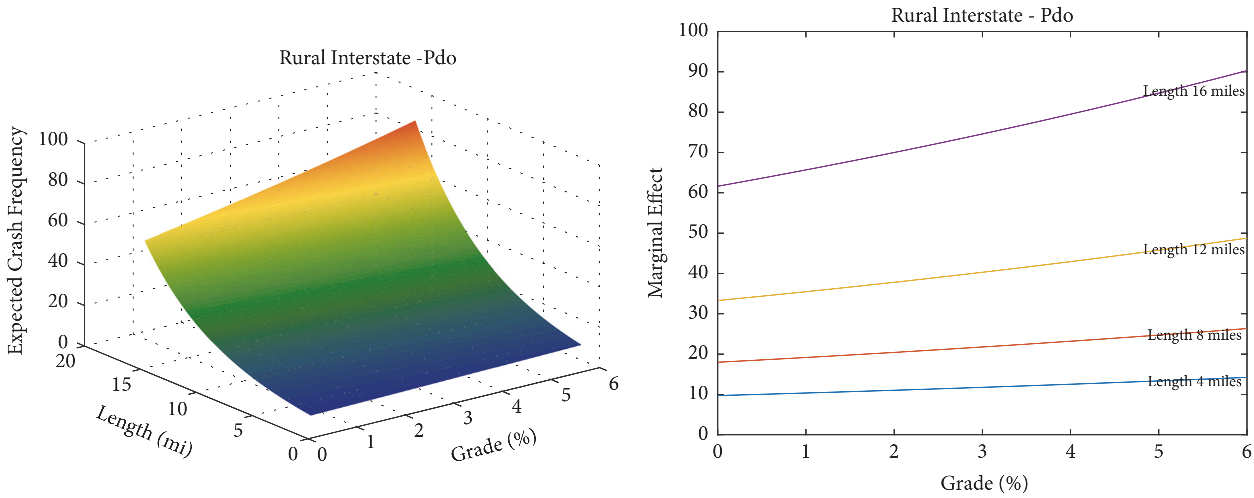
Figure 2: Rural interstate injury crashes.

frequency is found to be less sensitive to changes in the grade and segment length (as shown in the light blue area); however, it is considerably sensitive where the grade and length are relatively high.

5. Evaluation of Current Design Policy Across Different Countries

The traffic operating conditions at highways differ considerably from country to country, and therefore any comparison of design standards across countries must be done with circumspection. In this paper, we evaluate the current practice based on design standards, using a set of figures. Figures 7–10 present nomograms that indicate the relationship between the average vertical alignment grade and length, on one hand, and the expected number of crashes on the other hand. These relationships are represented by isodehns on the nomogram. In these figures, areas with lighter color represent a higher safety level of design (with respect to vertical alignment grade and length) compared to those with darker color.

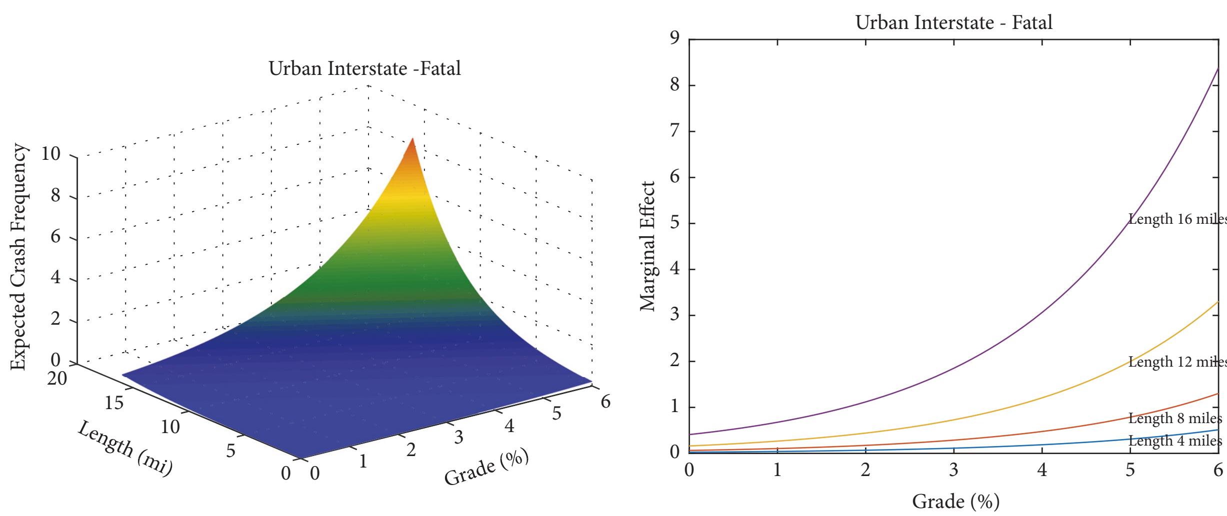
For purposes of illustration and to facilitate a representative and realistic evaluation, we define three levels of traffic volume based on the quartile values from the dataset for rural interstate and urban interstate highways: low traffic volume (corresponds to 25th percentile value, AADT = 29,000), medium traffic volume (corresponds to 50th percentile value, AADT = 37,000), and high traffic volume (corresponds to 75th percentile value, AADT = 74,000). Nomograms for the expected injury and PDO crashes were plotted separately but were not plotted for fatal crashes because the number of



(a) Expected frequency of crashes

(b) Marginal effect (crash sensitivity to grade)

FIGURE 3: Rural interstate PDO crashes.



(a) Expected frequency of crashes

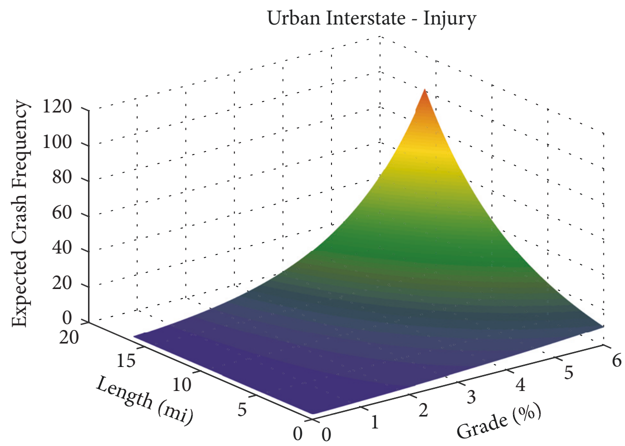
(b) Marginal effect (crash sensitivity to grade)

FIGURE 4: Urban interstate fatal crashes.

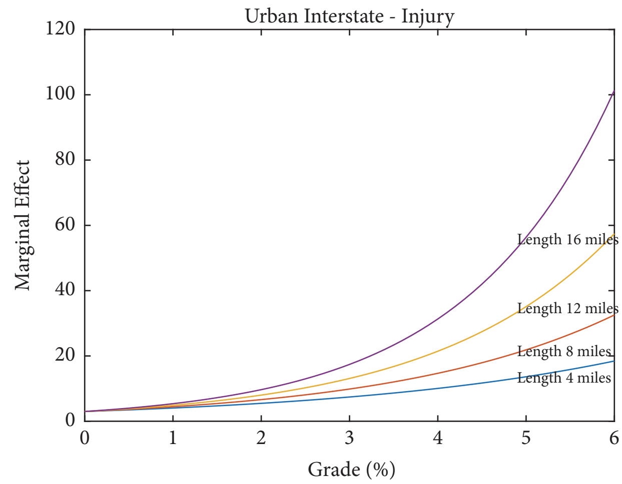
fatal crashes is low. Nevertheless, in the modeling process, fatal crashes are included in the presented SUNB framework during the model estimation because unobserved effects (of fatal crashes) associated with the explanatory variables, such as weather condition and speed limit, are shared with those of injury and PDO crashes.

For illustration purposes, the isodehns were plotted and compared with design standards/recommendations at USA, China, Japan, and Iran [5, 39–42]. Again, it is worth noting that the models presented in this paper were based on data collected in the USA, and, therefore, the model results (i.e., the relationship found between the number of crashes, segment length, and grade) are not necessarily transferable to other countries. This is because drivers in different countries have significant different driving behavior or culture, which was not captured in this paper. Nevertheless, it is expected that other countries may obtain useful insights from the results presented. In addition, the study methodology can be replicated by applying the proposed framework in this paper using data from the other countries, to evaluate their highway design. To make the comparisons across different countries more meaningful, the standards shown from other countries pertain to the highest class of roads in those countries: freeways, expressways, and national highways or motorways. Sinha et al. [43] showed that the operating conditions and geometric design policies (such as the design speed, lane and shoulder widths, horizontal curves, access control, and sight distances) for the highest class of highways in many countries share some similarity.

In order to compare design values of vertical curve grade and segment length across these countries, the recommended design values were chosen for a given design

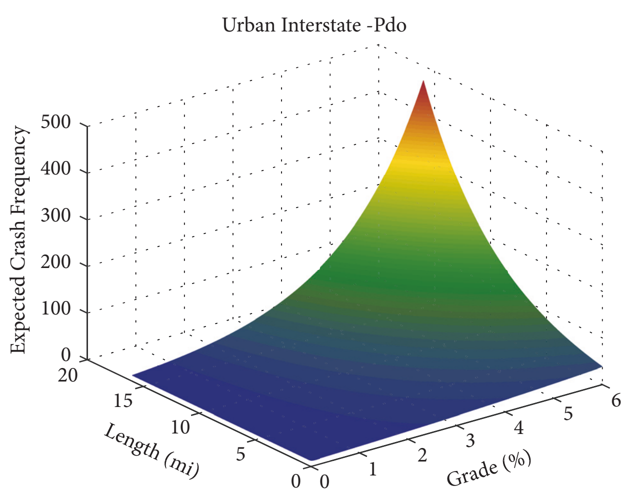


(a) Expected frequency of crashes

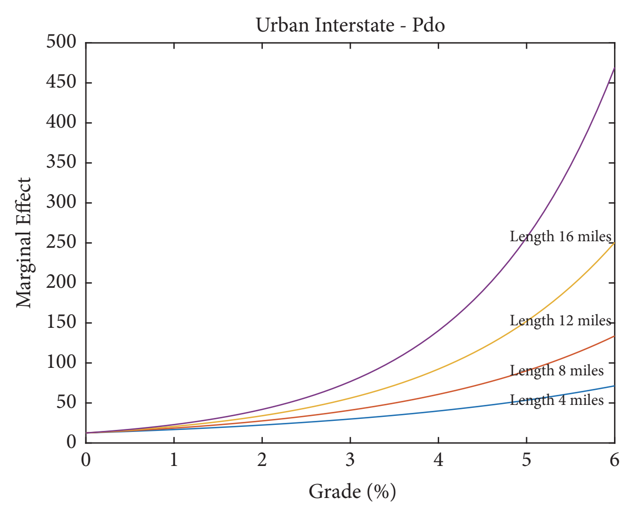


(b) Marginal effect (crash sensitivity to grade)

Figure 5: Urban interstate injury crashes.



(a) Expected frequency of crashes



(b) Marginal effect (crash sensitivity to grade)

Figure 6: Urban interstate PDO crashes.

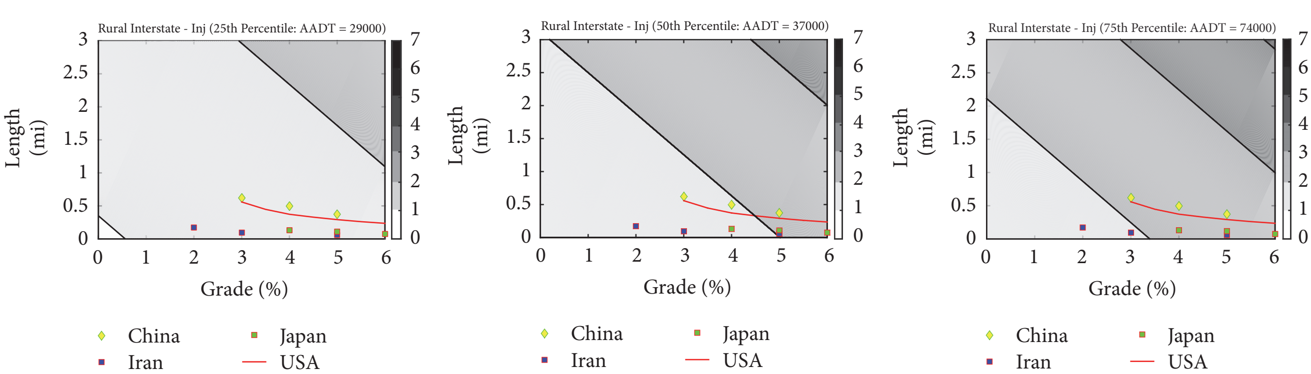


Figure 7: Prediction of rural interstate injury crash frequency.

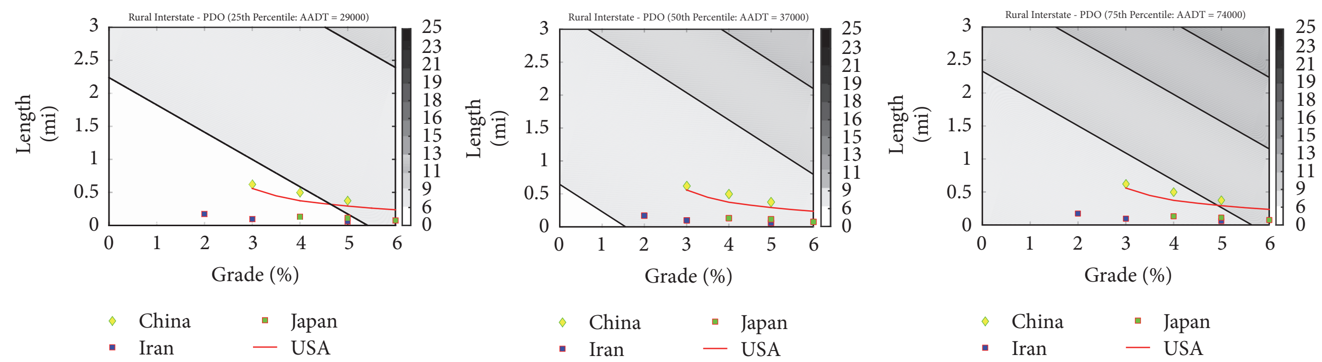


FIGURE 8: Prediction of rural interstate PDO crash frequency.

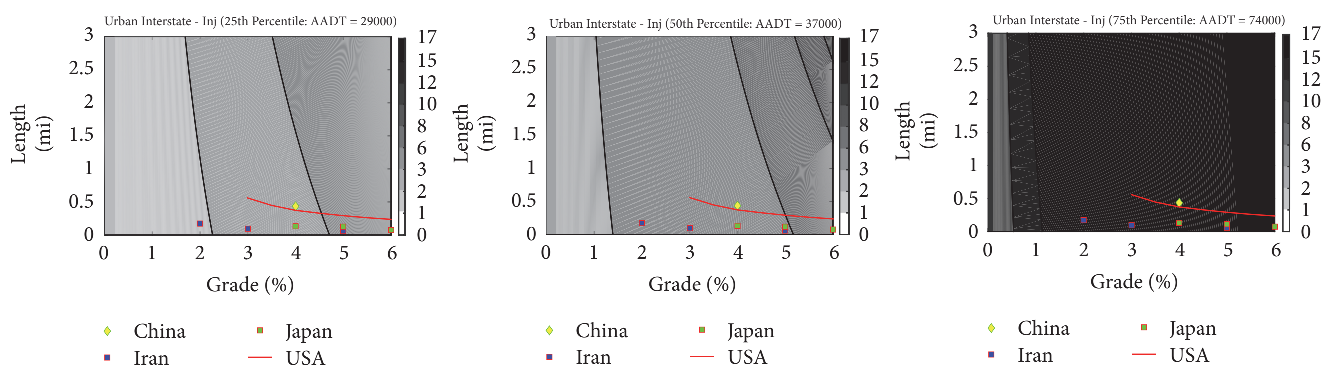


FIGURE 9: Prediction of urban interstate injury crash frequency.

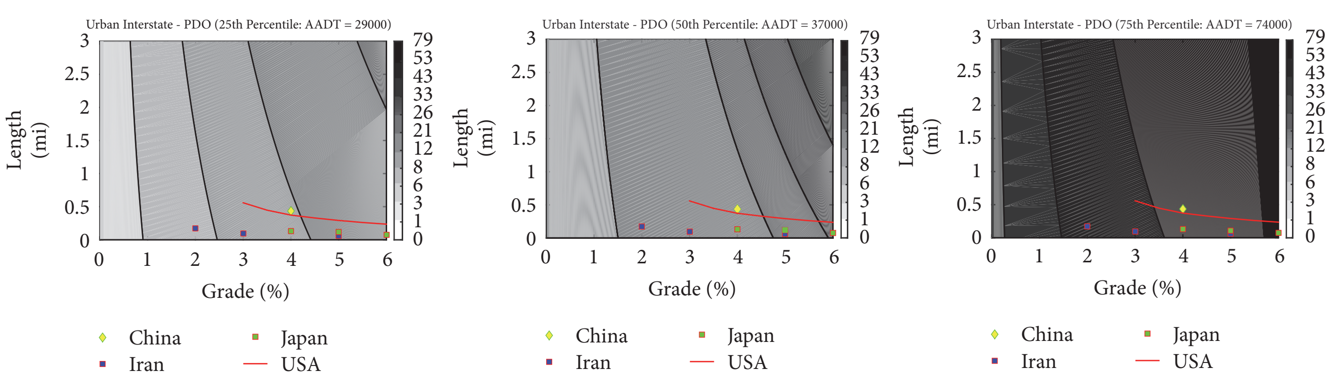


FIGURE 10: Prediction of urban interstate PDO crash frequency.

speed of 100 km/h for all four countries. In the case of China, the design codes for urban roads and nonurban roads in China are different. "Design Specification for Highway Alignments" (Specification) [39] is developed and published by the Ministry of Transport of China, whereas "Code for Design of Urban Road Engineering" (Code) [40] is developed and published by the Ministry of Housing and Urban-Rural Development of China. The Code and Specification specify that the maximum grades are required to be 3% and 4% for urban and nonurban roads with design speed of 100km/h, respectively. Moreover, grade can be 1% higher than regular value where topographical limits are excessive. For urban roads, the maximum length on 4% grade is 700m, according to the Code. For nonurban roads, however, the maximum length is 1000m, 800m, and 600m, on the grade of 3%, 4%, and 5%, respectively.

In the USA, highway design regarding the segment length and vertical curve grade is recommended by *A Policy on Geometric Design of Highways and Streets* (The Green Book) [5], which is developed by the American Association of State Highway and Transportation Officials (AASHTO). A maximum grade of 5% is considered appropriate for a design speed of 100km/h (approximately, 70 mph). The Green Book also suggests different speed reductions to multiple length curves. A speed reduction of 15mph can be used to analyze the relationship between the vertical curve grade and corresponding segment length (see the red lines in Figures 7–10). For Iran's high-class highways, similar values can be

Table 3: Maximum length (mi) for a certain grade with design speed of 70mph.

Vertical Grade (%)	2%	3%	4%	5%	6%
China	–	0.6214	0.4971	0.3728	–
Iran	0.1705	0.0947	–	0.0568	–
Japan	–	–	0.1326	0.0947	0.0758
USA	–	0.5592	0.3728	0.2920	–

found in Code 415 developed and published by the “Iran Vice Presidency for Strategic Planning and Supervision” for highway routes [42]. Even though continuous lines similar to the US cases can be drawn, discrete points were plotted on the figures to highlight the difference of the Iran policy from that of the USA.

With regard to highways in Japan, when the design speed is 100km/h, the maximum length of the grade is 700m, 500m, and 400m on grade of 4%, 5%, and 6%, respectively. Moreover, when design speed is 120km/h, maximum length for grade is 800m, 500m, and 400m on grade of 3%, 4%, and 5%, respectively. Unlike the continuous values provided by USA (AASHTO) and Iran, those of China and Japan are discrete in nature. The use of continuous lines rather than discrete points as design guidelines can be considered more suitable to the practice. The maximum length of a straight segment, for a given grade with a design speed of 70mph, is presented in Table 3.

In Table 3, it can be observed that critical length for a given grade varies extensively across the countries. For vertical grade of 3%, 4%, and 5%, China has the most liberal length limitation (longest maximum lengths), much more liberal compared to Iran or Japan. Design policy in USA provides grade-length curves for different speed reductions.

The “dots” for a specific country denotes the same “safety level” (corresponds to designs of 100km/h) based on the design standards/recommendations. For example, regarding China’s design policy, for a design speed of 100km/h, when the vertical grade is 3%, the segment length should be less than 1000m. In addition, if the vertical grade is 4%, the segment length should be less than 800m. When the vertical grade is 5%, the segment length should be less than 600m.

It is worth noting where the traffic volume is low that the dots tend to be located in lighter colored regions of the nomogram (i.e., areas representing relatively higher safety). On the other hand, where the traffic volume is high, the dots tend to be located in darker colored regions of the nomogram (i.e., areas representing relatively lower safety). In addition, the nomograms generally suggest that, in the case of urban interstates, safety is more sensitive to changes in traffic volume compared to rural interstates: where the traffic volume is high, the expected number of crashes is far more sensitive to changes in vertical alignment grade and length, compared to their rural counterparts. There are general observations, and, for any specific highway segment, additional factors must be considered to reach a more definitive assessment of the overall safety effects. The linear nature of the isodehns for rural highway nomograms suggests that, with regard to this class of highways, there is relatively little or no interaction between the vertical grade and length, at least within the ranges of lengths and grades in the available dataset. On the other hand, the isodehns for urban highways are not linear, indicating strong interaction between these two features of highway vertical alignment at urban locations.

The nomograms can be used to evaluate if the current design standards are consistent with what is found in the observed data: if the dots for a country are located in the same area (not located on different side of an isodehn), then there is consistency. Regarding the data from the USA, particularly for urban interstates, the figures suggest that the AASHTO design could be adjusted to become more conservative with respect to the grade (i.e., the maximum vertical alignment grade could be decreased) and less conservative with respect to the length (maximum length could be increased). In other words, an increase in length is less likely to make the existing AASHTO design policy cross the isodehn to darker (area of lower safety) territory; however, an increase in vertical alignment grade is likely to have such an effect.

6. Anecdotal Evidence from China

An interesting but extreme case that currently exists in China was used as a basis to provide further discussion on the issue of vertical alignment deign policy and safety implications. This is an expressway segment located at a rural area in Jiangsu Province of China. The expressway has a design speed of 120km/h. The segment consists of two vertical grades and one vertical (crest) curve. The first vertical grade is +2.90% and length is 1,775m. The second grade is −2.90% and length is 1,980m. The curve has radius of 20,000m. The segment is known for its high crash rate. According to specification for highway design in China, the maximum grade is 3% when design speed is 120km/h. In addition, maximum length for this grade is 900m. If the grade is less than 3%, there is no length restriction. Therefore, certain designers may be seeking to skirt the policy narrowly by designing very long segments that do not violate the existing design policy. These segments turn out to be dangerous for driving. For example, in the case study, the lengths of 1,775m and 1,980m are very close to the grade threshold of 3% but far exceed the maximum length of 900m specified for 3% grades according to design code in China. To avoid such borderline designs in future, the vertical alignment design policy needs to be tightened (i.e. made less liberal). This can be done only after investigating the safety consequences of various combinations of length and grade. Using the methodology in this paper, nomograms can be developed to show isodehns within the agency desires to have for their highways. Then appropriate locations on the nomogram can be selected as the new design policy to avoid hazardous designs that involve borderline slopes of excessive length or borderline lengths of excessive slope.

7. Summary, Conclusions, Limitations, and Future Research

At many agencies, design policies were established several decades ago. However, with changing operating characteristics due to changing vehicle designs and capabilities and driver capabilities and perceptions, it is often useful to update design policies by examining them based on the performance measures with which they are closely associated. This paper addressed this issue from the perspective of highway vertical alignment. Vertical grades and lengths are key components of highway vertical alignment and therefore constitute critical aspects of highway design policy that influences safety.

In this respect, a full understanding of the effect of vertical grade and segment length on highway safety can help agencies to evaluate or adjust their design policies regarding vertical alignment design features (grade and length). In throwing some light on this issue, this paper first established the statistical relationship between vertical grade and length on one hand and highway safety on the other hand. The paper expressed safety in terms of the three different levels of crash severity—fatal, injury, and property damage only. In developing the statistical relationship, the paper eschewed the traditional univariate models (where each crash severity is modeled separately) and instead used a multivariate model (specifically, a seemingly unrelated negative binomial (SUNB) technique), which duly accounts for the unobserved shared effects between the different levels of crash severity.

In addition, the paper's models duly recognized and attempted to account for the holistic nature of the grade and tangent length effects particularly where interaction exists between the two variables: the effect of the sum (interaction) of the vertical grade and length is not necessarily the same as the sum of their individual effects. The research findings showed that the isodehns for rural interstate highways were linear since there was little or no statistically significant interaction between the vertical grade and length for this road class or their coefficients of these two variables were rather small. However, the isodehns for urban highway were not linear because there was statistically significant interaction between the vertical grade and length coefficients, because these two variables had rather large coefficients, or both. The paper investigated the problem statement separately for rural and urban interstate highway segments. Against the background of the developed models, the paper evaluated current design policies (vertical alignment grade and length specifications) for similar classes of highways at a number of countries (USA, China, Iran, and Japan) and presented a set of nomograms that feature safety isodehns vis-à-vis existing practice. These charts can be used by the highway agencies to evaluate and compare their current or possible future highway design policies. In addition, the charts are indicative of the sensitivity of highway safety performance to changes in vertical alignment, which can be used to quantify the expected trade-off between geometry-improvement investments and safety benefits (an important aspect of highway asset management, as pointed out by Sinha et al., [44]).

For the analysis in this paper, the average vertical curve grade in a segment is used. This can be considered appropriate in the case of short segments with uniform grade throughout their length or segments with no crest or sag but with slight grade changes along their length. For instance, a segment with half of its length at +2% and half at −2% will have average grade of 0%, which can be misleading. As such, future studies should consider uniform-grade segments, that is, segments that have the same grade over their entire length. Further, a limitation in the data collection is that the Indiana Crash Dataset used in this paper reports the number of crashes at an aggregate level (i.e., for each road segment). The lack of disaggregate crash data may restrict models from calibrating the impact of vertical curve grade more precisely. In addition, the horizontal curve was shown to be not significant and therefore excluded from this paper. In future research where disaggregate crash data are available, the horizontal curve and its interaction with vertical curve should be further tested. In addition, the framework was demonstrated using crash data from a specific state (Indiana) that may not reflect situations at other states or countries. Nonetheless, the framework presented in this study can be considered general and flexible for use by agencies to evaluate the safety consequences of the highway vertical grade thresholds specified their design policies.

Data Availability

Crash data in this manuscript was provided by Indiana Department of Transportation. It is not currently publicly available.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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