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Accidents Prediction Model based on Speed Reduction on Spanish Two-Lane Rural Highways

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Abstract

The speed reductions can affect to the safety of the road. The Interactive Highway Safety Design Model (IHSDM) Design Consistency Module presents an analysis of the relation between the speed reduction and the accidents for horizontal curves on American two-lane rural highways. In this paper a similar study is performed for Spanish two-lane rural highways. A model for predicting accidents through regression analysis is presented using speed reduction between successive tangents and horizontal curves and between successive curves. Significant parameters related to exposure and geometry as explanatory variables are used.

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1. Introduction

Road accidents are one of the most relevant issues in today's society. To ensure road safety, we need to analyze road layouts from the project phase. One technique used to improve safety on roadways from the point of view of the infrastructure is to examine the consistency of the design. Design consistency refers to highway geometry's conformance to driver expectancy. Generally, drivers make fewer errors in the vicinity of geometric features that conform to their expectations than at features that violate their expectations. The worse the consistency, the more likely it is that drivers will be startled and an accident will occur.

In the 1970s, studies on the effect of consistency on road safety in isolated curves began to be undertaken in the United States [1,2]. The studies analyzed the relationship between several operational parameters and accidents for a limited number of horizontal curves. Subsequently, several studies [3,4,5] identified the degree of curvature as one of the key variables for estimating the number of accidents. Datta et al. [3] pointed out that the degree of curvature is the only variable that has statistical significance. The work by Terhurne and Parker [4] identified AADT and the degree of curvature as the best variables for estimating the number of accidents. The study by Zegeer et al. [5] identified the following variables to have a significant effect on accidents: degree of curvature, roadway width, curve length, AADT, presence of a spiral, super-elevation, and roadside condition. Fitzpatrick et al. [6] analyzed the relationship between several different roadway alignment indices and road safety. Of the candidate measures, three showed relationships to accident frequency that were statistically significant: ratio of an individual curve radius to the average radius for the roadway section as a whole, average rate of vertical curvature, and average radius of curvature.

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Another approach has been to analyze whole sections of roads [7,8,9]. Polus [7] analyzed the relationship between several different indices of roadway alignment indices and accidents. His main conclusion was that safety on the study roads increased as the indices became more uniform along the sections. In the same vein, for roads in Israel and Germany, Mattar-Habib et al. [8] related the number of accidents to road consistency, using Polus et al. [10]'s integration consistency index, which considers the global variation of speed along a section of road and results in a single consistency value for the entire section. Using the same methodology, Camacho et al. [9] recently proposed a model that relates the integration consistency index to the accident rate for Spanish roads.

Table 1. Design Safety Levels Proposed by Lamm et al. [11]

Good	Fair	Poor
$\Delta V_{85} < 10 \text{ km/h}$	$10 \text{ km/h} < \Delta V_{85} < 20 \text{ km/h}$	$\Delta V_{85} > 20 \text{ km/h}$
ΔV_{85} = difference in 85th percentile speed between successive geometric elements (km/h)		

However, given that the best known consistency criterion is among those proposed by Lamm et al. [11], based on speed reduction in the 85th percentile between consecutive geometric elements (ΔV_{85}) (see Table 1), there is an important number of models on operating-speed-based measures as predictors of accident rates at horizontal curves on rural two-lane highways [6,12,13,14].

Based on 261 two-lane rural highways sections in New York State, Lamm et al. [11] studied the 85th percentile speed and accident rates as a function of the degree of curvature. They used this as the basis for obtaining the relationship between speed reduction in the 85th percentile and accident rates. Anderson et al. [12] and Fitzpatrick et al. [6] studied the relationship between ΔV_{85} and accidents in 5.287 horizontal curves. Considering a Poisson distribution, they obtained a model that predicted accidents according to the volume of traffic, curve length and speed reduction (see Eq. 1), and another model that predicted accidents according to speed reduction and a combination of AADT and the curve length into million vehicle-kilometers of travel (see Eq. 2)

$$Y = \exp(-7.1977) \text{AADT}^{0.9224} \text{CL}^{0.8419} \exp(0.0662 \Delta V_{85}) \quad (1)$$

$$Y = \exp(-0.8571) \text{MVKT} \exp(0.0780 \Delta V_{85}) \quad (2)$$

where Y is the number of accidents that occurred on the horizontal curve during a 3-year period, AADT is the annual average daily traffic (vehicles per day), CL is the curve length and MVKT is the exposure (million veh-km of travel for a 3-year period).

Subsequently, Anderson and Krammes [13] related the accident rate (AR) (number of accidents per million vehicles-km) with ΔV_{85} , and obtained a high correlation between the two ($R^2=0.93$) (see Eq. 3). In this case, the reduction in operational speed was an intermediate value for each of the intervals used in the study. In other words, instead of calibrating the relationships for each of the curves recorded, they were grouped together by reductions in speed.

$$\text{mean AR} = 0.54 + 0.27 (\text{mean } \Delta V_{85}) \quad (3)$$

Based on 319 horizontal curves and 511 tangents from Canadian two-way rural highways, Ng and Sayed [14] developed eight models relating design consistency measures to safety. Three of those models ΔV_{85} as explicative variable for expected accident frequency per 5 years (see Eq. 4).

$$\text{Accidents per 5 years} = \exp(-3.796) \text{CL}^{0.8874} \text{V}^{0.5847} \exp(0.04828 \Delta V_{85}) \quad (4a)$$

$$\text{Accidents per 5 years} = \exp(-3.369) \text{CL}^{0.8858} \text{V}^{0.5841} \exp[0.0049(\text{V}_{85} - \text{V}_d) + 0.0253 \Delta V_{85} - 1.177 \Delta f_R] \quad (4b)$$

$$\text{Accidents per 5 years} = \exp(-2.338) \text{L}^{1.092} \text{V}^{0.4629} \exp[\text{IC} (0.022 \Delta V_{85} - 1.189 \Delta f_R)] \quad (4c)$$

Where CL is the length of the curve (km), L is the section length (km); AADT is the annual average daily traffic (vehicles per day); $V_{85}-V_d$ is the difference between operating and design speed (km/h) of a single element; $\Delta f_R=f_R-f_{RD}$, where f_R and f_{RD} are the side friction assumed and demanded on element I, respectively; and IC is a dummy variable (0 for tangents and 1 for horizontal curves).

All these models are based on certain operating speed profiles. Generally, operating speed profiles are based on discrete speed models for curves and straight sections, as well as deceleration and acceleration models in transitions between alignments, unless field data are available. In the past 50 years, many models for predicting operating speed in curves have been developed. They have also been developed to predict speed on straight sections and to estimate acceleration/deceleration between consecutive elements. A good review of these models can be found in [15].

However, the model format, independent variables, and regression coefficients are substantially different from one model to another. This fact is largely due to the difference of driver behavior in different locations. Therefore, most authors [6,15,16] maintain that a single model cannot be universally accepted, and different models adapted to local circumstances should be used.

This paper studies the effect of speed reduction as a consistency criterion for horizontal curves on two-way rural highways in Spain, and their relationship to accident frequency. The paper is organized in four major sections. Section 1 presents an introduction to the main concepts and previous models that reveal the relation between accidents and different parameters of consistency. Section 2 presents the database used and analysis methodology. Section 3 presents the results and discussion. And, finally, section 4 presents the main conclusions of the study.

2. Materials and methods

This paper followed the same methodology used for the Interactive Highway Safety Design Model (IHSDM) developed by the Federal Highway Administration [6], which gave rise to the models indicated in Eq. 1 and 2

Data were obtained from the Spanish General Traffic Accident Directorate (DGT) and from the Dirección General de Carreteras from the Andalucía Regional Government for all regional-maintained rural two-lane highways in the Province of Granada (Spain)—not just a sample. In total, we analysed 1,748 Km of rural two lane highways.

The Granada's rural two-lane highways data obtained from the Andalucía Regional Government included roadway inventories, traffic volume and horizontal alignment. The roadways were reviewed. Portions of the roadway were eliminated within small towns or speed zones or in the vicinity of intersections with Stop or signal control on the major road, intersections with major changes in AADT, and passing or climbing lanes. The remaining highway sections were subdivided into individual horizontal curves and tangents.

The predicted 85th percentile speed of motorists on each tangent and curve was determined using the speed profile models. Section 1 highlights the importance of using speed-prediction models that are calibrated according to local conditions. So, in this paper we use the model proposed by Castro et al. [17] calibrated for horizontal curves for two-way rural highways in Spain (see Eq. 5).

$$V_{85} = 120.16 - 5596.72/R \quad (5)$$

where V_{85} is the 85th percentile speed of passenger cars (km/h) and R is the radius of curvature (m).

The operating-speed profiles were built using the following hypotheses: (a) the speed in each curve is constant and its value is given by Eq. 5; and (b) the speed in tangents is that corresponding to infinite radius in Eq. 5 [17].

Two different operating-speed profiles were built based on the rates of deceleration and acceleration applied between tangent and curve in order to change from the speed in tangent to the speed in curve. The first profile

(PROFILE_1), adopt a constant acceleration and deceleration rate of 0.85 m/s² [18,19] and the second profile (PROFILE_2) adopt the variable acceleration and deceleration rates proposed by Fitzpatrick et al. [6] (see Table 2).

Table 2. Deceleration and acceleration rates for speed profile in horizontal curves with grade between -9% and 9% [6]

Deceleration Rate, d (m/s ²)		Acceleration Rate, a (m/s ²)	
Radius, R (m)	d	Radius, R (m)	a
R ≥ 436	0.00	R > 875	0.00
175 ≤ R < 436	0.6794 - 295.14/R	436 < R ≤ 875	0.21
		250 < R ≤ 436	0.43
R < 175	1.00	175 < R ≤ 250	0.54

These models allow determination of the speed profile for a two-lane highway accounting for the effects of horizontal alignment. In particular, the models can be used to evaluate the speed reductions between successive tangents and horizontal curves and between successive curves (i.e., tangent/curve, curve/tangent, or curve/curve).

Accident data were obtained from de DGT for a period of 3 years (2006–2008). These data were used to determine the 3-year accident experience of each individual horizontal curve. The accident analysis considered only non-intersection accidents that involved: (1) a single vehicle running off the road; (2) a multiple-vehicle collision between vehicles traveling in opposite directions; or (3) a multiple-vehicle collision between vehicles traveling in the same direction. These are the same accident types that Zegeer et al. [5] have identified as being “over-represented on curves as compared to tangents”. All accidents involving parking, turning, or passing maneuvers; animals in the roadway; or bicycles or motorcycles were also excluded.

The relationship between accident frequencies and selected variables (AADT, horizontal curve length and speed reduction) was investigated using loglinear regression models and Poisson or Negative Binomial (NB) distribution. The Poisson distribution is an appropriate choice since accident frequencies are: (1) integers, (2) relatively small numbers, and (3) necessarily non-negative. However, a basic assumption underlying the use of the Poisson distribution is that its mean and variance are equal. When this assumption is substantially violated the NB distribution can provide an improvement over the Poisson distribution.

Two approaches that have been successfully used previously [6,12] are used to treat exposure. First, AADT and curve length are included in the model and their coefficients are estimated separately. In this approach, the natural logarithms of AADT and curve length, rather than their untransformed values, are used in modeling. The functional form for this analysis is a multiplicative model in the form:

$$Y = \exp(\beta_0) \cdot \text{AADT}^{\beta_1} \cdot \text{CL}^{\beta_2} \cdot \exp(\beta_3 \cdot \Delta V_{85}) \tag{6}$$

where AADT is the annual average daily traffic volume (veh/d), and CL is the horizontal curve length (km)

The second approach combines AADT and curve length into million vehicle-kilometers of travel. In this case, the exposure measure is used in the analysis as a scale factor (i.e., its coefficient in the model is forced to be equal to 1.0).

$$Y = \exp(\alpha_0) \cdot \text{MVKT} \cdot \exp(\alpha_1 \cdot \Delta V_{85}) \tag{7}$$

where MVKT is exposure (million veh-km of travel for a 3-year period)

The models were fitted using STATA statistical package [20].

3. Results and discussion

Following the process described in Section 2, 306 highway sections with a total length of 1,748 Km were available for analysis. The traffic volumes of the study sections ranged from 210 to 8,681 veh/day (see Table 3). The final database included 10,289 horizontal curves for which the speed differences from adjacent features could be determined.

Table 3. Descriptive statistics for 10,289 horizontal curves

Parameter	Profile 1 and Profile 2			Fitzpatrick et al. [6]		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Number of accidents in 3 years	0	0.025	4	0	0.33	11
AADT (veh/day)	210	1,170	8,681	222	2,283	18,005
Horizontal curve length (Km)	0.015	0.082	1.071	0.016	0.238	2.977
Exposure (million veh-km)	0.004	0.118	2.847	0.006	0.638	19.777
Horizontal curve radius (m)	16	224.5	2,825	19.5	860.8	15,250
Speed reduction (Km/h) Profile 1	0	14.932	60.16	-	-	-
Speed reduction (Km/h) Profile 2	0	14.602	60.16	-	-	-
Speed reduction (Km/h)	-	-	-	0	3.91	32.4

The 10,289 curves experienced a total of 259 accidents over the 3-year period from 2006 to 2008, with an average value of 0.025 accidents per curve per year. However, a large proportion of the curves (99.85 percent) experienced one or no accident during the 3-year period. The distribution of these accidents is shown in Figure 1. The variance was verified as 0.030. As the mean and the variance were almost equal it was possible to use a Poisson distribution for the model calibration.

The 10,289 individual horizontal curves from the roadway in Granada were classified as good, fair, and poor with respect to design safety using the criteria in Table 1. Table 4 presents a summary of the accident frequencies, exposure, vehicle-kilometers of travel, and accident rates for these 10,289 curves.

It can be observed that the results were very similar, regardless of the operating-speed profile used (Profile 1 or Profile 2). The average accident rate is highest for the horizontal curves in the poor category and lowest for the horizontal curves in the good category. These results are similar to previous studies [6,9,12] and indicate that horizontal curves that require motorists to make greater speed reductions from the approach tangent are likely to have higher accident rates than horizontal curves requiring lower speed reductions.

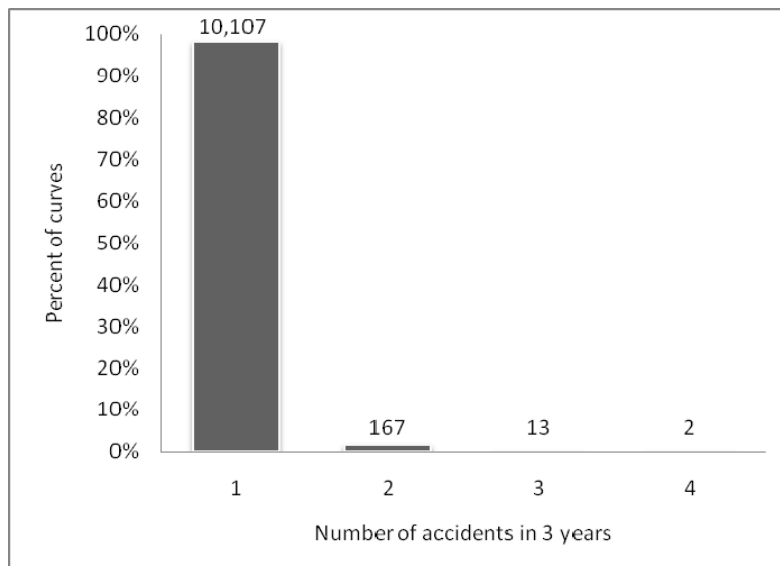


Figure 1.- Accident-frequency distribution at horizontal curves

Table 4. Accident rates at horizontal curves by design safety level

Design Safety Level	Number of Horizontal Curves		3-Year Accident Frequency		Exposure (million veh-km)		Accident Rate (accidents/million veh-km)		
	Profile 1	Profile 2	Profile 1	Profile 2	Profile 1	Profile 2	Profile 1	Profile 2	Fitzpatrick et al. [6]
	Good	5,042	5,155	115	125	661	712	0.17	0.18
Fair	2,185	2,047	61	52	264	202	0.23	0.26	1.44
Poor	3,062	3,087	83	82	276	287	0.30	0.29	2.76
Combined	10,289	10,289	259	259	1,201	1,201	0.22	0.22	0.52

Table 5 shows the results of the adjustment of the models indicated in Eq. 6 and 7. For the purposes of comparison, we have included the results of the models adjusted by Fitzpatrick et al. [6] for development of the Interactive Highway Safety Design Model (IHSDM) by the Federal Highway Administration (third row for each model). For Model 1, all three variables (AADT, CL and ΔV_{85}) were significant at the 95-percent confidence level.

The overall fit of a Poisson model can be assessed using the following goodness-of-fit criteria [21]: the deviance (a measure of over- or under-dispersion of the data, which, under ideal conditions, should be close to 1); the ordinary multiple correlation coefficient (R^2); and the Freeman-Tukey correlation coefficient (R^2_{FT}), each correlation with a maximum of 100 percent.

Table 5. Model adjustment parameters

	β_0	β_1	β_2	β_3	Deviance	$\chi^2_{0.05}/\chi^2$	R ²	R ² _{FT}
Profile 1	-3.1008	1.1228	0.9932	0.0128	0.888	1.14	17.83%	16.52%
p-value	<0.0001	$\chi^2=176$ <0.0001	$\chi^2=238$ <0.0001	$\chi^2=7.21$ 0.0070				
Profile 2	-3.0680	1.1236	1.0002	0.0124	0.890	1.14	17.85%	16.62%
p-value	<0.0001	$\chi^2=178$ <0.0001	$\chi^2=236$ <0.0001	$\chi^2=8.22$ 0.0040				
Fitzpatrick et al. [6]	-7.1977	0.9224	0.8419	0.0662	0.830	1.21	19.5%	17.9%
p-value	<0.0001	$\chi^2=863$ <0.0001	$\chi^2=638$ <0.0001	$\chi^2=200$ <0.0001				
	α_0	α_1			Deviance	$\chi^2_{0.05}/\chi^2$	R ²	R ² _{FT}
Profile 1	-1.9596	0.0124			0.819	1.24	17.74%	16.64%
p-value	<0.0001	$\chi^2=7.05$ 0.008						
Profile 2	-1.9420	0.0119			0.816	1.25	17.76%	16.60%
p-value	<0.0001	$\chi^2=7.98$ 0.0050						
Fitzpatrick et al. [6]	-0.8571	0.0780			0.836	1.34	15.6%	16.8%
p-value	<0.0001	$\chi^2=n.a.$ <0.0001						

For Model 1, the deviance was 0.888 in Profile 1 and 0.890 in Profile 2. The deviance value close to 1 is an indication that the model can be considered appropriate in modeling the data. The two values are very similar to the 0.830 obtained in the model by Fitzpatrick et al. [6]. For Model 1, the two correlation coefficients were R²=17.83% and R²_{FT}=16.52% for Profile 1, and R²=17.85% and R²_{FT}=16.62% for Profile 2. All of them are also very similar to those obtained by Fitzpatrick et al. [6] (R²=19.5% and R²_{FT}=17.9%). The coefficient between the chi-square value for a 95% confidence level and the sample's chi-square value gave values of 1.14 for both speed profiles, which is close to the 1.21 obtained by Fitzpatrick et al. [6]. For Model 2, in which exposure was used as a scale factor rather than incorporating AADT and curve length as separate variables, the values obtained were very close to those obtained by Fitzpatrick et al. [6] as well (see Table 5).

However, in the study by Fitzpatrick et al. [6] the adjustment for Model 1 was somewhat higher than the adjustment for Model 2. In this study the adjustment for both models was so similar that it is impossible to highlight one more than the other to explain the variation in accident data.

Although neither of the models explain a large proportion of the variation in accident data (ranging from 15.6% to 19.5%), this is often the case with regression relationships between geometric design elements and safety. A key finding is that both models show a relationship between the speed reduction on a horizontal curve and the accident frequency on that curve. In both relationships, the speed reduction effect is highly significant because the significance level in both cases was less than 0.05. The direction of both relationships indicates that the greater the speed reduction experienced by motorists on a horizontal curve, the greater the curve's accident experience. This also explains why speed reduction is one of the main measures of design consistency.

The comparison of the results of this research conducted on Spanish roads and American roads [6] shows that the speed reduction on a horizontal curve is significantly more important in the American model (p-value <0.0001) than in the Spanish models (p-value < 0.008). With regards to curve length and the AADT, although they are significantly similar in the American and Spanish models (p-value <0.0001), when one of the two variables was increased, the number of estimated or predicted accidents was higher in the Spanish models than in

the American ones (coefficients β_1 and β_2 higher or very close to 1 in the former case, as opposed to coefficients lower than 1 in the latter case).

4. Conclusions

In this paper, two models proposed by the American IHSDM Design Consistency Module that relate speed reduction to accidents for horizontal curves on two-lane rural highways were calibrated for Spanish roads. A Poisson distribution was used to study the relationship between accident frequencies and exposure, curve geometries, and speed-reduction variables, following the same procedure used by the IHSDM. Two models that differ in the manner of considering the exposure measure were analyzed. In the first model, annual average daily traffic (AADT) and curve length were estimated separately. In the second model, AADT and the curve length were combined into million vehicle-kilometers of travel. The two models show that curve length, AADT and the speed reduction between successive features (i.e., tangent/curve, curve/tangent, or curve/curve) are strongly related to accident frequency. The models calibrated for Spanish roads showed trends that were similar to the models obtained for American roads [6].

Two different speed profiles (Profile 1 and Profile 2) were used to calculate each of the two models. Profile 1 differed from Profile 2 insofar as the former considered a constant acceleration value and the latter considered an acceleration value that varied according to the radius of the curvature. The models calculated using the two different profiles gave very similar results.

In this study, as in previous studies [6,12], the independent variable used was the increase in operating speeds (ΔV_{85}) since discrete models of operating speeds are already being used to infer speed profiles. In the event that field data on vehicle traffic speeds are available, it would be interesting to calibrate the models using the 85 percentile for the difference in actual driving speeds ($\Delta_{85}V$), which indicates the speed that is not exceeded by 85% of vehicles under free flow conditions [22]. Hirsh [23] indicated that $\Delta_{85}V$ is substantially higher than ΔV_{85} . In the same vein, based on data from 28 sections of Spanish roads, Pérez et al. [24] developed a model that related the two variables, which gave the result that $\Delta_{85}V$ is around 5 km per hour higher than ΔV_{85} , with an R^2 of 0.79.

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