Llopis-Castelló, D.; Findley, DJ.; Camacho-Torregrosa, FJ.; García García, A. (2019). Calibration of Inertial Consistency Models on North Carolina Two-Lane Rural Roads. Accident Analysis & Prevention. 127:236-245. https://doi.org/10.1016/j.aap.2019.03.013

Calibration of Inertial Consistency Models on North Carolina Two-Lane Rural Roads

CALIBRATION OF INERTIAL CONSISTENCY MODELS ON NORTH CAROLINA TWO-LANE RURAL ROADS

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ABSTRACT

Road crash occurrence is closely related to the geometric design consistency, which can be defined as how drivers' expectancies and road behavior fit. To this regard, the crash rate on a road segment increases as its consistency level decreases.

To assess this phenomenon, inertial consistency models were recently developed. These models are based on the difference between the inertial operating speed, which represents drivers' expectancies, and the operating speed, which represents road behavior. The higher the difference between both speeds, the higher the likelihood of crash occurrence.

This research aims to validate and calibrate these consistency models on American two-lane rural roads. For this, a total of 194 homogeneous road segments and 977 horizontal curves along 665 km in North Carolina (US) were used.

As a result, the geometric design consistency was identified as a major factor of crash occurrence. The higher the difference between drivers' expectancies and road behavior, the higher the crash rate. Likewise, the greater the consistency level, the greater the percentage of horizontal curves without reported crashes.

A Safety Performance Function was also calibrated to estimate the number of crashes on a road segment. Consistency thresholds were defined and tested to identify where these crashes are more likely to take place.

Finally, the results obtained in this study were compared with those obtained previously on Spanish highways. To this regard, the crash rate on an American highway was 1.85 times greater than those observed on a Spanish highway under the same risk exposure and consistency conditions.

Therefore, different tools were developed to enhance the assessment of road safety to the geometric design of both new two-lane rural roads and improvements of existing highways.

Keywords: *geometric design consistency, road safety, operating speed, inertial operating speed, driver's behavior*

INTRODUCTION

Road safety is a public health concern due to the years of productive lives lost resulting from crashes. More than 35,000 people die in road crashes every year in the United States. Particularly in North Carolina (US), the number of fatal crashes increased by 7% between 2014 and 2015, which was similar to the mean increase in the country. In addition, 70% of fatal crashes took place on rural highways in this state (FHWA, 2015).

The most important factors for road crash occurrence are infrastructure, vehicle, and human factors. Particularly, the infrastructure factor is responsible for over 30% of road crashes (Treat et al., 1979). In fact, crashes tend to concentrate at certain road elements. For this, infrastructure and its interaction with human factors have been thoroughly studied in recent years through geometric design consistency, which can be defined as how drivers' expectations and road behavior relate.

The main objective of the geometric design consistency is to minimize the emergence of unexpected events when road users drive along a road segment. To this regard, a consistent road provides a harmonious driving free of surprises, which is associated with a low number of road crashes (Gibreel et al., 1999). On the contrary, an inconsistent road might present numerous unexpected events to drivers, leading to an anomalous behavior and increasing the likelihood of crash occurrence.

There are several methods to assess geometric design consistency: operating speed, vehicle stability, alignment indices, and driver workload (Gibreel et al., 1999). However, most of the consistency models are based on the analysis of the operating speed profile. Operating speed is frequently defined as the 85th percentile of the speed distribution for passenger cars under free-flow conditions with no external restrictions (V_{85}). One important advantage of its use is the possibility to estimate it using operating speed models.

There are two types of consistency models: local and global. Local models focus on localized issues, such as sudden speed reductions or high differences between the design and operating speeds (Lamm et al., 1999; Llopis-Castelló et al., 2018d). Those models are ideal to identify where road crashes are more likely to take place. On the other hand, global consistency models examine the overall speed variation throughout an entire road segment (Polus and Mattar-Habib, 2004; Garach et al., 2014; Camacho-Torregrosa, 2015; Llopis-Castelló et al., 2018c). Although they do not indicate where crashes are prone to take place, they can be introduced into a Safety Performance Function (SPF) to predict the number of crashes on an entire road segment.

To this regard, several researchers have tried to link the number of crashes to different variables related to risk exposure (traffic volume and road length), geometry, consistency and road environment by means of SPFs. Among those studies which incorporate the consistency as an explanatory variable, all of them concluded that the level of consistency has a major influence on road crash occurrence (Anderson et al. (1999); Ng and Sayed, 2004; Awatta et al., 2006; Montella et al., 2008; Cafiso et al., 2010; de Oña et al., 2013; Quddus, 2013; Wu et al., 2013; Garach et al., 2014; Camacho Torregrosa, 2015; Montella and Imbriani, 2015; Garach et al., 2016).

Additionally, other studies have been developed to analyze road safety by using the relationship between transverse and longitudinal accelerations and speed. Regarding this, Eboli et al. (2016) proposed a classification of car drivers' behavior (safe and unsafe) based on the relationship between speed and the g-g diagram, which relates the lateral and longitudinal accelerations, along a road segment. This relationship, which can be considered as a surrogate measure of the objective risk, was compared with the subjective risk perceived by drivers, determined through a numerical scale from -2 (aggressive) to +2 (cautious) (Eboli et al., 2017). As a result, different levels of risk were defined as a function of the percentage of points classified as unsafe (p) along a road segment: low ($p \leq 5\%$), medium ($5\% \leq p \leq 8\%$), and high ($p \geq 8\%$).

After this brief introduction, the literature review summarizes the salient efforts from previously developed consistency models. After which, the main objective of this research effort is defined, and the methodology and data are thoroughly described. Then, the new consistency models for North Carolina two-lane rural roads are defined which includes a detailed discussion. The paper finishes with a brief section on the most important conclusions of the research.

LITERATURE REVIEW

The most widely used local method was developed by Lamm et al. (1999). They proposed two design consistency criteria related to operating speed. Criterion I focuses on disparities between operating and design speeds; and criterion II examines operating speed differences between successive elements (ΔV_{85}). Different consistency thresholds were defined for both criteria, distinguishing between good, fair, and poor consistency based on average crash rates observed at several alignment layouts.

Although Criterion II has been incorporated into several road design guidelines, some authors proposed the use of $\Delta_{85}V$, defined as the 85th percentile of the individual speed reductions performed by drivers, rather than ΔV_{85} because this criterion underestimates the actual speed reduction (Misaghi and Hassan, 2005; Castro et al., 2011; Bella and Calvi, 2013; de Oña et al., 2013).

The first global consistency model was developed by Polus and Mattar-Habib (2004), which was based on two parameters: relative area (Ra) and operating speed dispersion (σ). The first parameter was defined as the area bounded by the operating speed profile and the average operating speed, divided by the length of the road segment. The same parameters were used by Garach et al. (2014) to calibrate a new consistency model on Spanish two-lane rural roads.

Later, Camacho-Torregrosa (2015) developed another global consistency model considering two operational parameters: the average operating speed and the average deceleration rate. Additionally, this research analyzed the influence of the selection of homogeneous road segments on the estimation of road crashes.

In this regard, the selection of the road segment is critical for the application of global consistency models. Selected road segments must be homogeneous, because the outcomes depend mainly on the identification procedure (Resende and Benekohal, 1997; Cafiso et al., 2010; García et al., 2013a; Camacho Torregrosa, 2015).

However, the Predictive Method proposed by the Highway Safety Manual (HSM) tries to assess the geometric design consistency on an entire road segment through the summation of the individual estimation of the number of crashes on each road element (AASHTO, 2010). To this regard, the Crash Modification Factors do not take into account the features of the entire road segment; they are only focused on the individual features of the assessed road element. In this way, a certain road element contained in two different homogeneous road segments will estimate the same number of crashes under the same risk exposure conditions. Thus, this method is not able to properly assess the geometric design consistency of an entire road segment.

Therefore, none of the abovementioned consistency models include the underlying consistency phenomenon in their formulation, i.e., they do not estimate drivers' expectancies while driving along a road segment.

To address this weakness, García et al. (2013b) defined a new speed concept - the inertial operating speed (V_i) - as a surrogate measure of drivers' expectancies, like previous researchers proposed the use of drivers' speed as a surrogate measure of their behavior (Lamm et al., 1988; Polus and Mattar-Habib, 2004; Garach et al., 2014; Camacho-Torregrosa, 2015). Nevertheless, this does not mean that drivers choose their speeds in a conscious way, since the driving task is defined as an automatic task (Charlton and Starkey, 2011).

Thus, the inertial operating speed was defined as the average operating speed of the previous 1,000 meter road segment. Conversely, road behavior was associated with the operating speed (V_{85}). A new local consistency parameter, the Inertial Consistency Index (ICI), was defined as the difference between V_i and V_{85}. Therefore, the larger this index, the greater the difference between drivers' expectations and road behavior and thus crashes are more likely to occur.

However, this definition of V_i does not properly match the drivers' expectation acquisition process, which is related to Short-Term Memory (STM), since the driving task is normally an unaware/automatic task that uses STM to remember and process information at the same time. To this regard, STM is gradually in decline over time, with the information lost in approximately 18 seconds (Revlin, 2012).

Drivers do not recall all locations of the previous road section with the same intensity. Therefore, the first and final parts of the section should not be considered equally to determine the inertial operating speed. In addition, given two homogeneous road segments with different average operating speeds, the periods of time needed to travel the same distance are different. Thus, estimating V_i as the weighted average operating speed based on time would possibly allow for a more accurate estimation of the phenomenon.

Studies have been developed to identify which period of time and weighting distribution should be considered to better explain drivers' expectancies (Llopis-Castelló et al., 2018a, 2018b, 2018c and 2018d). In this regard, periods of time from 10 to 60 seconds with a step of 5 seconds were analyzed. As a result, the inertial operating speed was defined for each point of the alignment as the weighted average operating speed of the last 15 seconds considering a linear weighting distribution. In addition, local and global inertial consistency models were proposed. The global consistency parameter was based on the difference between the inertial operating speed profile and the operating speed profile, whereas the local consistency parameter was the ICI. Likewise, a SPF was proposed to estimate the number of crashes on Spanish two-lane rural roads and different consistency thresholds were defined to identify where these crashes are more likely to take place (Table 1).

TABLE 1 Inertial consistency models

<table>
<tr><th colspan="3">Global consistency model (Llopis-Castelló et al., 2018c)</th></tr>
<tr><td colspan="3">$Y_{i,10} = e^{-6.6479} \cdot L^{1.02645} \cdot AADT^{0.86684} \cdot e^{0.14774 \cdot C}$</td></tr>
<tr><td>Good
$C \leq 2.75$ km/h</td><td>Fair
2.75 km/h $< C \leq$ 4.5 km/h</td><td>Poor
$C >$ 4.5 km/h</td></tr>
<tr><th colspan="3">Local consistency model (Llopis-Castelló et al., 2018d)</th></tr>
<tr><td>Good
ICI ≤ 5 km/h</td><td>Fair
5 km/h < ICI ≤ 12.5 km/h</td><td>Poor
ICI > 12.5 km/h</td></tr>
</table>

where $Y_{i,10}$ is the number of fatal-and-injury crashes on the homogeneous road segment in 10 years; L is the length of the homogeneous road segment (km); $AADT$ is the Average Annual Daily Traffic (vpd); C is the consistency parameter (km/h); and ICI is the Inertial Consistency Index (km/h).

Due to the successful performance of the inertial consistency models in Italy and Spain, the primary goal of this study was to validate their use on American two-lane rural roads. This will allow engineers to have new useful tools to assess road safety.

OBJECTIVES

The main objective of this research was to validate the global and local inertial consistency model comparing the difference between the inertial operating speed and the operating speed with the number of crashes on American two-lane rural roads.

Secondary objectives of this study were the calibration of a Safety Performance Function based on the global consistency model to estimate the number of crashes on a homogeneous road segment and the definition of different consistency thresholds to identify on which road geometric elements these crashes tend to concentrate.

METHODOLOGY AND DATA DESCRIPTION

Methodology

The methodology of this study was based on the analysis of the relationship between the inertial consistency parameters and road crashes.

Two-lane rural road sections located in North Carolina (US) were selected. Next, the geometry for each road section was recreated by means of the methodology proposed by Camacho-Torregrosa et al. (2015) and the operating speed profiles were estimated considering operating speed models and acceleration and deceleration rates calibrated on American two-lane rural roads. From this, the inertial operating speed profiles were calculated for every road segment considering 15 seconds and a linear weighting distribution (Llopis-Castelló et al., 2018c and 2018d). Crash and traffic data were also obtained. The analysis was focused on the study of the relationship between crash rates and consistency. Finally, a Safety Performance Function was calibrated and consistency thresholds were defined for both global and local inertial consistency models.

Road segments

A total of 94 two-lane rural road sections located in North Carolina (US) were selected for the study. This meant that the geometric recreation of approximately 665 km of highway produced 194 homogeneous road segments, which were identified following the same procedure as for the previous research on Spanish two-lane rural roads (Llopis-Castelló et al., 2018c).

First, road segments were divided into sections with similar traffic volume and cross-section. Major intersections, usually associated to roundabouts or interchanges, also influence drivers' expectancies, so they were also considered for segmentation (Cafiso et al., 2010). Finally, each road section was divided according to its geometric behavior using the German methodology (RAS-L, 1995), which is based on the analysis of the Curvature Change Rate (CCR). This parameter is defined as the rate between the sum of the absolute deflection angles and the length of the road segment. Figure 1 shows how this last step is carried out: a profile of the cumulative absolute deflection angle versus the road station must be plotted. In this way, homogeneous road segments can be distinguished according to similar CCR behavior.

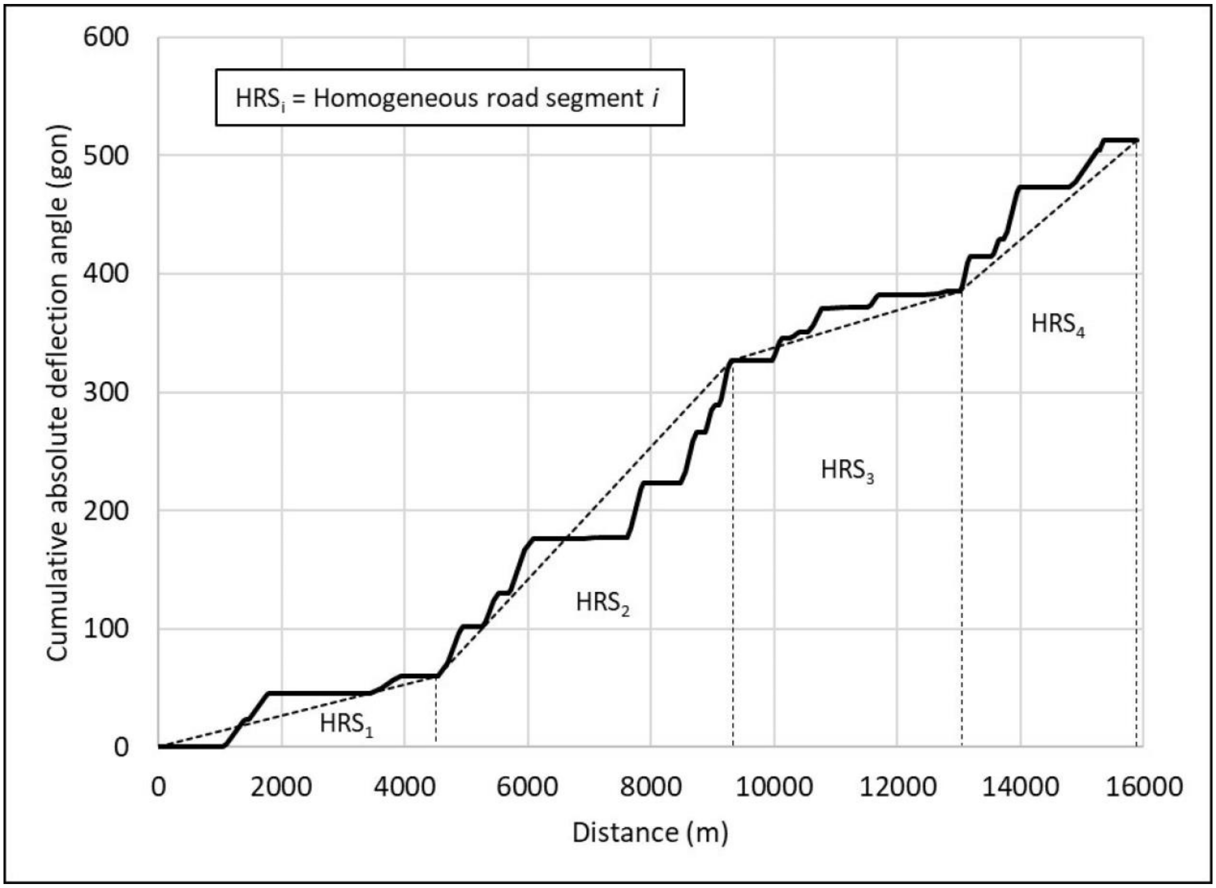


FIGURE 1 Identification of homogeneous road segments.

Table 2 shows the main geometric characteristics of the studied homogeneous road segments. Their length ranged from 575 m to 18,712 m, and their longitudinal grade did not exceed 4%. Regarding cross-section, lane widths ranged from 3.00 to 3.50 m, and the shoulder width varied from 0.5 to 1.50 m.

TABLE 2 Features of the homogeneous road segments

Road	**Length (km)**			***AADT* (vpd)**		***CCR* (gon/km)**		**Fatal-and-injury crashes**
	Total	**Min.**	**Max.**	**Min.**	**Max**	**Min.**	**Max.**	
NC41	149.6	1.8	13.0	1,325	7,040	0	56.07	211
NC42	141.8	0.8	10.9	634	5,033	0	175.80	186
NC43	87.4	1.0	18.7	1,499	6,860	0	86.20	155
NC49	109.5	0.9	11.1	788	7,300	0	92.21	162
NC96	102.7	1.2	7.3	1,230	7,700	6.59	116.32	178
NC268	73.8	0.6	4.9	378	6,880	0	490.11	124

Min=Minimum; Max=Maximum; *AADT*=Annual Average Daily Traffic; *CCR*=Curvature Change Rate.

Traffic and crash data

Traffic volume and crash data were provided by the North Carolina Department of Transportation (NCDOT). Thus, the Annual Average Daily Traffic (*AADT*) volumes and the number of fatal-and-injury crashes were identified for each homogeneous road segment and horizontal curve.

AADT was defined as the average traffic volume from 2012 to 2016. As a result, the homogeneous road segments had an *AADT* ranging from 378 to 7,700 vpd (Table 2).

In North Carolina, if people are involved in a crash but there are no injuries, the drivers only have to report the crash if the damage property value is equal to or greater than $1,000. Therefore, Property Damage Only (PDO) crashes are not always reported to authorities and, consequently, to include this type of crash might lead to biased results and an inaccurate interpretation of the phenomenon.

Thus, only fatal-and-injury crashes were considered over the same period of time. The cause of every crash was reviewed, so to only include those related to geometry (e.g., crashes caused by vehicles entering the road from minor roads or driveways were removed from the analysis, since their cause is not the road geometry per se). As a result, a total of 1,016 reported crashes were analyzed (Table 2).

Speed profiles

Operating speed profiles

The operating speed profile for each road segment was estimated using the speed model for horizontal curves calibrated by Ottesen and Krammes (2000), the speed model for tangents developed by Polus et al. (2000), and the acceleration and deceleration rates proposed by the Interactive Highway Safety Design Model (Figure 2). All these models were calibrated based on speed data collected on American two-lane rural roads. The primary reason for using these models is that the highways considered in this study have the same general characteristics of those used in the calibration of these models.

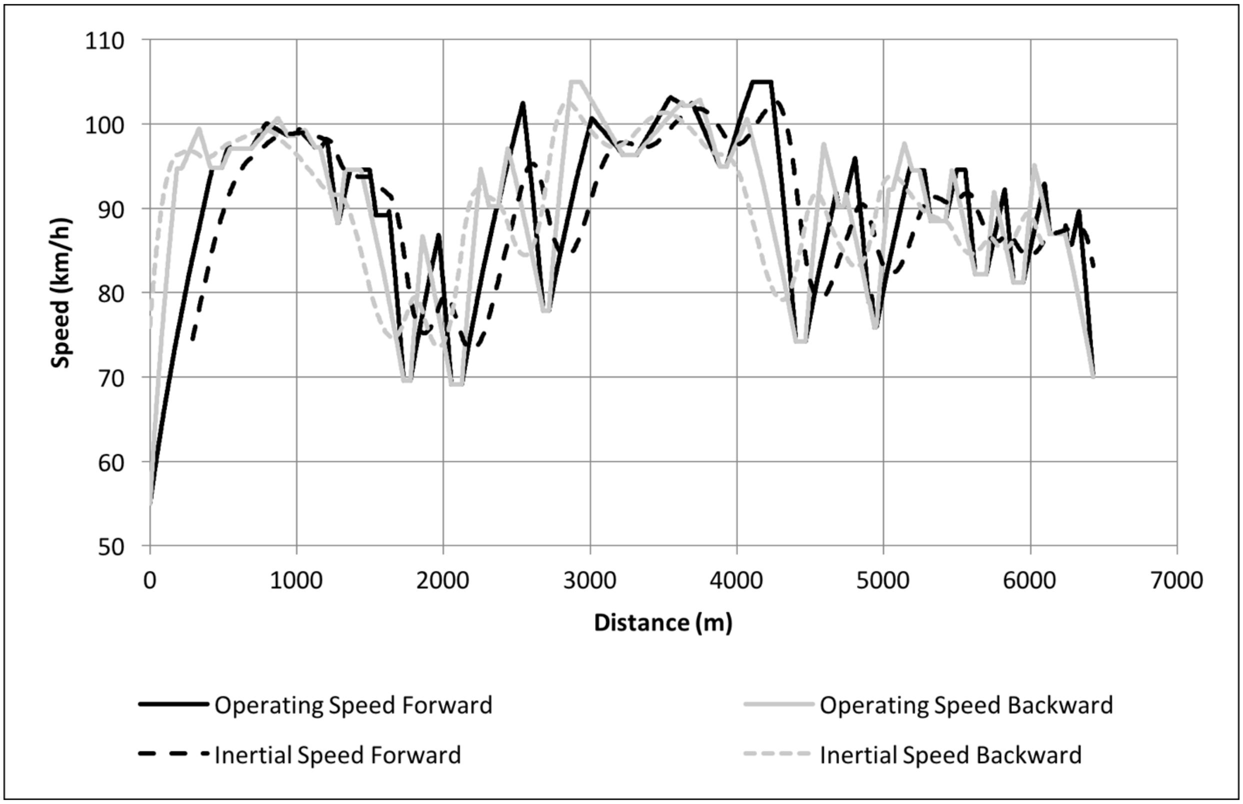


FIGURE 2 Speed profiles

Inertial speed profiles

The inertial operating speed profile was calculated for every road segment on the basis of its operating speed profile. According to Llopis-Castelló et al. (2018c and 2018d), the inertial operating speed is defined for each point of the alignment as the weighted average operating speed of the preceding 15 seconds considering a linear weighting distribution:

$$V_{i,k} = \frac{\sum w_j \cdot V_{85,j}}{\sum w_j} \qquad (1)$$

where $V_{i,k}$ is the inertial operating speed (km/h) at point k; $V_{85,j}$ is the operating speed at point j; and w_j is the weighting factor at point j.

To this regard, the weighting distribution ranges linearly from 0 for the furthest point to 1 for the closest point. This calculation was carried out for time intervals (j) of 0.1 s (Figure 2).

Consistency parameters

Global consistency model

The global consistency parameter proposed by Llopis-Castelló et al. (2018c) is calculated from the difference between the inertial operating speed profile and the operating speed profile (Figure 3). This parameter is defined as follows:

$$C = \sqrt{\frac{A(+) \cdot \sigma(+)}{L(+)}}\ [km/h] \qquad (2)$$

where C is the consistency parameter (km/h); $A(+)$ is the area bounded by the difference between V_i and V_{85} and the x axis considering only the positive differences (m·km/h); $L(+)$ is the length of the homogeneous road segment considering only the positive differences (m); and $\sigma(+)$ is the standard deviation of the difference between V_i and V_{85} considering only the positive differences (km/h). Only positive differences were included to focus on locations were the inertial operating speed (V_i) exceeds the operating speed (V_{85}).

The consistency of a homogeneous road segment is estimated as the average of the consistency parameters calculated for the forward and backward direction.

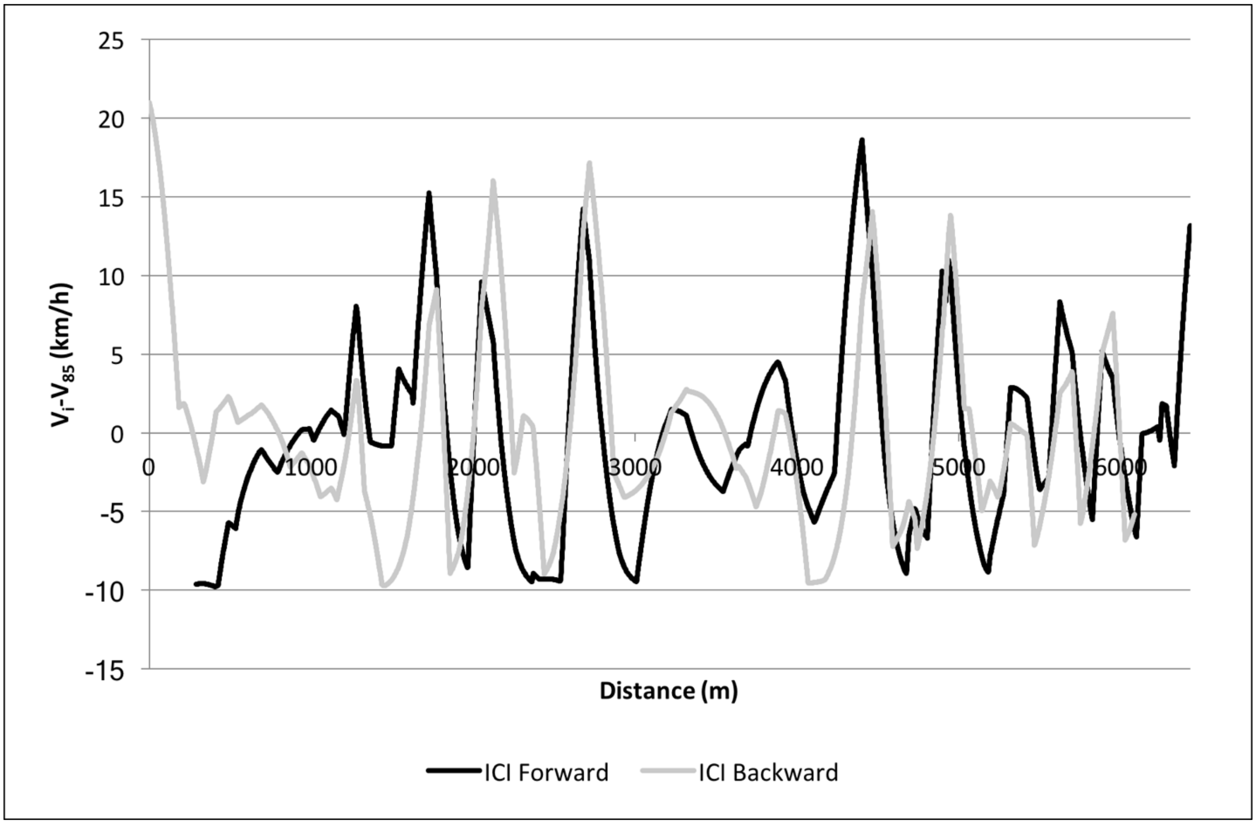


FIGURE 3 Difference between inertial operating speed profile and operating speed profile

Local consistency model

The local consistency parameter, called Inertial Consistency Index (ICI), is directly calculated by the difference between the inertial operating speed (V_i) and the operating speed (V_{85}) at the beginning point of the curve (Llopis-Castelló et al., 2018d). Specifically, a total of 977 horizontal curves were considered in this research to validate the local consistency model.

RESULTS

Global consistency model

First, the relationship between consistency and crash rate was analyzed. Figure 4 shows that as the consistency parameter increases, the crash rate increases. These results are consistent with the phenomenon studied, since the higher the difference between drivers' expectancies and road behavior, the higher the likelihood of crash occurrence.

Then, different consistency thresholds were defined by means of a cluster analysis. Regarding this, the studied road segments were classified into three groups considering the values of the consistency parameters through a k-means clustering, which used the squared Euclidean distance as a measure of cluster scatter. As a result, a homogenous road segment presents a good consistency level when the consistency parameter (C) is lower than 2 km/h, a poor consistency level when C is higher than 4.25 km/h, and a fair consistency level in all other cases (Figure 4).

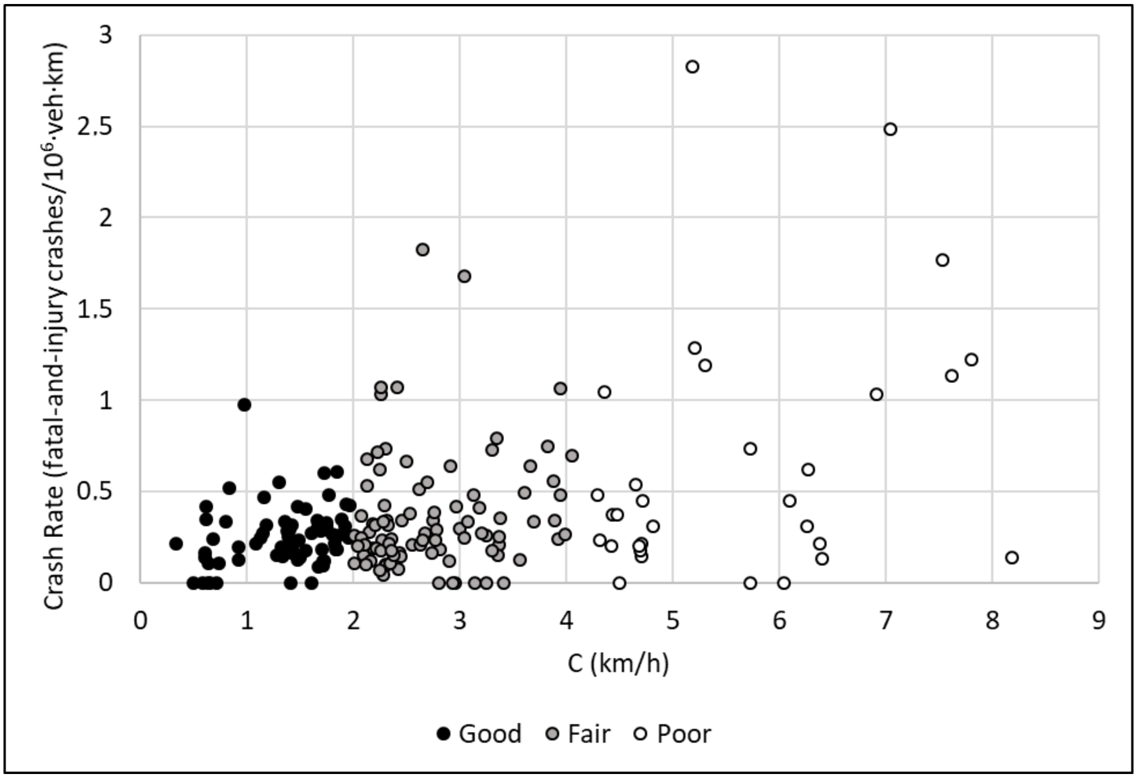


FIGURE 4 Global consistency model Vs. Crash rates

Additionally, the average crash rate for each consistency level was calculated and statistically significant differences at a 95% confidence level between these consistency levels were identified through a hypothesis test (Figure 5).

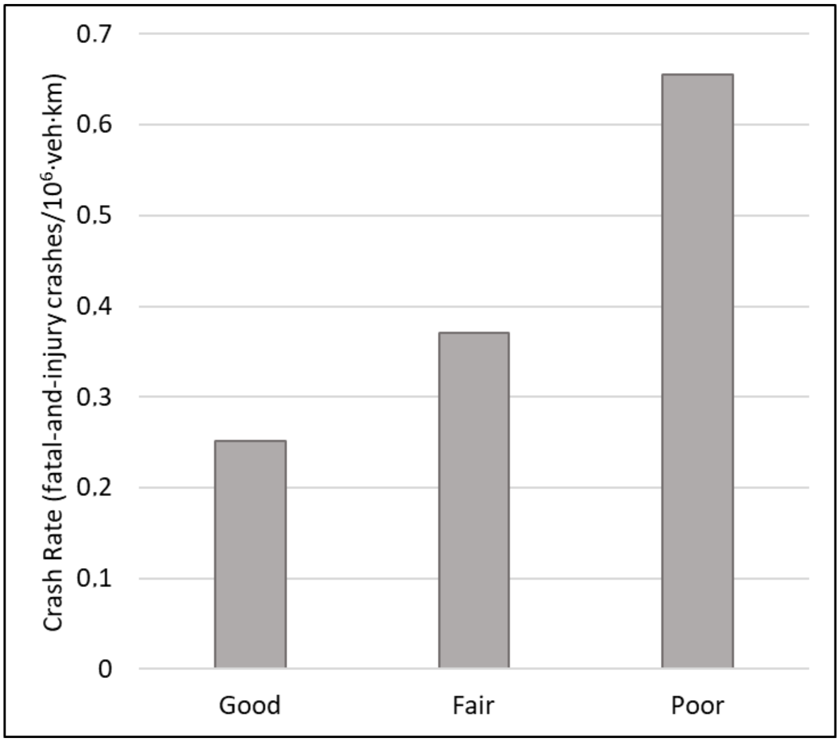


FIGURE 5 Average crash rate Vs. Consistency level. Global consistency model.

Finally, a Safety Performance Function (SPF) was calibrated to estimate the number of crashes on an entire homogeneous road segment. Following common practice, generalized linear modelling techniques were used to fit a SPF that relates exposure and consistency to the number of crashes (Equation 3). A negative binomial distribution was assumed, since it is an appropriate solution with over dispersed, count data (Lord et al., 2010).

$$\boldsymbol{Y_{i,5} = e^{\beta_0} \cdot L^{\beta_1} \cdot AADT^{\beta_2} \cdot e^{\beta_3 \cdot C}} \qquad (3)$$

where $Y_{i,5}$ is the number of fatal-and-injury crashes on the homogeneous road segment in 5 years; β_i are regression coefficients; L is the length of the homogeneous road segment (km); $AADT$ is the Average Annual Daily Traffic (vpd); and C is the consistency parameter (km/h).

However, it is well known that crashes are highly affected by risk exposure. Indeed, several previous researchers have developed safety performance functions that only depend on risk exposure (Harwood et al., 2000; Cafiso et al. 2010). The SPF which does not consider the consistency presents the following functional form:

$$\boldsymbol{Y_{i,5} = e^{\beta_0} \cdot L^{\beta_1} \cdot AADT^{\beta_2}} \qquad (4)$$

This model is not of major interest, but is useful to determine how important the inclusion of the consistency term is for crash estimation.

The results of these adjustments are summarized in Table 3. As expected, all parameters are statistically significant. The regression coefficients related to L and $AADT$ are lower than 1, so longer homogeneous road segments and higher traffic volumes induce lower crash rates. In addition, the SPF which jointly considers risk exposure and consistency resulted in better indexes of goodness of fit than the single-exposure SPF. To this regard, the lower the value of these indexes (*AIC*, *RMSE*, and *MAE*), the better the model.

Although *RMSE* and *MAE* do not take into account the number of explanatory variables in their calculation, the Akaike Information Criterion (*AIC*) includes a penalty for the models including more variables, thus discouraging overfitting.

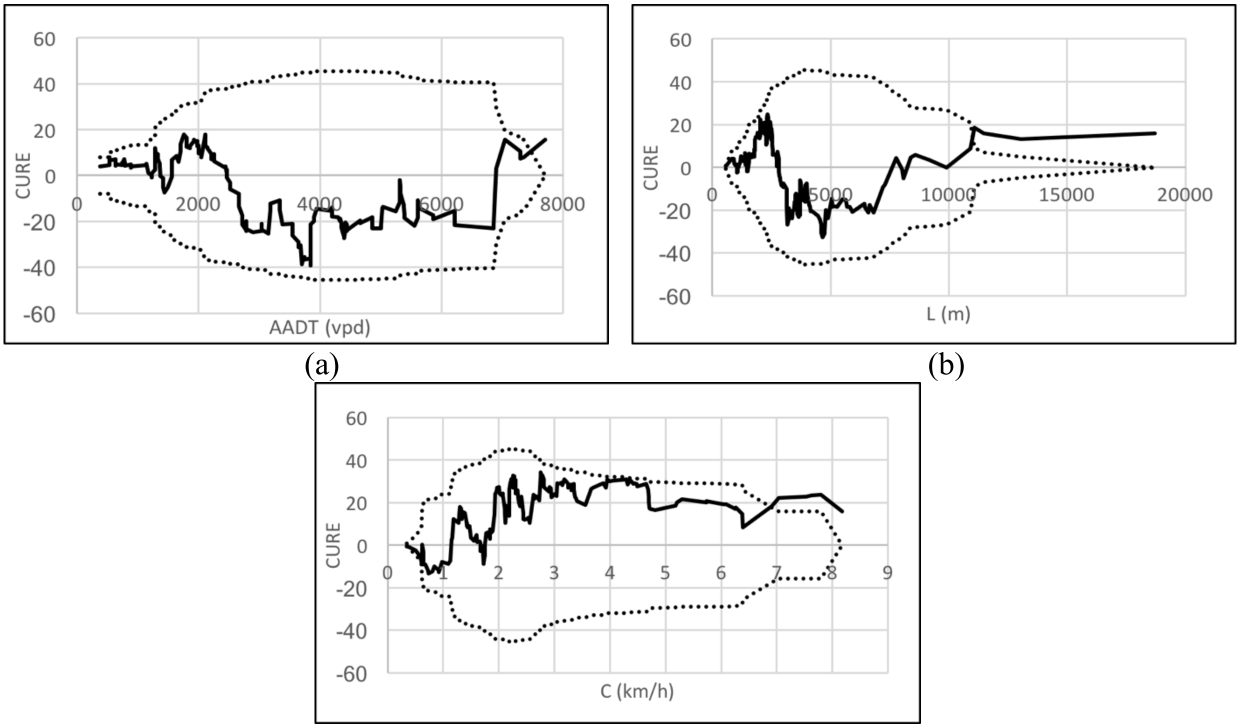
TABLE 3 Statistical adjustment of SPFs. Global consistency model.

	β_0	β_1	β_2	β_3	*AIC*	α	*RMSE*	*MAE*
	-	ln L	ln $AADT$	C				
Estimate	-5.46301	0.84067	0.73116	0.03055	899.98	0.1258	3.26	2.31
Pr(>|z|)	$< 2\cdot10^{-16}$	$< 2\cdot10^{-16}$	$< 2\cdot10^{-16}$	0.000395				
Estimate	-4.62152	0.77120	0.67107		909.61	0.1420	3.34	2.35
Pr(>|z|)	$< 5.8\cdot10^{-16}$	$< 2\cdot10^{-16}$	$< 2\cdot10^{-16}$					

AIC=Akaike Information Criterion; *RMSE*=Root Mean Squared Error; *MAE*=Mean Absolute Error; *α*=overdispersion parameter.

The quality of fit was also studied from the Cumulative Residuals (CURE) Plots (Hauer and Bamfo, 1997; Lord and Persaud, 2000). This method consists of plotting the cumulative residuals for each independent variable. The aim is to graphically observe how well the function fits the data set. The CURE method has the advantage of not being dependent on the number of observations, as are many other traditional statistical procedures. In general, a good cumulative residuals plot is one that oscillates around 0. Thus, a good fit is given when the residuals do not stray beyond the $\pm 2\sigma^*$ boundaries.

It can be observed that the plots against each explanatory variable do not stray beyond the $\pm 2\sigma^*$ boundaries, apart from a few points when L or C are high (Figure 6). It is mainly due to the limited available data for long lengths and road segments with very poor consistency. In these situations, the proposed model tends to underestimate the number of crashes. So, it is recommended to use the proposed SPF for homogeneous road segments which present a length shorter than 12 km. Despite this, the new SPF is a useful tool to estimate the number of crashes on American two-lane rural roads.



(a) (b)

(c)

FIGURE 6 CURE plots: (a) *AADT*; (b) Length; (c) Consistency. Global consistency model.

Local consistency model

The same procedure has been followed to analyze the local inertial consistency model. Figure 7 shows the relationship between the Inertial Consistency Index (ICI) and the crash rates considering all horizontal curves included in the studied homogeneous road segments. As expected, most of curves did not have reported crashes (≈70%). However, a clear trend was observed: the higher the ICI, the higher the crash rate.

Different consistency thresholds were defined by means of a cluster analysis. In this case, a horizontal curve has a good consistency level when the ICI is lower than 4 km/h, a poor consistency level when the ICI is higher than 11.5 km/h, and a fair consistency level in all other cases. Additionally, the percentage of horizontal curves without crashes was lower as the consistency level worsened. Specifically, 72% of horizontal curves with good consistency level did not have reported crashes during the study period, whereas this percentage was approximately 55% when the consistency level was poor. Therefore, the lower the consistency level, the higher the likelihood of crash occurrence.

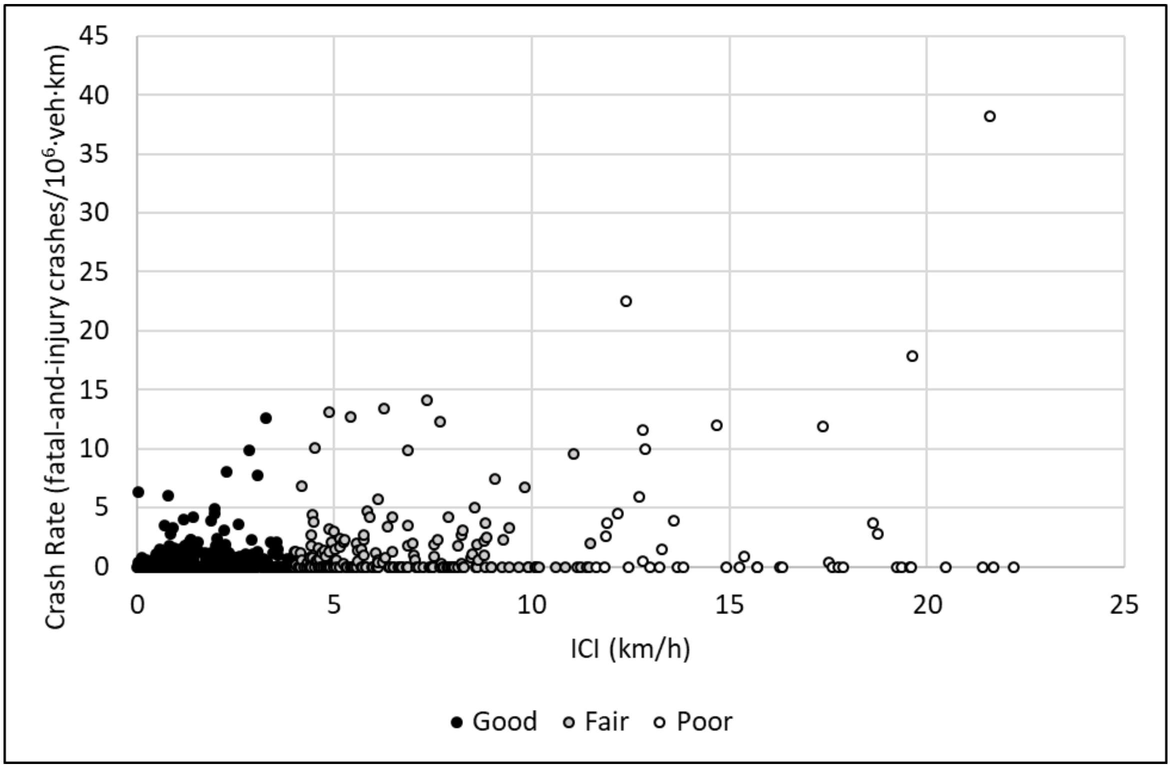


FIGURE 7 Local consistency model Vs. Crash rates

The average crash rate for each consistency level was also analyzed (Figure 8). To this regard, statistically significant differences between the consistency levels were identified at a 95% confidence level. Thus, this consistency model allows a determination of where crashes are more likely to occur.

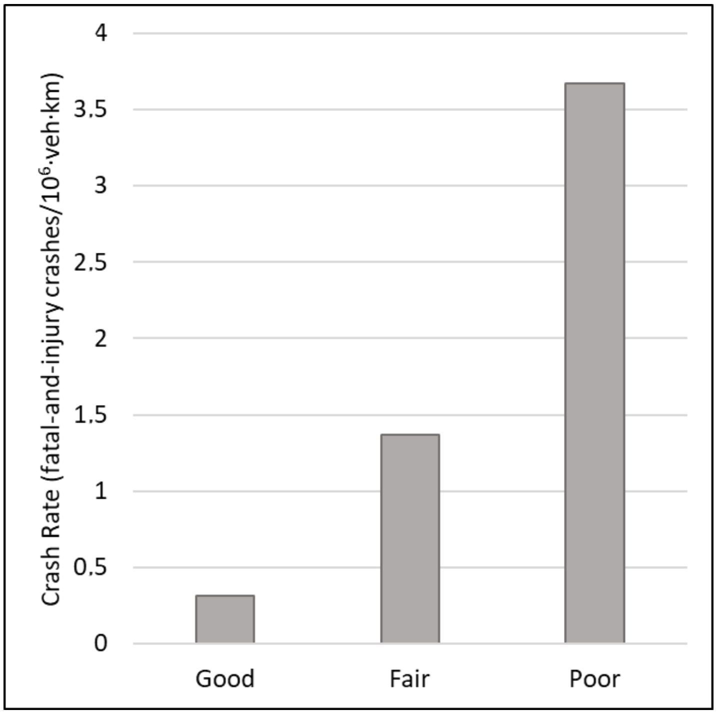


FIGURE 8 Average crash rate Vs. Consistency level. Local consistency model.

Finally, two Safety Performance Functions were developed. One of them considered only the exposure (Equation 4), whereas the other one also included the consistency (Equation 3). The main objective of this calibration is not the estimation of the number of crashes on horizontal curves, but to determine whether the consistency influences road crash occurrence or not.

A Negative Binomial-Generalized Exponential distribution was assumed, since it is an appropriate solution with over-dispersed crash data which are characterized by a large number of zeros (Vangala et al., 2015).

Table 4 shows a summary of the calibration of these SPFs. The Deviance Information Criterion (*DIC*) indicates the goodness of fit. To this regard, the lower the *DIC*, the better the model. Thus, the consistency is an important factor influencing crash occurrence, since the *DIC* value associated with the SPF, which jointly considered exposure and consistency, was significantly lower than that related to the single-exposure SPF.

TABLE 4 Statistical adjustment of SPFs. Local consistency model.

	$\boldsymbol{\beta_0}$ -	$\boldsymbol{\beta_1}$ $\ln L$	$\boldsymbol{\beta_2}$ $\ln AADT$	$\boldsymbol{\beta_3}$ ICI	DIC
Estimate	-6.8065	0.3976	0.778	0.1219	1650
Estimate	-5.6941	0.283	0.6747		1718

DISCUSSION

The inertial consistency models developed by Llopis-Castelló et al. (2018c and 2018d) have been validated for their application on American two-lane rural roads. A SPF was calibrated to estimate the number of crashes on an entire homogeneous road segment and consistency thresholds were defined for both global and local models to identify which road elements might have greater road safety problems.

To compare the results obtained in this research with those obtained in Spanish two-lane rural roads, the Spanish SPF (Table 1) was applied directly to American two-lane rural roads. Then, the observed crashes were compared with the predicted ones (Figure 9). As a result, this SPF underestimates the number of crashes on American highways. This means that American highways report more collisions than Spanish highways under the same risk exposure and consistency conditions.

Although the estimate for the consistency parameter *C* (0.03055) in the American SPF (Table 3) is lower than that estimate (0.14774) in the Spanish SPF (Table 1), this does not necessarily mean that consistency has a lower influence on American road users. This phenomenon and the influence of risk exposure (*AADT* and *L*) on crash occurrence need further research, considering the type of homogeneous road segment. Regarding this, homogeneous road segments can be divided into two categories: constrained and free (Camacho-Torregrosa, 2015). Constrained road segments are those that begin – or end – in an urban zone or major intersection. Otherwise, the road segment is free.

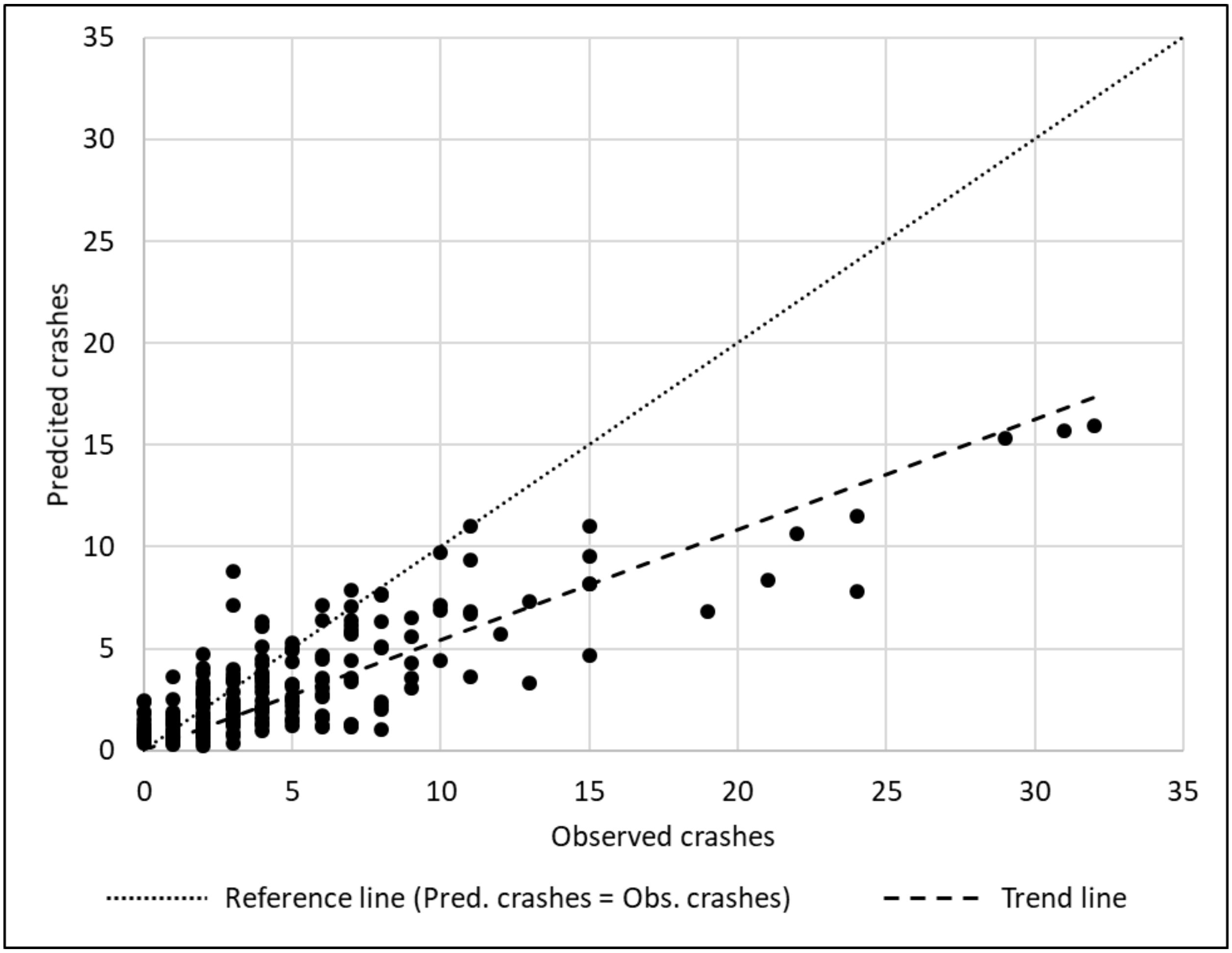


FIGURE 9 Observed crashes Vs. Predicted crashes (SPF$_{SPAIN}$).

Then, the following equation to calculate the number of crashes on American highways was used:

$$Y_{US} = \alpha \cdot Y_{SPAIN} \qquad (6)$$

where Y_{US} is the number of crashes on American highways; α is the correction factor; and Y_{SPAIN} is the number of crashes estimated with the SPF$_{SPAIN}$ (Table 1).

Figure 10 shows the results obtained considering a correction factor (α) equal to 1.85. In this case, the predicted crashes were much more similar to the observed ones (*RMSE*=3.38; *MAE*=2.53). As a conclusion, the crash rate on a specific American highway is 1.85 times greater than those obtained on a Spanish highway with the same risk exposure and consistency, which is consistent with the research developed by de Oña et al. (2013). This reveals that a consistency model developed in a specific country/region should be validated and calibrated for its use in another country/region.

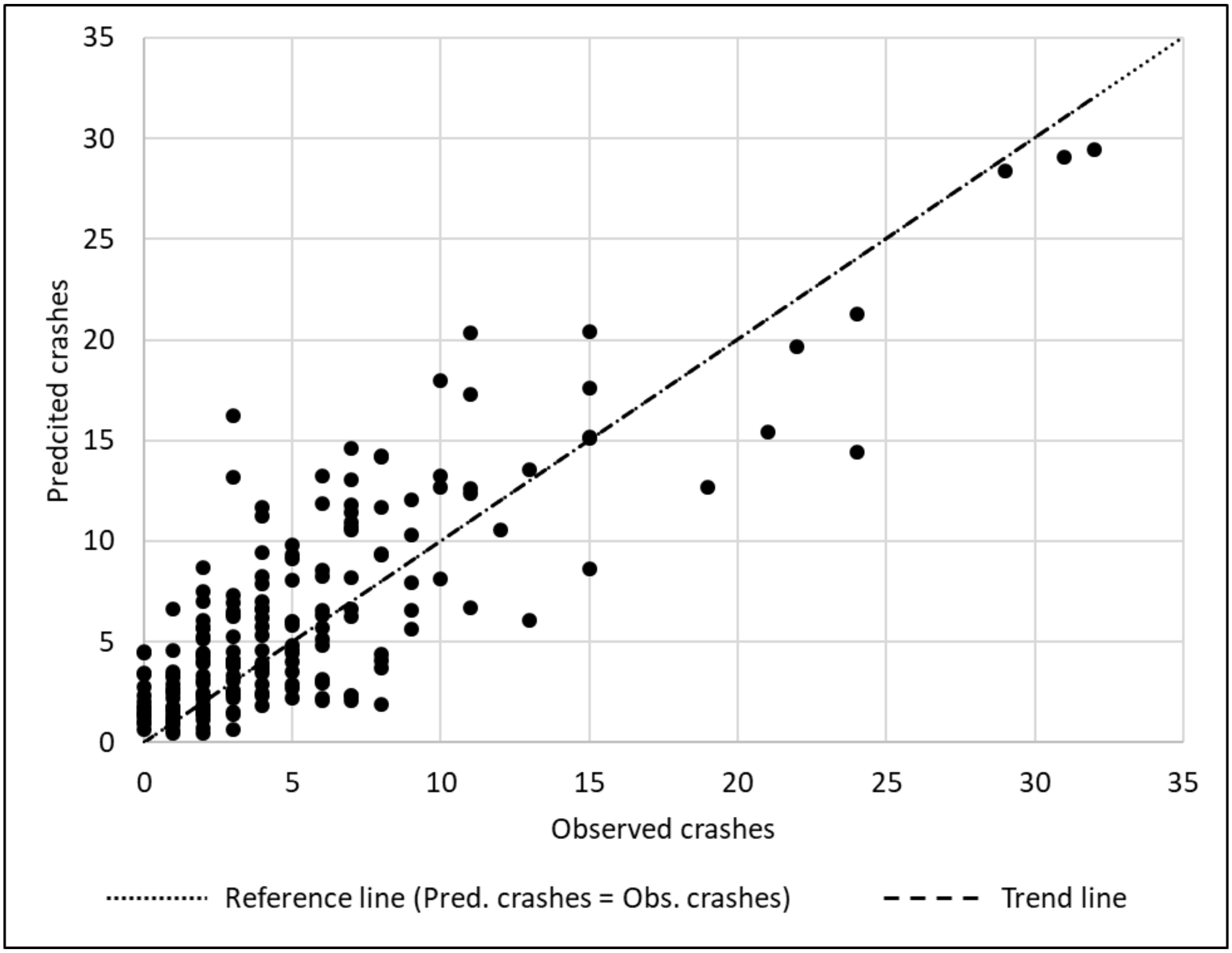


FIGURE 10 Observed crashes Vs. Predicted crashes ($Y_{US} = \alpha \cdot Y_{SPAIN}$).

This methodology might be applied in other states or countries to estimate the number of crashes on two-lane rural roads, since the inertial consistency models have shown reliable performance in Spain (Llopis-Castelló et al., 2018c and 2018d), Italy (Llopis-Castelló et al. 2018a and 2018b), and North Carolina (US).

The main difference between this method and the predictive method proposed by the Highway Safety Manual (HSM) is that the method proposed in this study allows an engineer to estimate the number of crashes on an entire road segment considering drivers' expectancies, whereas the HSM predictive method aims to estimate the number of crashes on a particular road element. To this regard, none of the Crash Modification Factors (CMF) are based on the preceding section, which influences drivers' behavior. Therefore, the predicted crashes on a certain horizontal curve will be similar in different road segments where drivers' behavior might be vastly different.

Additionally, the regression coefficients related to the traffic volume (*AADT*) and the length of the road element (L) used by the SPF proposed by the HSM are equal to one. This means that doubling the *AADT* or L would double the crash rate. However, many authors have studied this phenomenon and concluded that the influence of *AADT* and L on crash rates is not directly proportional (Lamm et al., 1999; Himes et al., 2010; Camacho-Torregrosa, 2015; Garach et al., 2016; Imprialou et al., 2016). To this regard, regression coefficients lower than 1 were obtained in this study. Therefore, longer homogeneous road segments and larger traffic volumes lead to lower crash rates, which would be expected, as drivers become familiar with the road features and traffic volume.

Thus, the SPF calibrated in this research should be used for the assessment of road safety rather than the predictive method proposed by the HSM.

CONCLUSIONS

The primary objective of this research effort was the validation of the inertial consistency models developed by Llopis-Castelló et al. (2018c and 2018d) on two-lane rural roads located in the United States.

For this, a total of 194 homogeneous road segments and 977 horizontal curves located in North Carolina (US) were considered. The operating speed profile and the inertial speed profile were estimated for each homogeneous road segment to estimate the inertial consistency parameters.

This study found that larger global and local parameters lead to higher crash rates. This means that the likelihood of crash occurrence increases as drivers' expectancies are not achieved. Likewise, the greater the consistency level, the greater the percentage of horizontal curves without reported crashes. These results were consistent with those obtained previously on Spanish two-lane rural roads.

In addition, geometric design consistency was identified as an important factor for crash occurrence. Thus, a SPF was calibrated to estimate the number of crashes on American two-lane rural roads and thresholds were defined for both consistency models to identify where these road crashes are more likely to occur.

Finally, the relationship between the observed and predicted crashes were studied. The SPF calibrated with Spanish data underestimates the predicted crashes in North Carolina. However, interesting results were obtained by applying a correction factor to this SPF. The crash rate on a particular American highway is 1.85 times greater than that one observed on a Spanish highway under the same exposure and consistency conditions. This methodology allows an easy application of these inertial consistency models to other states or countries to estimate the number of crashes on two-lane rural roads.

In this way, highway engineers have more accurate tools, which are much easier to apply than most previous models and incorporate the interaction between drivers' expectancies and road behavior, to enhance the assessment of road safety to the geometric design of both new American two-lane rural roads and improvements of existing highways.

ACKNOWLEDGMENTS

This research was subsidized by the Spanish Ministry of Economy, Industry, and Competitiveness through "Ayudas a la movilidad predoctoral para la realización de estancias breves en centros de I+D 2017" (EEBB-I-17-12154). The study presented in this paper is also part of the research project titled "CASEFU - Estudio experimental de la funcionalidad y seguridad de las carreteras convencionales" (TRA2013-42578-P), subsidized by the Spanish Ministry of Economy, Industry, and Competitiveness and the European Social Fund. In addition, the authors would like to thank the North Carolina Department of Transportation (NCDOT), which provided traffic and crash data.

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