CALIBRATION OF THE INERTIAL CONSISTENCY INDEX TO ASSESS ROAD SAFETY ON HORIZONTAL CURVES OF TWO-LANE RURAL ROADS

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Submission Date: 11th December 2017

ABSTRACT

One of every four road fatalities occurs on horizontal curves of two-lane rural roads. To this regard, many studies have been undertaken to analyze the crash risk on this road element. Most of them were based on the concept of geometric design consistency, which can be defined as how drivers' expectancies and road behavior relate. However, none of these studies included a variable which represents and estimates drivers' expectancies.

This research presents a new local consistency model based on the Inertial Consistency Index (ICI). This consistency parameter is defined as the difference between the inertial operating speed, which represents drivers' expectations, and the operating speed, which represents road behavior. The inertial operating speed was defined as the weighted average operating speed of the preceding road section. In this way, different lengths, periods of time, and weighting distributions were studied to identify how the inertial operating speed should be calculated.

As a result, drivers' expectancies should be estimated considering 15 seconds along the segment and a linear weighting distribution. This was consistent with drivers' expectancies acquirement process, which is closely related to Short-Term Memory.

A Safety Performance Function was proposed to predict the number of crashes on a horizontal curve and consistency thresholds were defined based on the ICI. To this regard, the crash rate increased as the ICI increased.

Finally, the proposed consistency model was compared with previous models. As a conclusion, the new Inertial Consistency Index allowed a more accurate estimation of the number of crashes and a better assessment of the consistency level on horizontal curves.

Therefore, highway engineers have a new tool to identify where road crashes are more likely to occur during the design stage 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*

1. INTRODUCTION

Road crashes produced approximately 26,000 fatalities and more than 1.3 million injuries in the Member States of the European Union in 2014. Excluding motorways, 55% of all road fatalities occurred on rural roads (ERSO, 2016). In Spain, a similar percentage (51%) was observed on two-lane rural roads in 2015, where one of every four fatalities occurred on horizontal curves (DGT, 2015).

Horizontal curves are a likely location to present crash concentration, so this is why several studies have been focused on examining the crash risk at them.

Lamm et al. (1999) indicated that 25-30% of all fatal crashes occur on horizontal curves, whereas Torbic et al. (2003) identified that most of these crashes concerned single vehicle run-off crash and head-on collision. To this regard, Hummer et al. (2010) pointed out that two-lane curve collisions most often involve only a collision with roadway or roadside features, which means safety countermeasures can have a disproportionately positive impact on collisions. In addition, the number of road crashes tended to increase as the radius of the horizontal curve decreased (Hauer, 1999 and 2000). In addition, Al-Masaeid et al. (1999) recommended to avoid large deflection angles, since these were associated with sharp horizontal curves without enough sight distance.

However, other authors highlighted that the characteristics of the preceding section had a great influence on crash rates. It was demonstrated that if a sharp curve was located on a road segment with low average curvature, crash risk increased significantly (Matthews and Barnes, 1988; Hauer, 2000). Related to this, Findley et al. (2012) studied the influence of the preceding road section in terms of spatial considerations (distance to adjacent curves, direction of turn of the adjacent curves, and radius and length of the adjacent curves) on the crash risk on horizontal curves. As a result, the distances to adjacent curves were found to be a reliable predictor of observed collisions. Later, Gooch et al. (2016) found that crash frequencies are expected to decrease when adjacent curves are close and the magnitude of the crash frequency reduction increases with the sharpness of the adjacent curves. Likewise, Practicò and Giunta (2012) analyzed the influence of the preceding road section on operating speed of two-lane rural roads. As a conclusion, speed prediction was more accurate considering the conditions of the preceding alignment.

Therefore, driver's behavior at a certain point of the alignment is influenced by the expectations generated from the preceding road section.

In this regard, geometric design consistency is defined as how drivers' expectancies relate to road behavior. The most common methods to assess geometric design consistency are based on the analysis of the operating speed (Gibreel et al., 1999), which 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 using operating speed is the possibility to estimate it with models.

There are two types of consistency models: local and global. Local models focus on short road sections, like a single road feature or a tangent-to-curve transition. Thus, sudden speed reductions or large differences between the design and operating speeds are possible inconsistencies obtained from local models. Those models are ideal to identify where road crashes are more likely to occur. On the other hand, global consistency models examine the overall speed variation throughout an entire road segment. 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.

The most well-known local method was developed by Lamm et al. (1999). Two design consistency criteria related to operating speed were proposed. Criterion I focuses on disparities between operating and design speeds (V_{85}-V_d); whereas criterion II examines operating speed differences between successive elements. 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 (Table 1).

TABLE 1 Consistency model developed by Lamm et al. (1999)

	Consistency level		
	Good	Fair	Poor
Criterion I	V_{85} - $V_d \leq$ 10 km/h	10 km/h < V_{85} - $V_d \leq$ 20 km/h	V_{85} - V_d < 20 km/h
Criterion II	$V_{85,\ i+1} - V_{85,\ i} \leq$ 10 km/h	10 km/h < $V_{85,\ i+1} - V_{85,\ i} \leq$ 20 km/h	$V_{85,\ i+1} - V_{85,\ i}$ < 20 km/h

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

Additionally, McFadden and Elefteriadou (2000) and Park and Saccomanno (2006) analyzed the difference between Criterion II and the 85th percentile of the maximum speed reduction (*85MSR*), which was calculated by using each driver's speed profile. The results showed that 85MSR was approximately two times larger than ΔV_{85}. Therefore, Criterion II does not represent the actual speed reduction experienced by drivers.

Regarding Criterion I, Wu et al. (2013) assessed the relationship between crash rate and design consistency density (δ), which was defined as the sum of the differences between the operating speed and inferred design speed on a certain road element and the road elements upstream and downstream. As a result, design inconsistencies were more likely to occur as δ increased, i.e., the lower the consistency level around a road element, the greater the risk of crash occurrence.

Other local consistency criteria were developed by Leisch and Leisch (1977) and Kanellaidis et al. (1990). The first one proposed the following three criteria:

- The difference between design speeds of two consecutive road segments should not exceed 10 mi/h.
- The difference between the operating speeds for passenger cars of two consecutive road geometric elements should not exceed 10 mi/h.
- The difference between operating speeds for passenger cars and trucks should not exceed 10 mi/h.

Likewise, Kanellaidis et al. (1990) suggested that a consistent road design could be achieved if the operating speed difference between two consecutive road geometric elements was lower than 10 km/h.

However, none of these consistency models included the consistency concept in their formulation, i.e., none embed a variable which represents and estimates drivers' expectancies, which do not only depend on the characteristics of the preceding element, but rather on the features of the preceding road section.

To this regard, García et al. (2013) defined a new speed concept: the inertial operating speed (V_i). This speed represents drivers' expectancies and was defined as the average operating speed of the preceding 1,000 m. Conversely, road behavior was associated with the operating speed (V_{85}). 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' expectancies and road behavior, so crashes are more likely to result.

However, this definition of the V_i does not match the drivers' expectancies acquirement process, which is related to Short-Term Memory (STM). To this regard, STM is gradually in decline as the driver proceeds and the information is lost in approximately 18 seconds (Revlin, 2012).

Drivers do not recall with the same intensity all locations of the previous road section. 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.

Recent studies have been developed to identify how the inertial operating speed should be calculated on Italian two-lane rural roads (Llopis-Castelló et al., 2018a and 2018b). As a conclusion, an inertial operating speed estimated as the weighted average operating speed based on time was able to better represent drivers' expectancies than a V_i based on distance and calculated as a simple average of the operating speed. In addition, a global consistency model was developed based on the difference between the inertial operating speed profile and the operating speed profile. As a result, this consistency model resulted in a more accurate estimation of the number of crashes than those developed previously.

Due to the successful performance of the time-based inertial operating speed profile, this research aims to identify how the inertial operating speed should be calculated to enhance the assessment of the local consistency through the Inertial Consistency Index.

2. OBJECTIVES AND HYPOTHESES

The main objective of this study was to calibrate the Inertial Consistency Index comparing the speed difference between the inertial operating speed and the operating speed with the number of crashes on horizontal curves of Spanish two-lane rural roads. To this regard, the inertial operating speed was studied considering different distances, periods of time, and weighting distributions to use as a surrogate measure to drivers' expectancies. A greater crash rate is expected as the difference between inertial operating speed and operating speed increases.

It is worth to mention the importance of time in this approach. The underlying hypothesis is that a time-based inertial operating speed will allow a more accurate estimation of the number of crashes than a distance-based one. As abovementioned, people's STM is based on time, not on distance travelled, so the sections used to determine the inertial operating speed should differ in length depending on the average speed.

3. METHODOLOGY AND DATA DESCRIPTION

3.1. Methodology

This study was based on two-lane rural road sections located in Spain. 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 the models developed by Pérez-Zuriaga (2012), which were calibrated on Spanish two-lane rural roads. From this, different inertial operating speed profiles were calculated for each road segment considering different distances, periods of time, and weighting distributions. Thus, the Inertial Consistency Index was obtained for every horizontal curve. Crash and traffic data were also obtained, which allowed us to calibrate a relationship between the Inertial Consistency Index and the number of crashes on horizontal curves, using several Safety Performance Functions. Every single SPF was calibrated using different variations of consistency and presenting different goodness of fit. The parameter included in the SPF that adjust the best will be our proposal for local consistency.

3.2. Road segments

A total of 98 two-lane rural road sections located in the Valencian Region (Spain) were selected for the study. They covered more than 650 km, with 3,229 horizontal curves identified.

Table 2 shows the geometric characteristics of these horizontal curves. In addition, their cross-section presented lane widths ranging from 3.00 to 3.50 m and shoulder widths varying from 0.5 to 1.50 m. The longitudinal grade did not exceed 5%.

TABLE 2 Geometric characteristics of the horizontal curves

Geometric variable	Minimum	Maximum	Average	Standard Deviation
Radius (m)	9.15	998.59	174.51	172.59
Length (m)	10	617	85.84	60.03
Deflection angle (gon)	2.24	259.92	39.58	32.47
CCR (gon/km)	36.57	5,227.45	592.55	538.71

*Curvature Change Rate (*CCR*) = Deflection angle (gon) / Length (km)

3.3. Traffic and crash data

Traffic volume and crash data were provided by the Department of Housing, Public Works and Spatial Planning of the Valencian Regional Government and the General Directorate of Traffic (Dirección General de Tráfico, DGT) of the Spanish Government, respectively. Thus, the Annual Average Daily Traffic (*AADT*) volumes and the number of fatal-and-injury crashes were determined for each horizontal curve.

AADT was determined from 2002 to 2011. The horizontal curves had an *AADT* ranging from 465 to 10,817 vpd. Only fatal-and-injury crashes were considered in the same period of time. The cause of each crash was analyzed so to include only those related to geometry (for instance, crashes caused by animals were removed from the analysis, since their cause is not the road geometry per se). In addition, all crashes taking place near the horizontal curve were analyzed. Therefore, some crashes located on nearby tangents were finally associated to horizontal curves and counted. As a result, a total of 839 reported crashes were considered.

3.4. Speed profiles

3.4.1. Operating speed profiles

The operating speed profile was estimated for each road segment, obtaining operating speed profiles in a meter basis, like the one in Figure 1.

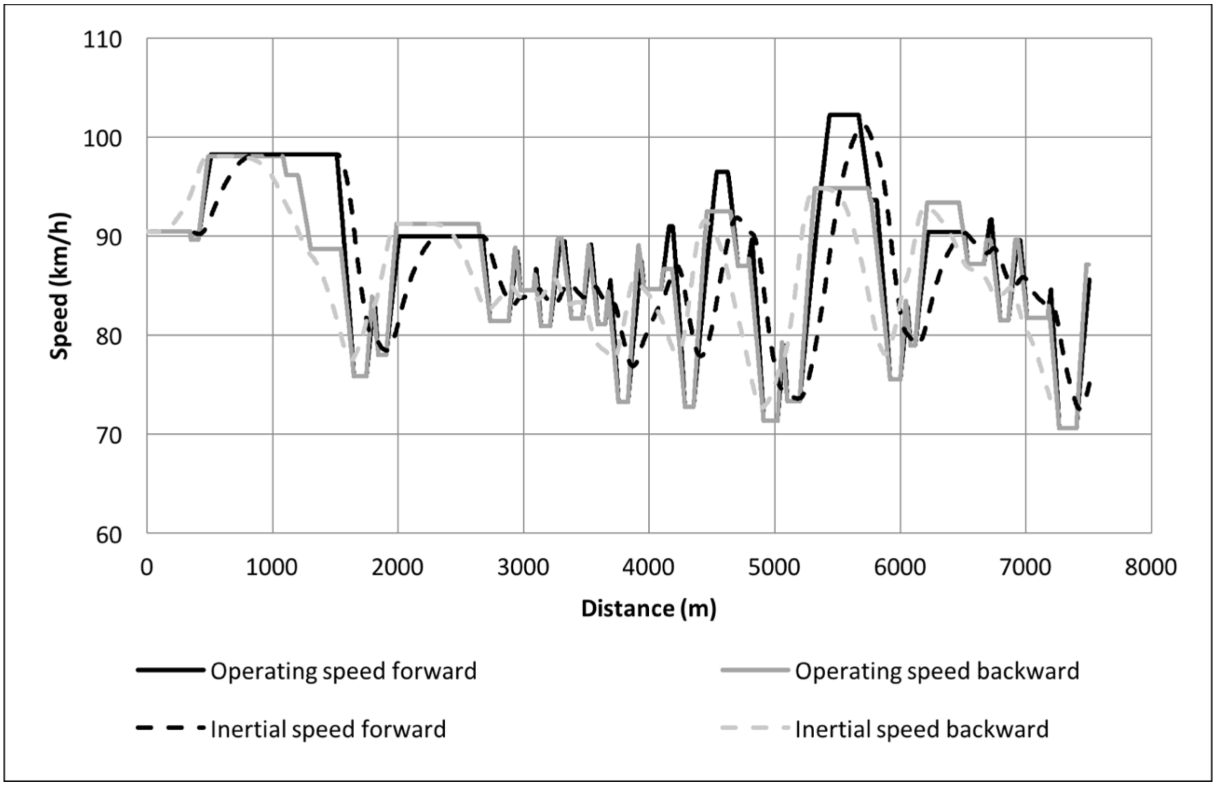

FIGURE 1 Speed profiles

3.4.2. Inertial speed profiles

In previous research, the authors concluded that an inertial operating speed (V_i) estimated as the weighted average operating speed based on time was more suitable to represent drivers' expectancies than a V_i based on distance, calculated as a simple average of the operating speed (Llopis-Castelló et al., 2018a and 2018b).

Thus, the inertial operating speed was calculated for this research by means of Equation 1. This expression attempts to model the expectation-acquirement-process by drivers, which is closely related to Short-Term Memory behavior.

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

where $V_{i,k}$ is the inertial operating speed (km/h) at station k; $V_{85,j}$ is the operating speed at station j; and w_j is the weighting factor at station j. Depending on the range covered by j, the result of the operating speed will vary.

Although Short-Term Memory depends on time, inertial operating speeds were determined considering different distances and periods of time to check the results obtained by Llopis-Castelló et al.

(2018a and 2018b):

- Distances (L) between 300 m and 800 m with a step of 100 m
- Periods of time (t) between 10 s and 40 s, with a step of 5 s

In addition, 11 weighting distributions were considered in order to identify which of them can better represent drivers' expectation acquirement process. These distributions were based on a parabolic functional form (ax^2+bx+c) and could take values from 0 to 1, increasing as the station j gets closer to the critical section k, with these constraints:

- $w_j = 0$ for the first station j considered for the calculation. It is the threshold between the zone that has not been included in the calculation (because it has no influence on driver's behavior), and the zone under consideration.
- $w_j = 1$ for $j = k$. It means that the station where the driver actually is located at a certain moment has to be the most important for the expectancy formation.

As a result, the parabolic function can only take certain a, b and c parameters. Moreover, it can be rewritten as a function of a single parameter α, which varies between 0 and 10 (Figure 2). In this equation, n is the number of intervals considered in the calculation. The number of the intervals (n) depended on whether the calculation was carried out considering a distance (L), in meters; or a period of time (t), in seconds. In the first case, n was equal to L (i.e., the calculation was performed meter by meter), whereas in the second case, n was equal to $10 \cdot t$, so the inertial operating speed was calculated considering intervals of 0.1 s.

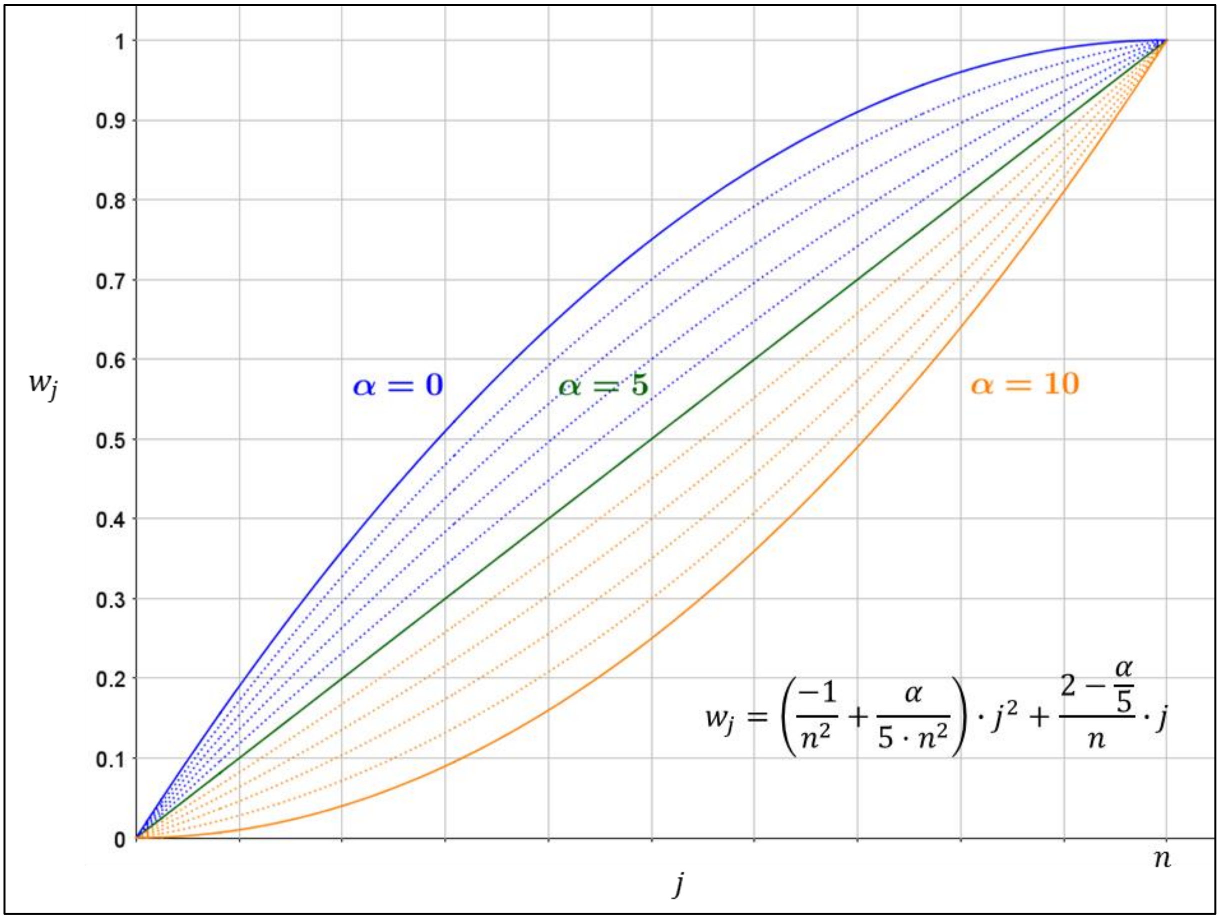

FIGURE 2 Weighting distributions.

The parameter α defines the concavity or convexity of the distribution. To this regard, a value of α equal to 0 was related to a convex parabolic distribution with the derivative equal to 0 when the weight is 1, whereas a value of α equal to 10 was related to a concave parabolic distribution with the derivative equal to 0 when the weight is 0. Likewise, a linear distribution was assumed for a value of α equal to 5.

It should be noted that Llopis-Castelló et al. (2018a and 2018b) only studied four weighting distributions: linear distribution (α=5), convex parabolic distribution (α=0), concave parabolic distribution (α=10), and constant distribution (w_j=1, coinciding with a simple average speed). Therefore, this research attempts to go a step further in the estimation of drivers' expectancies by analyzing 11 weighting distributions, which will allow a more accurate road safety assessment.

As a result, 143 ((6 distances + 7 periods of time) x (11 weighting distributions)) inertial operating speed profiles were obtained for each road section. As an example, Figure 1 shows the operating speed profile and its corresponding inertial operating speed profile considering 15 s and a linear weighting distribution for one of the studied road segments.

3.5. Consistency parameter

The local consistency parameter used in this research was the Inertial Consistency Index (ICI) defined by García et al. (2013). This parameter was directly calculated by the difference between the inertial operating speed (V_i) and the operating speed (V_{85}). To this regard, the maximum difference between both speeds along the horizontal curve was considered, which is produced at the beginning of the horizontal curve – at this point the inertial operating speed would represent drivers' expectancies just before that curve, i.e., without its influence, stressing inconsistencies.

$$ICI = V_i - V_{85} \qquad (2)$$

According to this definition, a positive speed difference means that drivers' expectancies are violated, because drivers' speed on the horizontal curve is lower than the speed they expect to travel at the curve. Therefore, the likelihood of crash occurrence increases with the magnitude of this difference.

4. ANALYSIS

A total of 143 Safety Performance Functions (SPF) were calibrated to identify how the inertial operating speed should be calculated. This was the result of the different ways to estimate the inertial operating speed.

A SPF is an expression that relates the risk exposure and consistency to the number of crashes. Following common practice, generalized linear modelling techniques were used to fit these functions (Equation 3) and 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). To this regard, it should be noted that more than 80% of horizontal curves did not have reported crashes during the study period.

This distribution was used instead of Zero Inflated Models. Related to this, Zero Inflated Models are based on the hypothesis that there are "safe" road elements, i.e., road elements with a likelihood of crash occurrence equal to 0. However, from a theoretical perspective, this assertion is not true (Lord et al., 2005; Warton, 2005).

$$\boldsymbol{Y_{i,10} = e^{\beta_0} \cdot L^{\beta_1} \cdot AADT^{\beta_2} \cdot e^{\beta_3 \cdot ICI}} \qquad (3)$$

where $Y_{i,10}$: fatal-and-injury crashes on the horizontal curve in 10 years; β_i: regression coefficients; L: length of the horizontal curve (km); *AADT*: Average Annual Daily Traffic (vpd); and *ICI*: Inertial Consistency Index (km/h).

The *DIC* (Deviance Information Criterion) was obtained for all regressions as a measure of goodness of fit. The smaller the *DIC*, the better the model. Additionally, the Root Mean Square Error (*RMSE*), the Mean Absolute Error (*MAE*), and the Absolute value of the Sum of Deviations (*ASD*) were calculated for the more accurate models.

Table 3 shows the best 25 models. The name of the model ($X_{i,j}$) indicates how the inertial operating speed was estimated. If this speed was based on distance X was L, whereas X was t when the inertial operating speed was based on time. Likewise, i indicates the distance in meters or the period of time in seconds and j the value of α of the weighting distribution.

However, it is well known that crashes are highly affected by exposure. Thus, a SPF only considering exposure was previously calibrated to determine how important the inclusion of the consistency term was for crash estimation:

$$y_{i,10} = e^{-7.2829} \cdot L^{0.4194} \cdot AADT^{0.9265} \qquad DIC = 3{,}392 \qquad (4)$$

To this regard, most of the calibrated SPFs which jointly considered the risk exposure and consistency produced a lower *DIC* value than the single-exposure SPF, so the consistency had a major influence on road crash occurrence.

In addition, it was observed that a time-based inertial operating speed could better represent the phenomenon than an inertial operating speed based on distance, since most of models in Table 3 depended on a period of time. Related to this, the best results were obtained considering a period of time equal to 15 seconds.

Finally, the weighting distributions were analyzed. As a conclusion, most of the best consistency models presented weighting distributions with values of the parameter α between 5 and 10.

TABLE 3 Best consistency models

Model	DIC	RMSE	MAE	ASD
$L_{500, 8}$	3,290	0.6433	0.3462	9.8425
$t_{15, 9}$	3,287	0.6442	0.3451	19.5314

$t_{15, 5}$	3,290	0.6450	0.3439	0.5352
$L_{300, 3}$	3,287	0.6480	0.3432	1.6289
$t_{15, 8}$	3,294	0.6444	0.3376	42.1625
$t_{20, 10}$	3,298	0.6442	0.3431	5.8023
$t_{20, 9}$	3,298	0.6437	0.3403	25.7869
$t_{15, 3}$	3,297	0.6455	0.3435	2.8378
$t_{10, 2}$	3,294	0.6467	0.3395	24.4064
$t_{15, 10}$	3,299	0.6440	0.3379	32.1703
$t_{30, 7}$	3,299	0.6426	0.3474	13.4363
$t_{10, 8}$	3,299	0.6452	0.3394	17.7958
$t_{20, 8}$	3,288	0.6447	0.3504	48.6337
$L_{500, 9}$	3,281	0.6450	0.3512	52.1987
$t_{10, 1}$	3,293	0.6477	0.3489	42.1020
$L_{500, 10}$	3,293	0.6457	0.3502	50.2893
$L_{300, 4}$	3,300	0.6477	0.3401	33.6636
$t_{10, 7}$	3,299	0.6460	0.3475	36.0618
$t_{20, 3}$	3,297	0.6449	0.3510	51.1946
$t_{25, 9}$	3,281	0.6475	0.3562	86.8078
$t_{10, 0}$	3,297	0.6479	0.3491	44.3592
$t_{15, 6}$	3,285	0.6493	0.3550	102.9912
$t_{20, 2}$	3,295	0.6480	0.3601	114.9137
$L_{300, 1}$	3,298	0.6503	0.3530	67.6350
$t_{25, 6}$	3,292	0.6575	0.3622	140.0967

5. LOCAL CONSISTENCY MODEL

A new way to estimate drivers' expectancies was proposed based on the previous results. In this regard, a time-based inertial operating speed profile was proposed. Thus, the inertial operating speed should be calculated for each point of the alignment as the weighted operating speed of the preceding 15 s considering a linear weighting distribution ($t_{15, 5}$). This distribution was selected because of its simplicity.

Equation 5 is the Safety Performance Function which allows estimating the number of crashes on a horizontal curve.

$$Y_{i,10} = e^{-6.9544} \cdot L^{0.6841} \cdot AADT^{0.8259} \cdot e^{0.1394 \cdot ICI} \qquad (5)$$

The results of this adjustment produced regression coefficients related to *L* and *AADT* lower than 1, so longer horizontal curves and higher traffic volumes induce lower crash rates.

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 ±2σ* boundaries.

It can be observed that the plots against each explanatory variable did not practically stray beyond the ±2σ* boundaries (Figure 3). So, the proposed SPF is a useful tool to estimate the number of crashes on horizontal curves of two-lane rural roads.

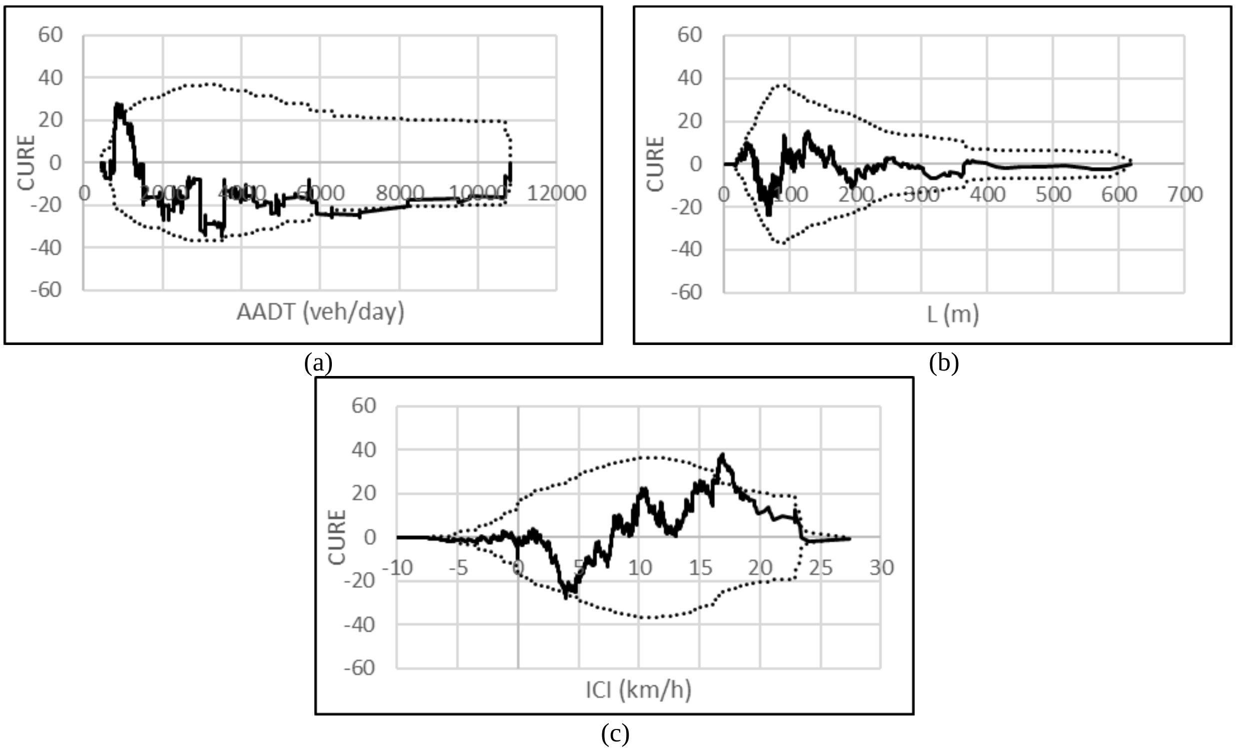

FIGURE 3 CURE plots: (a) AADT; (b) Length; (c) Inertial Consistency Index.

Figure 4 shows the relationship between the Inertial Consistency Index (ICI) and crash rate. Regarding this, the crash rate increased as the ICI increased. Therefore, the higher the difference between drivers' expectancies and road behavior, the higher the likelihood of crash occurrence. This means that the ICI is able to identify where drivers' expectancies are violated.

Three consistency levels were defined by means of a cluster analysis. As a result, a horizontal curve presents a good consistency level when the Inertial Consistency Parameter (ICI) is lower than 5 km/h, a poor consistency level when ICI is higher than 12.5 km/h, and a fair consistency level in all other cases (Figure 4 and Figure 5).

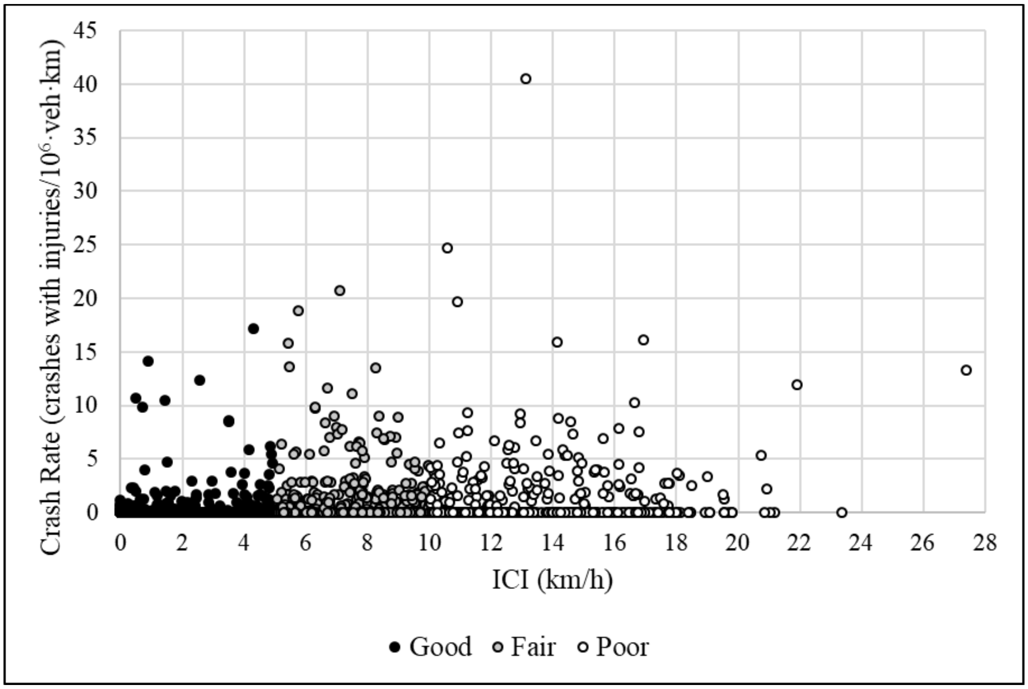

FIGURE 4 Global consistency model Vs. Crash rates.

In addition, the average crash rate was analyzed considering the defined consistency thresholds (Figure 5). A statistical test showed significant differences between these consistency levels at a 95% confidence level, so the proposed local consistency model is valid to properly assess road safety on a horizontal curve and distinguish between the proposed consistency thresholds.

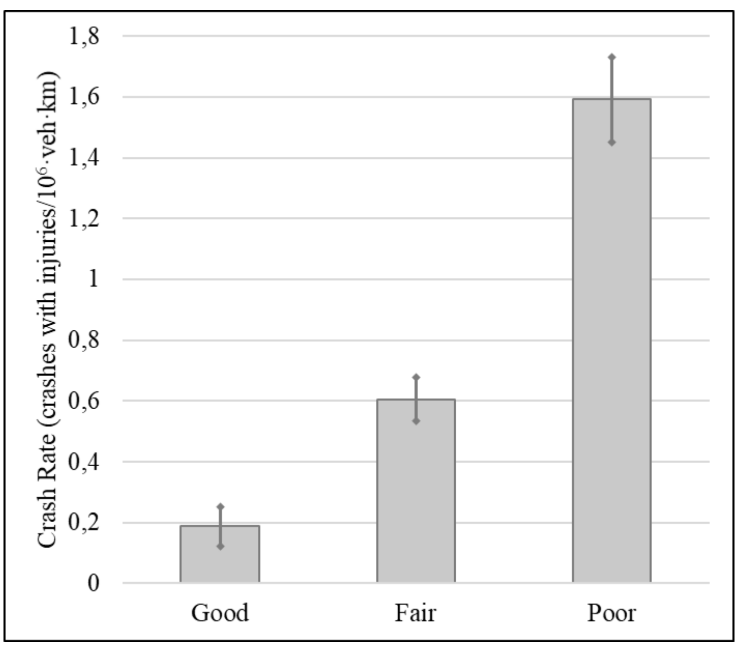

FIGURE 5 Average crash rate Vs. Consistency level.

Finally, the relationship between the percentage of horizontal curves without reported crashes and the consistency level was analyzed (Figure 6). As expected, this percentage was lower as the consistency level worsened. Therefore, the lower the consistency level, the higher the likelihood of crash occurrence.

FIGURE 6 %Horizontal curves without crashes Vs. Consistency level.

6. DISCUSSION

6.1. Inertial operating speed

Different distances, periods of time, and weighting distributions were analyzed to identified how drivers' expectancies should be estimated. As a result, a time-based inertial operating speed showed more consistent results than those based on distance, which supports the previous research developed by Llopis-Castelló et al. (2018a and 2018b). Likewise, an inertial operating speed calculated as the weighted average operating speed of the preceding section allowed a more accurate estimation of drivers' expectancies acquirement process, which is closely related to Short-Term Memory (STM). In addition, the best results were obtained considering a period of time equal to 15 s, which was very close to 18 s that STM used (Revlin, 2012).

6.2. Inertial Consistency Index Vs. Criterion II of Lamm et al. (1999)

The Inertial Consistency Index was identified as an appropriate parameter to accurately evaluate the consistency on horizontal curves. This consistency parameter was defined as the speed difference between the inertial operating speed and the operating speed itself. To this regard, the crash rate was greater as the ICI increased. These results were consistent with the studied phenomenon, since a larger likelihood of crash occurrence was associated with a greater difference between drivers' expectancies and road behavior.

The proposed local consistency model was compared with Criterion II developed by Lamm et al. (1999), which is included in several guidelines. For this, the speed difference between successive elements (ΔV_{85}) was obtained for each horizontal curve. Figure 7 shows the relationship between this consistency parameter and crash rates. It should be highlighted that some of the horizontal curves with a good or fair consistency level reported a high crash rate. This means that a low ΔV_{85} was not necessarily associated with a low likelihood of crash occurrence.

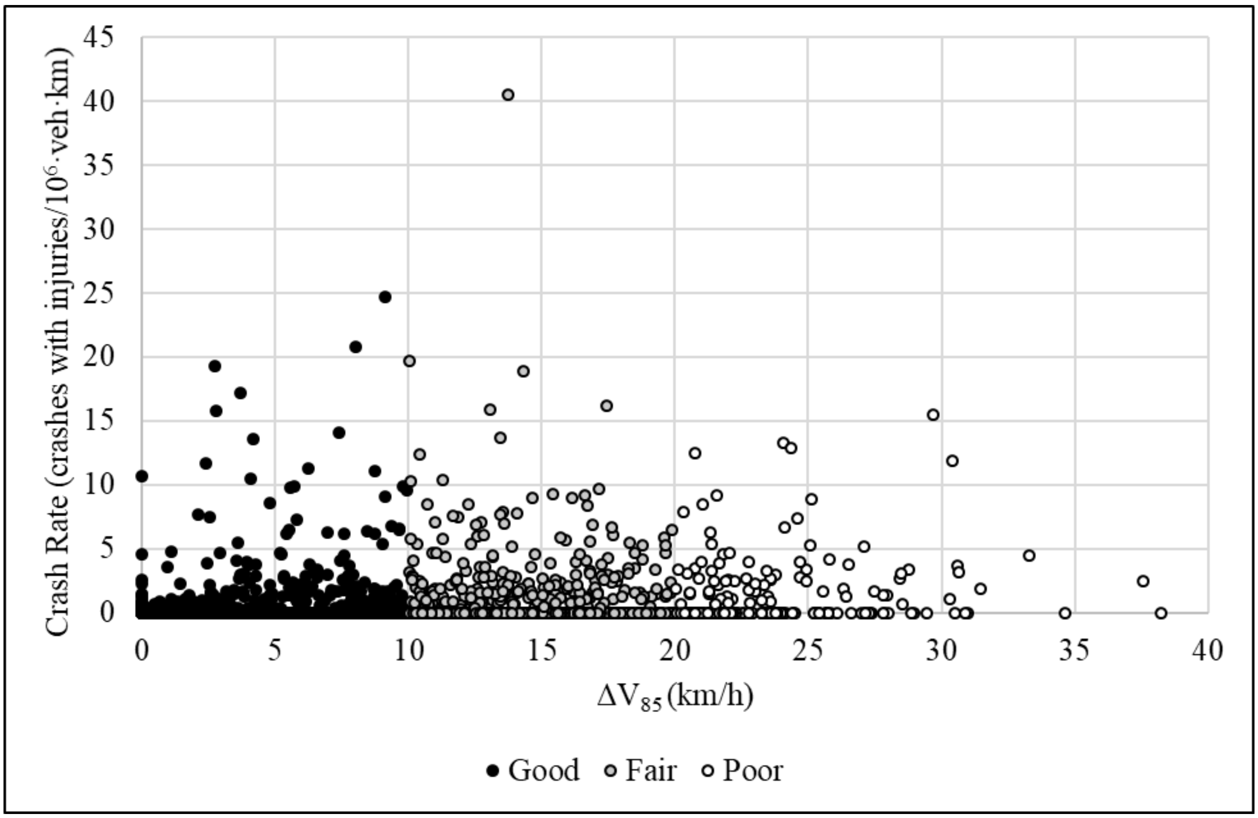

FIGURE 7 Crash rate Vs. ΔV_{85}.

Figure 8 shows the average crash rate for each consistency level considering both the ICI and Criterion II. As expected, the average crash rate increased as the consistency level was worse. However, the average crash rates for a good and fair consistency level were greater considering the Criterion II of Lamm et al. (1999). Conversely, the average crash rate for a poor consistency level was larger according to the proposed consistency model. These differences were due to Criterion II's assignment of a good or fair consistency level to horizontal curves with high crash rates.

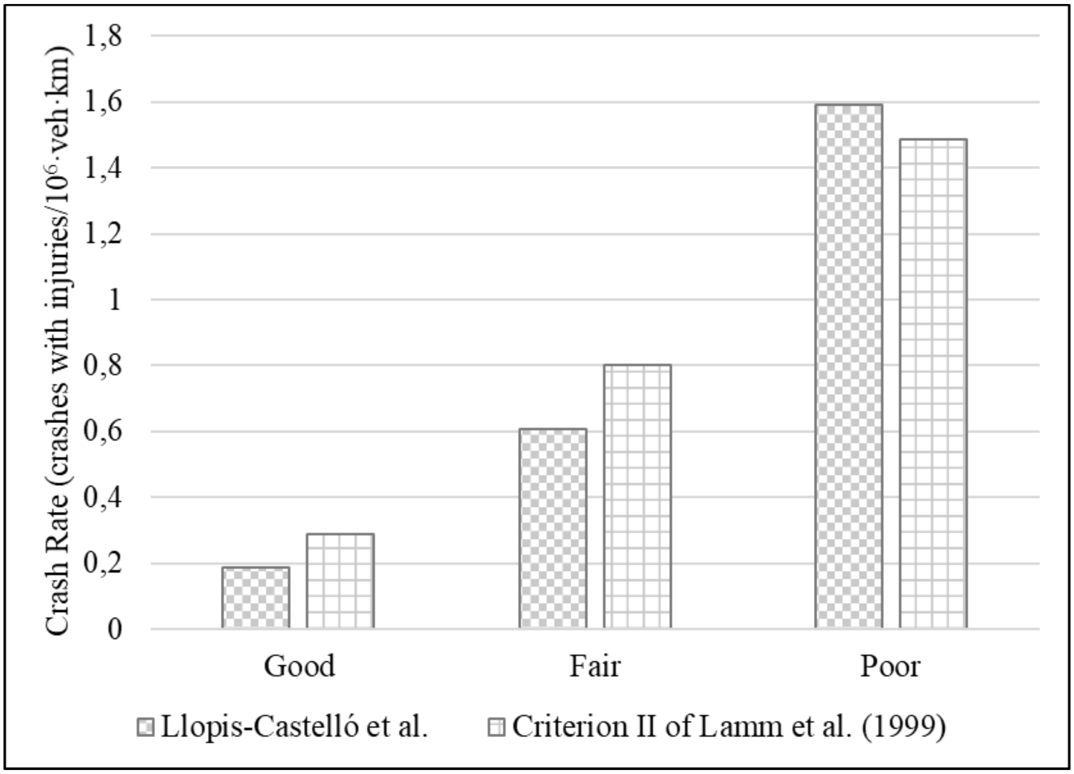

FIGURE 8 Average crash rate Vs. Consistency level considering both models.

To better understand these results, the relationship between both consistency parameters was evaluated. In Figure 9, each circle is a horizontal curve and its size represents its crash rate. Likewise, the dotted lines represent the consistency thresholds of both consistency models.

In this way, Figure 9 shows how the proposed consistency model was able to better identify the consistency level of a horizontal curve than Criterion II proposed by Lamm et al. (1999). To this regard, the circle size of the horizontal curves with the same consistency level according to the Inertial Consistency Index (ICI) was more homogeneous than the size according to Criterion II. This means that Criterion II assigned the same consistency level to horizontal curves with very different crash rates, whereas the proposed model was able to identify these differences and assign different consistency levels to these horizontal curves. Therefore, the consistency model proposed in this research was able to better cluster the horizontal curves with a similar risk crash.

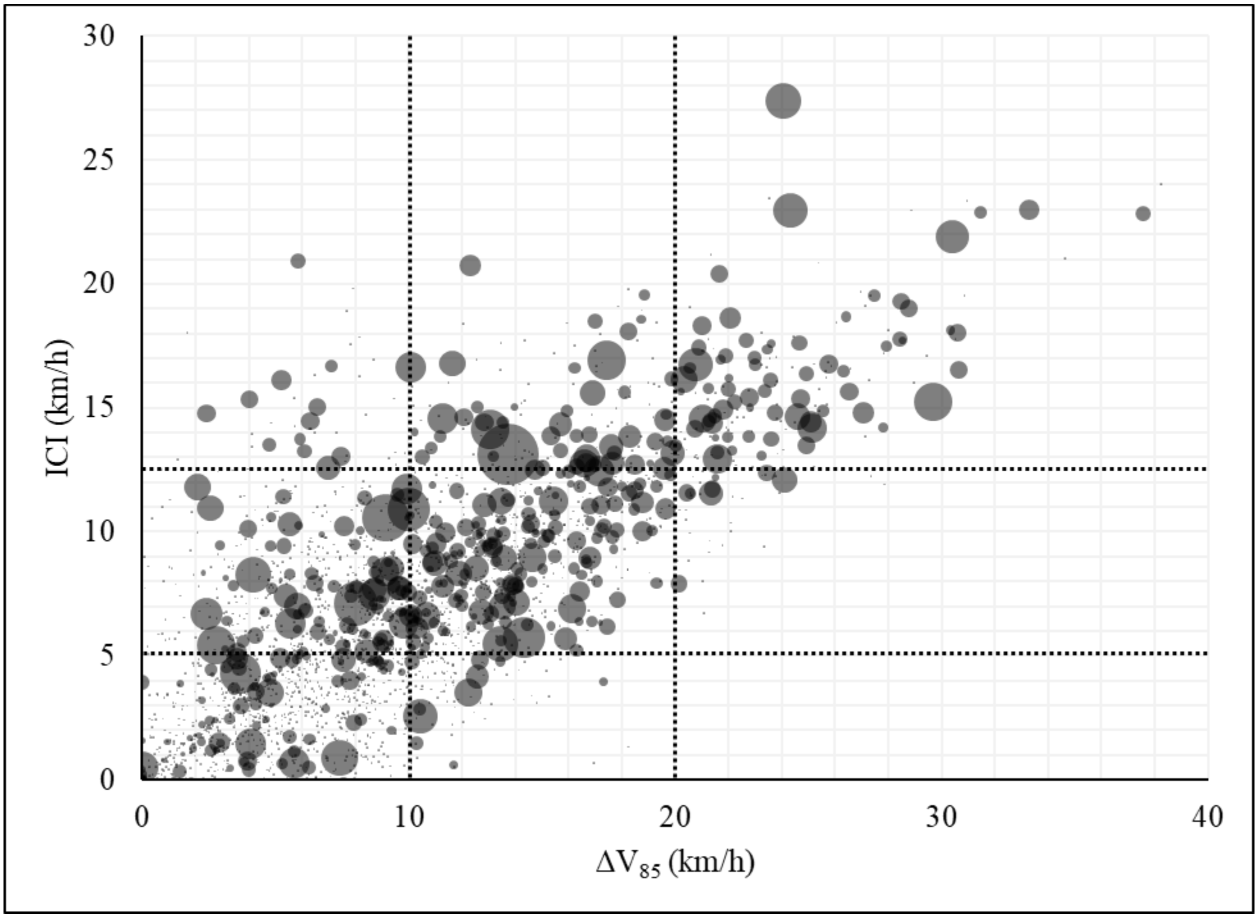

FIGURE 9 ICI Vs. ΔV_{85}.

Finally, a SPF was calibrated considering Criterion II to study the relationship between observed and predicted crashes (Equation 6). As a result, the proposed consistency model in this research showed better indexes of goodness of fit than Criterion II (*DIC*=3,353; *RMSE*=0.6519; *MAE*=0.354; *ASD*=31.962), i.e., the SPF based on the ICI estimated more accurately the number of crashes on horizontal curves.

$$Y_{i,10} = e^{-7.6089} \cdot L^{0.5908} \cdot AADT^{0.8947} \cdot e^{0.09376 \cdot \Delta V_{85}} \qquad (6)$$

Therefore, the new local consistency model can better represent the phenomenon than Criterion II of Lamm et al. (1999).

6.3. Inertial Consistency Index Vs. Alignment indexes

The Inertial Consistency Index was also compared to different alignment indexes to determine whether ICI is able to better represent the phenomenon studied. Thus, the radius of the horizontal curve (*R*), the ratio between the radius of the horizontal curve and the average radius of the road section (*CRR*), and the difference between the Curvature Change Rate (*CCR*) of the horizontal curve and the average *CCR* of the road section only considering horizontal curves (*ΔCCR*) were analyzed.

Table 4 shows the statistical adjustment of the Safety Performance Functions considering each alignment index. As a result, the SPF based on the Inertial Consistency Index resulted in better parameters of goodness of fit (*DIC*=3,290; *RMSE*=0.6450; *MAE*=0.343; *ASD*=0.5352) than those SPFs based on alignment indexes. Specifically, the SPFs based on alignment indexes tend to significantly overestimate (*CRR* and *CCR*) or underestimate (*R*) the number of fatal-and-injury crashes, since the absolute value of the sum of deviations (*ASD*) resulted significantly greater than 0. This can also be observed through the CURE plots associated with these SPFs (Figure 10), where the residuals strayed beyond the ±2σ* boundaries. Therefore, the proposed consistency model in this research is able to more accurately assess road safety than alignment indexes.

TABLE 4 Statistical adjustment of Safety Performance Functions based on alignment indexes

Alignment index	SPF	DIC	RMSE	MAE	ASD
CRR	$Y_{i,10} = e^{-5.06} \cdot L^{0.7311} \cdot AADT^{0.8554} \cdot e^{-1.411 \cdot CRR}$	3389	0.6637	0.344	82.1
ΔCCR (gon/km)	$Y_{i,10} = e^{-7.04} \cdot L^{0.6009} \cdot AADT^{0.9213} \cdot e^{0.0001273 \cdot \Delta CCR}$	3467	0.7036	0.366	110.7
R (m)	$Y_{i,10} = e^{-6.20} \cdot L^{1.009} \cdot AADT^{1.091} \cdot e^{-4.852 \cdot R}$	3395	0.6802	0.384	147.3

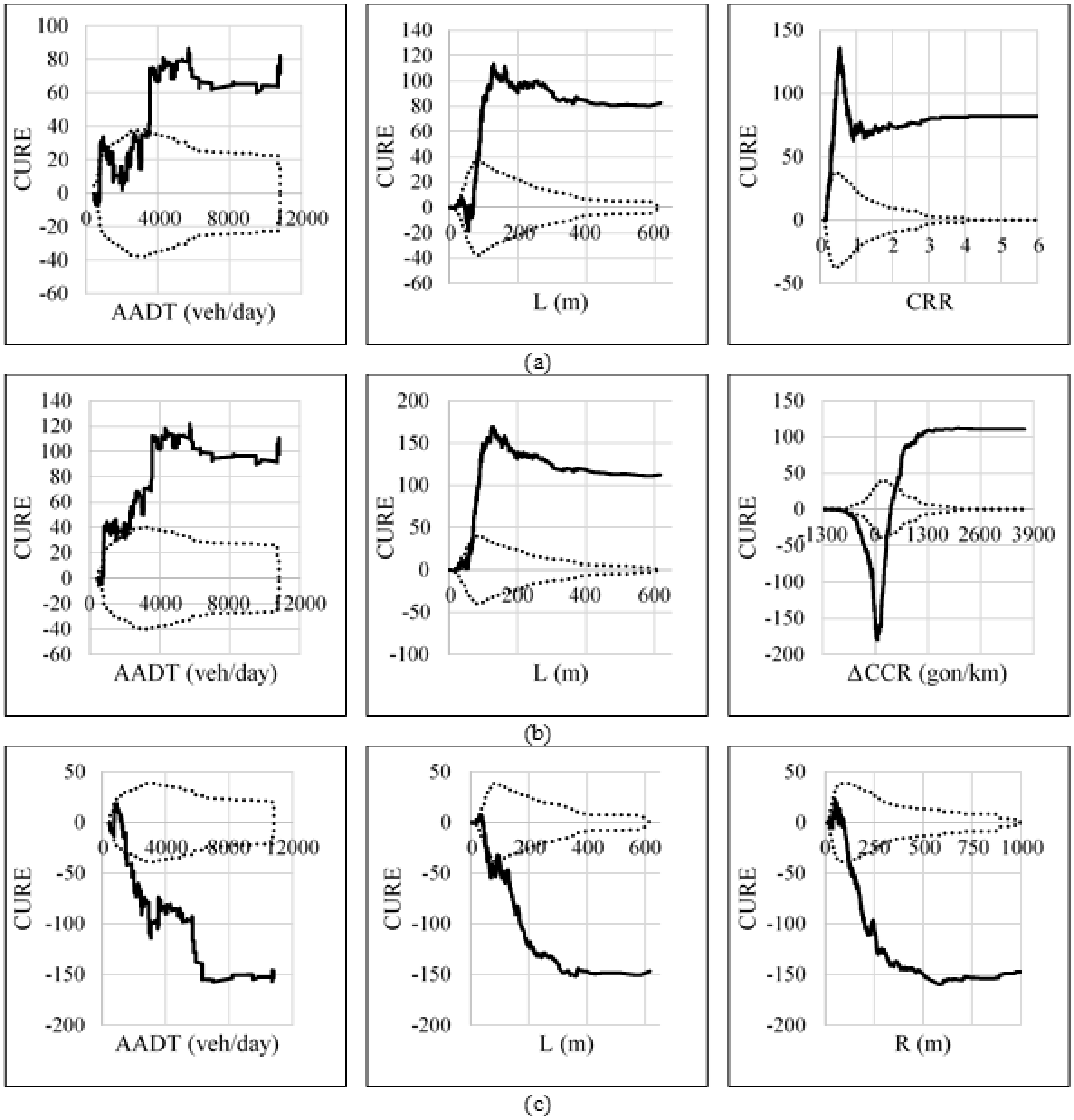

FIGURE 3 CURE plots of the SPFs based on alignment indexes: (a) *CRR*; (b) *CCR*; (c) *R*.

6.4. Calibration to other countries

The new local consistency model has been calibrated for Spanish two-lane rural roads. Therefore, Spanish engineers can use it to estimate the number of fatal-and-injury crashes and the consistency level for the regional network.

Although engineers from other countries cannot use the same SPF to estimate road crashes, they can still use the Inertial Consistency Index to calibrate a new SPF – and consistency thresholds, if needed – to assess road safety on their roads. The use of local operating speed models is also encouraged.

Likewise, it is recommended to consider only fatal-and-injury crashes to prevent underreporting bias. To this regard, in Spain and many other countries, drivers are typically responsible for reporting PDO crashes. Therefore, this reporting depends on many factors like expected damage cost, proximity to urban zones, number of vehicles involved, presence of police, etc. As a result, the reporting of PDO crashes is very biased and cannot be used as reliable data.

Finally, according to Vangala et al. (2015), a Negative Binomial-Generalized Exponential distribution is preferred instead of zero-inflated distributions for the calibration of the Safety Performance Function in case of having more than 80% of horizontal curves without reported crashes. Regarding this, zero-inflated distributions are based on the underlying assumption that road elements exist in two states: (i) zero-state: safe road element without crashes and (ii) non-zero state: road elements in which might occur crashes. However, there is no perfectly safe road element from a theoretical point of view, i.e., none road element has a null likelihood of crash occurrence (Lord et al., 2005).

7. CONCLUSIONS

A new local consistency model was defined based on the Inertial Consistency Index, as the difference between the inertial operating speed (V_i) and the operating speed (V_{85}). To this regard, V_i represents drivers' expectancies, whereas V_{85} represents road behavior.

The inertial operating speed at each point of the alignment was defined as the weighted average operating speed of the preceding road section (Llopis-Castelló et al., 2017 and 2018). Distances between 300 m and 800 m with a step of 100 m, periods of time between 10 s and 40 s with a step of 5 s, and 11 weighting distributions were studied to determine how V_i should be estimated.

In this way, 143 inertial operating speed profiles were calculated for each road section, so a total of 143 Safety Performance Functions were calibrated to identify which speed profile was able to better represent drivers' expectancies.

As a result, a time-based inertial operating speed showed better results than those based on distance. In addition, the use of weighting distributions allowed a more accurate estimation of the behavior of Short-Term Memory. Thus, the inertial operating speed was estimated considering 15 s and a linear weighting distribution, which was consistent with drivers' expectancies acquirement process.

A Safety Performance Function was proposed to estimate the number of crashes on a horizontal curve and consistency thresholds were defined. In this way, a horizontal curve has a good consistency level when the Inertial Consistency Index (ICI) is lower than 5 km/h, a poor consistency level when ICI is higher than 12.5 km/h, and a fair consistency level in all other cases (Figure 4 and Figure 5).

Finally, the proposed model was compared with Criterion II developed by Lamm et al. (1999) and different alignment indexes. As a conclusion, Criterion II assigned the same consistency level to horizontal curves with very different crash rates. This means that a low speed difference between successive elements (ΔV_{85}) was not necessarily associated with a low likelihood of crash occurrence. On the contrary, the new consistency model based on the Inertial Consistency Index was able to correctly group the horizontal curves depending on their consistency level. Likewise, the new calibrated model showed a more accurate estimation of the number of crashes than Criterion II proposed by Lamm et al. (1999) and those SPFs based on alignment indexes. Therefore, the proposed local consistency model better describes the studied phenomenon.

Thus, highway engineers have a new tool to identify where road crashes are more likely to occur during the design stage of both new two-lane rural roads and improvements of existing highways.

ACKNOWLEDGMENTS

The study presented in this paper is 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 Department of Housing, Public Works and Spatial Planning of the Valencian Regional Government and the Traffic Department of the Spanish Government, which provided traffic and crash data, respectively.

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