NEW GEOMETRIC DESIGN CONSISTENCY MODEL BASED ON OPERATING SPEED PROFILES FOR ROAD SAFETY EVALUATION

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ABSTRACT

In order to reduce road fatalities as maximum as possible, this paper presents a new methodology to evaluate road safety in both design and redesign stages of two-lane rural highways. This methodology is based on the evaluation of road geometric design consistency, determining one value which will be a surrogate measure of the safety level of a two-lane rural road segment. The consistency model presented in this paper is based on the consideration of continuous operating speed profiles. The models used for their construction have been obtained by using an innovative GPS-data collecting method, based on continuous operating speed profiles recorded from individual drivers. This new methodology allowed the researchers to observe the actual behavior of drivers and to develop more accurate operating speed models than those which are based on spot-speed data collection. That means a more accurate approximation to the real phenomenon, and thus a better consistency measurement.
Operating speed profiles were built for 33 Spanish two-lane rural road segments, and several consistency measurements based on the global and local operating speed were checked. The final consistency model takes into account not only the global dispersion of the operating speed, but also some indexes that consider both local speed decelerations and speeds over posted speeds.
For the development of the consistency model, the crash frequency for all sites was considered, obtaining a model directly related to safety. This allows estimating the number of crashes of a road segment by means of the calculation of its geometric design consistency. Consequently, the present consistency evaluation method becomes an innovative tool that can be used as a surrogate measure to estimate road safety of a road segment even before its construction.

Keywords: road safety, surrogate measures, design consistency, operating speed, crash estimation.

INTRODUCTION

Road crashes are one of the most important problems in our society. Every year 1.2 million of people are killed and between 20 and 50 million people are injured due to road accidents. If current trends continue road traffic injures are predicted to be the third leading contributor to the global burden of disease and injury by 2020. In Spain approximately 60% of rural road accident fatalities occur on two-lane rural roads.

Three factors may have influence on the occurrence of a road accident: human factor, vehicle and road infrastructure. Some studies pointed out that the infrastructure factor is behind over 30% of road crashes (Treat et al., 1979). In fact, previous research has shown that collisions tend to concentrate at certain road segments, indicating that besides driver's error, road characteristics play a major role in collision occurrence. One of the main reasons for accident occurrence can be lack of geometric design consistency. This concept can be defined as how drivers' expectancies and road behavior fit. Thus, a road with a good consistency level is the one in which its behavior and what drivers expect are very similar, so drivers will not be surprised while driving along them. A poor consistency means bad fitting, surprising events and also high speed variability along different road segments and among different drivers, which may increase the likelihood of crash occurrence.

Most of the research and development of design consistency measures focuses on four main areas: operating speed, vehicle stability, alignment indices and driver workload (Ng and Sayed, 2004; Awata and Hassan, 2002).

A simpler approach to evaluate design consistency can be based on the alignment indices (Hassan, 2004), which are quantitative measures of the general character of an alignment in a section of road. Examples of alignment indices include average radius (*AR*), ratio of maximum to minimum radius (*RR*), average rate of vertical curvature (*AVC*) and the *CRR* that is defined as the ratio of radius of a single horizontal curve to the average radius of the entire section. Analyses of collisions on the two-lane rural highways have shown that a significant relationship exists between collision frequency and alignment indices.

Other method to evaluate design consistency is the study of vehicle stability. When insufficient side friction is provided at a horizontal curve, vehicles may skid out, rollover or be involved in head-on accidents. According to this statement, locations that do not guaranty enough vehicle stability can be considered as geometric design inconsistencies.

In this sense, Lamm et al. (1999) presented a design consistency criterion which includes the difference between the assumed side friction of the road and the side friction demanded by the driver. The difference between side friction assumed (f_{RA}, that depends on the design speed) and demanded (f_{RD}, that depends on the operating speed), denoted as Δf_R, was used to represent vehicle stability at Lamm's criterion III. According to this criterion, consistency is considered good when Δf_R is higher than or equal to 0.01, fair when its value is between 0.01 and -0.014, and poor when Δf_R is lower than -0.04.

A third approach for evaluating design consistency is by means of drivers' workload. Driver workload is defined as the time rate at which drivers must perform a given amount of driving tasks that increases with the increase of the complexity in highway geometric features (Gibreel et al., 1999). Driver workload may be a more appealing approach for identifying inconsistencies than operating speed because it represents the effort that the roadway requires from drivers, while operating speed is only one of the observable outputs of the driving task (Ng and Sayed, 2004). Several methods and approaches have been tried to model driver workload including visual demand (*VD*) and workload rating (Hassan, 2004). However, compared with the other consistency evaluation measures, evaluation of drivers' workload, is much more complex, so it is less used.

The most commonly used criteria to evaluate highway design consistency are based on operating speed evaluation (Gibreel et al., 1999), often defined as the 85th percentile speed (v_{85}) of a sample of vehicles, and obtained by using operating speed prediction models. This specific measure of speed can be used in consistency evaluation by examining disparities between design speed (v_d) and v_{85} or examining the differences in v_{85} between successive elements of the road (Δv_{85}). Tangent-to-curve transitions are the most critical locations when considering safety measures. In fact, it is estimated that more than 50% of the total fatalities on rural highways take place on curved sections (Lamm et al., 1992).

Leisch and Leisch (1977) recommended a revised design speed concept that included guidelines on both operating speed reductions and differentials between design and operating speeds. In the same way, Kanellaidis et al. (1990) suggested that a good design can be achieved when the difference between v_{85} on the tangent and the following curve does not exceed 10 km/h.

However, the most commonly used method to evaluate road consistency was developed by Lamm et al. (1999) based on mean accident rates. They presented two design consistency criteria related to operating speed, which include the difference between design and operating speed and the difference between operating speeds on successive elements.

The difference between operating speed and design speed $|v_{85} - v_d|$ is a good indicator of the inconsistency at one single element, while the speed reduction between two successive elements (Δv_{85}) indicates the inconsistency experienced by drivers when traveling from one element to the next one. On Table 1, consistency thresholds for Criteria I and II are summarized.

Table 1 Thresholds for a determination of design consistency quality. Lamm's criteria I & II.

Consistency rating	Criterion I (km/h)	Criterion II (km/h)
Good	$\lvert v_{85} - v_d\rvert \le 10$	$\lvert v_{85_i} - v_{85_{i+1}}\rvert \le 10$
Fair	$10 < \lvert v_{85} - v_d\rvert \le 20$	$10 < \lvert v_{85_i} - v_{85_{i+1}}\rvert \le 20$
Poor	$\lvert v_{85} - v_d\rvert > 20$	$\lvert v_{85_i} - v_{85_{i+1}}\rvert > 20$

Although most consistency criteria give thresholds for good, fair and poor design consistency, other authors (Hassan, 2004) suggest continuous functions as a better tool for designers.

The consistency criteria previously presented allow evaluating the design consistency and estimating road safety only in a road element (the horizontal curve). Other studies, such as the one carried out by Polus and Mattar-Habib (2004), used continuous speed profiles to determine the global speed variation along a road segment, and determining a single consistency value for the whole road segment. Moreover, their design consistency index is a continuous function instead of being based on ranges.

They developed two new consistency measures. The first was the relative area bounded between the operating speed profile and the line of average weighted speed by length (*Ra*). The second was the standard deviation of operating speed in each design element along the whole section investigated (σ). It was necessary to use this additional measure to complement the first measure because the *Ra* measure by itself provided similar results for somewhat different geometric characteristics in a few cases.

Based on the two independent measures, a consistency model was developed; and thresholds for good, acceptable, and poor design consistency of any section were proposed (Table 2). The *Ra* and σ on several test sections provided a similar assessment of consistency as Lamm's measures.

Table 2 Thresholds for a determination of design consistency quality.

Design consistency quality $C = e^{-0.278 \cdot [Ra \cdot (\sigma/3.6)]}$		
Good	**Acceptable**	**Poor**
$C > 2\ (m/s)$	$1 < C \leq 2\ (m/s)$	$C \leq 1\ (m/s)$

The geographic environment at which consistency variables and their relationships to crash rates are obtained is also important. Extrapolation must be carried out carefully. For example, further test for the applicability of Lamm's criteria revealed that a 20 km/h limit for poor design is applicable to Korea (Lee et al., 2000), but a different limit was recommended for Italy (Cafiso, 2000).

Several research have studied the effect of geometric design consistency on road safety. Anderson et al. (1999) have investigated the relationship between design consistency and safety using loglinear regression models. Two models have been developed that relate accident frequency to traffic volume, curve length, and speed reduction (Δv_{85}). A separate model has been developed that relates accident frequency to curve length and *CRR*.

Ng and Sayed (2004) investigated the effects of several design consistency measures on safety and developed models that incorporate the measures to quantify their effects on safety. The design consistency measures mentioned were $v_{85} - v_d$, Δv_{85}, Δf_R, *CRR* and visual demand.

Finally, it is worthy highlighting the study carried out by Cafiso et al. (2007). They presented a methodological approach for the safety evaluation of two-lane rural highway segments that uses both analytical procedures referring to alignment design consistency models and safety inspection processes.

They developed a safety index (SI) that quantitatively measures the relative safety performance of a road segment. The SI is formulated by combining three components of risk: the exposure of road users to road hazards, the probability of a vehicle being involved in an accident and the resulting consequences should an accident occur.

To test the procedure, comparisons were carried out between SI scores and EB (Empirical Bayes) safety estimates. The results showed that ranking of segments gives comparable results in terms of SI or accident frequency.

Different studies show that improving design consistency leads to safer roads. The present paper shows a new geometric design consistency model based on continuous operating speed profiles. Its relationship to safety is also obtained, so it can be used as a surrogate measure for road safety evaluation.

OBJECTIVES

The objective of this study is to develop a design consistency model that may be used as a surrogate measure for road safety evaluation for two-lane rural roads. Several measures will be obtained based on operating speed profiles, with the aim of obtaining a single consistency value for the whole road segment instead of focusing only on individual or consecutive road geometric elements.

The design consistency parameter will be based on continuous operating speed models, developed in previous research through an innovative technique that uses GPS devices for monitoring actual drivers. Thus, operating speed profiles are more accurate, reflecting better the actual behavior of drivers.

The crash frequency will also be considered in the development of the model. Consequently, a relationship between consistency and crash rate will be obtained, being an important tool to assist engineers to design safer roads.

DATA COLLECTION

The consistency measure that will be developed in this research is based on the analysis of the operating speed profiles of two-lane rural road segments. For its calibration, some speed profile surrogate measures will be compared to crash data, in order to obtain a consistency model useful for designing safer roads. Thus, three main databases are necessary for this research: geometry characteristics, traffic volume and crash data. Those data were obtained for 65 two-lane rural road segments of the Valencian Community (Spain), so a high volume of data has been analyzed for the development of this investigation.

Data description: road segments characteristics, traffic volume, crash data

The purpose of the geometry data is, by means of some models, to develop their operating speed profiles. 65 road segments of the Valencian Community (Spain) were chosen, presenting a length between 2 and 5 km, longitudinal grades lower than 5% and without important intersections.

The availability of traffic volume data for those road segments is public, so it was downloaded from the official website. The database consisted on all crash data during last 15 years for all road segments. Having this large database is important for research, but it also has to be handled with care, because of possible changes at conditions or road geometry of some segments during this long period of time. In order to prevent this problem, traffic volume values were examined in order to determine irregular variations of the *AADT* through years; and also was the history for all road segments, checking for redesigns. Depending on each particular case, some specific years or road segments were no longer considered in the analysis.

Accident data was provided by the local Administration. It consisted on a list of all accidents reported on those roads during last 13 years. Accidents are characterized by location, day and hour, daylight conditions, severity, vehicle type, driver characteristics, external factors, causes and other conditions. Considering all data, a filtering process was done, deleting accidents that presented at least one of the following issues:

- Crashes that took place during the years that are not considered in the traffic volume data.
- Property Damage Only (PDO) accidents. In Spain, some of these accidents are reported and some are not, so the crash database does not show the accidents occurred, but the accidents reported. In order to not add external variation on crash data, there were only considered accidents with victims (they are always reported).
- The causes for all accidents were examined, taking out from the analysis those related to external factors (e.g. due to previous illness of the driver, or animals crossing the road), or minor intersections (because the consistency model does not consider this factor).

Operating speed models

The operating speed profiles were developed by means of two types of operating speed models: one for horizontal curves and other for tangents, and some construction keys. For developing the final operating speed profile, acceleration and deceleration rates are also calculated depending on geometric features. These models have been obtained and calibrated on previous research (Pérez et al., 2010) by using continuous operating speed profiles. Those profiles were obtained by means of GPS devices from individual drivers. The drivers used for calibration are actual drivers of the road, using their individual vehicles. Road characteristics and geographic region are similar than those used for calibration.

The main advantages of these operating speed models is that they are not based on speed-spot data collection, but calibrated based on continuous data. Thus, they reflect better the behavior of actual drivers.

The operating speed model for curves was developed by Pérez et al. (2010) and uses radius as the explanatory variable.

In that research, a big change in driver behavior was appreciated when radius of curves was higher or lower than 400 m. Thus, two models were developed: one for all curves and other for curves with radius lower than 400 m. Also, for curves with a radius lower than 70 m, the specific model underestimates the actual operating speed, so it needs to be replaced by the speed calculated by the side-friction expression. In this research, only a few number of curves had to consider this other model.

$$v_{85} = 97.4254 - \frac{3310.94}{R} \qquad 400\ \text{m} < R \leq 950\ \text{m} \tag{1}$$

$$v_{85} = 102.048 - \frac{3990.26}{R} \qquad 70\ \text{m} < R \leq 400\ \text{m} \tag{2}$$

$$v_{85}^2 = 127 \cdot R \cdot \left(f_t + \frac{e}{100}\right) \qquad R \leq 70\ \text{m} \tag{3}$$

where:
v_{85}: operating speed on curve (km/h)
R: radius (m)
f_t: side friction
e: superelevation rate (%)

An operating speed model for tangents was also developed, considering the length of the tangent and the speed of the previous curve. It was noticed that all drivers tended to reach a desired speed, which was set to 110 km/h. However, depending on the length of the tangent they could accelerate more or less departing from the operating speed of the previous curve. Thus, the higher the length of the tangent, the closer its operating speed will be to the desired speed.

$$v_{85T} = v_{85C} + \left(1 - e^{-\lambda \cdot L}\right) \cdot (v_{des} - v_{85C}) \quad (4)$$

where:
$\lambda = 0.00135 + (R - 100) \cdot 7.00625 \cdot 10^{-6}$
v_{85C}: operating speed on previous curve (km/h)
v_{85T}: operating speed on tangent (km/h)
v_{des}: desired speed (110 km/h)
R: horizontal curve radius (m)
L: length of the tangent (m)

The difference of this model compared to previous models is that the individual reached speed for each driver is accurately determined, regardless of the location where it was reached, based on the examination of their individual speed profiles. Previous models were based on spot-speed location methods, without considering whether the speed recorded for each driver was the maximum speed at the tangent or was not.

In order to plot the operating speed profile, acceleration and deceleration rates were obtained. Deceleration rates were obtained by Pérez et al. (2011), while acceleration rates being obtained for this research using the same methodology. Both of them are based on the radius of the curve. It is an important improvement compared to other operating speed profile models, since it depends on the curve radius, instead of using constant acceleration or deceleration rates.

$$d_{85} = 0.313 + \frac{114.436}{R} \quad (5)$$

$$a_{85} = 0.41706 + \frac{65.93588}{R} \quad (6)$$

where:
d_{85}: deceleration rate (m/s^2)
a_{85}: acceleration rate (m/s^2)
R: radius (m)

These deceleration and acceleration rates have been obtained by considering each driver individually, selecting the specific points at which each driver starts and ends speed variations, instead of considering the same speed transition length for all drivers. Thus, the acceleration and deceleration rates reflect better drivers' behavior. In this operating speed profile model, the 85^{th} percentile of acceleration and deceleration rates are used.

Operating speed profiles construction

Considering the previous models, a computer program was developed in order to calculate the operating speed profile for each road segment, both in forward and backward directions. It is done in two steps: determination of the horizontal alignment for each road segment, and calculation of the operating speed profiles based on the previous models.

As previously mentioned, the geometry was not directly available for all road segments. We only had the GPS coordinates of all road segments. The calculation of the horizontal alignment is based on the determination of the curvature diagram for each road segment. This calculation is based on two steps:

- The first one takes the succession of points of the axis and calculates the local curvature. In this calculation, not only three points are considered, the process is much more accurate. The result is an unprocessed curvature diagram, which allows to know the general behavior of the road, but still not composed by tangents, circular and spiral curves.
- The second step takes the previous curvature diagram and transforms it into a final diagram, composed by straight lines that represent the succession of tangents, spiral and circular curves that compose the horizontal alignment.

After processing all road segments, some of them were found to show errors in their coordinates, so they were removed from the analysis, establishing the number of road segments at this point in 43.

Once the horizontal alignment is determined for all road segments, their operating speed profiles can be determined. The same computer program performed the calculations, in two steps:

- Calculation and graphical representation of the operating speed for constant curvature elements (circular curves and tangents). It is based on the previous models.
- Development of the operating speed profile. Based on the acceleration and deceleration expressions and construction rules.

It is necessary to point out that each road segment presents two operating speed profiles: one for each direction of travel.

CONSISTENCY MODELS

For developing the design consistency parameter, the following process was carried out: in first place, crash rates were estimated for each road segment. Also, all operating speed profiles were determined, and by means of them, several variables were calculated. After this calculation, correlations among all variables were examined, and five of them were selected for calibrating the consistency model.

The consistency model was calibrated by means of examining its relationship to safety, selecting one model that could be easily used for designing the road and it was related to safety.

Number of accidents

For almost all road segments, accident data was available for 13 years. In order to improve the accuracy of the model, a Safety Performance Function for estimating the number of accidents in 10 years was developed. For its calibration, a logistic, negative binomial regression was carried out, considering exposure units (length and *AADT*) and an alignment index (Table 3).

Several Four alignment indices were obtained based on the developed geometry for all road segments: Average Radius (AR), Curvature Change Ratio (CCR), Ratio between maximum and minimum radius of the road segment (RR), and ratio between the minimum radius and the average radius of the road segment (Rmin/AR). Different regressions were made considering the exposure and each one of the alignment indices. Finally, only the last one had a significant effect over safety, so it was included in the final form of the Safety Performance Function.

$$Y_{i,10} = e^{-4.9462} \cdot L^{0.8645} \cdot \overline{AADT}^{0.7683} \cdot e^{-0.7285 \cdot \frac{R_{\min}}{AR}} \quad (7)$$

Where:
$Y_{i,10}$: Estimated number of crashes in 10 years for the road segment.
L: Length of the road segment (km).
$\overline{AADT}$: mean value of Average Annual Daily Traffic for 10 years (veh/day).
$R_{\min}$: Minimum radius of the road segment (m).
AR: Average Radius of the road segment (m).

Table 3 Negative binomial model of accident frequency

Independent Variable	Coefficient	t-statistics
Intercept	-4.9462	<.0001
Log of the length **of road segment (km)**	0.8645	0.0021
Log of $\overline{AADT}$ per lane	0.7683	<.0001
R_{min}/AR	-0.7285	0.0842
Overdispersion	0.1519	
Number of sections	43	
Log Likelihood at zero	167.8662	
Log Likelihood at convergence	-94.5553	
Pearson χ^2	38.9802	
AIC	199.1107	

Considering the expected number of accidents by the SPF and the occurred number of accidents, the Empirical Bayes method was used to estimate the final number of accidents expected for each site. With them, crash rates (accidents with victims by 10^6 veh-km) were obtained for each road segment. The overdispersion parameter of the Safety Performance Function is $\mu = 0.1519$. Then, $k = 1/\mu = 6.5832$.

Finally, the Empirical Bayes Method calculates the estimated number of accidents:

$$E(\lambda/r) = \alpha \cdot \lambda + (1 - \alpha) \cdot r \quad (8)$$

where:
$\alpha = \frac{1}{1+\frac{\lambda}{k}}$
λ: number of accidents estimated by the Safety Performance Function
r: number of observed crashes for the specific site

Correlation among variables

The operating speed profiles were developed in both directions for all road segments considered. By means of them, some measures of the speed dispersion and deceleration were obtained and processed. The speed limits for all road segments were also examined, and some variables considering the speed dispersion and the speed limit were checked. The total amount of examined variables was 14.

Considering the operating speed profiles, the average operating speed ($\bar{v}_{85}$) and the standard deviation of the operating speed (σ_{85}) are directly obtained. The first one is obtained in order to be an indicator of the road segment, while the second one is for determining the global dispersion of the operating speed. The higher the dispersion is, the more inconsistent the road segment is expected to be.

Considering the operating speed profile, the average speed and posted speed, some other measures were tried:

- R_a (m/s). First introduced by Polus and Mattar-Habib (2004), it measures the sum of the area between the operating speed profile and the average speed of each road segment, divided by its length. Thus, it measures the global variability of the speed, presenting higher values as the speed variability increases.
- $E_{a,10}$ (m/s). It is also a measurement of the speed dispersion. As the previous measure, it is the sum of the areas between the operating speed profile and the average operating speed profile plus and minus 10 km/h. Finally, it is divided by its length.
- $E_{a,20}$ (m/s). As the previous index, but considering 20 km/h.
- L_{10}. Rate (in %) between the total length of the road segment at which the absolute difference between the operating speed and the average operating speed is more than 10 km/h and the length of the road segment.
- L_{20}. As the previous variable, but using 20 km/h.

By means of the operating speed profiles, it is also easy to determine all the speed decrement transitions. They were detected for all road segments, calculating the speed differential (km/h) in absolute value (Δv_{85}), and the distance (m) used for each speed transition ($L_{\Delta v_{85}}$). After that, all decelerations lower than 1 km/h were not considered, because their low value might not be perceived by users. After that, some road segments presented a very low number of decelerations. In order to not influence further calculations, those road segments were also taken out from the analysis, because they behaved in a very different way than others. Thus, the final number of road segments was 33. Table 4 shows the main characteristics of alignment, traffic volume and crash data for each road segment.

Table 4 Characteristics of the road segments used on consistency model

Road Segment	**Length (km)**	**Mean *AADT* (veh/day)**	**Observed crashes in 10 years**
1	3.42	824	2
2	2.105	802	3
3	1.805	908	1
4	2.42	4546	5
5	2.565	2511	3
6	3.205	2511	3
7	4.84	985	6
8	2.24	918	1
9	2.31	403	1
10	4.035	2895	9
11	2.53	486	2
12	2.285	486	0
13	3.895	486	2
14	4.13	2750	6
15	1.41	425	2
16	3.925	1216	2
17	1.695	272	0
18	3.365	3292	8
19	3.04	2958	5
20	2.595	4550	3
21	4.675	1215	3
22	2.145	2522	8
23	3.825	3108	23
24	1.88	789	3
25	4.415	513	4
26	2.325	2231	3
27	1.865	577	1
28	1.42	577	1
29	1.805	7442	2
30	2.495	8252	22
31	1.32	6553	1
32	3.89	209	3
33	1.72	922	3

Considering all deceleration processes for each road segment in both directions, the following variables were obtained:

- Average speed reduction ($\overline{\Delta v_{85}}$). Average value of all speed reduction processes in each road segment. The higher this variable is, the more dramatic the speed reductions in the road segment will be, so the road segment will be more inconsistent.

- Standard deviation of the speed reductions ($\sigma_{\Delta v_{85}}$). It measures the standard deviation of the speed reduction value for each road segment. It is supposed that the higher the standard deviation is, the more disperse the drivers' behavior will be, so the road segment is more inconsistent.
- Deceleration average distance ($\bar{L}_{\Delta v_{85}}$). Average value of the distances used for deceleration in a road segment. Due to acceleration and deceleration rates are obtained from geometry relationships, similar speed differentials could be achieved by means of different distances. Thus, this measure could add more variability to the average deceleration value in its relationship to crash rates.
- Speed reduction intensity ($\bar{d}_{\Delta v_{85}}$). For all individual speed reduction processes, their magnitude were divided by the length used, determining the individual speed reduction intensity (km/h/m). This value represents the average value for each road segment.
- Deceleration length rate of each road segment (L_d). It is an index of the distance at which the road segment's speed profile is under deceleration conditions. It is obtained by adding the individual deceleration lengths on a road segment and dividing it into its total length.

All previous values are determined by considering the operating speed profile by itself for each road segment. Also considering the speed limits, two new variables were determined:

- Difference between the average operating speed and the speed limit (Δv_{85-l}). This value of speed limit has been calculated as the average of posted speed limits weighted by length. The difference has not been calculated in absolute value. It is intended to be an auxiliary variable for helping other variables to add correlation to the final model. For this consideration, the global speed limit has been selected for each road segment.
- $E_{a,l}$ (m/s). As $E_{a,10}$ and $E_{a,20}$, this variable is the sum of the areas between the operating speed and the speed limit for the road segment. Finally, it is divided by its length.

Some variables are correlated among them, showing some interesting relationships. The average speed reduction and its standard deviation are highly correlated: higher speed reduction values are combined with higher variability.

In Figure 1, the average standard deviation of all road segments are plotted against their average value. In that figure the values have been distinguished by different color taking into account their estimated crash rates. Those values have been obtained by dividing the total number of estimated accidents in each individual road segment by its total exposure (calculated from its length and its traffic volume for ten years).

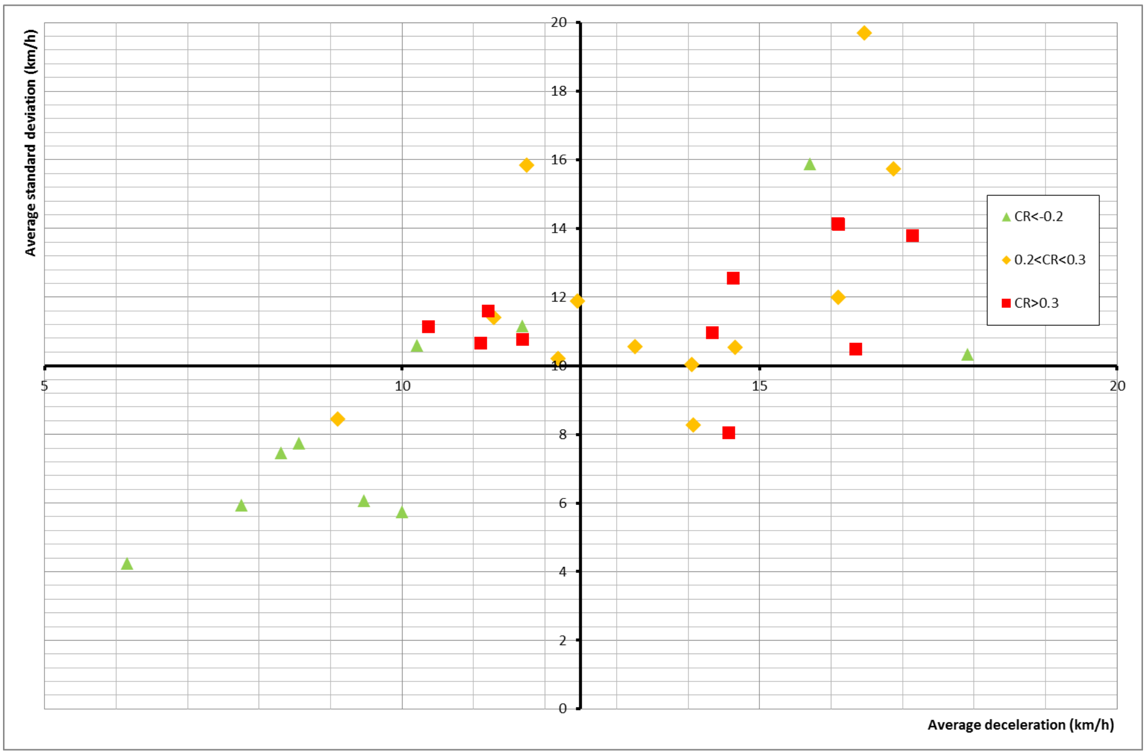

Figure 1 Average value vs standard deviation of operating speed reductions

R_a also presents a high correlation with the average operating speed. On road segments composed by sharp curves and short tangents, drivers are constrained by the road geometry and they cannot develop their desired speed, usually leading to low operating speeds and deviations. Thus, the R_a variable, which measures the speed variability, is low. At road segments where the geometry does not constraint drivers as in the previous segments, operating speeds are higher, resulting into lower speed variability and thus, into lower R_a values. So, the maximum values of R_a are reached with medium operating speeds. A graphical representation is shown on Figure 2.

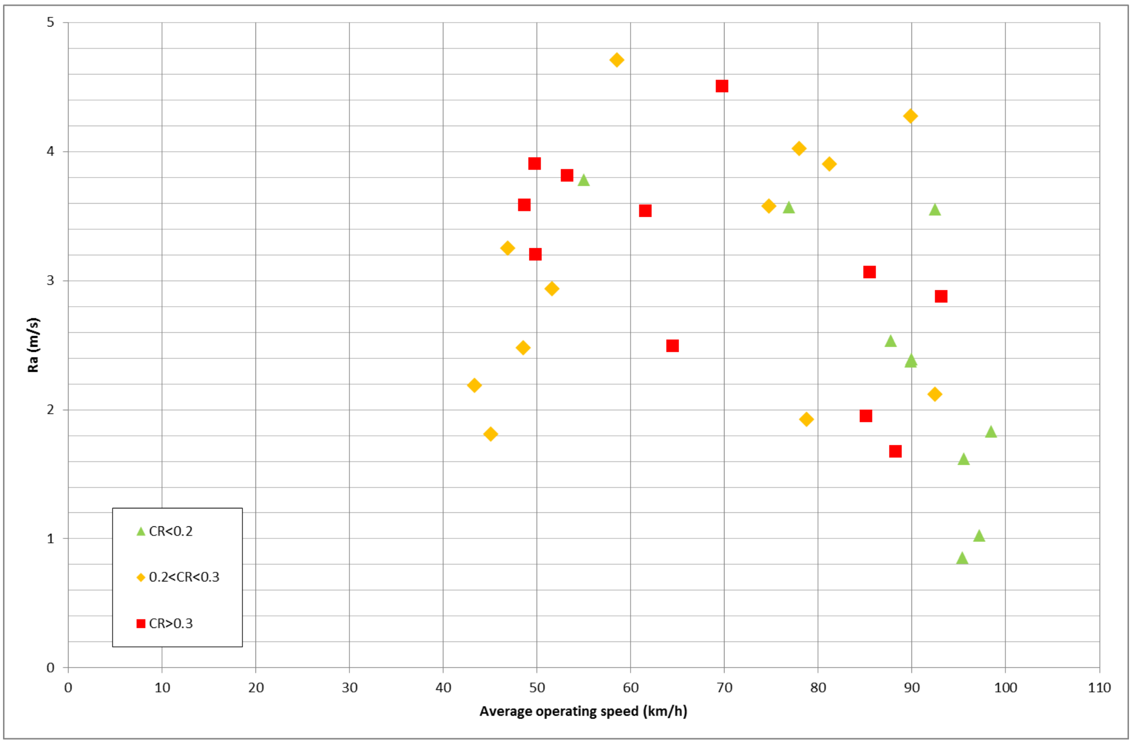

Figure 2 R_a vs average operating speed

Considering all 14 variables, an analysis of correlation was carried out in order to determine the final variables to consider in the model. The correlation matrix is shown on Table 5. High correlations are highlighted in dark grey, while medium correlations are in light grey.

Table 5 Correlation among independent variables

	$\bar{v}_{85}$	σ_{85}	R_a	L_{10}	L_{20}	$E_{a,10}$	$E_{a,20}$	$\overline{\Delta v_{85}}$	$\sigma_{\Delta v_{85}}$	$\bar{L}_{\Delta v_{85}}$	L_d	$\bar{d}_{\Delta v_{85}}$	Δv_{85-l}	$E_{a,l}$
$\bar{v}_{85}$		-0.391	-0.380	-0.377	-0.305	-0.338	-0.258	-0.372	-0.445	0.902	0.381	-0.975	0.691	0.453
σ_{85}	-0.391		0.992	0.942	0.955	0.980	0.839	0.645	0.765	-0.400	-0.201	0.447	-0.067	0.212
R_a	-0.380	0.992		0.955	0.953	0.970	0.806	0.615	0.746	-0.396	-0.166	0.437	-0.048	0.228
L_{10}	-0.377	0.942	0.955		0.869	0.89	0.636	0.593	0.627	-0.372	-0.207	0.415	-0.031	0.266
L_{20}	-0.305	0.955	0.953	0.869		0.977	0.871	0.595	0.734	-0.334	-0.045	0.369	0.004	0.247
$E_{a,10}$	-0.338	0.980	0.970	0.890	0.977		0.902	0.594	0.767	-0.377	-0.134	0.409	0.001	0.263
$E_{a,20}$	-0.258	0.839	0.806	0.636	0.871	0.902		0.538	0.741	-0.283	-0.090	0.356	0.003	0.174
$\overline{\Delta v_{85}}$	-0.372	0.645	0.615	0.593	0.595	0.594	0.538		0.673	-0.102	-0.157	0.402	-0.230	-0.150
$\sigma_{\Delta v_{85}}$	-0.445	0.765	0.746	0.627	0.734	0.767	0.741	0.673		-0.438	-0.190	0.459	-0.172	0.010
$\bar{L}_{\Delta v_{85}}$	0.902	-0.400	-0.396	-0.372	-0.334	-0.377	-0.283	-0.102	-0.438		0.353	-0.862	0.555	0.285
L_d	0.381	-0.201	-0.166	-0.207	-0.045	-0.134	-0.090	-0.157	-0.190	0.353		-0.419	0.207	-0.023
$\bar{d}_{\Delta v_{85}}$	-0.975	0.447	0.437	0.415	0.369	0.409	0.356	0.402	0.459	-0.862	-0.419		-0.634	-0.378
Δv_{85-l}	0.691	-0.067	-0.048	-0.031	0.004	0.001	0.003	-0.230	-0.172	0.555	0.207	-0.634		0.874
$E_{a,l}$	0.453	0.21	0.228	0.266	0.247	0.263	0.174	-0.150	0.010	0.285	-0.023	-0.378	0.874	

As can be seen in the correlation matrix, the following correlations are found:

- σ_{85}, R_a, L_{10}, L_{20}, $E_{a,10}$, $E_{a,20}$ and $\sigma_{\Delta v_{85}}$ present high correlation values. Considering that R_a was previously used by Polus and Mattar-Habib (2004), it was recommended for consideration in the following stages of the analysis.

- $\bar{L}_{\Delta v_{85}}$, $\bar{d}_{\Delta v_{85}}$ and $\bar{v}_{85}$. They present high correlation values, so only the operating speed average value is considered for further analysis.
- $\overline{\Delta v_{85}}$. It is medium-correlated with other variables, represented all of them by R_a in the models. As the correlation is medium, it is suggested to be maintained for further research.
- L_d. This variable is not correlated to any other variable.
- Those variables, under the influence of limit speeds, are correlated between them, and also a medium correlation is found with the average operating speed. Then, $E_{a,l}$ is suggested for consideration in the further research.

So, the variables that will be chosen for the next step are the following:

- R_a
- Average operating speed ($\bar{v}_{85}$)
- Percentage of road segment under deceleration conditions (L_d).
- Average speed reduction ($\overline{\Delta v_{85}}$).
- $E_{a,l}$

It is important to point out that the Global Consistency Model developed by Polus and Mattar-Habib (2004) consists on a combination of R_a and σ, variables which have been demonstrated here to have a high correlation. Then, it is suggested to use only one of them and combine with another variable, probably obtaining higher statistical significance.

Relationship to safety

Considering the previous variables, several models were checked in order to analyze the relationship between the Estimated Crash Rate (*ECR*) and all variables separately. Those models are shown on Table 6.

Table 6 Calibrated models for *ECR* by individual variable

Variable	Model	R^2
R_a	$ECR = \frac{1}{2.22562 + \frac{5.46248}{R_a}}$	30.9%
	$ECR = e^{-1.00383} \cdot e^{-\frac{0.988661}{R_a}}$	24.9%
	$ECR = e^{-1.89911} \cdot R_a^{0.497538}$	24.4%
$\bar{v}_{85}$	$ECR = \frac{1}{2.00006 + 0.000429405 \cdot \bar{v}_{85}^2}$	31.7%
	$ECR = e^{-0.915549} \cdot e^{-0.0000860305 \cdot \bar{v}_{85}^2}$	31.3%
	$ECR = e^{1.81969} \cdot \bar{v}_{85}^{-0.75763}$	25.8%

L_d	$ECR = \frac{1}{3.16716 + 27.9187 \cdot L_d^2}$	10.6%
	$ECR = e^{-1.23859} \cdot e^{-3.65402 \cdot L_d^2}$	4.5%
	$ECR = e^{-1.70654} \cdot L_d^{-0.186688}$	1.5%
$\overline{\Delta v_{85}}$	$ECR = \frac{1}{0.524925 + \frac{46.9038}{\overline{\Delta v_{85}}}}$	30.9%
	$ECR = e^{-0.675934} \cdot e^{-8.72905 \cdot \overline{\Delta v_{85}}}$	26.3%
	$ECR = e^{0.407621} \cdot \overline{\Delta v_{85}}^{-4.51153}$	25.9%
$E_{a,l}$	$ECR = 0.292265 - 0.0196406 \cdot E_{a,l}$	5.7%
	$ECR = e^{-1.31034} \cdot e^{-0.0692368 \cdot E_{a,l}}$	4.7%
	$ECR = e^{-1.42202} \cdot E_{a,l}^{0.0448093}$	2.7%

As can be seen on Table 6 variables with better fitting to Crash Rate are R_a, $\bar{v}_{85}$ and $\overline{\Delta v_{85}}$. The other variables had a very low correlation coefficient, so they did not fit to Crash Rate and they were only used for trying to improve the final model.

Considering only the best variables, additional models were checked, always combining them into a single index. Those models are presented on Table 7.

Table 7 Final calibrated models for ECR

Model number	**Expression**	**R²**
1	$ECR = \frac{1}{2.65897 + \frac{0.0570069}{\frac{R_a}{\bar{v}_{85}}}}$	39.8%
2	$ECR = \frac{1}{3.00826 + \frac{0.00056031}{\frac{R_a}{\bar{v}_{85}^2}}}$	42.3%
3	$ECR = e^{0.00516932} \cdot \left(\frac{R_a}{\bar{v}_{85}}\right)^{0.431919}$	35.8%
4	$ECR = \frac{1}{3.18601 + \frac{33.4686}{R_a \cdot \bar{v}_{85}}}$	32.8%
5	$ECR = \frac{1}{3.11287 + 0.0273507 \cdot \left(\frac{\bar{v}_{85}}{\overline{\Delta v_{85}}}\right)^2}$	45.7%

6	$ECR = e^{-0.866762} \cdot e^{-0.085472 \cdot \frac{\bar{v}_{85}}{\Delta v_{85}}}$	40.1%
7	$ECR = \frac{1}{3.36708 + 0.0000029176 \cdot \left(\frac{\bar{v}_{85}^2}{\Delta v_{85}}\right)^2}$	48.2%
8	$ECR = \frac{1}{2.40939 + 0.00403287 \cdot \left(\frac{\bar{v}_{85}^2}{\Delta v_{85}}\right)}$	46.3%

The strongest correlation to the crash rate is given by the division of the squared average operating speed and the average speed reduction value. Once the main expression was obtained, several attempts were made to add any of the two variables that were taken out from this analysis, but no good results were obtained.

Thus, the proposed design consistency index is the following:

$$C = \frac{\bar{v}_{85}^2}{\Delta v_{85}} \tag{9}$$

Both speeds are in km/h, so the final index is also in km/h.

Analyzing its composition, road segments with lower average speed reduction value will lead to higher consistency values, due to the more uniform speed. Higher operating speed average values are associated to better, more consistent roads.

It is worth to highlight that this model considers both the average speed and its variability. As a difference to other consistency indices, the model only considers decelerations in its determination, instead of both acceleration and decelerations, represented in the standard deviation of the operating speed.

Estimation of Crash Rates

After determining the composition of the consistency model, it is turn to determine its relationship to safety. Since the consistency model has been fitted according to the crash rates, the expressions are already obtained (models 7 and 8). As can be seen in Table 6, the model 7 has a bit more correlation to data than model 8, but for low-consistent road segments model 8 behaves slightly better. Both models are plotted on Figure 3, but model 8 is finally chosen for estimating crash rates.

On Figure 3, the estimated crash rates for all road segments are plotted as a function of their consistency index.

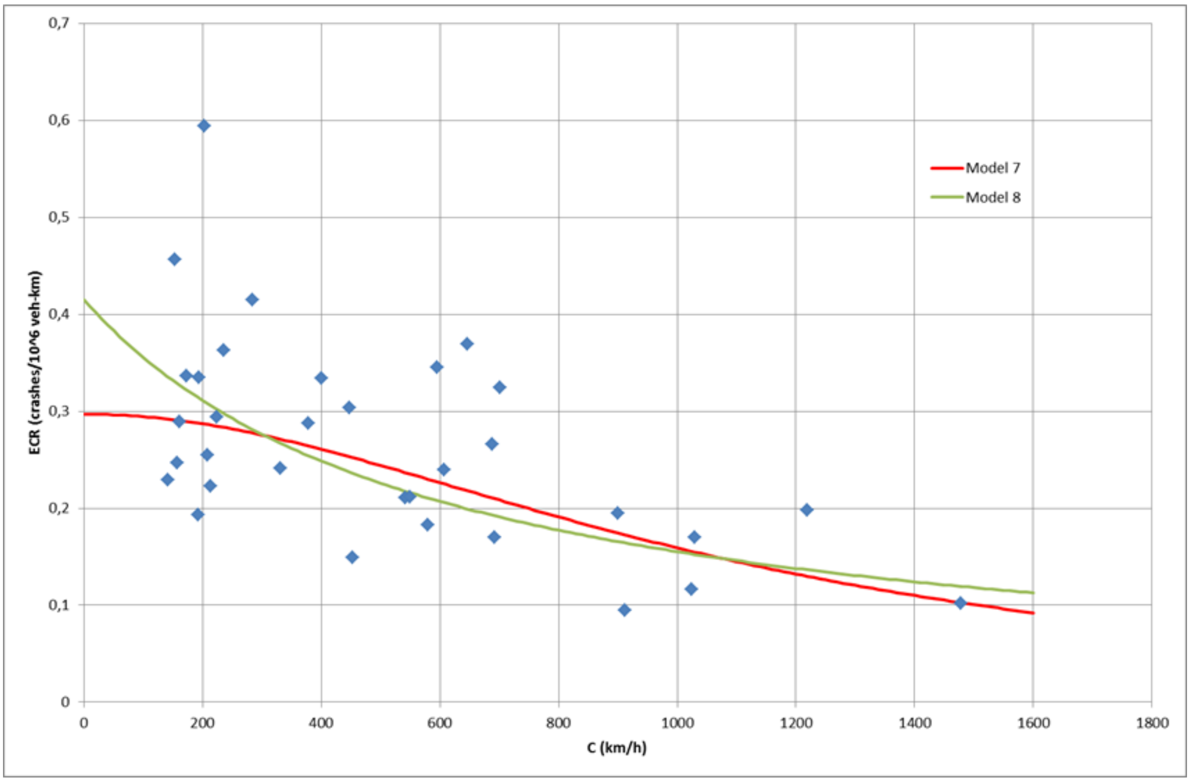

Figure 3 Estimated crash rate estimation models

CONCLUSIONS

Road fatalities are one of the most important problems in our society, causing thousands of victims every year. To contribute with the improvement of the road safety, this paper presents a new design consistency model that may be used as a surrogate measure for road safety evaluation of two-lane rural roads.

The consistency model has been developed from the regression analysis between several speed-measures variables and crash data.

The used speed-measures include not only variables related to operating speed but also related to deceleration and posted speed. All of them have been obtained from operating speed profiles built with the operating speed and deceleration/acceleration speed models developed in previous research. Those models were calibrated with continuous speed data recorded by an innovative technique that uses GPS devices for monitoring actual drivers' behavior. Thus, operating speed profiles are more accurate, presenting better approximation to the actual behavior of drivers.

The used crash data were not directly the observed accidents. With these accidents, a Safety Performance Function was calibrated showing an overdispersion of 0.1519. Then, based on this parameter and the observed accidents, the Empirical Bayes methodology was applied to estimate more accurately the number of accidents and thus the crash frequencies.
14 operating-speed-related variables were obtained from analyzing the operating speed profiles, crash data and speed limits for all road segments. A correlation analysis was made in order to reduce the final amount of parameters, reducing the final number of variables to five, being candidates to be used in the final consistency model form. Also, some interesting

relationships were found among variables, such as the higher crash rates reached when operating speed variability presents a medium value, or the high correlation between this parameter and the operating speed deviation.

After the statistical analysis, the proposed model for relating crash data to road geometry is the following:

$$ECR = \frac{1}{2.40939 + 0.00403287 \cdot C} \quad (10)$$

Where C is the design consistency index, calculated as:

$$C = \frac{\bar{v}_{85}^2}{\Delta v_{85}} \quad (11)$$

The development of the new model and consistency index leads to a new design consistency measure for a whole road segment. Moreover, since the model presents the relationship between consistency and crash rate, it is possible to use that parameter as a surrogate measure to evaluate road safety. Consequently, the results of this study can be an innovative tool for assisting engineers' decision. In fact, according to this methodology, the engineers may evaluate the consistency and road safety of several possible solutions and chose the safest one. Besides, the presented model can be also applied to the estimation of crash rates of an existing road where accident data are not available.

Further research is proposed to consist mainly on the determination of the consistency thresholds. Once the consistency model and the consistency index are defined, the thresholds for the consistency measure should be proposed after detailed crash data observation. Thus, taking into account the relationship between this index and the estimated crash rate, the adequacy of the road to drivers' expectancies will be able to be measured also from the value of this road safety parameter.

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