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# Calibration of the inertial consistency index to assess road safety on horizontal curves of two-lane rural roads

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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 s 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.

## 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 (European Road Safety Observatory (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 (Dirección General de Tráfico (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, 2000). In addition, Al-Masaeid et al. (1995) 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

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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, Praticò 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 85$^{th}$ 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).

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 85$^{th}$ percentile of the speed reductions, rather than $\Delta V_{85}$ 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 85$^{th}$ 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 $\Delta V_{85}$. 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 ($\delta$), 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 $\delta$ 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 1000 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 s (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,b). 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.

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

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