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# New geometric design consistency model based on operating speed profiles for road safety evaluation

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ABSTRACT

To assist in the on-going effort to reduce road fatalities as much as possible, this paper presents a new methodology to evaluate road safety in both the design and redesign stages of two-lane rural highways. This methodology is based on the analysis of road geometric design consistency, a value which will be a surrogate measure of the safety level of the 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 were obtained by using an innovative GPS-data collection method that is 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 was previously possible with spot-speed data collection, thereby enabling 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 as well.

For the development of the consistency model, the crash frequency for each study site was considered, which allowed estimating the number of crashes on a road segment by means of the calculation of its geometric design consistency. Consequently, the presented consistency evaluation method is a promising innovative tool that can be used as a surrogate measure to estimate the safety of a road segment.



## 1. Introduction

Road safety is one of the most important problems in our society. Every year 1.2 million people are killed, and 20–50 million people are injured in road accidents. If current trends continue, traffic accidents are predicted to be the third leading contributor to the global burden of disease and injury by 2020. In Spain, approximately 78.5% of rural road accident fatalities occur on two-lane rural roads.

Three factors influence the occurrence of road accidents: the human factor, the vehicle factor, and the road infrastructure factor. Past research has pointed out that the infrastructure factor is the cause of over 30% of road crashes (Treat et al., 1979). In fact, studies have shown that collisions tend to concentrate on certain road segments, indicating that the characteristics of that road segment may play a major role in some accidents.

One of the main reasons surmised is the lack of geometric design consistency. The geometric consistency of a road can be defined as how a driver's expectations and the road's behavior match up (i.e., when a road with a good consistency level matches a driver's expectations, the road user is not surprised while driving along it). A poor consistency may consist of surprising events and high speed variability along different road segments and among different drivers, increasing the likelihood of crashes. Self-explaining roads are those designed to be easily interpreted by drivers and hence induce adequate driver behavior. Although the concept of consistency or self-explaining roads is not widely known, most of the guidelines available include ways to produce better and more consistent roads (Weber and Matena, 2008).

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).

Operating speed evaluation is the most commonly used criteria to evaluate highway design consistency (Gibreel et al., 1999). The operating speed, often defined as the 85th percentile speed ($v_{85}$) of a sample of vehicles under free-flow conditions, can be

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**Table 1**
Thresholds for a determination of design consistency quality. Lamm's criteria I and 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 | $\lvert v_{85}-v_d\rvert > 20$ | $\lvert v_{85_i}-v_{85_{i+1}}\rvert > 20$ |

**Table 2**
Thresholds for a determination of design consistency quality.

| Design consistency quality (m/s) $C=e^{-0.278\cdot[R_a\cdot\sigma/3.6]}$ | | |
|---|---|---|
| Good | Acceptable | Poor |
| $C>20$ | $1<C\le 2$ | $C\le 1$ |

estimated by means of operating speed models. This specific measure of speed can be used for consistency evaluation by examining the disparities between design speed ($v_d$) and operating speed or examining the operating speed decrement $v_d$ between successive elements of the road ($\Delta v_{85}$). Tangent-to-curve transitions are the most critical locations when considering safety measures. In fact, it is estimated that more than 50% of all fatalities on rural highways take place at curved sections (Lamm et al., 1992). Consistency models based on operating speed evaluation are the most widely used because of the large number of operating speed models that exist worldwide (a summary can be seen at Transportation Research Board, 2011; Fitzpatrick et al., 2000). These models are powerful tools for accurately estimating driver operating speed profiles and thus for identifying sudden decelerations or important speed dispersion.

Leisch and Leisch (1977) recommended a revised design speed concept that included guidelines on both operating speed reductions and the differentials between the design and operating speeds. In the same way, Kanellaidis et al. (1990) suggested that a good design can be achieved when the difference between the $v_{85}$ 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 the design and operating speeds and the difference between the operating speeds on successive elements.

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

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 on a road geometric element or on a transition between two of them. 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. In this case, a single consistency value for the whole road segment was obtained. Moreover, their design consistency index is a continuous function instead of a threshold-based methodology. They developed two new consistency measures. The first one was the relative area bounded between the operating speed profile and the average weighted operating speed ($R_a$). The second one was the standard deviation of the operating speeds at every geometric element along the whole road segment ($\sigma$). This additional measure was used in order to complement the first one because $R_a$ by itself provided similar results for somewhat different geometric characteristics in a few cases.

The final consistency model was developed based on both of the previous indicators. Thresholds for the good, acceptable, and poor design consistency of any road segment were proposed (Table 2). The $R_a$ and $\sigma$ on several test sections provided a similar assessment of consistency as Lamm's measures.

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

Another method to evaluate geometric design consistency is the analysis 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 provide enough vehicle stability can be considered as inconsistent.

In this context, Lamm et al. (1999) presented a design consistency criterion which includes the difference between the assumed side friction provided by the curve and the side friction demanded by vehicles. The difference between the assumed side friction ($f_{RA}$, which depends on the design speed) and the demanded friction ($f_{RD}$, which depends on the operating speed), denoted as $\Delta f_R$, was used to represent vehicle stability at Lamm's criterion III. According to this criterion, consistency is considered good when $\Delta f_R$ is higher than 0.01, fair when its value is between 0.01 and −0.014, and poor when $\Delta f_R$ is lower than −0.04.

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

The last approach for evaluating geometric design consistency is by means of the driver workload. Driver workload is defined as the rate of time at which drivers must perform a given amount of driving tasks, which increases as long as the complexity in the highway geometric features increases (Gibreel et al., 1999). Driver workload may be a more appealing approach for identifying inconsistencies than operating speed because it is an indicator of the effort that the roadway requires from drivers, while the operating speed is only a measurable output 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, driver workload evaluation is much less used than other consistency evaluation methodologies because of its higher degree of measurement difficulty.

Several researchers have studied the effect of geometric design consistency on road safety. Anderson et al. (1999) analyzed the relationship between design consistency and safety using loglinear regression models. They developed two models that related accident frequency to traffic volume, curve length, and speed reduction ($\Delta v_{85}$). A separate model relating accident frequency to curve length and *CRR* was also obtained.

Ng and Sayed (2004) investigated the effects of several design consistency measures on safety. These variables were $v_{85}-v_d$,