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Assessment of Design Consistency for Two-Lane Rural Highways with Low Tortuosity Alignment

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Abstract: One technique employed to enhance road safety involves assessing the alignment's consistency. A prevalent measure of consistency is evaluating speed variations along the alignment. A key consideration in this assessment is determining the speed upon which the road alignment should be based. This research reveals that on two-lane rural highways with low tortuosity alignments, operating speeds on horizontal curves and tangents consistently exceeded not only the design speeds but also the maximum permissible design speed for the road category. Consequently, using the design speed to assess consistency on these roads is deemed impractical, and utilizing operating speed poses challenges due to speeds exceeding the maximum permissible limit. The objectives of this paper are twofold: to explore the relationship between design consistency and safety levels on two-lane rural highways with low tortuosity alignments (which have been insufficiently covered in research) and to propose speed-control measures to limit the maximum operating speed to the maximum permissible speed. The study findings suggest that on roads with a low tortuosity alignment, operating speeds depend much more on the general characteristics of the alignment (evaluated in the operating speed models through the desired speed). Further, assessing speed consistency is feasible only with a rigorous control of the maximum operating speed (desired speed). Additionally, a specific type of speed control is recommended, achieved by limiting the curvature change rate (CCR) of the road section based on the desired speed (environmental speed), whose evaluation becomes a crucial factor.

Keywords: road safety; road consistency; operating speed; desired speed; environmental speed; highway geometric design

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1. Introduction

In the period from 2011 to 2020, an estimated 13 million people lost their lives in road crashes, and many others sustained serious injuries. Road crashes persist as the primary cause of death among children and young adults aged 5–29 years, resulting in substantial social and economic costs.

In 2020, the international community made two significant strides towards progress in road safety. Firstly, the Third Global Ministerial Conference on Road Safety adopted the Stockholm Declaration, proposing a new United Nations (UN) target to reduce road deaths and serious injuries by half. Secondly, the UN General Assembly passed Resolution 74/299, focusing on enhancing global road safety. The resolution established the period from 2021 to 2030 as the Second Decade of Action for Road Safety, with the overarching aim of reducing road traffic deaths and injuries by at least 50 percent. Both decisions align seamlessly with the commitment made by UN Member States to accelerate action in support of the 2030 Agenda and the Sustainable Development Goals, with road-injury prevention explicitly addressed within the Health Goals.

In light of this, road designers bear a significant responsibility to establish a road system that safeguards all road users, achievable through the implementation of appropriate designs for road infrastructure.

The safety and efficiency of road traffic is greatly influenced by the geometric features of the highway. Various studies [1–8] have indicated that the number of accidents tends to be higher on curves, even when designers correctly apply driving dynamics formulas for curve design found in standards.

These studies also note that the accident risk decreases as the radius of the curve increases, although differing opinions exist on the extent of this influence. Substantial differences in accident rates between bends of the same radius are attributed mainly to the characteristics of the upstream horizontal alignment.

According to several research studies, the alignment where the curve is situated has a substantial impact on the curve's safety. Baldwin [1] demonstrated that while the accident rate increased as the radius of horizontal curves decreased, the accident rate for small-radius curves generally decreased as the frequency of curves (per length of highway) increased.

Other studies [9–14] revealed that the accident rate at small-radius bends is very high when the average curvature of the entire alignment is low, but relatively low when the average curvature is high. These findings also suggest that an alignment with a significant degree of curvature can be safer than relatively straight alignments. Consequently, the expected number of roadway departure crashes on a horizontal curve not only increases with that curve's radius but also with the upstream and downstream tangent lengths. In general, most of these accidents can be attributed to inconsistencies in horizontal alignment that surprise the driver with abrupt changes in road characteristics, leading the driver to exceed the critical speed of a curve and lose control of the vehicle. To address these inconsistencies, researchers have been developing various tools and strategies.

One technique employed to enhance road safety is checking the consistency of the alignment, a procedure that has replaced the traditional design speed approach in several countries. Design consistency implies that the road geometry and environment do not violate either the expectation or the ability of the motorist to guide and control a vehicle in a safe and predictable manner.

Despite the promising theory of design consistency in terms of safety improvement, and despite efforts to translate this theory into quantitative guidelines, challenges persist in implementing the concept on a wide scale.

The objectives of this paper are twofold: to explore the relationship between design consistency and safety levels on two-lane rural highways with low tortuosity alignments (which have been insufficiently covered in research) and to propose speed-control measures to limit the maximum operating speed to the maximum permissible speed.

The paper examines how the concepts of design speed, operating speed, and consistency are utilized in international practices, particularly in Italy. Based on experimental research, the paper suggests revisions to the Italian standards for two-lane rural highways with a low tortuosity alignment, but which are also applicable to other countries.

The study results indicate that it is possible to use speed consistency on roads with a low tortuosity alignment in accordance with Italian speed limits only if there is control over the maximum operating speed. Additionally, a specific type of speed control is recommended.

The paper is structured as follows. Section 2 provides a background on the most relevant literature of the consistency methods and of the operating speed prediction models. Section 3 introduces the research context and illustrates data and the models adopted to estimate the operating speed. Section 4 provides and discusses the results of consistency analysis in the context of the different standards. Finally, Section 5 presents the conclusions and provides future perspectives.

2. Literature Review

Design consistency has been defined in the literature as the degree to which highway systems are designed and constructed to avoid critical driving maneuvers and ensure safe traffic operation [15], or the condition in which the design or geometry of a road does not violate either the expectation of the motorist or the ability of the motorist to guide and control a vehicle in a safe manner [16], or the situation in which successive geometric elements act in a coordinated way, so that they produce harmonized driver performance consistent with driver expectations [17]. Despite slightly different wording, all definitions essentially carry the same meaning: a consistent highway design ensures that successive geometric elements are coordinated to produce harmonious driver performance without unexpected events [18].

The causes and consequences of alignment inconsistencies are best explained within the context of driver–vehicle–roadway interactions. Information processing and decision-making processes, and hence driver behavior, are affected by driver expectancy, which has been defined [19] as "*an inclination, based upon previous experience, to respond in a set manner to a roadway or traffic situation*". That is, drivers tend to "*react to what they expect rather than to the roadway or traffic situation as it actually exists*" [20].

Lunenfeld and Alexander [17] categorized expectancies as either a priori (or long-term) if based on experience accumulated over a long period, or ad hoc (or short-term) if based on experience gained very recently. A priori expectancies are based upon a driver's collective previous experience. Unusual geometric features (e.g., a one-lane bridge), features with unusual dimensions for a road category (e.g., a very long and/or very sharp horizontal curve), and features combined in unusual ways (e.g., an intersection hidden beyond a crest vertical curve) may violate a priori expectancies. Ad hoc expectancies are developed during a particular trip on a particular roadway and are related to the speed at which the next curve can be traversed, based upon the speed at which the immediately preceding curves were able to be traversed. Geometric inconsistencies may violate a priori and/or ad hoc expectancies, leading to drivers being surprised by what they encounter, and increasing the probability of drivers making errors and accidents occurring.

Methods for evaluating design consistency and driver expectancy have been classified into the following areas: vehicle operations-based consistency (speed or vehicle dynamics), roadway geometrics-based consistency, performance consideration, and consistency checklists.

In speed category design, consistency is evaluated through the use of operating speed, usually determined as the 85th-percentile speed (V_{85}) of a sample of vehicles, or other characteristic speeds, like design speed (V_d).

There are two types of speed consistency models: local and global. Local consistency models are used to assess the design consistency of a single element (tangent or curve) or successive geometric elements (tangent and curve) by comparing speed. Whereas global consistency models are used to evaluate the geometric design consistency of the entire road segment.

The evaluation of design consistency, based on the local consistency models, is generally determined in two different ways, either by examining disparities between the V_d and V_{85}, or by examining the differences in the V_{85} on successive elements of the road (ΔV85, Δ85V) [21,22], or by a combination of both ways; but more recent methods are using the difference between the V_{85} of a road element and the inertial operating speed (Vi), defined as the average operating speed on the previous 1 km road segment [23,24].

Global consistency models evaluate geometric design consistency by considering overall speed variation indexes for the entire road segment [25–29].

In the vehicle dynamics category, attention is given to the vehicle's stability on horizontal curves and therefore to side friction and superelevation design, both for the single curve [30] and for the curve's sequence [31,32].

Geometric-based road consistency, which uses alignment indices, employs quantitative measures of the general character of an alignment in a road section [7,30,33]. The premise is that geometric inconsistencies arise when the general character of an alignment changes significantly. Alignment indices include the average radius (AR), ratio of maximum radius to minimum radius (RR), and average rate of vertical curvature (AVC) [34]. An additional parameter, the curvature change rate (CRR), is defined as the ratio of the radius of a single horizontal curve to the average radius of the entire section. This parameter was suggested based on the premise that "*when the radius of a given horizontal curve deviates greatly from* *the average radius along the highway section, the curve may violate driver expectancy, create a geometric inconsistency, and experience high accident rates*" [33].

Performance considerations that monitor design consistency using drivers' mental workload or drivers' anticipation can be classified as "user-side" measures of consistency, compared with the previous measures of consistency that can be classified as "designer-side" measures of consistency. Driver workload was 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 [35]. Locations with a high workload or large positive change in workload were found to be associated with high accident rates [36]. However, compared with the other consistency evaluation measures, the evaluation of drivers' workload is much more complex.

The expectancy checklist largely consists of examining various design features [37]. The attention of designers is called to possible expectancy violations, and they are then tasked to either remedy the problem or to provide mitigating treatments. The checklist, while encompassing many aspects of design that could influence design consistency, provides little in the way of a discussion of principles or specific measures. In the face of this lack of information, a designer could face problems in applying the recommendations.

To assess the road alignment consistency, several current standards [38–41] only provide methodologies using speed differences or differences between geometric indices of the alignment.

Several studies [33,42–46] have also indicated that speed variation is the most useful measure for explaining accidents rather than changes in geometric indices. Speed reduction was found to have a stronger association with accident rates than the curve radius when both were used as independent variables in the same models. However, the second approach has limitations in accounting for the factors affecting speeds on the approach tangent, including the sharpness of the preceding curve, tangent length, and general alignment characteristics.

Generally, and even in the present research, geometry design consistency is evaluated using criteria developed by Lamm et al. [47] and Fitzpatrick et al. [48]. Safety Criterion I (SC I) evaluates the difference of the operating speed from the design speed at a specified curve, and it is a good indicator of inconsistency at a single element. Safety Criterion II (SC II) evaluates the difference between the operating speeds of two consecutive road elements and is a good indicator of the consistency experienced by drivers when travelling from one element to the next.

One method for using operating speed as a consistency check involves predicting speed using a continuous speed-profile model [25,29,34,45,48–53]. Most models assume a constant speed on circular curves, with deceleration and acceleration occurring entirely on the approach and departure tangent or transition curve (spiral). These models also define a desired speed (V_{des}) or environmental speed (V_{env}) as the maximum speed on straights and wide-radius curves.

Various models exist for defining the V_{85} on circular curves, providing reliable values within the contexts in which they were developed. There are few models for defining accelerations and decelerations, but they generally yield similar values. However, there are very few models for estimating the V_{des}, with some models defining it as the V_{85} that drivers select when not constrained by the vertical or horizontal alignment. Operating speeds on horizontal curves are very similar to speeds on long tangents when the curve radius is higher or equal to approximately 800 m [54].

For the evaluation of consistency using the V_{85}, the estimation of the V_{des} therefore becomes a crucial factor.

Most studies [11,20,22,23,34,50,53,55–60] estimated the desired speed on two-lane highways and obtained a rounded value, between 100 and 110 km/h. Australia uses assumed standard values that represent the desired speed for different terrain types (flat, undulating, hilly, mountainous) and ranges of horizontal curve radii [38,61,62]. Switzerland assigns the posted speed limit as the desired speed [41]. Germany assigns the desired speed as a function of the CCR of the section with a maximum of 100 km/h [39]. Italy assigns the desired speed as the maximum design speed for a road category (100 km/h for rural two-lane highway) [40].

Few studies have defined a model for the V_{des}; of these, some predict maximum desired speeds lower or equal to 100 km/h [63], while others predict maximum speeds above 110 km/h [49,64–66].

Research on design speed and operating speed has found that on curves of rural two-lane highways with design speeds (V_d) below about 90 km/h, actual speeds (V_{85}) are typically higher than the design speed, while for roads with a $V_d > 100$, the V_{85} is lower than the V_d.

In general, on roads with a V_d that is higher or equal to 100 km/h, the first safety criterion is usually fulfilled. On roads with low tortuosity (wide bends and long straight roads), the second criterion is also likely satisfied, since differences in the V_{85} would be small or even zero.

However, in Italy and some other countries, this is not always the case, as higher operating speeds have been found even when the design speed is greater than or equal to 100 km/h. A survey [64] conducted by the Department of Engineering and Architecture at the University of Trieste on a two-lane rural highway, road category C according to the Italian standards, showed that, on roads with a low tortuosity alignment, the operating speeds on horizontal curves and tangents were not only always higher than the design speeds, but even higher than the maximum permissible speed of the road category and of roads where a high run-off accident rate was found; for this reason, it was impossible to use the design speed defined by the Italian standards to check the consistency of these roads. This aligns with the results of other studies in Italy and Germany [67], where road users adopt speeds higher than in other countries, especially for low values of the curvature change rate (CCR). Furthermore, it was impossible to use the design speed defined by Italian standards to check for consistency on these roads due to the higher operating speeds.

3. Materials and Methods

The studied road (SR 177 in the Friuli Venezia Giulia Region, Figure 1) was constructed in Italy in the 1990s, adhering to the existing norms of that time and also meeting current regulations.

Figure 1. Cross-section of SR 177.

The road features a single carriageway with two lanes, each measuring 3.75 m, accommodating one lane for each direction of travel. Paved shoulders of a 1.50 m width are present on both sides, resulting in a total cross-section width of 10.50 m. This configuration represents the maximum cross-section for a C category road as specified by

Italian regulations. Additionally, the road lacks grade-level intersections, only incorporating interchanges, and does not have any private access points. The entire route of the road is flat, and there are ample lateral spaces without obstacles that might impede an unobstructed view.

From a planimetric layout perspective, the road features a variety of curve radii (ranging from 480 to 10,000 m), long tangents (up to 1506 m), and transition curves (clothoids with scale parameters from 200 to 679 m) connecting the aforementioned elements. From a global standpoint, the route can be divided into two longitudinal sections with an average curvature change rate (CCR) of 64.75 gon/km from 0 to 3.573 km and 21.13 gon/km from 3.573 to 26.609 km (Figure 2).

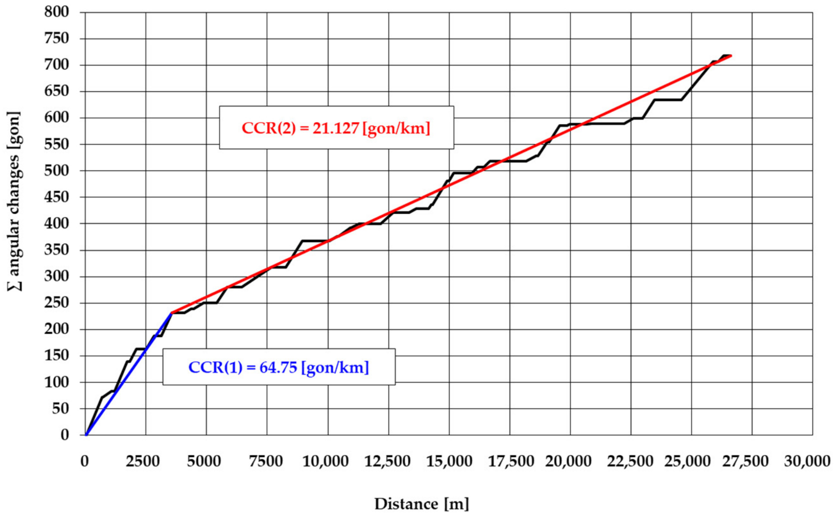

Figure 2. Subdivision of the road into homogeneous CCR sections.

The generous geometric alignment of the road leads to the adoption of a constant design speed, as per Italian legislation, set at 100 km/h for all planimetric elements of the road.

Speed measurements conducted along the entire route revealed V_{85} values ranging from 95 to 136 km/h, depending on the different elements of the alignment and the direction of travel. Consequently, all values exceed the speed limit of 90 km/h, with the majority exceeding the road-design speed of 100 km/h as per existing regulations. The elevated speed values are likely attributed to the unique nature of the (SR 177) Cimpello–Sequals highway, characterized by very long tangents and curves with a significantly large radius. All intersections with other roads are designed as interchanges, and there are no private accesses. Additionally, the overall road environment is flat, and a large space along the sides of the road remains consistently free from obstacles. In these conditions, the recorded speeds are naturally high.

We analyzed accidents that occurred on a two-lane rural road, conducting the analysis within a GIS (Geographic Information System) environment using the open-source software QGIS version 3.28. The accident data used in this study were provided, upon request, by the Central Directorate of Infrastructures and Territory of the Autonomous Region Friuli Venezia Giulia. These data are part of the database of the Regional Road Safety Monitoring Center (Centro Regionale di Monitoraggio della Sicurezza Stradale—CRMSS), which aggregates information related to road accidents surveyed in the regional territory by Carabinieri, Traffic Police, and Local Police teams.

In particular, we identified critical road network segments and points by analyzing the more frequent behavioral causes associated with accidents. This approach allows us to have comprehensive, consistent, and quickly accessible data regarding accidents, along with their geographical locations on the road network.

Fatal run-off accidents were identified and georeferenced along the road, with all incidents displayed in Figure 3. Several accidents were found to overlap at the same location.

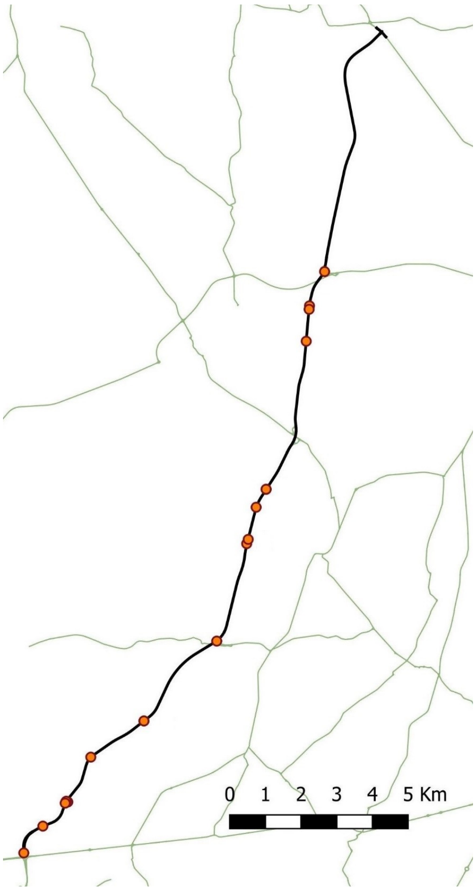

Figure 3. Accident location.

It is evident from the data that most accidents occur at locations with significant changes in the tortuosity of the alignment, particularly during transitions from low to high tortuosity. Consequently, we decided to investigate the consistency of the road alignment at these specific locations.

Italy employs a design speed (V_d) for checking the driving safety dynamics on curves, sight distances, and consistency control in speed changes between adjacent elements.

Consistency is determined based on a speed profile model that relies on three pieces of information:

- Design speed (V_d) on curves: This is obtained from a physical model using an equilibrium model during curve driving. It is derived from the equation

$$V_d = \sqrt{127 \cdot R \cdot (f_R + q)}, \quad (1)$$

where R = curve radius, f_R = side friction part (radial) of the slide friction coefficient, and q = superelevation in circular arc;

- Maximum design speed ($V_{d,max}$): this varies by road category, and for rural two-lane highways, the $V_{d,max}$ is 100 km/h;
- Deceleration and acceleration rates entering and exiting horizontal curves: these rates are determined to be 0.8 m/s^2.

Driver performance during deceleration is crucial for traffic safety, necessitating the evaluation of the speed profile in both travel directions. The design standard establishes various conditions for admissible speed differences, ΔV_d, between adjacent alignment elements.

Italian standards do not utilize operating speed. Safety is assured only if the operating speed is less than the V_d, including the $V_{d,max}$. However, the weakness of the Italian speed profile model lies in the fact that the operating speed is never less than the design speed, even for the maximum design speed. Therefore, the application of this model as a control instrument can become problematic.

If operating speeds are to be considered, a model providing the maximum operating speeds (desired speed or environmental speed) compatible with the specific road should be used. As mentioned earlier, there are few models with desired speeds on rural two-lane highways exceeding 100 km/h. In the study, seven operating speed models were utilized, each defining the V_{des} (V_{env}, V_{max}). Five of these models are Italian, one is Australian, and one is American. Additionally, the design speed model of the Italian standard was employed (see Table 1).

Table 1. Speed models used to assess the road alignment consistency.

Model	Type of Road Element	Equation/Value (km/h)
McLean [62]/Australian standards	Tangent ($90 \leq V_d \leq 120$)	$V_{des} = 115$
	Curve	$V_{85} = 53.8 + 0.464 \cdot V_{des} - \frac{3.26 \cdot 10^3}{R} + \frac{8.50 \cdot 10^4}{R^2}$
Fitzpatrick [56]	Tangent	$V_{max} = V_{des} = 100$
	Curve	$V_{85} = 104.82 - \frac{3584.51}{R}$
Crisman et al. [64]	Tangent	$V_{des} = 210.83 \cdot CCR^{-0.17}$
	Curve	$V_{85} = V_{des} \cdot \left(1 - \frac{V_{des}^2}{298.27 \cdot R}\right)$
Dell'Acqua et al. [65]	Tangent	$V_{des} = 82.84 - 0.10 \cdot CCR + 3.44 \cdot L$
	Curve	$V_{85} = 0.87 \cdot V_{des} - \frac{2073.70}{R} + \frac{31{,}029.00}{R^2}$
Cafiso et al. [66]	Tangent	$V_{des} = 100.05 - 0.197 \cdot CCR + 2.147 \cdot W$
	Curve	$V_{85} = 0.987 \cdot V_{des} - 0.0418 \cdot CCR_S \cdot \frac{V_{des}}{100}$
Perco [49]	Tangent	$V_{des} = 123.54 - 2.79 \cdot CCR^{0.47}$
	Curve (CCR < 30 gon/km)	$V_{85} = 124.08 - \frac{563.68}{\sqrt{R}}$
	Curve ($30 \leq$ CCR < 80 gon/km)	$V_{85} = 118.11 - \frac{510.56}{\sqrt{R}}$
	Curve ($80 \leq$ CCR < 160 gon/km)	$V_{85} = 111.65 - \frac{437.44}{\sqrt{R}}$
	Curve (CCR $\geq$ 160 gon/km)	$V_{85} = 100.85 - \frac{346.62}{\sqrt{R}}$
Dell'Acqua [63]	Tangent	$V_{des} = 97.49 - 0.05 \cdot CCR$
	Curve	$V_{85} = 46.47 + 0.35 \cdot V_{des} - \frac{1678.12}{R} + \frac{22{,}013.83}{R^2}$
Italian standards [40]	Tangent ($60 \leq V_d \leq 100$)	Vmax = 100
	Curve	$V_d = 127 \cdot R \cdot (f_t + q)$

Note: V_d = design speed (km/h); V_{des} = desired speed (km/h); V_{85} = operative speed on curve; V_{max} = maximum speed (km/h); R = curve radius (m); CCR = curvature change rate of a section (gon/km); L = lane width (m); W = width of paved section (lanes + shoulders); CCR_S = curvature change rate of single curve (gon/km); f_t = side friction coefficient; q = superelevation in circular curve.

The models were employed to assess the road's consistency and verify its compatibility with accident locations. Concerning the consistency criteria, Lamm's criteria were adopted for the operating speed models, while the criteria outlined in the Italian legislation were applied for the model incorporating design speeds.

4. Results and Discussion

The consistency of the entire track was evaluated using different V_{85} models to understand if varied results were obtained. Exclusively reported below is the assessment of the most critical point in terms of accidents, namely the transition between the two sections with a different CCR (CCR1, CCR2). Specifically, the consistency evaluation is presented for a curve with a radius of 500 located at the beginning of the section with the highest CCR (CCR2) and at the end of the section with the lowest CCR (CCR1) in the Sequals–Cimpello (S–C) direction.

Consistency was assessed using the Lamm criteria (refer to Table 2) for the models with the V85, while Italian rules were applied for the model with the design speed.

Table 2. Quantitative ranges for Lamm's Safety Criteria I to II for Good, Fair, and Poor Design Classes.

Safety Criterion	Design Class Good	Fair	Poor
I	$\lvert V_{85,i} - V_d \rvert \leq 10$ km/h	$10 < \lvert V_{85,i} - V_d \rvert \leq 20$ km/h	$\lvert V_{85,i} - V_d \rvert > 10$ km/h
II	$\lvert V_{85,i} - V_{85,i+1} \rvert \leq 10$ km/h	$10 < \lvert V_{85,i} - V_{85,i+1} \rvert \leq 20$ km/h	$\lvert V_{85,i} - V_{85,1+1} \rvert > 10$ km/h

Note: V_d = design speed; $V_{85,i}$ = operating speed element i; $V_{85,i+1}$ = operating speed element i + 1.

According to the Italian legislation, when transitioning between sections characterized by the $V_{d,max}$ and lower-speed curves, the speed difference cannot exceed 10 km/h. The characteristics of the alignment used to evaluate consistency are outlined in Table 3.

Table 3. Summary of site characteristics.

Control	Value
Terrain type	Level
Speed limit	90 (km/h)
Circular curve radius: R	500 (m)
Circular curve length: LR	230.29 (m)
Circular curve superelevation q	5.0 (%)
Clotoid scale parameter	234.52 (m)
Side friction coefficient (Italian standards): ft	0.10
Circular curve (R = 500 m) design speed: Vd	100 km/h
Curvature change rate of curve (R = 500): CCRs	96.0 (gon/km)
Preceding tangent length	510.38 (m)
Preceding circular curve radius	2000 (m)
Lane width: L	3.75 (m)
Pavement width (lanes + shoulders): W	10.50 (m)
Curvature change rate of road section preceding the curve: CCR1	21.13 (gon/km)
Curvature change rate of road section of curve: CCR2	64.75 (gon/km)
Speed measured on the curve S–C direction	108 km/h
Speed measured on the previous tangent	130 km/h
Speed measured on the curve C–S direction	101 km/h

We also present (Tables 4 and 5) the results of the calculations for assessing various speeds obtained with different models and the corresponding differences, as an illustrative example for evaluating consistency. Since the curve is situated at the beginning of the second section (in the S–C travel direction), the curve's speed using the models was computed using both the V_{des} of the second section (Table 4) and the V_{des} of the first section (Table 5), representing the preceding section's speed. This could potentially influence driver behavior on the initial curves following the CCR change. Additionally, the speed was computed (Table 6) on the same curve but with the opposite direction (Cimpello–Sequals, C–S).

Table 4. Consistency evaluation, curve 500 with model $V_{85,c\ (500\ m)} = f(V_{des,CCR2})$, direction S–C.

Model	V_d	V_{des} (V_{max}) (CCR1)	V_{des} (V_{max}) (CCR2)	$V_{85,c\ (500\ m)}$	$\lvert V_{85,c} - V_d \rvert$	$\lvert V_{85,c} - V_{des,CCR1} \rvert$
McLean [62]	100 km/h	115 km/h	115 km/h	101 km/h	1 km/h	14 km/h
Fitzpatrick [56]	100 km/h	100 km/h	100 km/h	98 km/h	2 km/h	2 km/h
Crisman et al. [64]	100 km/h	126 km/h	104 km/h	96 km/h	4 km/h	30 km/h
Dell'Acqua et al. [65]	100 km/h	94 km/h	89 km/h	73 km/h	27 km/h	21 km/h
Cafiso et al. [66]	100 km/h	118 km/h	110 km/h	104 km/h	4 km/h	14 km/h
Perco [49]	100 km/h	112 km/h	104 km/h	95 km/h	5 km/h	17 km/h
Dell'Acqua [63]	100 km/h	96 km/h	94 km/h	76 km/h	24 km/h	20 km/h
Italian standards [40]	100 km/h	100 km/h	100 km/h	100 km/h	0 km/h	0 km/h

Note: $V_{85,c\ (500\ m)} = f(V_{des,CCR2})$ = V85 computed on the curve with R = 500 m using V_{des} of the stretch of road to which the curve belongs. For Italian standards $V_{85c} = V_d$ and $V_{des} = V_{max}$.

Table 5. Consistency evaluation, curve 500 with model V_{85c}= f($V_{des,CCR1}$), direction S–C.

Model	V_d	V_{des} (V_{max}) (CCR1)	V_{des} (V_{max}) (CCR2)	$V_{85,c\ (500\ m)}$	$\lvert V_{85,c} - V_d \rvert$	$\lvert V_{85,c} - V_{des,CCR1} \rvert$
McLean [62]	100 km/h	115 km/h	115 km/h	101 km/h	1 km/h	14 km/h
Fitzpatrick [56]	100 km/h	100 km/h	100 km/h	98 km/h	2 km/h	2 km/h
Crisman et al. [64]	100 km/h	126 km/h	104 km/h	112 km/h	12 km/h	14 km/h
Dell'Acqua et al. [65]	100 km/h	94 km/h	89 km/h	78 km/h	22 km/h	16 km/h
Cafiso et al. [66]	100 km/h	118 km/h	110 km/h	112 km/h	12 km/h	6 km/h
Perco [49]	100 km/h	112 km/h	104 km/h	99 km/h	1 km/h	13 km/h
Dell'Acqua [63]	100 km/h	96 km/h	94 km/h	77 km/h	23 km/h	19 km/h
Italian standards [40]	100 km/h	100 km/h	100 km/h	100 km/h	0 km/h	0 km/h

Note: $V_{85,c\ (500\ m)}$ = f($V_{des,CCR1}$) = V_{85} computed on the curve with R = 500 m using V_{des} of the stretch of road to which the curve belongs. For Italian standards V_{85c} = V_d and V_{des} = V_{max}.

Table 6. Consistency evaluation, curve 500 with model $V_{85,c\ (500\ m)}$ = f($V_{des,CCR2}$), direction C–S.

Model	V_d	V_{des} (V_{max}) (CCR1)	V_{des} (V_{max}) (CCR2)	$V_{85,c\ (500\ m)}$	$\lvert V_{85,c} - V_d \rvert$	$\lvert V_{85,c} - V_{des,CCR2} \rvert$
McLean [62]	100 km/h	115 km/h	115 km/h	101 km/h	1 km/h	14 km/h
Fitzpatrick [56]	100 km/h	100 km/h	100 km/h	98 km/h	2 km/h	2 km/h
Crisman et al. [64]	100 km/h	126 km/h	104 km/h	96 km/h	4 km/h	8 km/h
Dell'Acqua et al. [65]	100 km/h	94 km/h	89 km/h	73 km/h	27 km/h	16 km/h
Cafiso et al. [66]	100 km/h	118 km/h	110 km/h	104 km/h	4 km/h	6 km/h
Perco [49]	100 km/h	112 km/h	104 km/h	95 km/h	5 km/h	9 km/h
Dell'Acqua [63]	100 km/h	96 km/h	94 km/h	76 km/h	24 km/h	18 km/h
Italian standards [40]	100 km/h	100 km/h	100 km/h	100 km/h	0 km/h	0 km/h

Note: $V_{85,c\ (500\ m)}$ = f($V_{des,CCR2}$) = V_{85} computed on the curve with R = 500 m using V_{des} of the stretch of road to which the curve belongs. For Italian standards V_{85c} = V_d and V_{des} = V_{max}.

The different models yield significantly divergent speed values for both the V_{des} (from 94 to 126 km/h for CCR1, and from 89 to 115 km/h for CCR2) and the $V_{85,c}$ (from 73 to 112 km/h); some manage to predict values quite similar to those actually measured (108 km/h for curve with R = 500 m), while others do not. This discrepancy arises from the fact that certain models were derived under different conditions of the cross-section, tortuosity, and lateral environment.

It is noteworthy that when using models to calculate the V_{des}, it becomes possible to better discern differences in speeds measured in different directions. It is evident that for some models, the alignment's consistency is not guaranteed, primarily due to incorrect V_{des} values. Generally, adopting higher V_{des} values results in larger speed differences between two curves of different radii, potentially making consistency more problematic for roads with a high V_{des}.

For higher radii, in Italy and other countries, operating speeds can exceed both the design and maximum allowed speeds for the road category (100 km/h). This occurs when the environmental speed (desired speed) exceeds the permissible speed. In such cases, differences of up to 30 km/h were observed between the operating and maximum permissible speeds. This underscores the need to adopt operating and desired speeds for evaluating road safety on Italian roads.

Furthermore, it was found that the driver's choice of speed is heavily influenced not only by the geometric features of a single element but also by the characteristics of the preceding road section and the overall road environment. To account for not only the features of individual geometric elements but also a variable representing the overall horizontal alignment, a numerical prediction model of operating speeds on curves should use environmental speed as an independent variable.

On Italian roads, even with generous alignments, significant differences exist between the operating speeds of adjacent features. Therefore, unlike the Australian guidelines, the evaluation of consistency must be verified in these cases as well.

For generous alignments, consistency cannot be checked solely using the variation in the degree of curvature, according to Lamm's alignment index safety criterion (CCRi–

CCRi+1 < 180 gon/km), as it would always be satisfied. Therefore, consistency must be assessed through speed differences.

These findings highlight another important aspect: the need to appropriately define the maximum desired speed for road sections for drivers. Establishing a superior limit for design speed that is inconsistent with the actual maximum desired speeds of road users (environmental speed) can lead to problems not only from a dynamic perspective but also in terms of consistency.

Regarding consistency criteria, the weakness of Italian standards, and even Swiss standards, lies not only in assuming that design speeds differ from operating speeds, but also in assuming that the maximum design speed, for road categories, is less than the desired speed on low tortuosity alignments. Tying the maximum design speed to speed limits, rather than operating speed, is a fundamental flaw in the speed model on rural highways (Figure 4).

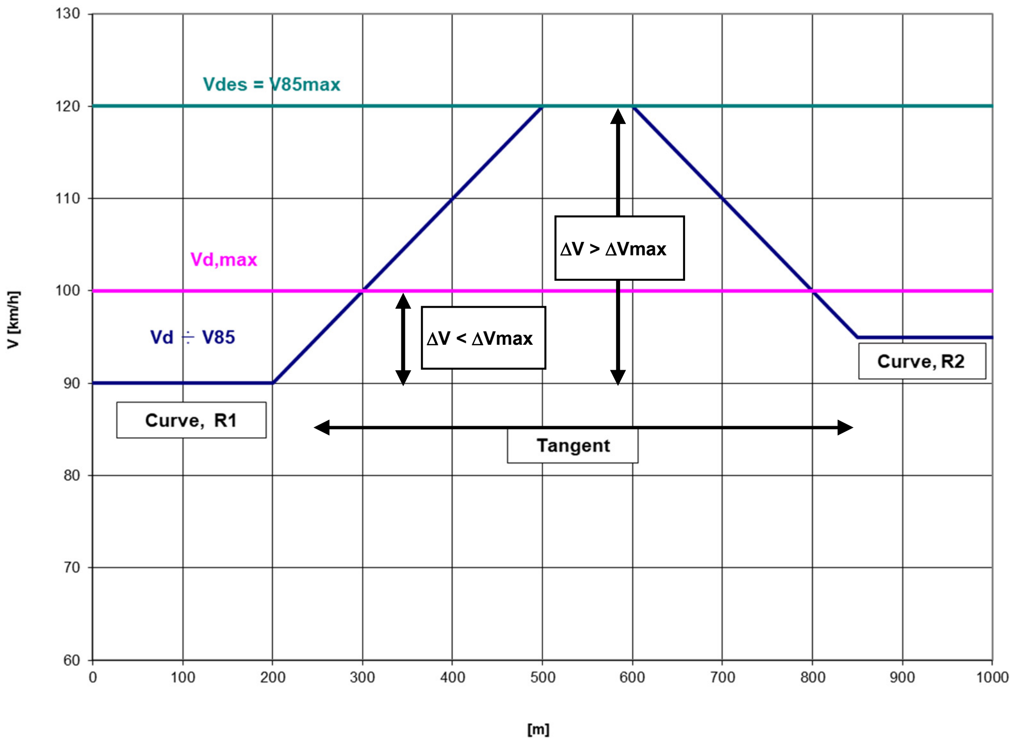

Figure 4. Example of speed profile on two-lane rural roads with high V_{des}.

The tool's control function in achieving a balanced and technically sound alignment, in terms of traffic safety, is largely lost. This poses the risk of assigning only secondary importance to the quality of the alignment design. To have a suitable evaluation of consistency on roads with low tortuosity alignments, operating speeds should not be the only measure used. Further, evaluations should not be conducted without setting any external limit to the maximum speed, defined, for example, through general speed limits on the road. However, without appropriate controls, the maximum operating speed on low tortuosity roads will always be higher than the maximum permissible speed, necessitating the design of roads (superelevation, sight distance, etc.) for these high speeds.

A simplified yet well-founded policy that can be applied to these categories of rural highways is therefore required. Control over the maximum operating speed, consistent with driver behavior, can be exercised through road sections with an environmental speed that does not permit exceeding the maximum permissible speed for that road category ($V_{env} = V_{d,max}$).

In previous research, Crisman et al. [64] also presented a prediction model to calculate the environmental speed of a homogenous section, as a function of the CCR:

$$V_{des} = 210.83 \cdot CCR^{-0.17} \quad (2)$$

To limit the desired (environmental) speed, it is possible to act upon the minimum value of the average CCR of the section. For Italian two-lane rural highways, where the maximum design speed is 100 km/h, using the results of the previous environmental speed model, a minimum average CCR of about 90 gon/km could be established.

5. Conclusions

This paper presents a critical review of the concept of highway geometric design consistency, criteria, and parameters for its evaluation, focusing particularly on Italian roads with a low tortuosity alignment. Several concerns and challenges to the current state of knowledge and practice are outlined with the objective of refining and improving the concept and its applicability. The main conclusion drawn from this review is that, despite these challenges and concerns, the theory remains promising but requires improvements.

The analysis of the relationship between different criteria for evaluating consistency and safety performance indicates that speed differences are better indicators than CCR differences.

To obtain the best approximations of operating speeds to the actually measured values, especially for roads with low tortuosity, models must consider not only the characteristics of the individual elements but also the general characteristics of the road (cross-section, tortuosity, lateral environment). This can be achieved, for example, through the use of desired speed models, which will need to be improved in future research.

By adopting appropriate desired speed models, it is possible to better predict the V_{85} values of individual elements and grasp the speed differences on the same curve traveled in different directions, particularly for roads with generous alignments.

Even on roads with generous alignments in Italy, the operating speed consistently exceeds the design speeds and the maximum permissible speed of the road category. Moreover, there are significant differences in the V_{85} on curves with large radii.

This aspect has been clearly illustrated in the tables of the previous section, where, on roads with these curvature characteristics, the models used in the literature are not always consistent. The difference in terms of expected speed can be even greater than 30 km/h among the various models.

On roads with very low tortuosity, traditional consistency criteria do not provide any indication, as accidents alone do not allow for the detection of inconsistency in the route.

For low tortuosity roads, an appropriate control of the maximum operating speed is needed, consistent with driver behavior, allowing adjustments to the maximum permissible speed of the road category. Ultimately, it is believed that control should be achieved through environmental speed limitation.

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