EVALUATING CONSISTENCY OF TWO-LANE RURAL HIGHWAYS: AN APPROACH FOR LITTLE TWISTY ALIGNMENTS

Roberti R.
Associate Professor, Department of Civil and Environmental Engineering, University of Trieste. - *roberti@dica.units.it*

ABSTRACT

One technique used to improve road safety is to check the consistency of the alignment. Design consistency implies that road geometry and environment does not violate either the expectation or the ability of the motorist to guide and control a vehicle in a safe manner and in predictable ways.

One of the most common consistency measure is check speed variation along the alignment. A fundamental question in checking consistency is the speed upon which the road alignment should be based.

The design speed concept was used, in the past, and is used again in some standard like Italian one. Recently, in many standards, the use of design speed, to check consistency or to determine individual geometric elements like superelevation rates, was replaced by operating speed, indicated like 85th percentile speed.

Operating speed is the real answer to the driver expectancy and is, generally, higher than design speed. In particular all studies have indicated that operating speeds exceed design speeds less than 90 km/h at horizontal curves on rural two lane highways.

A recent research in the Department of civil Engineering of University of Trieste on two lane rural highways, showed that, on roads with little twisty alignments, the operating speeds, on horizontal curves and tangents, was not only always higher than design speeds but even higher than maximum permissible speed of road category; for that reason was impossible to use design speed of Italian standards to check consistency on these roads. Moreover it was impossible to use operating speed for checking consistency because these speeds were higher than maximum permissible speed.

In these road it should be made provision for a speed control in order to limit the maximum operating speed to the maximum permissible speed.

The results of the study indicate that it is possible to use speed consistency on roads with little twisty alignment, according with Italian speed limits, only if there is a control of the maximum operating speed, moreover it is suggested a particular kind of speed control.

Speed control was realized limiting inferiorly the curvature change rate (CCR) of the road section according with the environmental speed.

Keywords: Design speed, Operating speed, Environmental speed, Road consistency, Speed limits

1. INTRODUCTION

One technique used to improve road safety is to check the consistency of the alignment. This procedure, in several countries, has substituted the traditional design speed approach.

Design consistency implies that road geometry and environment does not violate either the expectation or the ability of the motorist to guide and control a vehicle in a safe manner and in predictable ways.

In spite of the promising theory of design consistency, in terms of safety improvement, and in spite of all the efforts exerted in translating this theory into quantitative guidelines, many challenges still persist in any wide scale implementation of the concept.

One of the most common consistency measure is check speed variation along the alignment. A fundamental question in checking consistency is the speed upon which the road alignment should be based.

The design speed was used, in the past, and is used again in some standard like Italian one (Ministero Infrastrutture e Trasporti, 1992). Recently, in many standards, (Forschungsgesellschaft fur strassen-und verkehrswesen, 1995; Austroads, 1997), the use of design speed, to check consistency or to determine individual geometric elements like superelevation rates, was replaced by operating speed, indicated like 85th percentile speed.

Operating speed is the real answer to the driver expectancy and is, generally, higher than design speed. Basically, design speed and operating speed research (Krammes R et al., 1995; Mclean J., 1981) in a number of countries has found that, on curves of rural two-lane highway with design speeds less than about 90 km/h, actual speeds are typically in excess of the design speed.

A recent research in the Department of Civil Engineering of University of Trieste on two lane rural highway, road category C of Italian standard, showed that, on road with a little twisty alignments, the operating speeds on horizontal curves and tangents was not only always higher than design speeds but even higher than maximum permissible speed of road category; for that reason was impossible to use design speed of Italian standards to check consistency on these roads. This confirm the results of other studies in Italy and Germany (Figure 1, Cafiso et al. 2004,), where the road users adopt a speed higher than other countries, especially for little values of Curvature Change Rate (CCR).

Moreover it was impossible to use operating speed for checking consistency because these speeds were higher than maximum permissible speed, for such road category.

The objective of this paper is twofold: to explore the relationship between the design consistency and safety level on such roads; to make provision for a speed control in order to limit the maximum operating speed to the maximum permissible speed.

The paper analyzed the design speed, and operating speed concepts for some standards, moreover a literary review of methodology for checking road consistency are presented.

The paper identifies how the concepts of design speed, operating speed and consistency are used, in international practices and in particular in Italy, and on the base of experimental research provide a proposal of how the Italian standard may need to be revised for two-lane rural highways with a little twisty alignment.

The results of the study indicate that, it is possible to use speed consistency on roads with little twisty alignment, according with Italian speed limits, only if there is a control of the maximum operating speed, and it is suggested a particular kind of speed control.

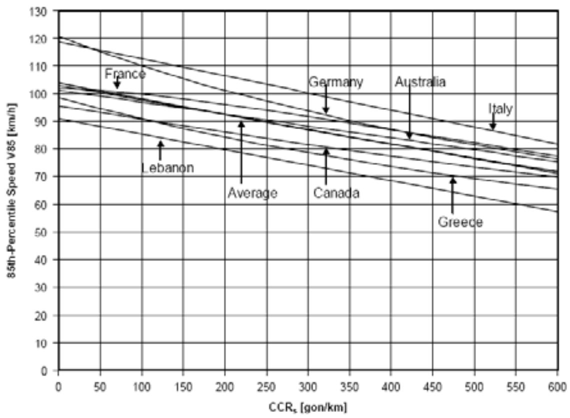

Figure 1 - Operating speed backgrounds for two-lane rural roads in different countries (Cafiso et al. 2004)

2. CONSISTENCY LITERARY REVIEW

The safe and efficient movement of traffic is greatly influenced by the geometric features of the highway. Several research showed that accidents tend to cluster on curves, even though the design engineer uses correctly driving dynamic formulas for curves design. Many of these accidents may be related to inconsistencies in horizontal alignment that cause the driver to be surprised by abrupt changes in road characteristics, to exceed the critical speed of a curve, and to lose control of the vehicle. To control these inconsistencies researchers have been working on developing several tools and strategies.

In that context, applications of the concept of design consistency have been among the most promising approaches. Several research efforts have concentrated on translating this concept into quantitative guidelines. However, a number of concerns and challenges in applying the concept and the guidelines still persist and may limit their applicability.

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 (Al-Maseied et al., 1995) 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 (Glennon et al. 1978) or the situation in which successive geometric elements act in a coordinated way, so that they produce harmonized driver performance consistent with driver expectations

(Lunenfeld and Alexander 1990). Despite the slightly different wording, all definitions essentially carry the same meaning; that is, a consistent highway design refers to one that ensures that successive geometric elements are coordinated in a manner to produce harmonious driver performance without surprising events (Gibreel et al., 1999).

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 (Rowan et al. 1980) 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" (Krammes et al. 1995).

Lunenfeld and Alexander (1990) categorized expectancies as either a priori (or long-held) 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 their collective previous experience. Unusual geometric features (e.g., a one-lane bridge), features with unusual dimensions for 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 relate 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.

2.1 Consistency methodologies

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 (V85) of a sample of vehicles. This specific measure can be used, in consistency evaluation, by examining disparities between design speed (Vd) and V85, or examining the differences in V85 on successive elements of the road (ΔV85) (Lamm and Choueiri 1995).

In vehicle dynamic category attention is given to, vehicle stability on horizontal curves, and therefore to side friction and superelevation design, both for the single curve (Lamm et al., 1988) and for curves sequence (Nicholson 1988, Easa 2003).

Road geometric-based consistency, that uses the alignment indices, are quantitative measures of the general character of an alignment in a section of road (Anderson et al., 1999). The main premise for using alignment indices, as design consistency measures, is that geometric inconsistencies will result when the general character of an alignment changes significantly.

Examples of alignment indices include average radius (AR), ratio of maximum radius to minimum radius (RR), and average rate of vertical curvature (AVC)

(Fitzpatrick et al. 2000). An additional parameter, named CRR and defined as the ratio of radius of a single horizontal curve to the average radius of the entire section, 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” (Anderson et. al. 1999).

Performance considerations, that monitoring design consistency by drivers' mental workload or drivers' anticipation, can be classified as a “user-side” measure 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 (Messer 1980). Locations with high workload or large positive change in workload were found to be associated with high accident rates (Wooldridge 1994). However, compared with the other consistency evaluation measures, evaluation of drivers’ workload, is much more complex.

The expectancy checklist largely consists of examining various design features (Rowan et al., 1972). Designers’ attention is called to possible expectancy violations and is 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 discussion of principles or specific measures. In the face of this lack of information, a designer could face problems in applying the recommendations.

2.2 Consistency evaluation criteria and safety

The general opinion today is that the accident risk decrease as the radius of the curve increase (Zegeer et al. 1992), however different opinions exist regarding the extent of this influence on accident situation, for instance great differences of accident rate between bends of the same radius exist, mainly due to the characteristics of the upstream horizontal alignment.

According to several accident studies, the alignment in which the curve is located greatly influences the safety of the curve. Kosasih et al. (1987) shows that the accident rate at small-radius bends is very high when the average curvature of the whole alignment is low, but relatively low when the average curvature is great. These results also show that an alignment with a great degree of curvature can be safer than relatively straight alignments. Baldwin (1946) showed 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.

Lamm (1988) and Choueiri (1994) evaluated relationship between the variation of degree of curvature and accident rates. They stated:

- gentle curvilinear horizontal alignments consisting of tangents or transition curves, combined with curves up to 5 degrees experienced the lowest average accident risk;
- accident risk on sections with a change in curve between 5 and 10 degrees was at least twice or three times as high as that on sections with change in curve of between 1 and 5 degrees;

- accident risk on sections with a change in curve between 10 and 15 degrees was at least twice or three times as high as that on sections with change in curve of between 1 and 5 degrees;
- for changes in curve of greater than 15 degrees, the average accident rate was even higher.

Lamm and Choueri evaluated even a relationship between the change of curvature and speed reduction and then they inferred a relationship between 85th percentile speed reductions and accident rate.

Anderson et al. (1999) analyzed 291 highway sections in which the average tangent length was 0,7 km. The database included 5287 horizontal curves for which the speed differences from adjacent features were determined, moreover alignment indices were computed and correlated to accident experience.

In particular the functional relationship between accident frequencies and the independent variables like speed reduction and curve radius. A strong relationship between the speed reduction on a horizontal curve and the accident frequency on that curve was showed. Furthermore, a sensitivity analysis found that predicted accident frequency varies with speed reduction. The relationship indicates that the greater the speed reduction experienced by motorists on a horizontal curve, the greater the curve's accident experience.

Regression models analogous were developed using radius of curvature rather than speed reduction as an independent variable. Radius of curvature was found to be statistically significant in these models, but predicted accident experience was much less sensitive to radius of curvature than to speed reduction;

When both speed reduction and radius of curvature were used as independent variables in the same models, speed reduction was found to have a stronger association with accident rate than curve radius. These findings indicate that there is potential value in improving the safety of proposed highway design, through use of a design-consistency procedure based on speed reduction, because speed reduction is a better predictor of accident experience than curve radius alone.

A limitation of the second approach is that it is more difficult to account for factors that affect speeds on the approach tangent including the sharpness of the preceding curve, the length of the tangent and general characters of alignment.

Anderson and Krammes (2000) analyzed the relation between speed reduction, degree of curvature and accident rate for 563 curves. The results suggest that estimated speed reduction is a useful measure that helps explain how accident experience at horizontal curves on rural two-lane highways varies with degree of curvature. Horizontal curves that require speed reductions have higher accident rates than curves that do not require speed reductions. The mean accident rate increases approximately linearly with the mean speed reduction.

Therefore several studies have been indicated that speed reduction is the best useful measure to explain accidents. For that reason speed reduction was the basis for the criteria suggested by Lamm et al. (1999), that are commonly accepted criteria for evaluating consistency.

Lamm developed three safety (Table 1) quantitative criteria that provide:

- design consistency, through Safety Criterion (SC) I; the difference between design speed and driving behavior as expressed by variations in observed 85th percentile speeds;

- operating speed consistency, through SC II; the difference between observed 85th percentile speeds on successive design elements;
- driving dynamic consistency, through SC III; the difference between side-friction assumed and side-friction demanded for design at the 85th percentile speed level on curves.

Table 1 Quantitative Ranges for Safety Criteria I, II and III (Cafiso et al. 2004)

Safety Criterion	Design (CCR_S) Classes		
	Good Permissible Differences	**Fair** Tolerated Differences	**Poor** Nonpermissible Differences
	$\lvert CCR_{Si} - CCR_{Si+1}\rvert \leq 180$ gon/km	180 gon/km $< \lvert CCR_{Si} - CCR_{Si+1}\rvert \leq 360$ gon/km	$\lvert CCR_{Si} - CCR_{Si+1}\rvert > 360$ gon/km
I[1]	$\lvert V85_i - V_d\rvert \leq 10$ km/h	10 km/h $< \lvert V85_i - V_d\rvert \leq 20$ km/h	$\lvert V85_i - V_d\rvert > 20$ km/h
II[2]	$\lvert V85_i - V85_{i+1}\rvert \leq 10$ km/h	10 km/h $< \lvert V85_i - V85_{i+1}\rvert \leq 20$ km/h	$\lvert V85_i - V85_{i+1}\rvert > 20$ km/h
III[3]	$f_{RA} - f_{RD} \geq +0.01$	$-0.04 \leq f_{RA} - f_{RD} < +0.01$	$f_{RA} - f_{RD} < -0.04$

[1] Related to the individual design elements "i" (independent tangent or curve) in the course of the observed roadway section
[2] Related to two successive design elements, "i" and "i+1" (independent tangent to curve or curve to curve)
[3] Related to one individual curve

NOTE:
CCR_S = curvature change rate of the single curve [gon/km] ,
V_d = design speed [km/h] ,
$V85_i$ = expected 85th-percentile speed of design element "i" [km/h] ,
f_{RA} = side friction "assumed" [-] ,
f_{RD} = side friction "demanded" [-] .

All three criteria are evaluated with regard to three ranges, described as "good," "fair," and "poor." Cutoff values among the three ranges are developed and applied to both curves and tangents.

SC I is a measure of the consistency of the alignment; That means the design speed (Vd) shall remain constant on longer roadway sections and shall be tuned at the same time with the actual driving behavior, expressed by the 85th percentile speed (V85) of passenger cars under free-flow conditions. In this way, the road characteristic is well balanced for the motorist along the course of the road section. SC II reflects the harmony (or disharmony) between operating speeds on successive design elements. SC III refers to the adequacy of the safety dynamics provided at each curve individually. A well-balanced driving dynamic sequence of individual design elements within a road section with the same design speed (Vd) promotes a consistent and economic driving dynamics pattern.

3. DESIGN AND OPERATING SPEED BACKGROUND

Before using any of the aforementioned consistency evaluation criteria, the parameter examined in the evaluation criteria must be defined, predicted or estimated.

According with the Lamm's criteria, for the safety evaluation process, sound information is needed on how to determine: design speed (Vd), 85th percentile speed (V85), side-friction assumed (f_{RA}) and side-friction demanded (f_{RD}).

Moreover, in order to develop the speed profile model, and because the V85 or the Vd was well known only on bends and not along tangents is necessary defining even the deceleration and acceleration rate and the maximum speed (Vmax) on tangents.

Basically design speed is defined as “a speed selected as a basis to establish appropriate geometric design for a particular section of road”, but a summary of international practices demonstrates substantial variation in the processes used to select design speed. Whereas the United States continue to adhere to the design speed concept as classically applied, many European countries and Australia have enhanced their use of design speed to incorporate explicit consideration of actual driver speed behaviour in terms of 85th percentile operating speed.

The intent of the design speed concept is to provide a roadway that has consistent features. Therefore, speed is used both as a performance measure to evaluate roadway design as well as a criterion to design and to coordinate a roadway’s physical elements.

For the first issue design speed (Vd) is chosen on environmental and economic conditions, based on the assumed network function of the road and the desired quality of traffic flow. In some countries design speed is defined like the minimum speed for the section of the road, and is used to determine the minimum radius of curvature for the preliminary alignment design. In other countries design speed is defined as the maximum speed of road category and is related to general speed limits. Only these kinds of Vd would be used for the SC I.

For the second issue design speed is related to safety. In most countries, however, superelevation rates and sight distances are designed based on the estimated 85th percentile speed when it exceeds the design speed. This kind of Vd (or V85) would be used for the SCII.

In standard of most countries, there is an assumption that curve radii (R) exert the dominant influence on operating speeds (V). The functional relationship V = f (R) can be derived empirically or by mechanichistic bases.

The empirical approach is oriented by the behaviors recorded in traffic flow. The 85th percentile (V85) are generally used for this description. V85 is well known on curves but is less simple to evaluate on tangents.

The second approach is founded on a physical model. A correlation is defined between a theoretical notion of speed (described as the design speed Vd) and the determining design elements. These definitions are based on specified conditions (such as friction capacity on wet pavement). Drivers are thus offered adequate security if they adopt speeds within the scope of the defined model. However, because the road user is not aware of these physical model definitions, could rise disparities between the speeds driven and those specified in the model. In particular this aspect is problematic if a speed limit (or a maximum design speed) is considered in the model.

Vmax is the desired speed along roadway and it is the speed that driver selected when not constrained by horizontal and vertical alignment. Desired speed can be observed on long tangents, that is long enough for a driver to accelerate to and, for some distance, maintain at he desired speed. Vmax can be estimated through an empirical approach as the V85max on long tangents and depend on general characteristics of road but often is defined as the maximum permissible speed (Vp) for that road category that is generally related to speed limits. This second approach can be used only if Vp and V85max are not too different, otherwise the consistency controls could be largely lost.

In developing a speed-profile model the next step is knowing Vd or V85 outside curves. Basically the driver decelerates when approaching the curve and then accelerates after departing the curve up to the desired speed if no constrains exist. Acceleration and deceleration rates are defined through empirical measures, and are constant or function of curve radius.

In every road element commonly accepted highway design theory suggests that the design speed should be higher than the posted speed, which, in turn, should be equal to or higher than the 85th percentile operating speed. However, realistically, the design speed, operating speed, and posted speed on a roadway should at least be similar in magnitude.

The side friction assumed is a function of Vd (based on grip data produced by measurements on pavements) and of utilization ratio "n".

The side friction demanded is expressed as

$$f_{RD} = \frac{V85^2}{127 \cdot R} - e \qquad \text{(Eq. 1)}$$

Where R is radius of curve [m] and "e" is superelevation rate.

Design consistency policies and practices for USA, Germany, Switzerland, Australia and Italy were briefly evaluated.

3.1 U.S.A.

In U.S.A. design speed is now defined as "a selected speed used to determine the various geometric features of the roadway" such as curvature, superelavation and sight distance. The assumed design speed should be a logical one with respect to the topography, the adjacent land use, and the functional classification of the highway. Although the selected design speed establishes the minimum curve radius and minimum sight distance necessary for safe operation, there should be no restriction on the use of flatter horizontal curves or greater sight distances. The design speed concept, which was developed in the 1930s, as a mechanism for designing rural highway alignments, permitted most drivers to operate uniformly at their desired speed. As design practice and driver behavior evolved, however, the design-speed concept lost effectiveness at producing consistent alignments. The design-speed concept presumes that a design will be consistent if each alignment feature shares the same design speed. Unfortunately, the concept, as implemented in the United States, cannot guarantee producing an alignment that promotes uniform operating speeds. AASHTO (2001) policy on the distribution of superelevation on curves less sharp than the minimum-radius curve is the principal mechanism for ensuring horizontal alignment consistency in the design-speed concept.

The method used by AASHTO to distribute the maximum superelevation throughout the range of intermediate curve radii has weakened the relationship between design speed and the limiting speeds suggested through the laws of physics and not thorough driver behaviour. AASHTO computes the corresponding distribution of side-friction factor assuming that drivers are constrained to operate uniformly at the design speed even on curves where they could operate at higher speeds without exceeding the assumed maximum side-friction factor. AASHTO's maximum side-friction factors are based on passenger comfort measurements during the 1940s. These factors appear to be obsolete because of changes in vehicle design and driver preferences and tolerances. It is evident that many of today's drivers accept values higher than the assumed maximums. Clearly, drivers are not constrained, as policy suggests, by the assumed distribution of side-friction factors that are lower than the maximum. Without this assumption, AASHTO policy has no basis for ensuring speed consistency among alignment features.

Moreover a fundamental limitation is that the design speed applies directly only to horizontal curves and not to the tangents. Design speed has no practical meaning on horizontal tangents. It provides no basis for establishing maximum tangent lengths to promote consistency by controlling the maximum operating speeds that can be attained.

3.2 Australia

Austroads (1997) defines road design category as function of speed environment that is the desired speed a driver will adopt on less constrained element. The speed environment (Venv) is equal to the 85th percentile of the observed free speed distribution on longer straight, or large radius curves, on section al low traffic volumes. Speed environment is influenced by geographic location, general topography, and general standard of the road. Austroads determined that different design philosophies should be applied for determining alignment standards for high (Venv > 100 km/h) and intermediate (Venv < 100 km/h) speed alignments

For alignments with speed environments of 100 km/h or greater, the traditional practice of providing conservative designs for high-speed alignments should continue as it is consistent with the high levels of safety and operational efficiency expected of highways of this type. In this case high uniform travel speeds are expected. Design speed will approximate speed environment, so a ruling design speed is selected in keeping with the terrain or the importance of the road. The ruling design speed should be used in the design of geometric elements of the roads.

For intermediate speed alignments, with speed environment below 100 km/h, design standards were based as follows:

- curve design speed will be the predicted 85th percentile speed;
- speed environment is the maximum speed of section
- design speed on long tangents is speed environment on short tangent speed is function of preceding curve speed and length of tangents
- then design speed is used to check consistency (as design speed difference on successive geometric elements), safety on curves, and sight distances.

In other words for intermediate speed alignments (< 100 km/h), the predicted 85th percentile speed is used as the design speed. For high speed (≥ 100 km/h) alignments the classical design speed concept is used, because for such alignments studies revealed that the 85th percentile speeds were less than the design speed.

3.3 Germany

German design guidelines (RAS-L 1995) use both design speed and 85th percentile operating speed for alignment of rural highways.

The design speed is used, as in the United States, to determine the minimum radius of horizontal curves, maximum grades, and minimum values for crest vertical curves. Design speed depends on environmental and economic conditions based on the assumed network function of the road and the desired quality of traffic flow.

German research in the 1970's indicated that actual speeds often exceeded traditional design speed values. The 85th percentile speed is estimated from empirical relationships based on the curvature rate and pavement width, maximum speed is indicated as 100 km/h even if recent research have found higher speed on tangents and large curves. Operating speed is used both for check consistency and for selecting superelevation on curves.

German guidelines provide several instructions for achieving consistency.

First they state that acceptable ranges are specified for the radii of successive curves, and minimum radii following a tangent are also specified.

Second German guidelines state that 85th percentile speed between successive road section can not differ more than 10 km/h

In the previous guidelines the expected 85th percentile speed should not exceed the design speed by more than 20 km/h, otherwise the guidelines require that either the design speed be increased or the design be modified to reduce the expected 85th percentile speed. Thus, the design process involves a feedback loop in which the driver speed behaviour resulting from the designed alignment is estimated and compared with the assumed design speed. In RAS-L (1995) this control there is not more.

3.4 Switzerland

The Swiss guidelines have origins 1970's, and is detailed in Swiss Norm 640 080b. Switzerland defines a base speed, that is used, as Germany does with design speed, to determine minimum radii of horizontal curves, maximum grades, and minimum values for crest vertical curves. Base speed depends on road category, for rural two-lane highway it varies from 50 to 80 km/h, where 80 km/h is the speed limit on these roads.

Moreover Switzerland uses a design speed (Vd) both for checking driving safety dynamic on curves, sight distances and consistency control as speed changes between adjacent elements.

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

- Design speed (Vd) on curves that is derived from a physical model; the function Vd = f (R) is derived from an equilibrium model during curve driving. It is derived from the simplifying equation

$$V_d = \sqrt{127 \cdot R \cdot (f_R + q)} \qquad \text{(Eq. 2)}$$

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

- maximum speed (Vdmax) on long tangents, that is coupled to the general speed limit applicable to the category of highway in question (80 km/h for two lane rural highways);
- deceleration and acceleration rates entering and exiting horizontal curves.

Driver performance during deceleration is fundamental to traffic safety, which is why the speed profile must be evaluated and assessed in both directions of travel. The design standard therefore stipulates various conditions for the admissible speed differences ΔVd between adjacent alignment elements.

For such standard operating speed is not used. Safety is guaranteed only is operating speed is less than Vd, included Vdmax. This is not true, as stated by Spacek (2004), so the application of this model, as a control instrument, has become problematic.

3.5 Italy

The italian standard is similar to Swiss standard, but there is not the base speed. Moreover the design speed depends by road category and for rural two-lane highway it varies from 60 to 100 km/h, the speed limit is 90 km/h.

Italy, as Switzerland, have derived their design speed Vd from a physical model, and, as in Switzerland, design speed model regulates driving dynamics on curves and consistency between adjacent elements. Deceleration and acceleration rates are the same of Swiss standards, maximum speed is related to road category. Operating speed is not used. Consistency is checked like in Swiss guidelines.

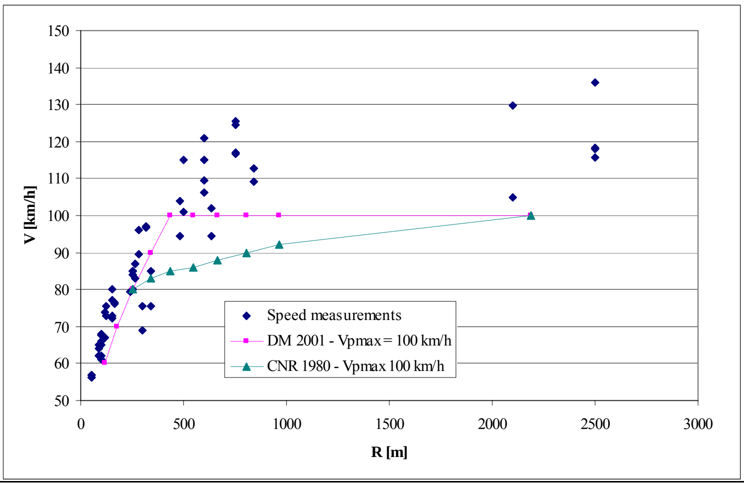

Figure 2 Comparison of operating speed and design sped speed for Italian two lane rural highways

The weakness of Italian, as Swiss, speed profile model is that operating speed is never less than design speed, also for maximum design speed. Figure 2 compares operating speed data and Vd for new Italian standards (DM 2001) and old Italian standard (CNR 1980).

4. CONSISTENCY OF LITTLE TWISTY ROADS

Into Italian standards both the consistency and driving dynamic safety is checked by a design speed, that is derived from a physical model.

A previous research (Crisman et al., 2005) carried out by University of Trieste indicated that operating speed always is higher than design speed, as previously defined. (Figure 3). This was the results also of other researchers for operating speeds less 100 km/h and radii less about 400 m.

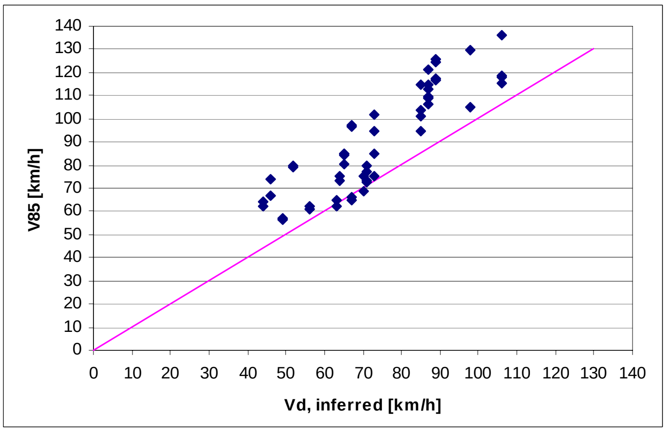

Figure 3 The 85th percentile speed versus inferred design speed on Italian roads

For higher radii, in Italy, but also in Germany, several studies have been indicated that operating speeds can be higher than both design speed and the maximum speed allowed for the road category (100 km/h). Basically this happens when the environmental speed (desired speed) is higher than permissible speed, moreover in this case differences up to 30 km/h were found between operating speed and maximum permissible speed. This already supported that, also in the Italian roads, it is necessary the adoption of the operating speeds for the evaluation of the safety.

Moreover Crisman et al. (2005) had found, like Mclean (1981), that the driver's choice of speed is heavily conditioned not only by the geometric features of the single geometric element, but also by the geometric features of the preceding road section and by the overall road environment. To consider not only the features of the single geometric element, but also a variable that represents the overall horizontal alignment, a numerical prediction model of the operating speeds on curves was developed, making use of environmental speed as independent variable.

$$V85_C = V_{env} \cdot \left[1 - \frac{V_{env}^2}{298{,}27 \cdot R} \right] \qquad \text{(Eq. 3)}$$

where: V85c (km/h) is the operative speed on curves; Venv (km/h) is the environmental speed, R (m) radius of curve.

Moreover in the Italian roads, also with generous alignments, relevant differences exist between operating speeds of adjacent features and therefore, differently for example than Australian guidelines, the evaluation of the consistency has to be also in these cases verified.

For generous alignments, checking consistency could not be made with the variation of the degree of curvature, according to the safety criterion of Lamm (CCRi - CCRi+1 <180 gon/km), because it would be always satisfied, and therefore consistency must be checked through speed differences.

These evidences place emphasis on another important aspect: that it is necessary to define, in opportune way, the maximum desired speed on road section of the drivers. Establishing a superior limit for design speed, not consistent with the actual maximum desired speeds of road users (environmental speed), can induce not only problems from the dynamic point of view but also in terms of consistency.

With regard to the dynamic safety in Figure 4 it is illustrated as, in the Italian standards (new and old guidelines), the side friction demanded is always higher than assumed one.

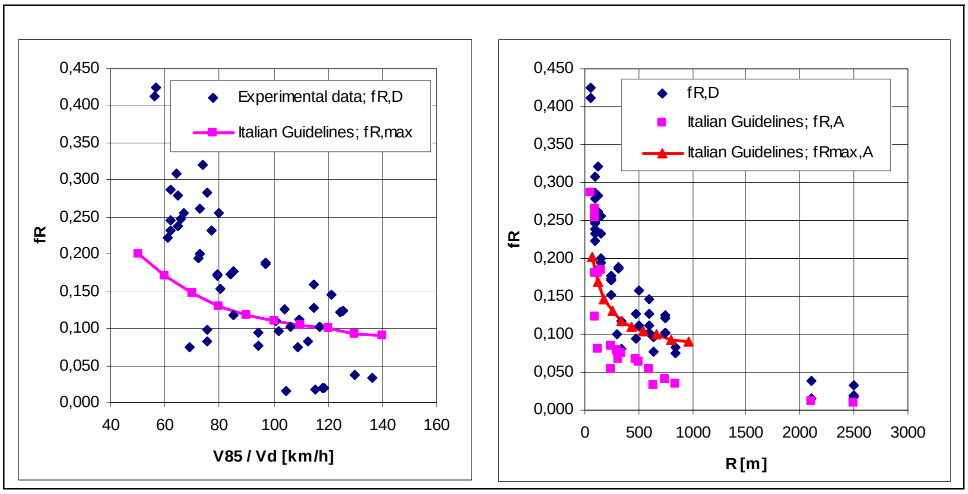

Figure 4 Side friction assumed $f_{R,A}$ and demanded $f_{R,D}$ as function of speed and curve radius

With regard to the consistency criteria the weakness of Italian standards, but even of Swiss one, is, not only, in the assumption that the design speeds are different from the operating speed but also that the maximum design speed for road category is less than desired speed, on little twisty alignments (Crisman et al 2005).

Pegging of maximum design speed to the speed limits, and not to operating speed, emerges as a fundamental defect in the speed model on rural highways (Figure 5). The control function of this tool in attaining alignment that is balanced and technically sound, in terms of traffic safety, is largely lost, and to carry with it the danger of according only secondary importance to the quality of alignment design. To have a suitable evaluation of the consistency, in the roads with little twisty alignments, it should be used, not only, the operating speeds but also not to set any external limit to the maximum speed, defined for example through the general speed limits on the road. But without appropriate controls, maximum operating speed, on little twisty roads, will be always higher than maximum permissible speed therefore it need to design the roads (superelevation, sight distance, etc.) for these high speeds.

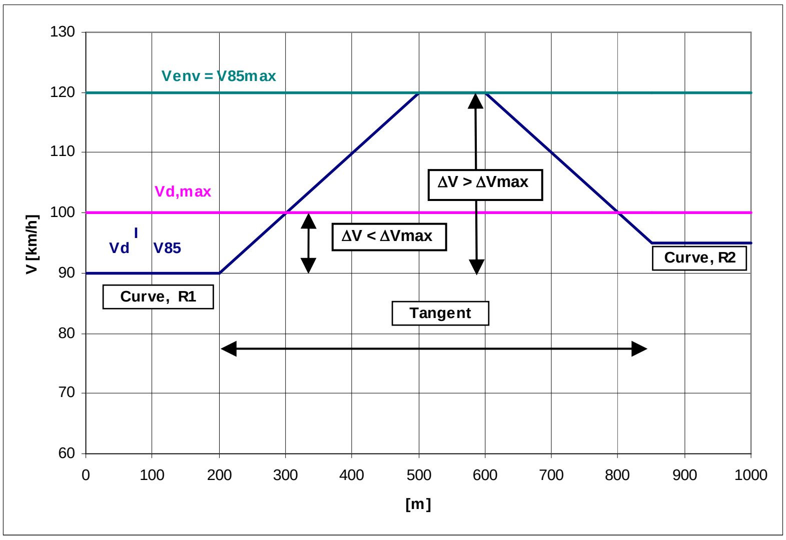

Figure 5 Example of speed profile on two-lane rural roads

A simplified but nevertheless well-founded policy, that can be applied to these categories of rural highway, is therefore required.

A control on the maximum operating speed, consistent with driver behaviour, can be carried through road sections with an environmental speed that doesn't allow, in the section, to overcome the maximum permissible speed for that road category (Venv = Vdmax).

Into a previous research Crisman et al. (2005) had presented also a prediction model to calculate the environmental speed of a homogenous sections, as a function of CCR (Figure 6).

$$V_{env} = 69{,}98 - 0{,}08 \cdot CCR + 5{,}30 \cdot Lp \qquad \text{(Eq. 4)}$$

where Venv is environmental speed (km/h), CCR is the average Curvature change rate (gon/km) of section and Lp (m) is the road width (shoulders+ lanes).

To limit the environmental speed therefore it is possible to operate upon the minimum value of average CCR of the section.

For Italian two-lane rural highway, where maximum design speed is 100 km/h, using the results of previous environmental speed model, it could be set a minimum average CCR equal to 200 gon/km.

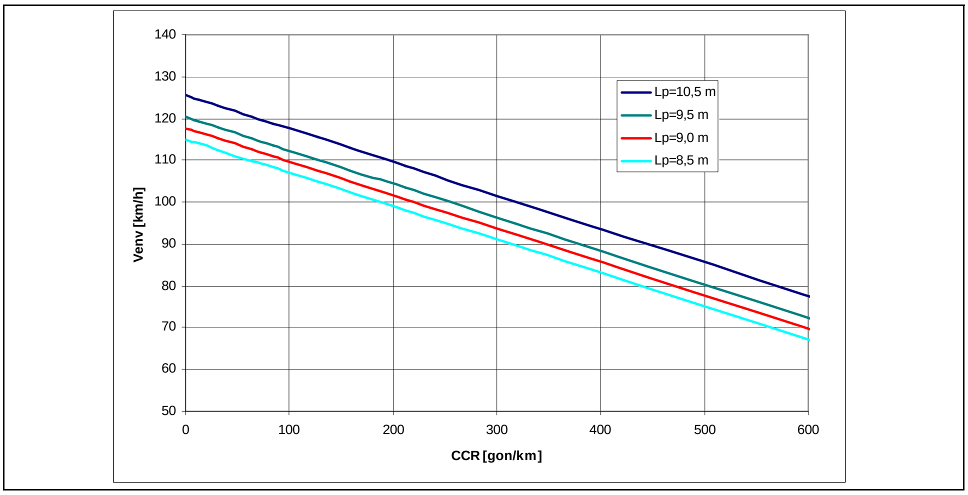

Figure 6 Environmental speed as function of CCR and Lp

5. CONCLUSIONS

This paper presented a critical review of the concept of highway geometric design consistency, criteria and parameters for its evaluation, and its relationship to safety performance, in particular for Italian roads with little twisty alignment. A number of concerns or challenges to the current state of knowledge and practice were outlined with the objective of refining and improving the concept and its applicability. The main conclusion that can be drawn based, on this review, is that despite these challenges and concerns, the theory remains promising but improvements are necessary.

Analysis of the relationship between the different candidate for evaluation consistency criteria and safety performance indicate that speed differences is better than CCR differences.

A summary of international practices with regard to design speed demonstrates substantial variation in the process used to select design speed therefore attention must be given in application of first Lamm safety criteria.

Even for generous alignment, on Italian roads, operating speed is always higher design speeds, and maximum permissible speed of road category, moreover there are large differences of V85 on curves with large radii.

On little twisty roads it need a appropriate controls of maximum operating speed, consistent with driver behaviour, and that allow to adjust it to the maximum permissible speed of the road category; such control can be got through the limitation of the environmental speed.

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