A PROPOSAL TO UPDATE THE CLOTHOID PARAMETER LIMITING CRITERIA OF THE ITALIAN STANDARD

Marchionna A.
Full professor – University of Trieste – Marchionna@dica.units.it
Perco P.
Ph.D. Research fellow – University of Trieste – Perco@dica.units.it

ABSTRACT

Most design standards recommend the use of the clothoid in the transition design. In particular, the Italian Standard always requires the clothoid between two elements with constant curvature (tangent or circular curve), independently of the curve radius or the road category. The advantages usually connected with the use of the clothoid are a gradual increase in the centrifugal force, a convenient arrangement for super-elevation and a satisfactory roadway appearance. The Italian Standard uses three criteria to define the limits of the spiral length according to all three of these controls. These criteria lead to a wide range of the spiral length within which practitioners can choose. In particular, very long spiral curves, contrary to other foreign standards, are allowed without any warning about the possible consequences of their use. In fact, a long clothoid can have a potentially negative effect on the driver's curve perception and safety. Therefore, a proposal to update the existing Italian standard is presented. The aim of this update is to guarantee the choice of a spiral length consistent with driver behaviour. The proposal provides a minimum and a maximum length of clothoids dependent on the curve radius which is calculated considering all the aspects affected by the presence of the clothoid. The choice of the clothoid length within this range ensures optimal operating conditions for drivers by avoiding problems of curvature perception and, therefore, improving road safety.

Keywords: clothoid, horizontal alignment, geometric design

1. INTRODUCTION

Many road standards and guidelines, including the Italian standard (Norme Funzionali 2001), require or recommend the use of the clothoid in the transition design. The advantages that are usually connected with its use are a gradual increase in centrifugal force, a convenient and desirable arrangement for superelevation and a satisfactory roadway appearance. However, some studies showed a potentially negative effect of long clothoids on the driver's curve perception and safety (Stewart et al. 1990, Tom 1995, Perco 2005), in particular if the curve requires a speed reduction to be traveled safely. Some studies showed that the most desirable clothoid length, which provides advantages compared to the tangent-to-curve transition, is equal to the distance traveled during the steering action (Perco 2005, Bonneson 2000),which will be defined further on. Therefore a model to estimate the distance traveled during the steering time on the basis of the radius of curvature of the impending curve was recently proposed (Perco 2006). However, this model is not directly usable in the Italian context because it is based on the operating speed and on a variable deceleration rate model whereas the Italian standard uses the design speed and a constant deceleration rate. Unfortunately, the clothoid parameter limiting criteria of the Italian standard allow very long clothoid without any warning about the possible consequences of their use. Therefore, a new model consistent with the Italian standard was developed. This model and a complete review of the literature were used to propose an update of the actual criteria.

2. EFFECT OF CLOTHOID LENGTH ON DRIVER BEHAVIOR

Previous studies (Perco 2006) describe the effect of the clothoid length on driver steering behaviour using the steering model developed by Godthelp (1986) and the visual information collection process before a curve (Land et al. 1994, Land et al. 1995). The clothoid, in particular, can influence this process. In fact, clothoid length affects curve perception, as proved by Riemersma (1989). The presence of a long clothoid may lead the driver to a misleading perception about the sharpness of the impending curve. When the clothoid is too long, the driver looks at the first part of the clothoid which has a lower average curvature than the following circular arc, and uses this wrong information to decide his steering action. This behavior would appear to be confirmed by Yerpez and Ferrandez (1986) who established a connection between accidents and excessive curvature variation along the curve, as in the case of a long clothoid. To verify if the presence and length of a clothoid affect driver behavior, Perco conducted a comparative analysis between vehicle paths along clothoids of different lengths (Perco et al. 2004) and between transition sections with and without clothoids (Perco 2005). All the curves surveyed required a speed reduction to be travelled by the vehicles. The results of path analysis strongly supported the negative effect of an excessive clothoid length on driver steering behavior. If the clothoid is too long, the driver steers along the first part of the clothoid and then, at the end of the steering action, which corresponds to the steering time, starts steering and speed corrections in an attempt to follow the increasing curvature along the clothoid. These steering corrections and braking action force the vehicle away from the path planned by the driver. If the clothoid length corresponds to the distance traveled during the steering time, then the path is regular with a linear lateral shift executed more or less on the clothoid. The driver steers along the clothoid and travels the curve entry correctly.

3. THE CLOTHOID IN FOREIGN DESIGN STANDARDS

Most design standards require or recommend the use of the transition curve even though there is a general lack of uniformity in the conditions of its use and the controls of its length. The curve usually adopted is the clothoid which is characterized by a curvature that increases linearly along the arc length. The standards usually define the limits of the clothoid length according to three criteria: the comfort criterion (rate of change in lateral acceleration), the roadway appearance criterion and the gradient criterion. The criterion based on driver comfort is intended to provide a clothoid length that allows for a comfortable increase in lateral acceleration as the vehicle enters a curve. The roadway appearance criterion ensures that the visual perception of the curve is correct. The gradient criterion defines the minimum clothoid length based on limiting the relative gradient of the edge of the pavement in relation to the grade of the axis of rotation because the superelevation is usually attained along the clothoid. A brief description of the principal foreign standards makes it possible to evaluate the subsequent proposal to upgrade the Italian standard.

The minimum clothoid parameters allowed by the Swiss (Norm SN 640-100a 1981) and German standards (RAS-L 1995) are calculated using the comfort criterion and are presented in a table as a function of the design speed and curve radius. Moreover, these two standards recommend that the clothoid parameter is contained within the range $R/3 \leq A \leq R$ even though it should be chosen also considering the minimum (Δi_{min}) and the maximum (Δi_{max}) relative gradient (relative change of grade of the edge of the travelled way in relation to the grade of the axis of rotation) because the superelevation must be attained along the clothoid. If necessary, these standards allow us to attain the superelevation in two stages in order to respect the minimum relative gradient (Δi_{min}) along the first part of the pavement edge. However, the Swiss standard recommends that the rotation should be made using the maximum relative gradient (Δi_{max}) before the curves of rural roads so that the perception of the curve ahead is improved, whereas the German standard recommends using clothoid lengths that respect the minimum relative gradient (Δi_{min}) to avoid attaining the superelevation in two stages because this configuration could compromise the curve perception and the vehicle dynamic. The German standard recommends using a short clothoid ($A=R/3$) to ensure a good perception of the curve if this curve follows a tangent or another curve which has a much larger radius. The French standard (Aménagement des Routes Principales 1994) reports the results of some studies (Stewart et al. 1990, Yerpez et al. 1986) in order to underline the fact that the clothoid must be short to prevent drivers being misled about the sharpness of the impending curve. In fact, the clothoid lengths calculated with the formulae included in this standard are very short. The superelevation is normally attained along the clothoid even though the rotation can start before the beginning of the clothoid if its length does not respect the maximum relative gradient (Δi_{max}) or, on the contrary, the superelevation can be attained at the end of the clothoid if its length does not respect the minimum relative gradient (Δi_{min}). The United Kingdom standard (Road Geometry: Highway Link Design 1993) calculates the clothoid length using the equation of the comfort control (without the change in the cross slope) using a rate of change in lateral acceleration ranging from 0.3 m/s^3 to 0.6 m/s^3 only if the radius is not sharp and the curve does not require a significant speed reduction in respect of the design speed of the road section to which the curve belongs. On the contrary, if the curve requires a speed reduction to be travelled safely the driver must perceive its curvature correctly, therefore the standard recommends that the maximum offset between tangent and circular arc is below 1.0 m. The superelevation is usually attained along the clothoid even though it can be attained along the final part if its length does not respect the minimum relative gradient (Δi_{min}). Finally, the Australian and the United States guidelines (Rural Road Design 1997, A Policy on Geometric Design of Highways and Streets 2001) do not require the use of the clothoid even though these standards recognize the advantages connected with the presence of a transition curve before a circular curve. These guidelines require that the superelevation from +0.0% to the final superelevation is attained along the clothoid, while the initial superelevation between -2.5% and +2.5% is attained along the tangent. The Australian guideline suggests not using a clothoid longer than the length necessary to attain the superelevation, especially on roads with a low speed environment. The standard recommends an offset of 0.50 m for curves on roads with a high speed environment in flat terrain. The United States guideline reports the equation of the comfort control (without the change in the cross slope) using a rate of change in lateral acceleration ranging from 0.3 m/s^3 to 0.9 m/s^3, even though the resulting length can be shortened to take into account the superelevation. Moreover, the guideline suggests that the rate of change in lateral acceleration consistent with driver comfort is 1.2 m/s^3. To avoid the driver being misled about the sharpness of the impending curve, the standard recommends that the maximum offset between the tangent and circular arc is 1.0 m. Finally, the United States guideline has introduced a desirable clothoid length that is the distance travelled in 2.0 seconds at the design speed, since this time was found to be representative of the natural steering time of most drivers. All the standards and guidelines set a curve radius above which the clothoid is not necessary.

4. THE CLOTHOID IN THE ITALIAN STANDARD

The Italian standard (Norme Funzionali 2001) requires the clothoid to be inserted between two geometric elements with constant curvature. Namely, the clothoid must be used for the whole rural and urban road categories. Moreover, the standard does not fix an upper limit to the radius above which the clothoid cannot be used. The Italian standard considers the usual three criteria: comfort, gradient and roadway appearance. The first and the second criteria are used to establish only minimum lengths whereas the third is used to establish minimum and maximum lengths.

The Italian standard reports the general equation of the comfort control that contains the change in the cross slope but it also suggests a simplified equation that does not consider the change in the cross slope ($A \geq 0.021\ V^2$ with V in km/h). The standard requires the use of the maximum speed reached on the clothoid deduced from the design speed-profile. This requirement produces an iterative calculation because when the clothoid parameter is selected the maximum speed reached along the clothoid length must be calculated and used to verify the clothoid parameter. If the clothoid parameter is not verified a new parameter must be selected and the procedure must be repeated. Moreover, the simplified formula, that leads to very long clothoids, makes it impossible to find a solution to this iterative calculation for sharp radii.

The Italian standard requires that the superelevation is attained along the clothoid. The gradient criterion ensures that the clothoid length respects the maximum relative gradient Δi_{max} between the axis of rotation and the edge of the travelled way. On the contrary, if the minimum relative gradient Δi_{min} is not respected, the standard requires the attainment of the superelevation in two stages to respect the minimum relative gradient (Δi_{min}) along the edge of the travelled way with a grade smaller than ±2.5%.

The roadway appearance criterion requires that the clothoid parameter is greater than R/3 to ensure the visual perception of the clothoid and that the clothoid parameter is smaller than R to ensure the visual perception of the circular curve. This is the only upper limit proposed by the standard.

In all, the Italian standard makes it possible to use the longest clothoids from all the standards analyzed .

5. A PROPOSAL TO UPDATE THE ITALIAN STANDARD

The analysis of the Italian standard clothoid criteria reveals three critical points:

- The standard makes the use of long clothoids possible and does not report any suggestion about a possible negative effect of this length on driver perception of curvature, in particular if the curve requires a speed reduction to be travelled safely.
- The standard requires the attainment of the superelevation in two stages if the minimum relative gradient Δi_{min} is not respected along the clothoid. This is the opposite of some foreign standards that suggest shortening the clothoid.
- The lack of an upper limit for the radii above which the clothoid cannot be used produces situations the utility of which should be further investigated (for example: R = 5.000 m → clothoid L_{min} = 555 m corresponding to 14 s at 140 km/h – L_{max} = 5.000 m corresponding to 129 s at 140 km/h).

The first problem is the most important one because it directly affects the safety of sharp curves. However, the second problem also could compromise driver comfort and curve perception (RAS-L 1995). This negative effect is particularly evident along long clothoids, when the initial rotation (-2.5% to +2.5%) is attained at a long distance from the circular curve, where the shift of the clothoid is so small that the driver still perceives the road as a tangent. In this case, when the curve is on the left, the driver has to steer on the right (the opposite direction in respect of the impending curve) to balance the unexpected rotation of the travelled way. Finally, the third problem, even though it involves aspects such as the optical appearance of the road and its influence on the driving task that have not yet been studied, represents a significant complication for the insertion of the road alignment in the environment because it needs very long curves. Therefore, the possibility of eliminating these critical point leads to the following update proposal.

5.1 Comfort criterion

Recently, Perco (2006) proposed a model to estimate the desirable length of clothoids starting from the radius of the impending curve that gives a good description of real driver steering behavior as observed in the field surveys. This model is based on the steering time observed during real steering actions (Perco 2004, Perco 2005) and uses operating speed and deceleration rate models derived from experimental surveys. However, this model is not directly usable to update the Italian standard because it uses the operating speed instead of the design speed and a deceleration rate model instead of the constant rate of 0.8 m/s^2 defined by the Italian standard. Therefore to propose an update of the comfort criterion a new model consistent with these elements was developed. Considering that the comfort criterion uses the rate of change in lateral acceleration as the limiting parameter, the model proposed (Perco 2006) was used to evaluate the real rate of change in lateral acceleration accepted by drivers. Assuming that the steering path is a clothoid and considering the change in cross slope q, the rate of change in lateral acceleration c is defined as

$$c = \frac{d(\frac{v^2}{r} - g \cdot q)}{dt} = \frac{d(\frac{v^2}{r})}{dt} - \frac{d(g \cdot q)}{dt} \qquad \text{(Eq. 1)}$$

Where v = speed (m/s)
r = radius of curvature (m)
g = gravitational constant (m/s^2)
q = superelevation rate

This equation, for a final circular curve with a radius R and a clothoid length L, can be solved considering that the curvature $1/r$ increases linearly with the arc length (from ∞ for $s=0$ to $1/R$ for $s=L$); the superelevation q varies linearly with the arc length (from q_i for $s=0$ to q_f for $s=L$); the variation of the speed v can be estimated starting from the speed of the circular curve v_c, presuming a uniformly decelerated motion along the clothoid and considering the deceleration rate a (the experimental surveys proved that the speed v varies along the clothoid (Perco 2005)):

$$(L - s) = \frac{v^2 - {v_c}^2}{2a} \qquad \text{(Eq. 2)}$$

therefore, the rate of change in lateral acceleration c calculated from the Eq. 1 is:

$$c = \sqrt{(L-s) \cdot 2a + {v_c}^2} \cdot \frac{2a \cdot L - 4a \cdot s + {v_c}^2}{RL} - \sqrt{(L-s) \cdot 2a + {v_c}^2} \cdot g \cdot \frac{q_f - q_i}{L} \qquad \text{(Eq. 3)}$$

The rate of change in lateral acceleration c calculated with Eq. 3 varies along the clothoid because it depends on the arc length s and reaches the maximum value for s=0, therefore at the beginning of the steering action. Figure 1 shows an example of the variation of c along the clothoid calculated using a change in cross slope from 0.0% to 7.0%. The rate c varies significantly and it decreases almost linearly. The contribution of the superelevation is quite constant and small in respect of the total rate of change in lateral acceleration.

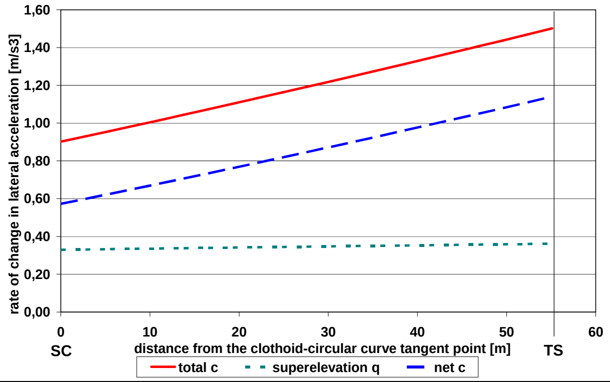

Figure 1 Rate of change in lateral acceleration *c* (*R* 118 m – *A* 100 m)

Using Eq. 3 and the experimental data (v_c; a; L) (Perco 2006), it is now possible to calculate the real maximum rate of change in lateral acceleration c_{max} accepted by drivers. The rate c_{max} thus obtained is not constant but shows a very good correlation with the operating speed and with the radius (figure 2). The correlation with the radius of curve is particularly useful because it makes it possible to shift the values of c_{max} in a comfort criterion consistent with the design speed of the Italian standard. In fact, this correlation can be used to calculate the length of the clothoid which, by using the design speed on curve and the deceleration rate of the Italian standard, ensures the rate c_{max} at the initial point (s=0) of the clothoid. This length, extended up to a radius of 964 m, is showed in figure 3. The Italian standard has a relationship between the curve radius and the design speed that is bijective up to a radius equal to 437 m (Vp equal to 100 km/h). Above this radius the relationship depends on the road category, therefore on the maximum design speed. To extend the relationship of figure 3 the road category with the maximum design speed (140 km/h) was considered. Hence, if the road category has a lower maximum design speed, the clothoid lengths of figure 3 corresponding to curve radii travelled at the maximum design speed ensure a rate of change in lateral acceleration at the initial point (s=0) smaller than the maximum limit c_{max} of figure 2.

It should be noted that the function in figure 3 has a linear form different in respect of that proposed by the original model (Perco 2006). This difference is due to the form of the relationship between the radius and the speed on curve. In fact, the original model uses an operating speed model instead of the Italian design speed and a deceleration rate model developed using experimental surveys instead of a constant rate of 0.8 m/s^2. The original model (Perco 2006) probably estimates better the distance travelled during the steering action, but on the whole it is not consistent with the Italian standard. Table 1 shows the length of clothoids derived from figure 3, the corresponding clothoid parameter A and the maximum rate c_{max}. The lengths proposed are very similar to the minimum lengths required by the Swiss (Norm SN 640-100a 1981) and German standards (RAS-L 1995).

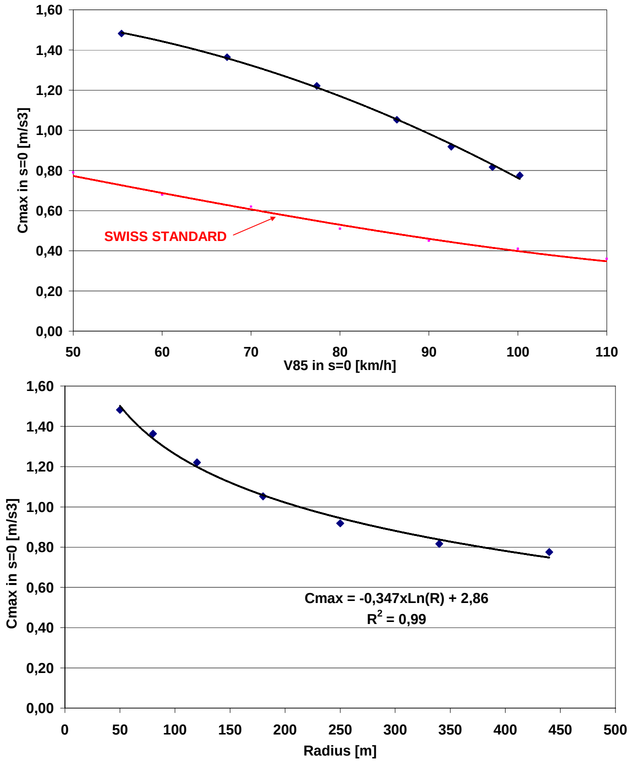

Figure 2 Maximum rate of change in lateral acceleration c_{max} versus $V85_{s=0}$ and R

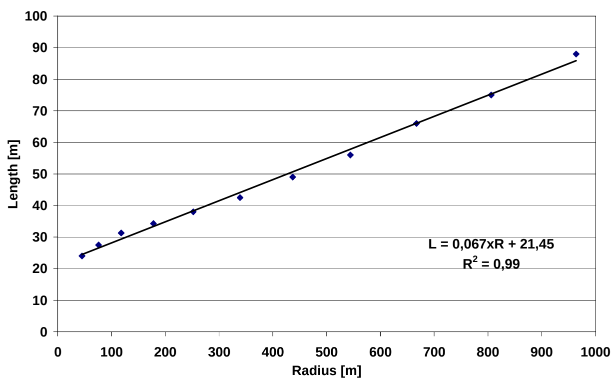

Figure 3 Clothoid length *L* to have c_{max} in s=0 versus curve radius *R*

Table 1 Clothoid length *L* corresponding to c_{max} in s=0

Vp	40	50	60	70	80	90	100	110	120	130	140
R	45	76	118	178	252	339	437	544	667	806	964
L	27.2	26.6	30.5	36.0	39.7	42.5	48.1	56.3	66.1	74.5	87.2
A	35	45	60	80	100	120	145	175	210	245	290
c_{max}	1.54	1.36	1.21	1.06	0.94	0.84	0.75	0.68	0.60	0.54	0.48

It should be noted that the clothoid lengths calculated by verifying c_{max} at the initial point with the maximum speed on the clothoid, also verify those particular cases that can be deduced from the design speed-profile, when the speed reaches the maximum value in another point of the clothoid (for example along a reverse curve). In conclusion, the clothoid lengths reported in table 1 ensure that these lengths are similar to the distance travelled during the steering action (evaluated using the design speed and the deceleration rate of the Italian standard) and that the maximum rate of change in lateral acceleration is consistent with the rate usually accepted by drivers.

5.2 Gradient Criterion

The Italian standard limits the minimum clothoid length to respect the maximum relative gradient Δi_{max} between the axis of rotation and the edge of the travelled way. On the contrary, it does not require that the minimum relative gradient (Δi_{min}) along the clothoid is respected. The introduction of this maximum limit for the clothoid length makes it possible not to attain the superelevation in two stages, therefore avoiding possible problems of curve perception and vehicle dynamic (14). The length L_{max} along which the gradient Δi is equal to Δi_{min} is showed in figure 4 ($q_i = 2.5\%$; $q_f = 7.0\%$). Each curve corresponds to a maximum design speed, therefore to one or more road categories.

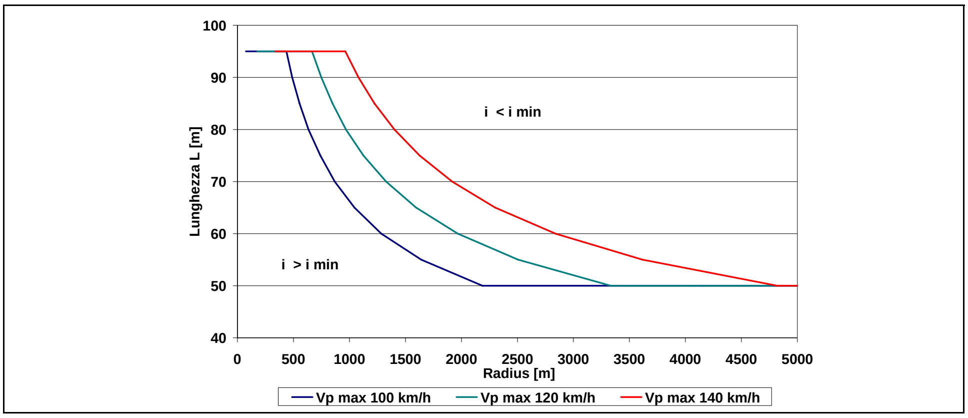

Figure 4 *L* corresponding to minimum relative gradient Δi_{min} versus curve radius

For each curve the length is constant until the radius is smaller than the radius R* (minimum radius for the maximum design speed) because the superelevation of the curve is constant (7.0 %). In the same way, the length is constant when the radius is higher than $R_{2.5}$ (minimum radius with a superelevation of 2.5%). To avoid the presence of three different limits, only the parameters corresponding to the maximum design speed of 100 km/h was selected for this update proposal. In fact, these parameters lead to the shorter lengths in respect of the parameters of the other maximum design speeds, therefore they also respect the minimum relative gradient Δi_{min} corresponding to the other maximum design speeds.

5.3 Roadway Appearance Criterion

The actual upper limit of the roadway appearance criterion (A = R) makes possible the use of a very long clothoid that may result in misleading impressions about the sharpness of the impending curve, in particular before sharp curves. To avoid this potentially negative effect, a limit of 1m for the offset between the tangent and the circular curve is proposed. This limit derives from literature reviews (it is recommended by the United States guideline (A Policy on Geometric Design of Highways and Streets 2001) to avoid the driver being misled about the sharpness of the impending curve and by the British standard (Road Geometry: Highway Link Design 1993) when the curve requires a speed reduction to be travelled safely) and ensures that the clothoid length is consistent with the distance at which the driver collects the visual information to plan the steering action (Land et al. 1994, Land et al. 1995). The clothoid parameters that correspond to this offset are shown in table 2. The actual minimum limit of the roadway appearance criterion (A=R/3), that leads to clothoid lengths similar to the comfort criterion, can be maintained.

Table 2 Clothoid parameters corresponding to the tangent offset of 1.0 m

Vp	40	50	60	70	80	90	100	110	120	130	140
R	45	76	118	178	252	339	437	544	667	806	964
A_{max}	40	55	80	105	140	175	210	250	290	335	380

5.4 Update proposal

The three criteria proposed define an area in the plan R-A shown in figure 5 inside which the choice of the clothoid parameter ensures the optimal operating condition for drivers, avoiding the use of clothoids that are too short, and above all, clothoids that are too long and therefore potentially dangerous. This area is bounded on the bottom by the comfort criterion and by the roadway appearance criterion, whereas it is bounded on the top by the roadway appearance criterion and by the gradient criterion. The curve of the gradient criterion and the curve of the roadway appearance criterion intersect at a radius R_{int} equal to about 700 m. Above the radius R_{int} the gradient criterion leads to short clothoids with a very small tangent offset (0.20 m for R=964 m).

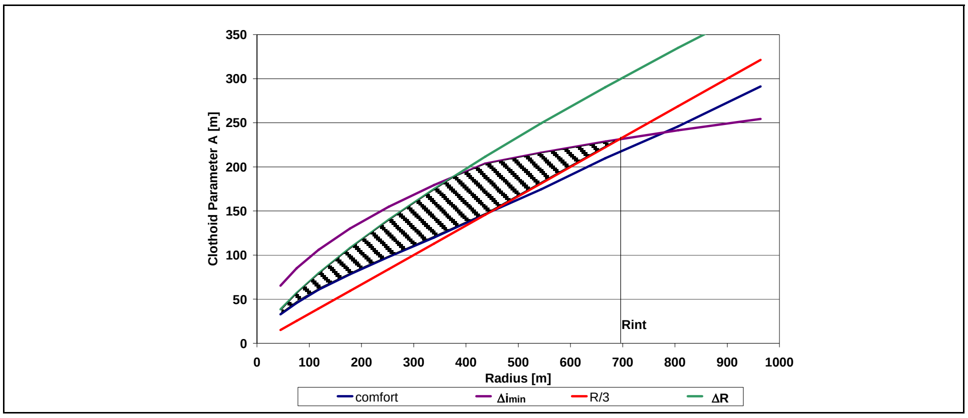

Figure 5 Clothoid parameter *A* versus curve radius *R*

However, for radii above R_{int} the clothoid is used principally for aesthetic reasons because these curves do not usually require considerable speed reductions to be travelled safely. Therefore, it seems to be reasonable to propose that for radii above the R_{int} the clothoid length should be chosen considering the roadway appearance criterion (R/3), even though this leads to attaining the rotation of the roadway in two stages. The final proposal to update the Italian standard is presented in table 3 which is derived from figure 5. The use of a single table that immediately shows the minimum and maximum clothoid parameters allowed ensures greater simplicity of use in respect of the actual criteria. To evaluate the parameter for a radius not present in the table it is possible to interpolate it between the parameters of the two adjacent radii.

Table 3 Final update proposal

R	45	76	118	178	252	339	437	544	667	806	964
A_{min}	35	45	60	80	100	120	145	180	220	270	320
A_{max}	40	55	80	105	140	175	205	215	230	270	320

Finally, the foreign standard recommend a limiting radius above which the use of the clothoid is not necessary. These limits present significant differences between the standards because actually it is not clear what the value of the radius is above which the clothoid is not necessary. If the clothoid is used only for comfort reasons this limit is probably quite low because with large radii the steering time is extremely small, but if the clothoid is used also for aesthetic reasons this limit can significantly increase. A proposal that is consistent with the present Italian standard could be the minimum radius without superelevation. However, this argument needs to be further studied with regard to the effect of the presence of clothoids that precede wide curves on driver visual perception and on his driving task.

6. CONCLUSION

The influence of the clothoid length on the driver's curve perception was recently highlighted. In particular, the presence of long clothoids may lead the driver to a misleading perception about the sharpness of the impending curve. Many foreign standards take into account this possible negative effect by limiting the clothoid length before sharp and medium curves. Moreover, many standards also recognize the inopportunity of attaining the rotation of the roadway in two stages when the relative gradient between the axis of rotation and the edge of the pavement is too low; these standards advise, instead, shortening the clothoid. The Italian standard uses three traditional criteria to calculate the clothoid length that are not revised in light of these considerations. Therefore, this study proposes an update of these criteria based on recent research results. The three different criteria are substituted only by one simple table that shows the minimum and maximum clothoid parameters allowed in function of the curve radius. The choice of the clothoid parameter inside the range proposed, ensures that the length of the clothoid selected corresponds to the optimal operating conditions for drivers.

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