EFFECTS OF TRANSITION CURVES ON SIGHT DISTANCES

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ABSTRACT

This paper presents an ongoing study on the effects of introducing transition curves into an existing road alignment on safety in terms of sight distances and design consistency conditions. Transition curves were firstly adopted in geometric design of railways in order to introduce circular curve naturally and the centrifugal force associated with it gradually in the alignment of transition sections. Later, they were also employed in geometric design of rural roads. In many Countries road geometric standards recommend their use to improve safe conditions.

The main objective of the reported study was to evaluate the effect of transition curves on the respect of sight distances and design consistency conditions of a rural road with a high number of car accidents.

Existing horizontal alignment of a rural road, with "tangent-to-curve" transition, was analyzed. Sight distances were calculated and verified with the imposed values by standards. Also speed gradients between contiguous elements were analyzed. A new alignment with transition curves and limited works out of the existing infrastructure, to keep the two alignments still comparable, was proposed. Then sight distances and speed variability along the proposed alignment were calculated and verified with the values imposed by the standards.

The results obtained revealed that the introduction of transition curves reduces the percentage of verified sight distances along the horizontal alignment. However, different conclusions were obtained analysing the effectiveness of transition curves using design consistency criteria: the new alignment with transition curves have shown a more acceptable speed variation between contiguous elements.

INTRODUCTION

The design of a road infrastructure is mainly divided in the study of the axis and the cross section of the road. The horizontal alignment is composed of straight parts and curves that form a continuous line, which in optimal conditions, should give the user a justified and reasoned sequence of elements responding to a precise logic easy to understand (1). Such a path ensures the safety and comfort of driving.

Road safety actually is a very important problem worldwide because of social and economic implications it involves. It depends on uncontrollable several factors such as road, vehicle, human behavior, environment, and their interactions.

A correct design of the road alignment is the first step toward a safety infrastructure. Road geometric design carries out a critical role in assuring drivers' safety. Being able to assess, in a best possible way, how horizontal and vertical alignment could affect road user safety and comfort is a key element in the process of defining design standards (2).

One technique used to improve safety on roadways is to examine the consistency of the design. According to Wooldridge et al. (3) design consistency is the conformance of a highway's geometric and operational features with driver expectancy and it is assessed by consistency checklists, speed consistency measures or driver workload measures. Speed consistency measures is the oldest of the approaches used in evaluating design consistency: in thirties Barnett (4) developed the concept of design speed to ensure consistency. The goal of this criteria is to promote uniform vehicular speed along the highway reducing speed variability between adjacent geometric elements of the alignment.

Road should send right information along its total length in order to guarantee users' expectancies of traveling safely with a low mental workload, since driving is a complex process of acquiring and processing information and making decision (5).

Every geometric element of the alignment should be recognized by driver and should assure sight distances, so that it can influence users' behavior in choosing the right speed and in making braking and overtaking manoeuvre in safety conditions.

Italian Standard requires that horizontal alignment is made of straights, circular curves and transition curves. The latter were initially adopted in geometric design of railways to introduce the circular curve naturally and the centrifugal force associated with the curve gradually in the alignment of transition sections. Later, they were also employed in geometric design of rural roads. Road geometric standards recommend their use to guarantee a gradual increase in the centrifugal force, a convenient superelevation transition section, constant speed of steering and, a good perception of horizontal alignment of road (6).

In the last twenty years the transition curves have been object of several studies to determine if their presence increase road safety or not. Results are in contradiction: some authors argue that clothoid give a significant contribution to safety, meanwhile others affirm the contrary. The reviewed studies relate mainly two lanes rural road. They concern three main aspects: accident, vehicle dynamics and user behavior in the transition zone (7).

Zegeer (8) shows a reduction of about 5% of accidents on curves with clothoid. Council (9) comes to the conclusion that the presence of the clothoid reduces accidents only in curves with a radius less than 600 m and placed in tracks located on flat land. Lamm (10) concludes that the presence of the clothoid can have a positive effect on security only for curves with a radius less than 200 meters and it should not be used for radii greater than 800 m and a speed above 105 km/h. Tom (11) asserts that clothoid does not influence accident in curves with radii less than 170 m, meanwhile for radii comprised between 170 and 350 m leads to an increase in the accident rate of 65%; for radii greater than 350 m, the increase appears to be as much as 136%. Stewart (12) also assesses the accident on some curves, before and after adjustments along the alignment. He finds that elimination of clothoids leads a reduction of accidents of 80%.

Bonnenson (13) calculates lateral acceleration along the transition zone in the two cases with and without clothoid finding that clothoid reduces the peak lateral acceleration minimizing speed and lateral displacements. The minimum of transversal acceleration peak is obtained for values of clothoid length that correspond to the time of steering.

Concerning user behavior in the transition zone, Donges (14) and Godthelp (15) argue that without clothoid, the driver starts to steer along straight and ends after the point of tangency with the curve; also they find that the steering angle varies linearly in time. This happen if driver recognizes discontinuity point of curvature. Clothoid denies the driver this reference and so he applies the "stabilization level" of steering task, driving by means of real time information collected from the moving vehicle.

Perco (6) describes the effect of a clothoid length on the driver's curve perception and safety. Long spiral curve influences driver's curve perception and leads the user to correct speed and path. A model to predict the desirable spiral length was developed on the basis of data collected in three studies on two lane rural roads. The model gives a good description of real driver behavior, starting from the radius of the impending curve. In an another work Marchionna and Perco (16) propose an update of the three criteria which Italian Standards uses to calculate the clothoid length. They find a minimum and a maximum values of spiral parameters in function of the curve radius. Choosing a parameter value within this range, good operating conditions for drivers are assured, problems of curvature perception are avoided and an increased road safety is obtained.

Blue (17) and Harvood (18) use the driving simulator to study the lateral acceleration along spiral curves. They come to the conclusion that the presence of clothoid leads to a more gradual variation and comfortable lateral acceleration and roll angle for heavy vehicles that could reduce the number of accident due to overturning in curve.

Zakowska (19) analyses clothoid effect on driving behavior by a driver simulator. She notices that curves without clothoids are driven at lower speed than the same curves with clothoids and this effect is stronger at curves with larger radii and increases with the road category. All that can be explained by a better perception of the curve by the user when it is preceded by a clothoid so that he adopts higher speed without significant deceleration before the curve. But, the author affirm, the strongest effects of clothoid presence consists in a decrease of the "Pathologic Discomfort" and "Dispersion of Trajectories" two indicators presented by Zakowska and Benedetto et al. (20) (21) (22). These results support the current design rules of the road that prescribe transition curves for all the curves of new road projects.

OBJECTIVES AND AIMS

The objective of this study is to evaluate the effect of introducing transition curves into an existing road alignment on safety in terms of sight distances and speed consistency.

In a previous work Maltinti (23) presented a study conducted on the S.S. n°292, a two lane rural road located in Sardinia (Italy), with great problem of visibility. The analysis of the existing road alignment suggested two different solutions to improve visual distances. Both were chosen to limit works out of the existing infrastructure because of the sensitivity of its surroundings. The first one contemplated insertion of regular curves and variable radius curves, the second one insertion of regular curves and variable radius curves, widening of shoulders and the insertion of a straight stretch in the most critical tract. The results of the analysis showed that the only insertion of regular curves and clothoids did not guarantee sight distances as Italian Standards prescribes. Thus this paper presents another case study to evaluate the effect of transition curves on sight distances and speed consistency.

Actual horizontal alignment of a rural road located in Sardinia, with "tangent-to-curve" transition, was analyzed. Sight distances were calculated and checked with distance of unobstructed view. Related speed diagram was constructed. Then a new design of the road alignment was proposed inserting transition curves and calculating the new sight distances and the new speed diagram. The new horizontal alignment was designed limiting works out of the existing infrastructure to compare the results in terms of percentage of sight distance verified along the horizontal alignment and of speed variability between contiguous geometrical elements.

SIGHT DISTANCES

Motor vehicles are not confined to a prescribed path as the train on the railroad where a trained operator has to follow block signal system to drive in a safe way. Differently, on highways and streets the choice of path and speed of vehicles are controlled by drivers whose ability, training and experience are quite different. Therefore the road designer should provide sight distance of sufficient length to allow drivers to stop their vehicle in safe condition in presence of an unexpected object in the traveled way. Furthermore on two lane highways sufficient sight distance to enable drivers to occupy the opposing traffic lane for safe overtaking should be guarantee. So, generally, traffic safety and quality of traffic require certain minimum sight distances for stopping in time or for safe overtaking (24).

According to Italian Decree about "Functional and Geometric Design Standards for Road Design" (25), sight distances along a road alignment are verified in terms of the distance of unobstructed view (Duv), which is defined as the length of the road stretch that the driver can see ahead regardless of traffic, weather and lighting conditions. Duv is calculated along the road alignment as the difference between curvilinear abscissas of the object to be seen (Po) and the point of view (Pv) when line sight which connects Pv and Po encounters an obstacle (see Figure 1)

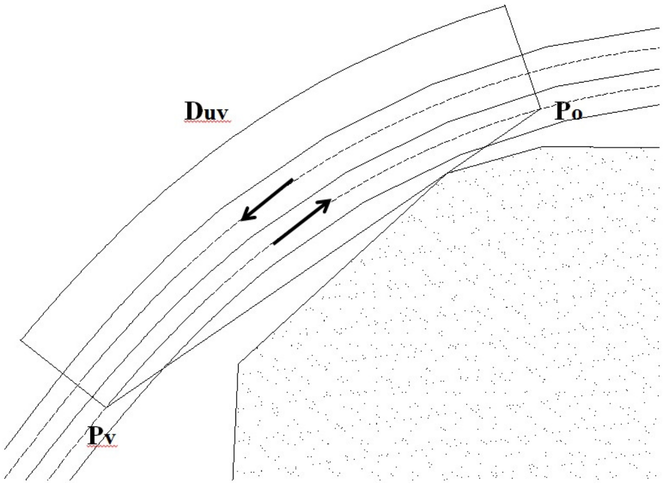

FIGURE 1 Estimation of the distance of unobstructed view for stopping sight distance

Visibility conditions are satisfied, whenever the distance of unobstructed view is equal or higher than the stopping sight distance, minimum distance necessary to safely stop a vehicle in front of an unexpected obstacle, and the passing sight distance, the length of road stretch necessary to safely complete a passing maneuver (25).

The stopping sight distance has to be verified at every point along the alignment. Meanwhile, the passing sight distance should be present for a sufficient portion of two lane roads. The length of path where passing sight distance is assured influences the functionality of a two lane rural road in terms of service level, whenever overtaking is not admissible, platoons arise and the level of service of the road decays. As standard value, for average conditions, at least 20-25% of the observed roadway section should guarantee passing maneuvers, however a distribution of section with passing possibilities should be as uniform as possible (10).

Italian Decree (25) provide also the changing lane sight distance which is the length of road stretch necessary to change lanes in deviation manoeuvre in correspondence of particular point like intersections, exits and so on. It should be guaranteed along roads which have more than one lane for each traffic direction or in correspondence of a special point (intersections, turnings, etc.).

Stopping sight distance (D_a), passing sight distance (D_s) and changing lane sight distance (D_c) are respectively expressed by, (25)

$$D_a = D_1 + D_2 = \frac{V_0}{3,6}\cdot\tau - \frac{1}{3,6^2}\cdot\int_{v_0}^{v_1}\frac{V}{g\cdot\left[f_l(V)\pm\frac{i\%}{100}\right]+r_0(V)+\frac{R_a(V)}{1000\cdot P}}\cdot dV \qquad [\text{m}] \qquad (1)$$

$$Ds = 5,5\cdot V \qquad [\text{m}] \qquad (2)$$

$$Dc = 2,6\cdot V \qquad [\text{m}] \qquad (3)$$

where:

- D_1: distance covered in τ time (perception-reaction distance) [m]
- D_2: braking distance [m]
- V_0: vehicle speed at the beginning of braking manoeuvre [km/h]
- V_1: vehicle speed at the end of manoeuvre (V=0 [km/h])
- i: grade of the road [%]
- τ: brake reaction time [s] expressed by: $\tau = 2,8 - 0,01V$
- g: acceleration of gravity [m/s^2]
- R_a: aerodynamic strength [N]
- M: vehicle mass [kg]
- f_l: longitudinal adherence coefficient
- r_0: unit rolling strength [N/kg].
- V: design speed of the vehicle (deduced from speed diagram) [km/h]

Harwood et al. (26) conducted a review of the stopping sight distance criteria used in Australia, Britain, Canada, France, Germany, Greece, South Africa, Sweden, Switzerland and United States and they found that most countries' stopping sight distance criteria are based on the same model. Stopping sight distance is generally defined as the sum of two components: perception-reaction distance and braking deceleration distance. Also Italian Standards adopts this model. Two different criteria are used to define passing sight distance: geometric criteria, used in design, and marking criteria, used to define the beginnings and the ends of the no-passing barrier lines that are marked on the roadway. In this study geometric criteria was considered, since it assures that highway in project will operate efficiently. Parameters used in models to determine stopping and passing sight distance vary depending to the assumption made by different countries. The graphs reported in Figure 2 show a comparison of minimum required stopping sight distance for level terrain and passing sight distance adopted in different countries. They reveal that sight distances values calculated according to Italian Rules are largely lower than those required by other countries.

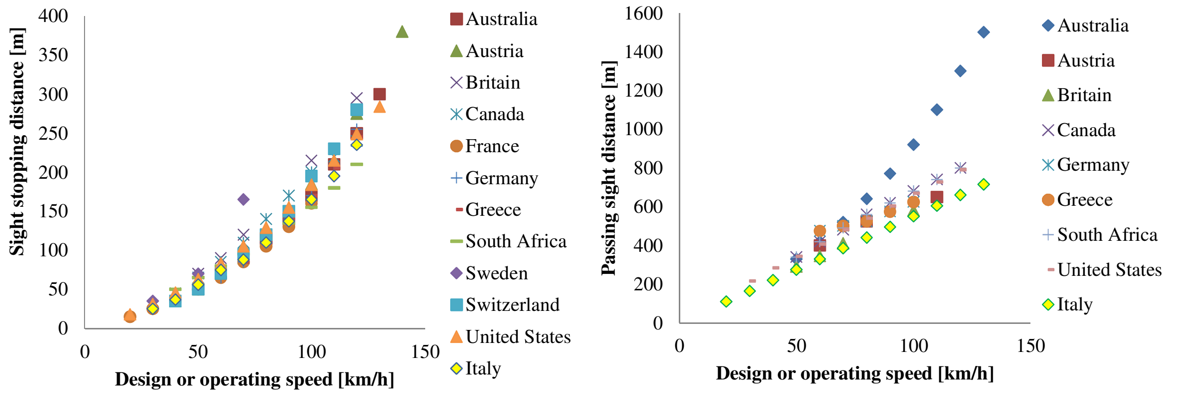

FIGURE 2 Comparison of required stopping and passing sight distance in different countries

CASE STUDY: EXISTING TWO LANE RURAL ROAD

Actual alignment

The object of this study is to evaluate the opportunity of introducing transition curves along the existing alignment of the state road SS n. 387, a two lane rural road, which connects Cagliari, the most important town in Sardinia (Italy), with the internal area of the region called Sarrabus Gerrei to improve road safety condition. The total length of the road is about 90 km. The analysed segment is 13 km long and its horizontal actual alignment was reconstructed employing a cad software.

FIGURE 3 Localization of the case study, the SS n.387

The actual alignment is composed by a succession of 47 straight parts and 46 circular curves without transition curves. Most of the curves presents radii measures higher than 45 m which is the minimum for a two lane rural road type F2 (the lowest type of rural road for Italian Standard), whereas they are less than the value calculated with the optical criterion that takes into account human-road system and it is suggested by different authors (1), (27), (28) and is expressed by the following equation:

$$R_o = \frac{l_0}{sen 2\varphi} \tag{4}$$

where:

R_o: optical radius
l_0: distance of optical arrangement, depends on speed [m]
2φ: field of peripheral vision, depends on speed.

The percentage of radii which do not respect the optical radius is about 89%. This high percentage of curves with low values of radius influences negatively travel speed and road safety conditions in terms of sight distances.

To analyse the actual alignment, stopping and passing sight distances were calculated for the two ways and considering observer's height at 1,10 m and obstacle height at 0,10 for the first one and at 1,10 m for the second one, as prescribed by the Italian Standards. In the alignment analysis also lateral safety barriers were considered as fixed obstacles. During the analysis it was found that on right curves, sight is obstructed by safety barriers, slope of cutting or containing wall; on left curves, it is mostly obstructed by the safety barriers. In Figure 4 diagrams of stopping and passing sight distances of existing alignment are represented.

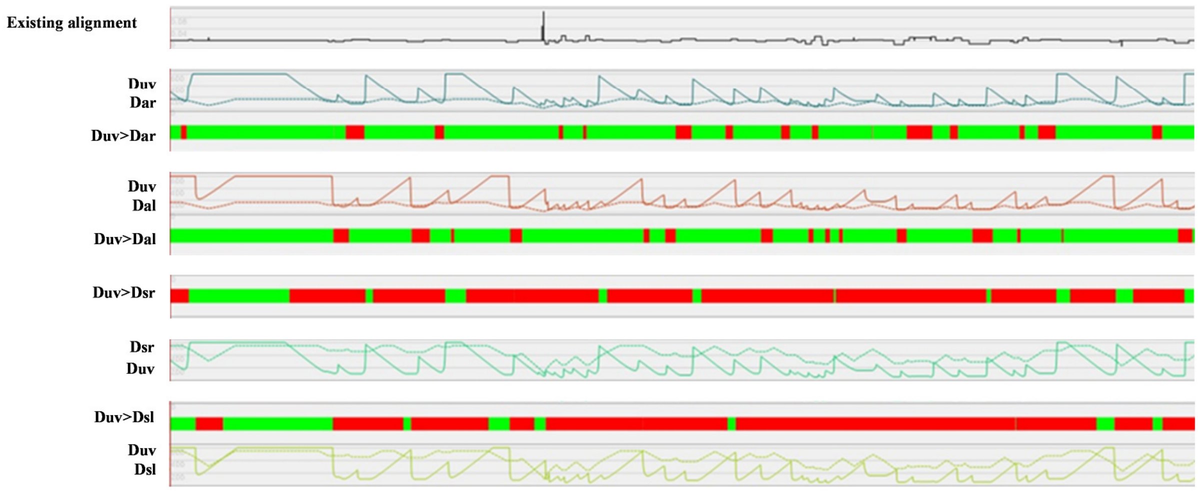

FIGURE 4 Sight distances diagrams of the existing alignment

The analysis conducted on the right and left ways of existing alignment have highlight the verification of the stopping sight distance for about 86% in the two ways, of the total road length investigated, as reported in Figure 5. These graphs show that the actual alignment of SS n°387 doesn't respect safe conditions imposed by Standards, since they prescribes that the stopping sight distance must be verified along all the road.

The passing sight is verified only for the 21% and 19%, respectively in the left and in the right way, of the total road length investigated, as reported in Figure 5.

Moreover, the passing sight distance is assured along the first stretch of the examined road, thus this percentage is not opportunely spread on the alignment, as shown in Figure 4.

According with the results obtained, geometrical characteristics of the current alignment of SS n°387 are above the safety standards which prescribes that the stopping sight distance has to be verified at every point along the alignment, meanwhile the passing sight distance should be present for about 20-25% of the alignment of two lane roads.

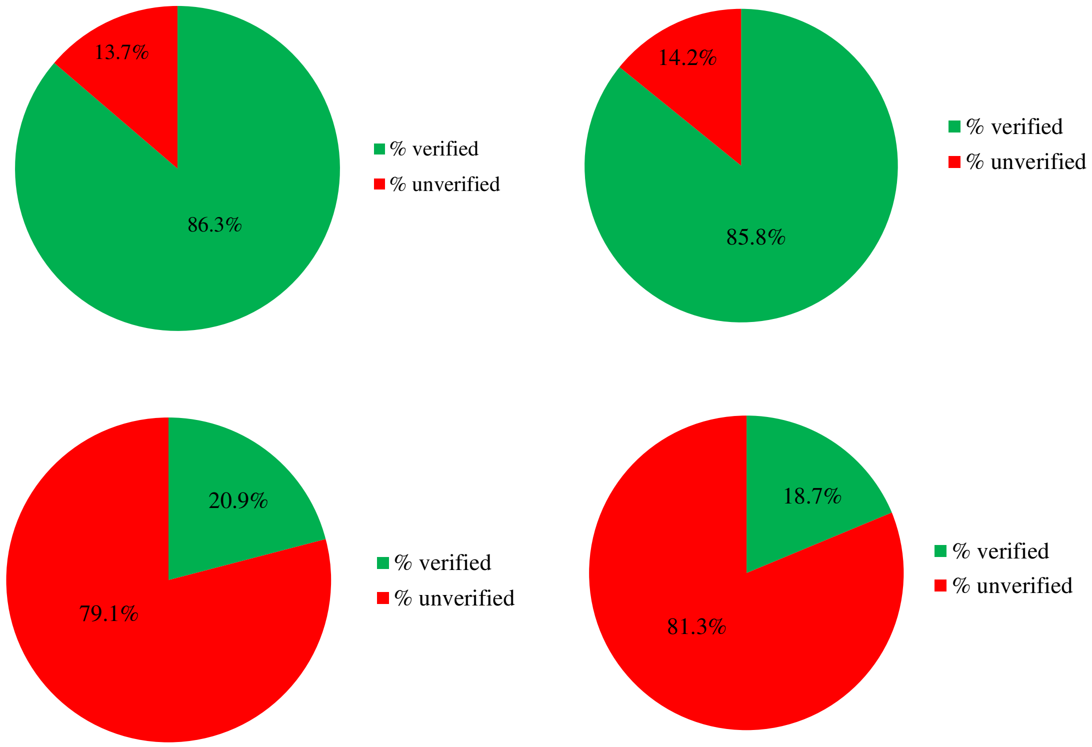

FIGURA 5 Existing Alignment: a) Percentage of stopping sight distance on left and right way(top).b) Percentage of passing sight distance on left and right way (bottom)

Revision of the existing alignment inserting clothoids

Once completed the analysis of sight distance on the existing alignment, a new alignment was designed inserting clothoids and replacing some curves radii which did not verify the minimum radius value.

Stopping sight and passing sight distances were calculated on the new alignment with the same criteria used for the existing alignment.

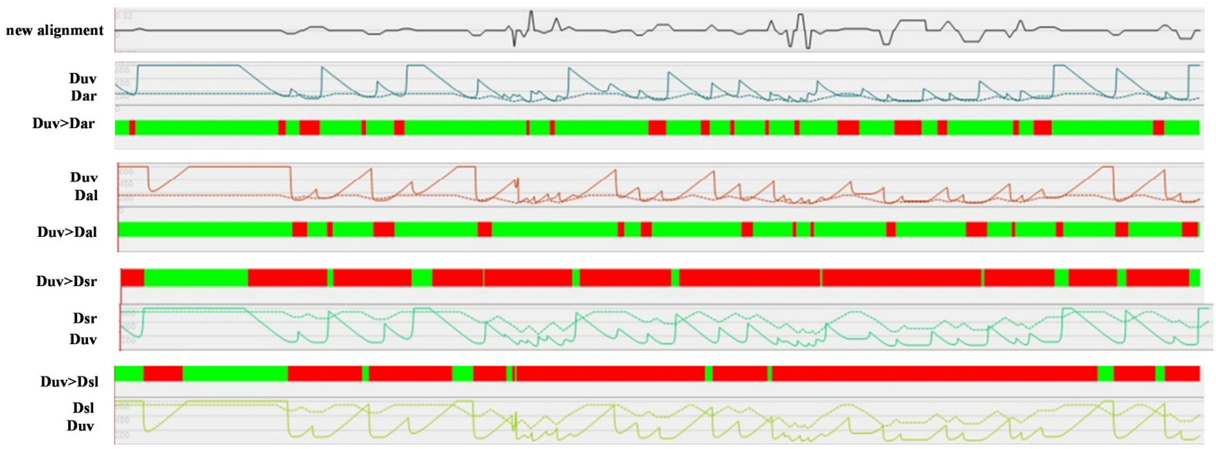

FIGURE 6 Sight distances diagram of the revised alignment

On the diagrams reported in Figure 6 the distribution of verified and no of stopping and passing sight distances along the designed alignment are shown.

According to the results obtained with the analysis conducted on the new horizontal alignment the conditions of visibility, are worse than the existing configuration. The stopping sight distance is verified approximately for the 84% of the total length on the left way, and 81% on the right way. The percentage of verified passing sight distance goes from about 21% in the existing alignment to 19% in the new alignment on the left way, and from 19% to 18% on the right way (see Figure 7).

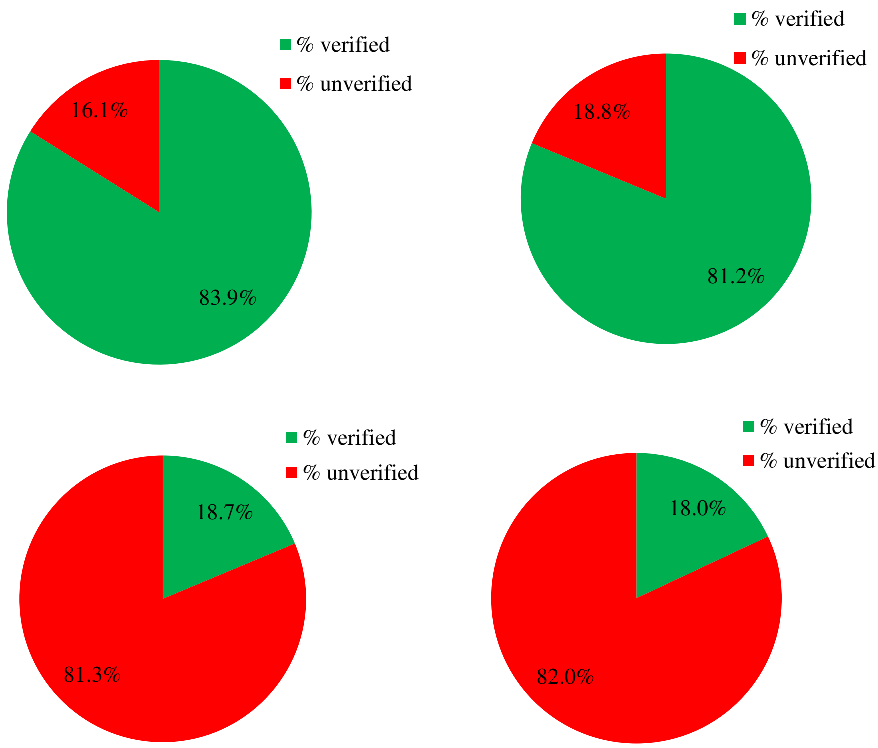

FIGURE 7 Proposed alignment: a) Percentage of stopping sight distance on left and right way (top). b) Passing sight distance on left and right way (bottom).

ANALYSIS AND DISCUSSION

The results obtained revealed that presence of transition curves doesn't increase the percentage of verified sight distances along the horizontal alignment, confirming the results obtained by Maltinti (23) in another case study. In particular, in the two studies it was highlighted that the presence of clothoids reduces percentage of verified sight distances along the alignment.

The geometric characteristics of both alignments of SS n°387 are not homogeneous; consequently, as shown on the results obtained, the verification of sight distances is also unevenly distributed.

The existing alignment presents a percentage of verified sight distances about 20% which is the minimum threshold required by Standards. Moreover, according to the good practices, if the 20-25% of passing possibilities is not uniform along the alignment (10) it could be not enough, thus a further investigation was conducted to evaluate this uniformity along the entire alignment.

Further analysis have shown that along the first half of the existing alignment the percent of verified sight distances is equal to 17% of the total alignment on the left way, and to 13% on the right way. Along the second half, driver can overtake only in very short and spotted stretches in the two directions. The irregular distribution of sight distances along the analyzed alignment is such that half of the analyzed alignments do not meet the requirements of Standards.

In the proposed alignment with clothoids sight distances are guaranteed along the first half for the 15% of the considered length on the left way, and for the 13% on the right way. Along the second half in the two directions respectively is less than 3-5%. Also in the alignment with clothoids passing possibilities is not uniform besides be insufficient.

The analysis conducted in this study was based on sight distances values calculated according to Italian Standard criteria which are less severe than all the other exanimated, consequently the visibility distances of the analyzed alignments a fortiori are not verified for other countries.

Furthermore speed variability between adjacent elements of the existing alignment and the new one were analysed and compared to highlight if the presence of clothoids increase speed consistency and so safety conditions and comfort for drivers. Italian Standard introduces the diagram of design speed as a tool for examining speed variability. It shows the design speed of each elements of the alignment as a function of progressives. Italian Standard imposes limitations on speed difference between speeds of adjacent elements. Through the diagram it is possible to verify if speed gradients comply or not with those limits. For the type of road studied, between two curves speed difference must not exceed 20 km/h or, preferably, 15 km/h; while between an element characterized by the maximum speed and a curve, speed difference must be lower than 10 km/h. The speed diagrams of the two alignments, reported in Figure 8, show that the presence of the clothoid ensures greater speed consistency: on the new alignment design consistency conditions are verified for 58% of the alignment, whereas for 55% on the existing alignment.

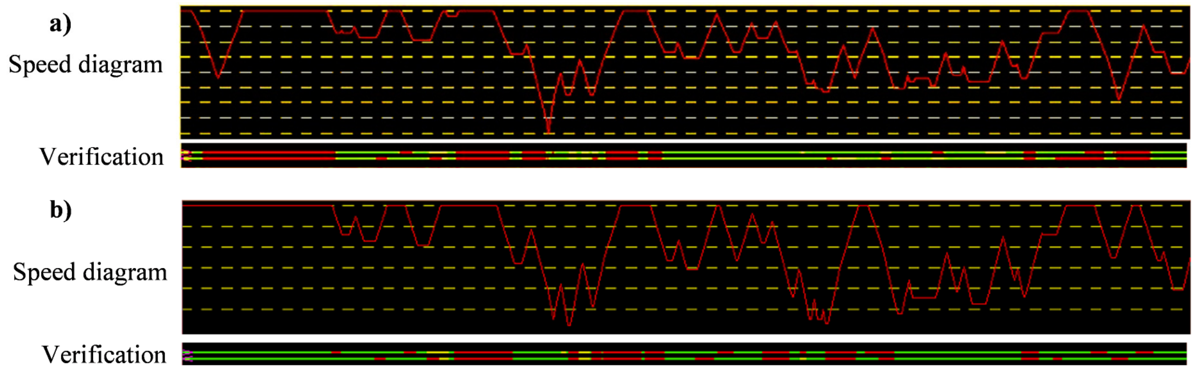

FIGURE 8: a)Speed diagram in the existing alignment and b) Speed diagram in the new alignment

CONCLUSIONS

This paper presents a study on the effects of introducing transition curves into an existing road alignment on safety in terms of sight distances and design consistency conditions. In many Countries road geometric standards recommend the use of clothoids to improve safe conditions. In the last twenty years the transition curves have been object of several studies to determine if their presence increases road safety or not. Results are in contradiction: some authors argue that clothoid give a significant contribution to safety, meanwhile others affirm the contrary. So the objective of this study was to evaluate the effect of introducing transition curves into an existing road alignment on sight distances and speed consistency.

Actual horizontal alignment of the state road SS n. 387, a two lane rural road, located in Sardinia, with “tangent-to-curve” transition, was analyzed. Sight distances were calculated and checked with distance of unobstructed view. Related speed diagram was constructed. Then a new design of the road alignment was proposed inserting transition curves and calculating the new sight distances and the new speed diagram. The results were compared in terms of percentage of sight distance verified along the horizontal alignment and of speed variability between geometrical elements.

The results obtained revealed that presence of transition curves doesn’t increase the percentage of verified sight distances along the horizontal alignment. In particular, it was highlighted that the presence of clothoids reduces percentage of verified sight distances along the alignment. The geometric characteristics of both alignments are not homogeneous; consequently, as shown on the results obtained, the verification of sight distances is also unevenly distributed.

However different conclusions were obtained analysing the effectiveness of transition curves using design consistency criteria: the presence of the clothoid ensures greater speed consistency in terms of more limited speed variations between contiguous elements.

Further studies are needed to decide on the proper use of transition curves in order to design road alignments ensuring both comfort and safety driving conditions. Moreover, future researches will focus on the influence of other factors such as the length, and therefore the clothoid parameter on sight distances and consistency.

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