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EVALUATION OF 3D COORDINATION TO MAXIMIZE AVAILABLE STOPPING SIGHT DISTANCE IN TWO-LANE RURAL HIGHWAYS

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Abstract. Sight distance is one of the most important factors of road safety since it allows the driver perceiving, at real time, road characteristics and its surroundings. A misperception of this crucial information could induce a decision to drive with a manoeuvre with less margin of safety. A finite element based software application was developed in Matlab to calculate the sight distance profile at vertical crest curves overlapped with horizontal curves. It was observed that the layout visibility gets principally lost where the superelevation changes its sign; thus, the vertical curve midpoint does not present the highest available sight distance, contrary to the bidimensional analysis. Later, available stopping sight distance was maximized considering different geometric parameters combinations. Stopping sight distance depended mainly on the ratio between the vertical crest curve parameter and horizontal radius, rather than the vertical crest curve parameter. Moreover, values of vertical crest curve parameter lower than the minimal values established in the Spanish design guidelines satisfied the required stopping distance. The offset between horizontal and vertical vertices slightly affects the results; however, the effect of the approach grade is important even if algebraic difference of vertical grades is kept fixed.

Keywords: alignment, alignment coordination, *3D* sight distance, stopping sight distance, available stopping sight distance, cross section design.

1. Introduction

Geometric design has a profound effect on safety. Road safety depends on several factors; available sight distance is considered as one of the most important. Sight distance allows drivers perceiving with enough anticipation road characteristics and its surroundings. A misperception of this crucial information could induce a decision to drive with a manoeuvre with less margin of safety.

2D and *3D* methods are used to calculate available sight distance (Chen *et al.* 2011). Current standards and guidelines are based on *2D* analysis, although several researchers have expanded it to *3D* highway analysis. By comparing *2D* and *3D* methods, *2D* design may underestimate or overestimate available sight distance (Hassan *et al.* 1997). *3D* methods are more accurate on sight distance evaluation despite the difficulty on their development. Graphical (Sanchez 1994), finite element (Castro *et al.* 2014; García, Romero 2007; Hassan *et al.* 1996; Hassan, Easa 1998; Ibrahim *et al.* 2012; Jha *et al.* 2011; Romero, Garcia 2007; Yan *et al.* 2008) and analytical (García 2004; Ismail, Sayed 2007; Lovell *et al.* 2001; Kim, Lovell 2010; Sarhan, Hassan 2008, 2011) approaches were studied by others. However, only the finite element methods were applied to optimize available sight distance (Romero, García 2007).

Available sight distance depends on road's geometry. Current design practice leads to frequent overlapping of vertical and horizontal curves because of their better adaptation to the terrain what is able to minimize both total amount of earthworks and environmental impacts. On the other hand, coordination of both horizontal and vertical alignments enhances safety, operation and appearance (Hassan, Easa 1998). Furthermore, a poor coordination generates zones with less available sight distance than required (Hassan, Easa 2000).

Up to now, general coordination criteria are given. Design guidelines, such as the American: *A Policy on Geometric Design of Highways and Streets* (2011) or Spanish: *Norma 3.1 IC* (1999), specify that both horizontal and vertical alignments should not be designed independently. The Green Book stipulates that vertical transition curve must be completely contained in the horizontal curve. Moreover, the Spanish design guideline *Norma 3.1 IC* specifies that a vertical crest curve must be fully contained in a horizontal curve including spirals; and that a crest curve should be

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separated from the adjacent horizontal tangent segments as much as practical. Sight distance profiles of vertical curves were analysed (Hassan 2003; Taiganidis 1998). Nevertheless, the design was based on 2*D* stopping sight distance calculation. Hassan and Easa (1998) studied locations where a horizontal curve should not start in relation to a vertical curve; which were defined as red zones. The range of red zones decreased with the increase of the superelevation rate of the horizontal curve and with the use of flatter crest curves. However, optimal offset between horizontal and vertical vertices was not studied and only 2*D* methods were applied.

Another coordination criterion is the ratio between the crest curve parameter and the horizontal curve radius $\left(\frac{Kv}{R}\right)$. Spanish design guideline *Norma 3.1 IC* recommends this ratio to be the inverse of the superelevation rate on the superimposed circular curve (%) to avoid optical effects. This criterion should be applied to two-lane roads where possible; or be at least equal to 0.06. Garcia (2004) used an analytical approach to determine the optimal $\frac{Kv}{R}$. An assumption was made of a road section composed by a vertical crest curve overlapped with a horizontal curve inscribed into the superelevation plane. Consequently, the whole curve is completely visible even though the *2D* analysis shows hidden zones. The optimal $\frac{Kv}{R}$ was within the interval [0.11, 0.212]. Later, an optimization software application was also developed to maximize available sight distance using genetic algorithms (Romero, García 2007). The optimal $\frac{Kv}{R}$ was between 0.055 and 0.168. The same authors concluded that values of *Kv* lower than the recommended ones achieved a suitable available sight distance when good alignment coordination was performed.

2. Research approach

The main objective of the research was to maximize Available Stopping Sight Distance (ASSD) at vertical crest curves overlapped with horizontal curves in two-lane roads. The experimental design involved the development of a 3*D* sight distance calculation method to determinate available sight distance within a curve. The methodology to calculate 3*D* sight distance in Matlab was developed in four main stages:

1) obtain the 3D road surface;
2) calculate the 3D sight distance;
3) deduce the available sight distance profile;
4) obtain the minimum available sight distance along the curve.

The methodology was applied to different scenarios. The variation of the following parameters was considered:

a) horizontal curve: radius; deflection angle; parameter of the spirals; and superelevation rate;
b) vertical curve: approach and exit grades and transition curve parameter;
c) horizontal and vertical alignment coordination: the offset between the horizontal and vertical vertices;
d) cross section: lane width and shoulder width;
e) driver point of view position: lateral distance to the right edge of the corresponding lane and its height;
f) position of the obstacle: lateral distance to the right edge of the corresponding lane and its height;
g) turning direction.

A total of 665.280 geometries were analysed by varying those parameters.

2.1. 3*D* Road surface idealization

The first step of 3*D* sight distance calculation was to obtain the grid that represents road surface. Four-node rectangular elements were used on the finite-element model. The initial step of the algorithm was to parameterize all horizontal features relative to the centreline; and vertical alignment was similarly parameterized. Entry data allow the algorithm calculating the coordinates of each node of a cross section from the centreline, and distance between cross sections could be controlled by users. By indexing all features to the centreline, it was possible to model the most generic horizontal or vertical geometry.

One example of the road is modelled in Fig. 1. The example consists of one vertical crest curve superimposed on one horizontal curve.

2.2. 3*D* sight distance

Sight distance was calculated by an iterative methodology based on a checking location loop. A driver was located in a cross section and an object was settled at a changing distance *S* ahead of driver's position. Then, the sightline between the driver and the object was checked to be obstructed by any road surface element. This loop continued until the object was not visible or was located further than road segment. Thus, in this study, the basic iteration process was the following:

– Step 1: initialize *S* (at first object location).
– Step 2: update *S* ($S = S + \Delta S$).
– Step 3: settle an object at a distance of *S* ahead of the driver's position with height *H* over road surface.
– Step 4: check if there is an element obstructing a driver's sightline to the object.
– Step 5: if the sightline is not obstructed by any element, repeat steps 2–4.

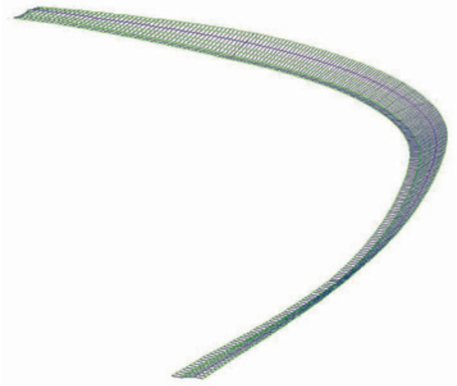

Fig. 1. Representation of the road in the model

– Step 6: if the sightline is obstructed by any element, available sight distance becomes ($S - \Delta S$) and the iteration process is completed.

In order to optimize the computation procedure, the first object was located where the sightline between the driver and the object with height H was tangent to the vertical crest curve projection. Fig. 2 shows the available sight distance method flowchart.

If the first object was visible, the basic iteration process was followed. Otherwise, the basic iteration process was modified as following:

– Step 1: initialize S (at first object location).

– Step 2: update S ($S = S - \Delta S$).

– Step 3: settle an object at a distance of S ahead of the driver's position with height H over road surface.

– Step 4: check if there is an element obstructing driver's sightline to the object.

– Step 5: if the sightline is obstructed by any element, repeat steps 2–4.

– Step 6: if the sightline is not obstructed by any element, available sight distance becomes (S) and the iteration process is completed.

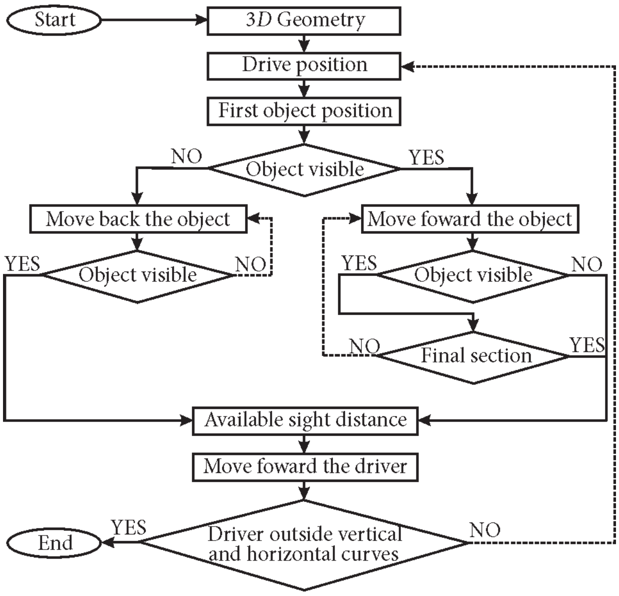

Fig. 2. Methodology to calculate available sight distance

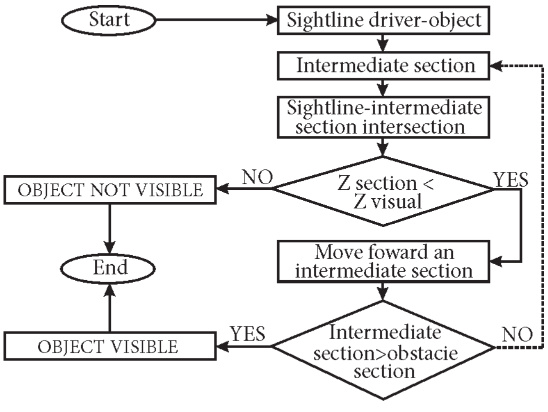

Fig. 3. Methodology to determine visual obstructions

Once the location of the driver and the object had been selected, visibility condition was checked within all intermediate cross sections. At each intermediate section, the intersection between the sightline and the section was obtained. Afterwards, the coordinate Z at the intersection point was calculated for both sightline and cross section. If the coordinate Z of the sightline was higher than the one on the intermediate section, the sightline had not been obstructed by the intermediate section. Thus, the intermediate cross section was not an obstacle to the sightline. Then, the next intermediate section was evaluated. If the coordinate Z of the sightline was lower than the one in the intermediate section, the visual between the driver and the object had been intercepted by an intermediate cross section. Consequently, the object was not visible from the location of the driver. The flowchart is shown in Fig. 3.

2.3. Available sight distance profile and minimum available sight distance

Available sight distance profile indicated available sight distance of each evaluated position of one driver within the curve. Minimum available sight distance of each alignment value and location were also recorded. The accuracy of the algorithm was checked with commercial design software. Several curves were tested to have the same minimal sight distance and the results were favourable.

2.4. Optimization model

The research was focused on the optimization of ASSD. According to the Spanish design guideline *Norma 3.1 IC,* both obstacle and driver heights were set on 0.2 m and 1.1 m, respectively. ASSD was calculated on a parallel line to the centreline located 1.5 m from the right edge of each line. Therefore, the lateral position of the driver and the object was 1.5 m from the edge of the carriageway. By varying these parameters, alignment sight distance and passing sight distance can also be calculated. A total of 665 280 geometries were analysed. The scenarios were simulated varying the following parameters:

- of the horizontal curve: radius between 100 m and 350 m; deflection angle between 30 gon and 100 gon; parameter of the spirals between the minimum and the maximum following the Spanish design guideline *Norma 3.1 IC*; approach and exit tangents length 200 m;
- of the vertical curve: approach grade between –5% and +5%; exit grade between –5% and +5% (a total of 55 combinations of algebraic grade difference rating from 1% to 10%); crest vertical curve parameter between 80% of the minimum and the desirable parameter following the Spanish design guideline *Norma 3.1 IC*;
- of the horizontal and vertical alignments coordination: offset between the horizontal and vertical vertices between –18 m and +18 m;
- of the cross section: 3.5 m lane width, 7% superelevation; 1.5 m shoulder width, 7% superelevation; 0.5 m verge width, 4% side slope; triangular ditch:

1.5 m width and 0.5 m depth; lateral clearance: 100 m; no lateral obstacles; distance between consecutive or successive cross sections of 2 m;

– Turning direction: left-handed; right-handed.

Some vertical curve length exceeded the superimposed circular horizontal curve length.

3. Results and analysis

Firstly, an analysis of ASSD profile of crest curves overlapped with horizontal curves was carried out. Secondly, the effect of geometric parameters on the minimum ASSD location and value were studied. The results of the software application are presented in tables where available stopping sight distance depends on four parameters.

3.1. Available stopping sight distance profile

Available stopping sight distance profile determinates ASSD on each driver position. The presence of continuous lateral obstructions, such as barriers or the terrain slope in cutting sections, modifies the ASSD. Thus, both geometries were included: without lateral obstructions and with lateral obstructions.

On the first type, the profile depends only on the 3*D* view of the road. Two local minimum points and one local maximum were presented, for both left and right turns (Fig. 4). The ASSD on the left turn curve is greater than the right turn curve because the driver on the left turn is located on the top of the superelevation plain and has more clearance. The results differ from the *2D* analysis that presented only one local minimum and the vertical midpoint is the point with longer ASSD. In fact, this point is included on the 3*D* first local minimum. Two crests and one hollow were generated by the 3*D* effect of the road. Both 3*D* crests were located before and after the midpoint of the vertical curve and the 3*D* hollow included the vertical midpoint; so, the vertical midpoint was obstructed by both adjacent 3*D* crests. Consequently, the vertical midpoint presented shorter ASSD.

The second type of ASSD profile is shown in Fig. 5. Only one local minimum area was generated by the lateral obstruction inside the curve. The cross section in this case is: lane width 3.5 m; shoulder width 1.5 m; verge 0.5 m; and 6.5 m lateral clearance (measured from the inner border of the shoulder). Minimal ASSD value was constant on the minimum area because sight distance had been limited by the lateral obstacle. Besides, the difference on the minimum ASSD between left-handed and right-handed was greater than on a curve without lateral obstacles. In left-handed direction, the driver was located on the outer lane; therefore, the road itself provided an extra clearance; and, consequently, the ASSD was greater.

3.2. Effect of geometric parameters

Effect of offset between the horizontal and vertical vertices (*O*, m), approach grade (g_1, %), length of horizontal curve (*L*, m), and ratio between the crest curve parameter and radius $\left(\frac{Kv}{R}, -\right)$ were studied by comparing minimum ASSD on the simulated scenarios. Specifically, minimum ASSD was compared using four parameters. The analysis included figures where rows and columns represented two parameters: deflection angle (ω, gon) and algebraic difference on grades (*A*, %), respectively. Then, each cell contained a 2D graph where abscissas represent the third parameter and the ordinates ASSD, and the colour legend included the forth parameter. Only the most representative figures are included on the paper.

Firstly, the effect of the offset between horizontal and vertical vertices was analysed. The offset was defined as positive when the horizontal vertex was before the vertical vertex considering right-handed direction of the curve.

Fig. 6 represents ASSD profile of a left-handed curve with horizontal radius equal to 250 m depending on the offset. Each one of the lines corresponds to one ASSD profile associated to one offset; thus, the ASSD profile is represented on the transverse axis to the main plain. The minimum ASSD of the whole curve was maximized when

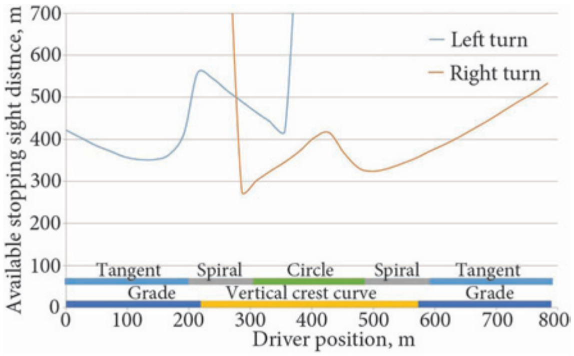

Fig. 4. Available stopping sight distance profile without lateral obstructions

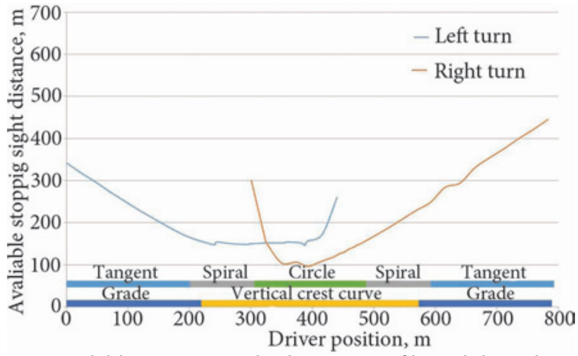

Fig. 5. Available stopping sight distance profile with lateral obstructions

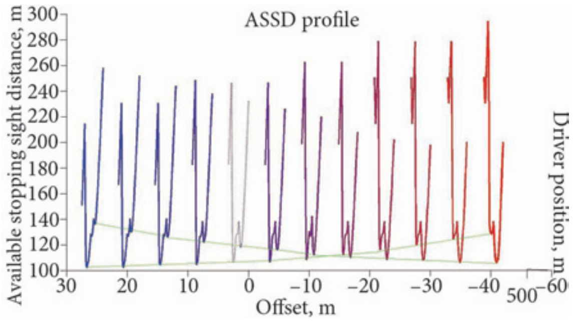

Fig. 6. Effect of the offset on ASSD profile on a left-handed curve

both local minimums had the same value, which corresponded with a slightly negative offset. This effect was the opposite on right-handed curves: the optimal offset was slightly positive. In other words, available sight distance is maximized when the centre of the horizontal curve is located before the vertical crest curve vertex in the turning direction. As right-handed curves presented lower ASSD, the minimal ASSD is limited by right-handed turning direction; therefore, the optimal offset was slightly positive. Comparing different geometries, the optimal offset was equal to zero in most cases. Slightly negative offset was favourable on sharper curves, whilst positive offset was preferred on short and flatter curves. Consequently, the general coordination criterion is offset equal to zero.

Secondly, the effect of the ratio between crest curve parameter and radius $\left(\frac{Kv}{R}\right)$ on ASSD varied depending on algebraic difference of grades. On Fig. 7, $\frac{Kv}{R}$ (abscissa), ASSD (ordinate) and R (colour) were represented on each cell, where ω and A remained constant. $\frac{Kv}{R}$ influenced on ASSD on curves with high difference on grades. The higher $\frac{Kv}{R}$ was, the longer ASSD was obtained. In flat curves, two effects were observed. In curves with radius longer than 250 m, high $\frac{Kv}{R}$ reduced ASSD; however, ASSD did not depend on $\frac{Kv}{R}$ on flatter curves with radius shorter than 250 m. Available stopping sight distance must be compared with the required stopping sight distance (RSSD). RSSD was calculated following the Spanish design guideline: *Norma 3.1 IC*. Fig. 8 shows the ratio between ASSD and RSSD on ordinates and $\frac{Kv}{R}$ on abscissas. The highest values of the ASSD/RSSD corresponded to the lower radii. Thus, the RSSD demand increase was greater than the actual ASSD supply increase. On the other hand, all ratios were higher than the unit; so, required stopping sight distance was satisfied even with parameters of the crest curve lower than the recommended ones.

Thirdly, the effect of the approach grade was greater on curves with less difference on grades as well as longer curves. The optimal values of approach grade were positive between 0% and 3%. The effect of the difference on grades was also important on ASSD: the sharper a curve the shorter ASSD. Variability on ASSD was higher on curves with more deflection angle; and the influence of the difference on grades was higher on curves with shorter radii. Finally, as the length of the curve increased, ASSD also increased and their relationship was logarithmic for all differences on grades.

4. Conclusions and recommendations

The objective of this study was to maximize available stopping sight distance at vertical crest curves overlapped with horizontal curves in two-lane roads. This paper presents a finite element method to calculate stopping sight distance and specific criteria on overlapping horizontal and vertical crest curves to maximize available stopping sight distance. The analysis of tridimensional sight distance profile is also included. The main conclusions of the research were:

1. The layout visibility gets principally lost in the superelevation transition point of the exterior side of the

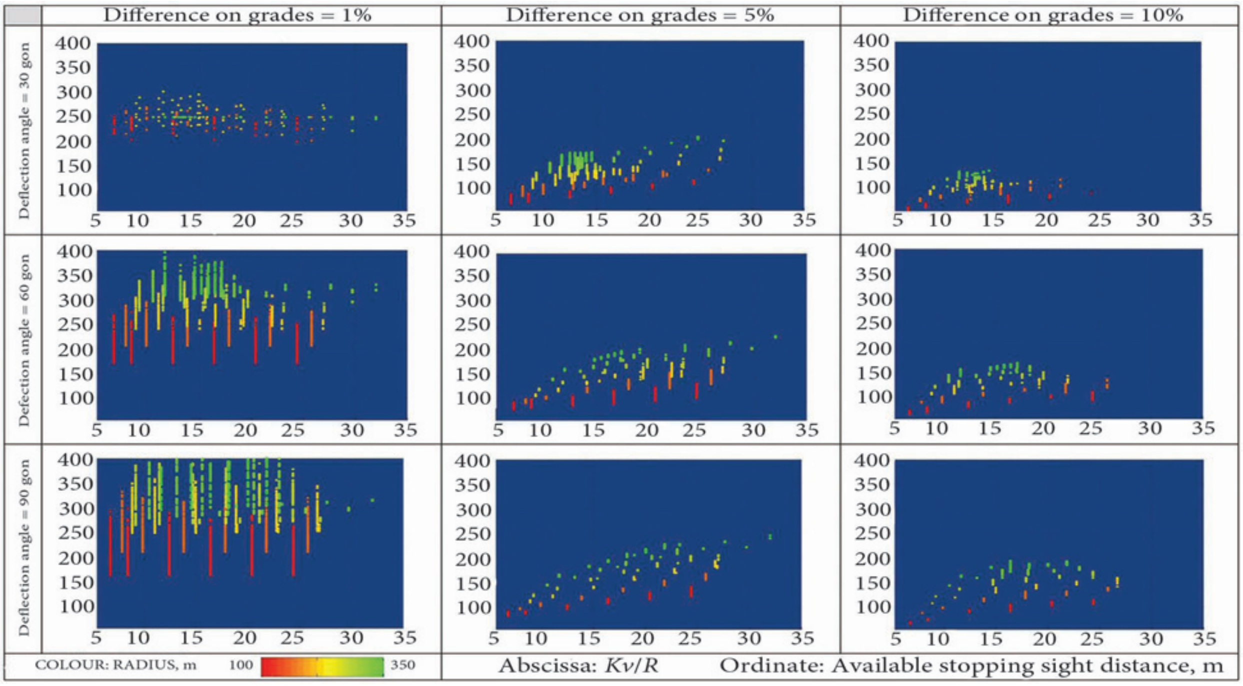

Fig. 7. Effect of $\frac{Kv}{R}$ on available sight distance depending on radius, deflection angle and algebraic difference on grades

curve, specifically, in the point where the superelevation changes its sign. Thus, the vertical midpoint is not the point with the highest available sight distance and the bi-dimensional analysis will induce to error.

2. The ratio between the vertical crest curve parameter (*Kv)* and the horizontal radius (*R*) affects the available stopping sight distance. The optimal proportion of $\frac{Kv}{R}$ that maximizes the available sight distance is generally in the interval [0.05, 0.15] m.

3. As the radius increase, available stopping sight distance improved. However, the increase of required stopping sight distance was higher than the actual improvement on available stopping sight distance. Therefore, shorter radius present higher safety margin.

4. The values of the vertical crest curve (*Kv)* that maximize the sight distance are sometimes lower than the minimal values established in the Spanish design guideline: *Norma 3.1 IC*. Therefore, it is possible to reduce *Kv* values.

5. Increasing the crest curve parameter reduced the available stopping sight distance when algebraic differences between consecutive grades are less than 3% for the same radius.

6. The impact of the offset between the horizontal and vertical vertices on the available sight distance was weak and opposite depending on the turning direction. Consequently, the general coordination criterion is designing with null offset.

7. The effect of the approach grade is important even if the algebraic difference of vertical grades was kept fixed, finding the optimal between 0 and 3%.

Further research is planned, including lateral obstacles with different positions and the application of this methodology to actual road projects, balancing cost differentials and sight distance improvements. Moreover, the subjective perception of the geometrical improvements will be checked.

References

Castro, M.; Anta, J. A.; Iglesias, L.; Sánchez, J. A. 2014. GIS-Based System for Sight Distance Analysis of Highways, *Journal of Computing in Civil Engineering* 28(3): 04014005. http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000317

Chen, J.; Yuan, H.; Shi, G.; Huang, X. 2011. Revision of Calculation of Stopping Sight Distance, *The Baltic Journal of Road and Bridge Engineering* 6(2): 96–101. http://dx.doi.org/10.3846/bjrbe.2011.13

García, A. 2004. Discussion of "Optimal Vertical Alignment Analysis for Highway Design" by Fwa, T. F.; Chan, W. T.; Sim, Y. P., *Journal of Transportation Engineering* 130(1): 138. http://dx.doi.org/10.1061/(ASCE)0733-947X(2004)130:1(138)

García, A.; Romero, M. A. 2007. Discussion of "3D Calculation of Stopping-Sight Distance from GPS Data" by Nehate, G.; Rys, M., *Journal of Transportation Engineering* 133(11): 645–646. http://dx.doi.org/10.1061/(ASCE)0733-947X(2007)133:11(645)

Hassan, Y. 2003. Improved Design of Vertical Curves with Sight Distance Profiles, *Transportation Research Record* 1851: 13–24. http://dx.doi.org/10.3141/1851-02

Hassan, Y.; Easa, S. M. 2000. Modeling of Required Preview Sight Distance, *Journal of Transportation Engineering* 126(1): 13–20. http://dx.doi.org/10.1061/(ASCE)0733-947X(2000)126:1(13)

Hassan, Y.; Easa, S. M. 1998. Design Considerations of Sight Distance Red Zones on Crest Curves, *Journal of Transportation Engineering* 124(4): 343–352. http://dx.doi.org/10.1061/(ASCE)0733-947X(1998)124:4(343)

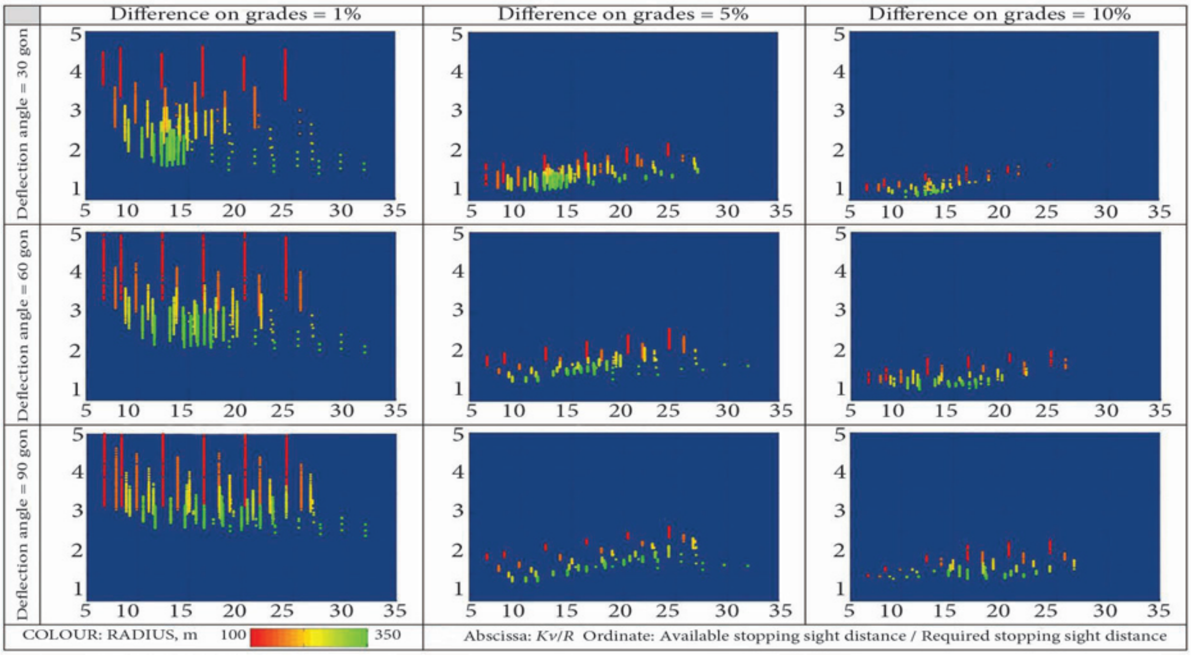

Fig. 8. Effect of $\frac{Kv}{R}$ on the ratio between available and required sight distance depending on radius, deflection angle and algebraic difference on grades

Hassan, Y.; Easa, S. M.; Abd El Halim, A. O. 1996. Analytical Model for Sight Distance Analysis on Three-Dimensional Highway Alignments, *Transportation Research Record* 1523: 1–10. http://dx.doi.org/10.3141/1523-01

Hassan, Y.; Easa, S. M.; Abd El Halim, A. O. 1997. Design Considerations for Combined Highway Alignments, *Journal of Transportation Engineering* 123(1): 60–68. http://dx.doi.org/10.1061/(ASCE)0733-947X(1997)123:1(60)

Ismail, K.; Sayed, T. 2007. New Algorithm for Calculating 3D Available Sight Distance, *Journal of Transportation Engineering* 133(10): 572–581. http://dx.doi.org/10.1061/(ASCE)0733-947X(2007)133:10(572)

Jha, M. K.; Kumar Karri, G. A.; Kuhn, W. 2011. New Three-Dimensional Highway Design Methodology for Sight Distance Measurement, *Transportation Research Record* 2262: 74–82. http://dx.doi.org/10.3141/2262-08

Kim, D. G.; Lovell, D. 2010. A Procedure for 3-D Sight Distance Evaluation Using Thin Plate Splines, in *Proc. of the 4th International Symposium on Highway Geometric Design.* June 2–5, 2010, Valencia, Spain. Available from Internet: <http://www.4ishgd.valencia.upv.es/index_archivos/57.pdf>.

Lovell, D.; Jong, J. C.; Chang, P. 2001. Improvements to Sight Distance Algorithm, *Journal of Transportation Engineering* 127(4): 283–288. http://dx.doi.org/10.1061/(ASCE)0733-947X(2001)127:4(283)

Moreno, A. T; García, A.; Camacho-Torregrosa, F. J.; Llorca, C. 2013. Influence of Highway Three-Dimensional Coordination on Drivers' Perception of Horizontal Curvature and Available Sight Distance, *Intelligent Transport Systems, IET* 7(2): 244–250. http://dx.doi.org/10.1049/iet-its.2012.0146

Romero, M. A.; García, A. 2007. Optimal Overlapping of Horizontal and Vertical Curves Maximizing Sight Distance by Genetic Algorithms, [CD-ROM], in *Proc. of the 86th Annual Meeting of the Transportation Research Board.* Ed. by Transportation Research Board. January 21–25, 2007, Washington, D. C., USA.

Sanchez, E. 1994. A 3-dimensional Analysis of Sight Distance on Interchange Connectors, *Transportation Research Record* 1445: 101–108.

Sarhan, M.; Hassan, Y. 2008. Three-Dimensional, Probabilistic Highway Design Sight Distance Application, *Transportation Research Record* 2060: 10–18. http://dx.doi.org/10.3141/2060-02

Sarhan, M.; Hassan, Y. 2011. Reliability-Based Three-Dimensional Design of Horizontal Lateral Clearance, *Canadian Journal of Civil Engineering* 38(8): 900–908. http://dx.doi.org/10.1139/l11-060

Taiganidis, I. 1998. Aspects of Stopping-Sight Distance on Crest Vertical Curves, *Journal of Transportation Engineering* 124(4): 335–342. http://dx.doi.org/10.1061/(ASCE)0733-947X(1998)124:4(335)

Yan, X.; Radwan, E.; Zhang, F.; Parker, J. C. 2008. Evaluation of Dynamic Passing Sight Distance Problem Using a Finite-Element Model, *Journal of Transportation Engineering* 134(6): 225–235. http://dx.doi.org/10.1061/(ASCE)0733-947X(2008)134:6(225)

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