

**OPTIMAL 3D COORDINATION TO MAXIMIZE THE AVAILABLE STOPPING SIGHT
DISTANCE IN TWO-LANE ROADS**

Ana Tsui Moreno Chou

PhD Candidate, Department of Transportation
Polytechnic University of Valencia
Camino de Vera, s/n. 46022 – Valencia, Spain
Tel: (34) 96 3877374
Fax: (34) 96 3877379
E-mail: anmoch@cam.upv.es

Vicente Melchor Ferrer Pérez

Lecturer, Department of Transportation
Polytechnic University of Valencia

Alfredo García García

Professor, Department of Transportation
Polytechnic University of Valencia

Mario Alfonso Romero Rojas

PhD Candidate, Department of Transportation
Polytechnic University of Valencia

Topic area: Alignment; sight distance; cross section design

Word count: Manuscript 4124
Figures (13*250) 3250
TOTAL 7374

ABSTRACT

Sight distance is one of the most important factors of road safety since it allows the driver perceiving, at real time, the characteristics of the road and its surroundings. A misperception of this crucial information could induce to a decision to drive with a maneuver with less margin of safety.

A finite element optimization has been carried out to maximize the available stopping sight distance at vertical crest curves overlapped with horizontal curves in two-lane roads. A software application in Matlab was developed to calculate the sight distance profile. In order to simulate possible scenarios, different combinations of the parameters on the model have been taken into account.

The results of the software application are presented in tables. The stopping sight distance was found dependent on the ratio between the vertical crest curve parameter (K_v) and the horizontal radius. Values of K_v lower than the minimal values established in the Spanish design guidelines satisfy the required stopping distance. On the other hand, the offset between the horizontal and vertical vertices slightly affects the available stopping sight distance. Finally, the effect of the approach grade is important even if the algebraic difference of vertical grades is kept fixed.

The three dimensional effect of the road was analyzed by the sight distance profile. It was observed that the layout visibility gets principally lost in the point where the superelevation changes its sign. Thus, the vertical curve midpoint is not the point with the highest available sight distance.

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 at real time the characteristics of the road and its surroundings. A misperception of this crucial information could induce to a decision to drive with a maneuver with less margin of safety.

The sight distance analysis can be based on both 2D and 3D methods. The current standards and guidelines use 2D analysis, although several researchers have been expanded to 3D highway analysis. By comparing 2D and 3D methods, 2D design may underestimate or overestimate the available sight distance (1). The 3D methods are more accurate on the sight distance evaluation despite the difficulty on the development. Graphical (2), finite element (3-8) and analytical (9, 10) approaches were studied by others. However, only finite element methods were applied to optimize available sight distance (7).

Available sight distance depends on the geometry of the road. Current design practice leads to frequent overlapping of vertical and horizontal curves because of their better adaptation to the terrain, which is able to minimize both the total amount of earthworks and environmental impacts. The coordination of both horizontal and vertical alignments enhances safety, operation and appearance (4). Furthermore, a poor coordination can generate zones with less available sight distance than required (9).

Up to now, general coordination criteria are given. Design guidelines, such as the Green Book (12) or the Spanish design standards (13) specify that both horizontal and vertical alignments should not be designed independently. The Green Book (12) stipulates that vertical transition curve must be completely contained in the horizontal curve. Moreover, the Spanish design standards (13) specify that a vertical crest curve must be fully contained in a horizontal curve including spirals; and that a crest curve should be separated from the adjacent horizontal tangent segments as much as practical. Hassan and Easa (1) studied the locations where a horizontal curve should not start in relation to a vertical curve; which were defined as red zones. The criteria were to obtain a stopping sight distance or a preview sight distance longer than the required. It was found that the range of red zones decreases with the increase of the superelevation rate of the horizontal curve and with the use of flatter crest curves. However, the optimal offset between the horizontal and vertical vertices was not studied. Sight distance profiles of vertical curves were analyzed (14, 15). Nevertheless, the design was based on 2D stopping sight distance calculation.

Another coordination criterion is the ratio between the crest curve parameter and the horizontal curve radius (K_v/R). The Spanish design standards (13) recommend that the ratio should be the inverse of the superelevation rate on the superimposed circular curve (%) to avoid optical effects. The criteria should be applied to two-lane roads where possible; or be at least equal to 0.06. García (5) proposed that the proportion of K_v/R to maximize available sight distance should be within 0.06 and 0.14. Mathematical analysis was carried out to determinate the optimal ratio K_v/R (5). It was assumed a road section composed by a vertical crest curve overlapped with a horizontal curve inscribed into the superelevation plane. Consequently, complete visibility of the curve was obtained. However, a 2D analysis showed hidden zones by highest point on the vertical projection. The optimal ratio K_v/R was found within the interval [0.11, 0.212]. An optimization software application was also developed to maximize available sight distance using genetic algorithms (7). The results indicated that the optimal K_v/R was between 0.055 and 0.168. Besides, values of K_v lower than the recommended ones achieved a suitable available sight distance when good alignment coordination was done.

RESEARCH APPROACH

The main objective of the research was to maximize the 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 3D sight distance calculation method to determinate the available sight distance within a curve. The methodology to calculate 3D 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; and (4) obtain the minimum available sight distance along the curve.

The methodology was applied to different scenarios. It were considered the variation of the following parameters: (a) horizontal curve: radius; deflection angle; parameter of the clothoids; and superelevation rate; (b) vertical curve: the approach and exit grades and the transition curve parameter; (c) horizontal and vertical alignment coordination: the offset between the horizontal and vertical vertices; (d) cross section: the width of the lane and of the shoulder; (e) driver point of view position: the lateral distance to the right edge of the corresponding lane and its height; (f) position of the obstacle: the lateral distance to the right edge of the corresponding lane and its height; (g) turning direction. A total of 665.280 geometries were analyzed varying those parameters.

3D Road Surface Idealization

The first step of the 3D sight distance calculation was to obtain the grid that represents the 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 centerline; the vertical alignment was similarly parameterized. The entry data allow the algorithm calculating the coordinates of each node of a cross section from the centerline, and the distance between cross sections could be controlled by the user. By indexing all the features to the centerline, it was possible to model the most generic horizontal or vertical geometry.

The road surface model is shown in Fig.1. The vertical slope on the cross section is represented by a vertical plane.

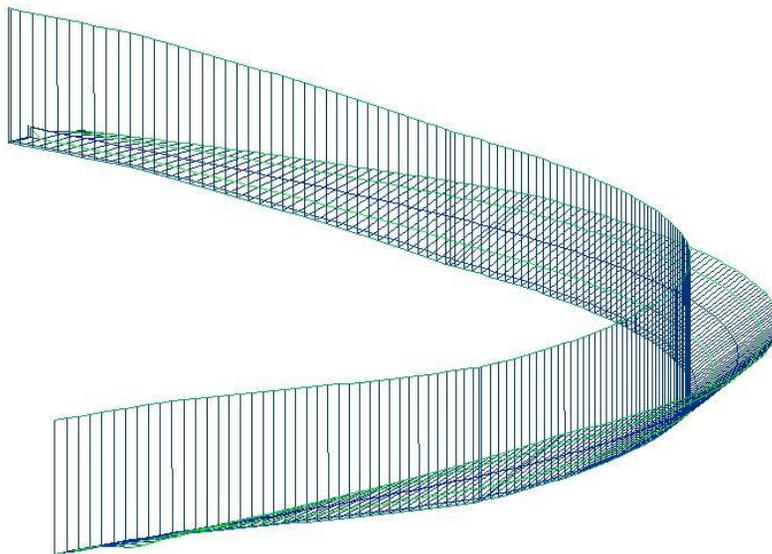


FIGURE 1 Road surface model.

3D Sight Distance

Sight distance was calculated by an iterative methodology based on a checking location loop. The driver was located in a cross section and an object was settled at a changing distance S ahead of the driver's position. Then, the sightline between the driver and the object was checked to be obstructed by any road surface element. The loop continued until the object was not visible or the object was located further than the 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 the object at a distance of S ahead of the driver's position with height H over the road surface.
- Step 4: check if there is an element obstructing the driver's sightline to the object.
- Step 5: if the sightline is not obstructed by any element, repeat steps 2-4.

- Step 6: if the sightline is obstructed by any element, the 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 an object with height H was tangent to the vertical crest curve projection (Fig. 2a).

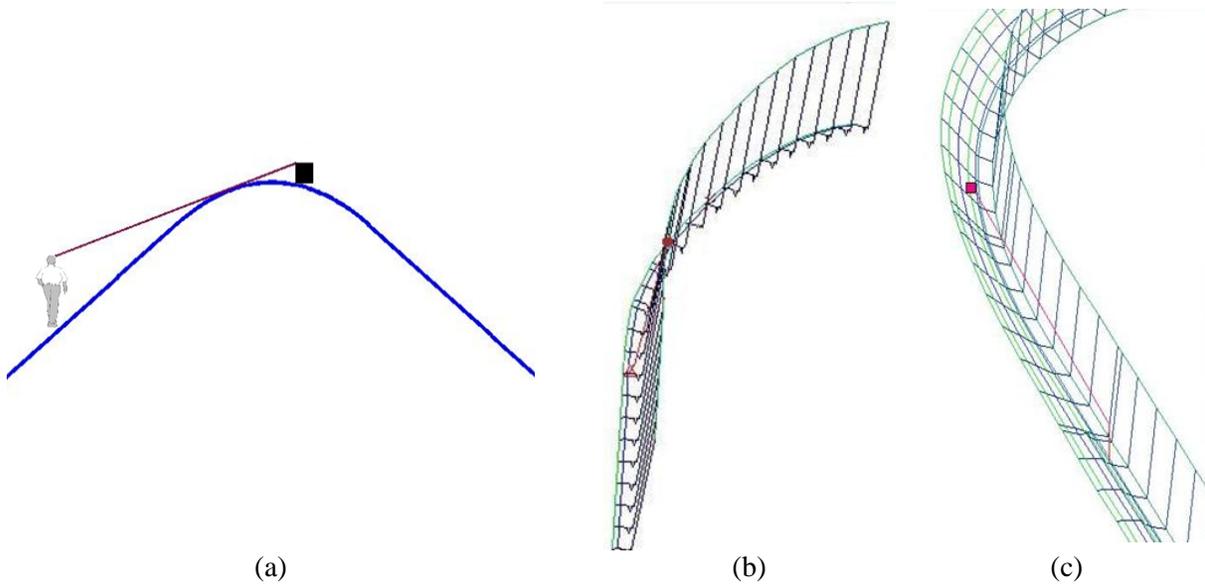


FIGURE 2 First Object: (a) Location, (b) Case not Visible, (c) Case Visible.

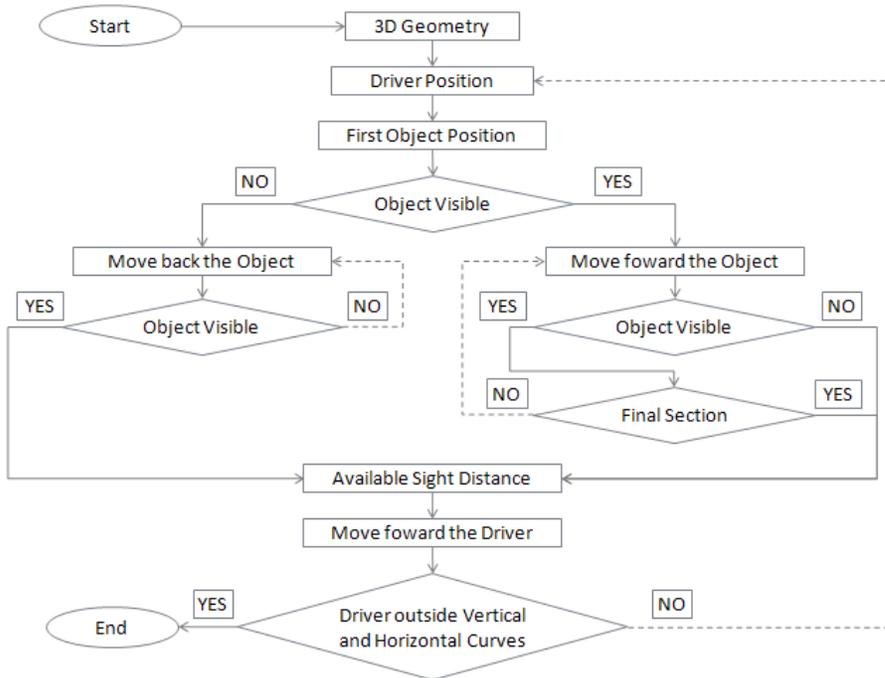


FIGURE 3 Available Sight Distance Method Flowchart.

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 the object at a distance of S ahead of the driver's position with height H over the road surface.
- Step 4: check is there is an element obstructing the 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, the available sight distance becomes (S) and the iteration process is completed.

Figure 3 shows the available sight distance method flowchart.

Besides, an algorithm to evaluate if an object was visible had been developed. The flowchart is shown in Fig. 4. Once the location of a driver and an object had been selected, the visibility condition was checked within all the 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. So, 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. Fig. 5 illustrates the checking process.

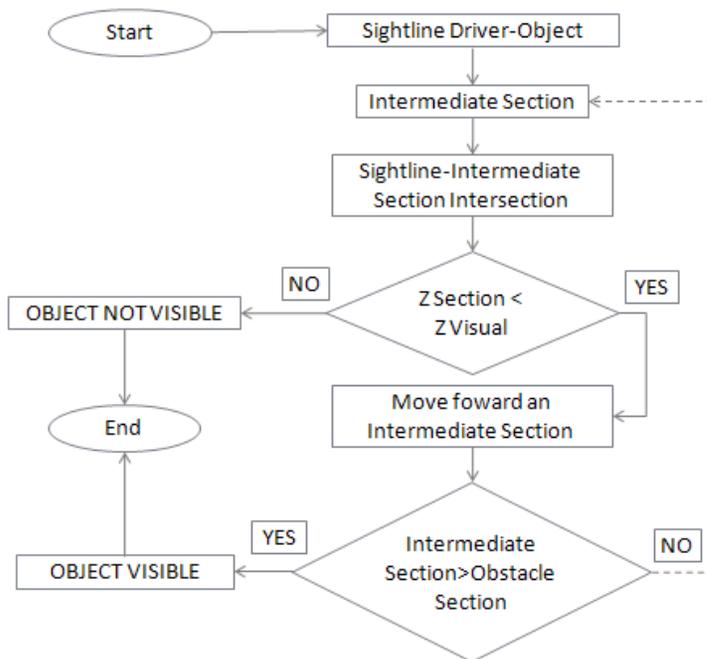


FIGURE 4 Visual Obstruction Flowchart.

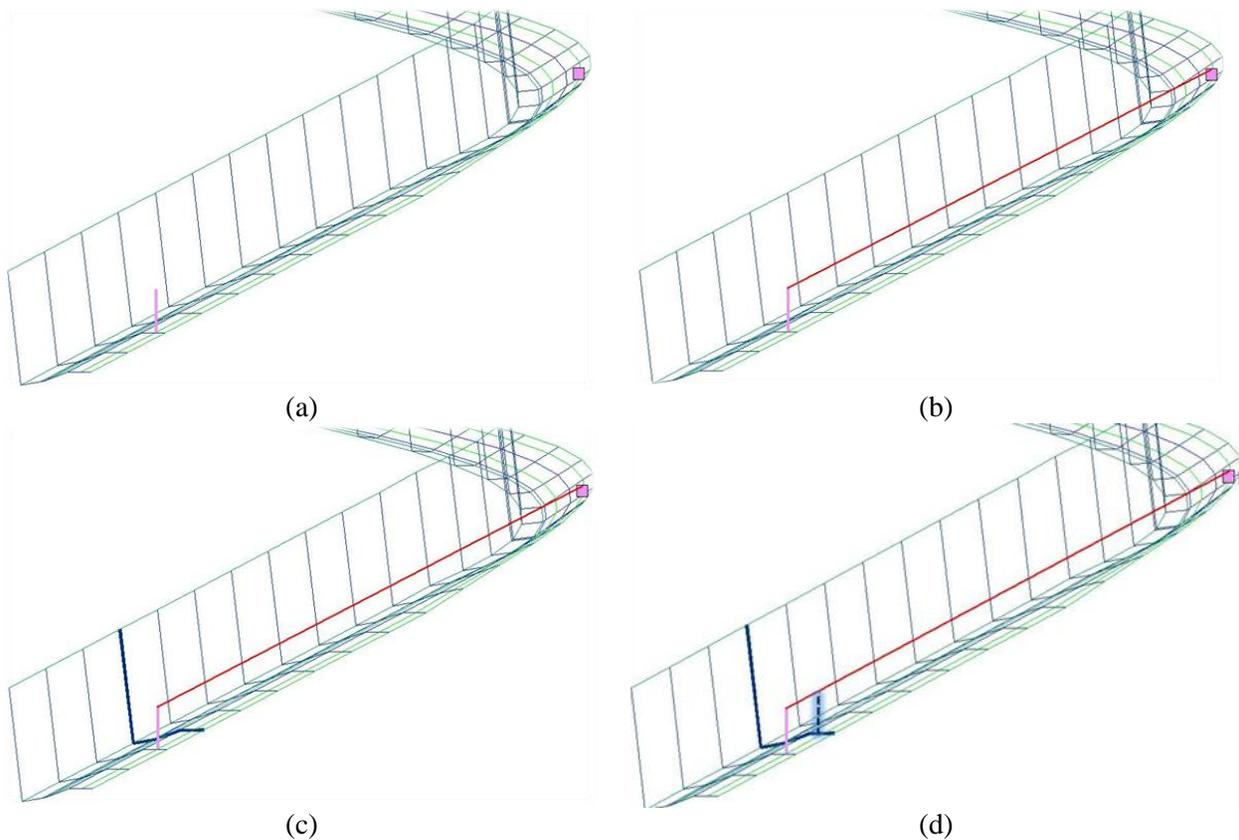


FIGURE 5 Visual Obstruction Checking Process: (a) Locate both Driver and Object, (b) Sightline, (c) Intermediate Section, (d) Sightline and Intermediate Section Intersection.

Available Sight Distance Profile and Minimum Available Sight Distance

The available sight distance profile indicated the available sight distance of each evaluated position of the driver. The minimum available sight distance of each alignment was also deduced. The value could reflect where the curve should be improved, as the minimum sight distance among the curve was lower than the required. 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 favorable.

Optimization Model

The research was focused on the optimization of the available stopping sight distance (ASSD). According to the Spanish design guidelines, both obstacle and driver heights were set on 0.2 and 1.1 m, respectively. The ASSD was calculated on a parallel line to the centerline 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 analyzed using different combinations of the parameters on the model. The possible scenarios were simulated taken into account the following parameters:

- Of the horizontal curve:
 - Radius: between 100 and 350 m.
 - Deflection angle: between 30 and 100 °.
 - Parameter of the clothoids: between the minimum and the maximum following the Spanish design guidelines.
 - 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 guidelines.
- Of the horizontal and vertical alignments coordination:
 - Offset between the horizontal and vertical vertices: between -18 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: 2 m.
- Turning direction:
 - Left-handed.
 - Right-handed.

The vertical curve can be not completely included on the superimposed horizontal curve.

RESULTS AND ANALYSIS

An analysis of the ASSD profile was carried out. The ASSD of the generated scenarios were also evaluated as the minimum ASSD among the ASSD profile to study the effect of geometric parameters. Both minimal ASSD and its location were obtained. The results of the software application are presented in tables where the available stopping sight distance depends on four parameters.

Available Stopping Sight Distance Profile

The three-dimensional effect of the road without lateral obstruction was analyzed by using the 3D ASSD profile. The 2D analysis of a vertical crest curve indicated that the vertical midpoint was the point with longer ASSD. However, this point was included on a local minimum area on the ASSD profile. Therefore, the 2D concept was not validated with a 3D analysis. In fact, two crests and one hollow were generated by the 3D effect of the road (See Fig. 6). Both 3D crests were located within the midpoint of the vertical curve and the 3D hollow included the vertical midpoint; so, the vertical midpoint was obstructed by the adjacent 3D crests. Consequently, the vertical midpoint presented shorter ASSD.

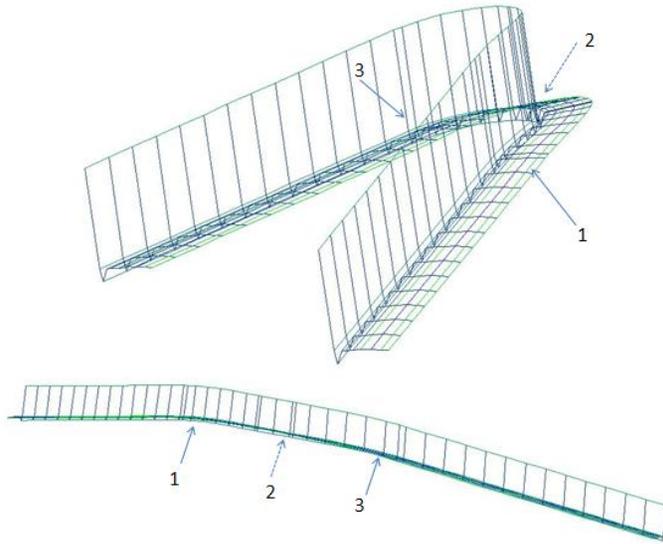
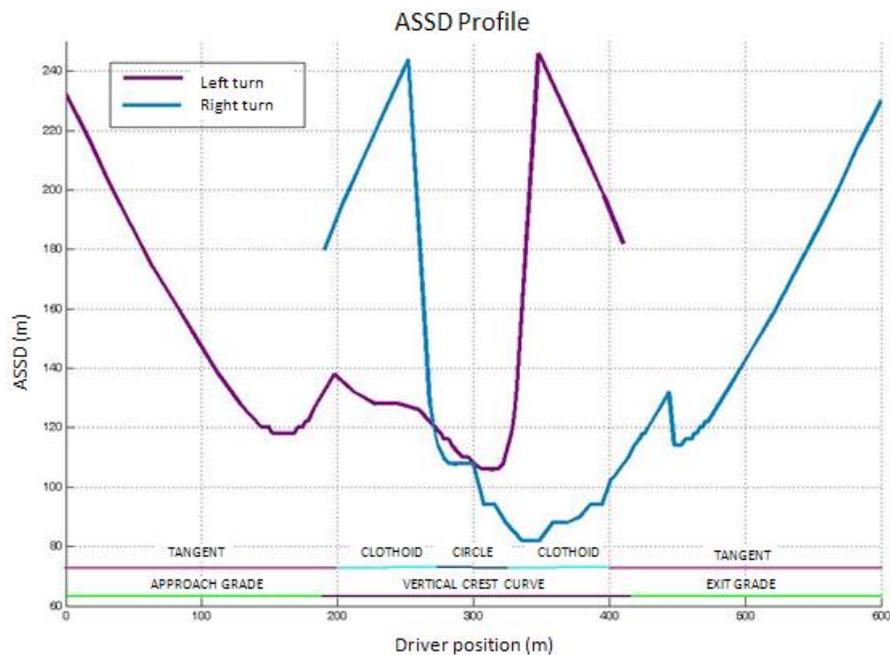


FIGURE 6 3D Coordination Effect.

The available stopping sight distance profile determine the ASSD on each driver position. Two types of ASSD profile can be distinguished. The first ASSD profile type was generated on road segments where the plan view was not an obstacle to the sightline; the second ASSD profile corresponded to a road segment where the sightline was obstructed by obstructions. On the first type, the profile depended only on the 3D view of the road. At this profile, two local minimum points were presented (Fig. 7(a)). Both relative minimum ASSD points were located before the two 3D crests while a relative maximum was set coincident with the 3D crest. Both right and left turning directions have the same 3D effect. Nevertheless, the ASSD on the left turn curve is greater than the right turn curve. The driver on the right turn is located on the bottom of the superelevation plain. Thus, the sight distance limitation coming from the vertical curve is greater and the ASSD is shorter.



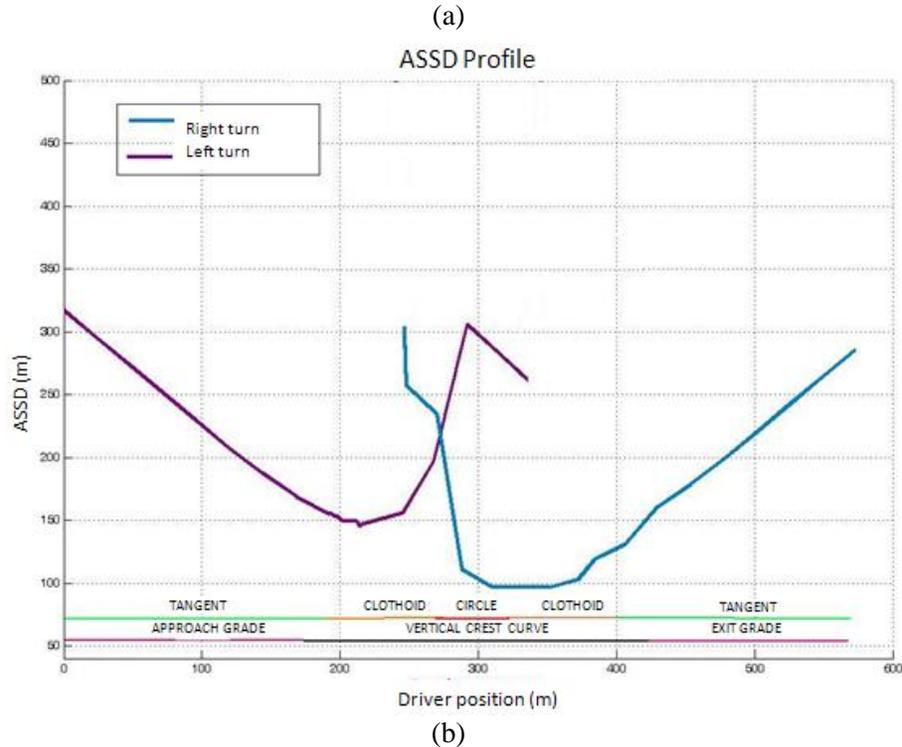


FIGURE 7 ASSD Profile: (a) without Lateral Obstruction, (b) with Lateral Obstruction.

The second type of ASSD profile is shown in Fig. 7 (b). Only one local minimum area was generated by the lateral obstruction. The minimal ASSD value was the same on the minimum area because the 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. On 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.

Effect of Geometric Parameters

The effect of the offset between the horizontal and vertical vertices (O), the approach grade (g_1), the length of the horizontal curve (L), and the ratio Kv/R were studied by comparing the minimum ASSD on the simulated scenarios. Specifically, the minimum ASSD was compared using four parameters. The presentation method includes figures where files and columns represent two parameters: deflection angle (ω) and algebraic difference on grades (A), respectively. Then, each cell contains a 2D graph where abscissas represent one parameter and ordinates the ASSD. A color legend is included. Thus, available stopping sight distance depends on four parameters.

Offset between the horizontal and vertical vertices

The effect of the offset between the horizontal and vertical vertices was analyzed. When the horizontal vertex was before the vertical vertex on left-handed direction, the offset was defined as positive. It was found that a positive offset was favorable on right-handed curves whilst on left-handed curves was negative. Therefore, the location of the vertical midpoint that maximizes available sight distance was before the horizontal vertex. The optimal location was found on curves with equal ASSD for both local minimum areas on the ASSD profile (Fig. 8). As right-handed direction had less clearance distance, the optimal offset was slightly positive.

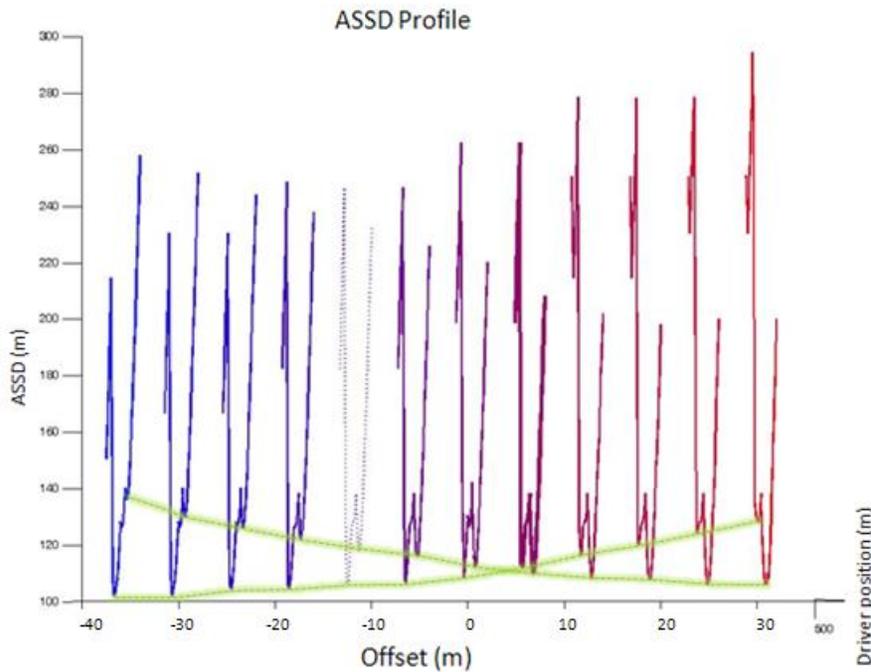


FIGURE 8 Offset Effect on ASD Profile.

The influence of the offset, O , on different curves is shown on Fig. 9. The rows and columns represent two parameters: deflection angle and algebraic difference on grades. On each cell, the ASD is presented against the offset between the horizontal and vertical vertices. Color legend indicates the radius. The optimal offset was equal to zero on most cases. Slightly negative offset was favorable on sharper curves, whilst positive O was preferred on short and flatter curves. Nevertheless, only a weak impact of the offset on the ASD could be concluded.

Approach grade

As before, the approach grade impact on ASD is presented on Fig. 10 depending on four parameters. Both rows and columns show ω and A respectively. Each cell contains the results of curves with same ω and A for ASD depending on approach grade (coordinate X) and radius (color). The effect of the approach grade was greater on curves with less A , as well as longer curves. The optimal values of the approach grade were positive within the interval $[0, 3]$ %. Spread on ASD was higher on curves with more deflection angle. The influence of A was higher on curves with shorter radii.

Ratio Kv/R

The effect of the ratio between the crest curve parameter and the radius of the curve on ASD varied depending on algebraic difference of grades. On Fig. 11, Kv/R , ASD and R are represented on each cell, where ω and A remain constant. Kv/R influenced on ASD on curves with high A . The higher Kv/R was, the longer ASD was obtained. On the contrary, ASD did not depend on Kv/R on flatter curves with radius shorter than 250 m. Furthermore, a high Kv/R reduced ASD on flatter curves with radius longer than 250 m.

Available stopping sight distance must be compared with the required stopping sight distance (RSSD). Fig. 12 shows the ratio between the ASD and the RSSD on ordinates and Kv/R on abscissas. As Fig. 11 shows, a higher radius was associated with a longer ASD. However, the ratio between the ASD

and the RSSD ($ASSD/RSSD$) should be checked since RSSD depends on the radius. On Fig.12, the highest values of the ratio $ASSD/RSSD$ corresponded to lower radius. Thus, the RSSD increase was greater than the actual ASSD increase.

Length of the horizontal curve: radius and deflection angle

The dependence of the ASSD on the length of the curve is presented on Fig. 13. Both deflection angle (ω) and algebraic difference on grades (A) are presented with the rows and columns of the figure. Each cell represents a curve with same ω and A but changes the values of K_v/R and R . Comparing the results of a cell, the longer the curve was, the longer the ASSD was achieved. Consequently, longer radius was associated with longer ASSD. A logarithm relationship between ASSD and the length of the curve was presented for all algebraic difference on grades (A). The effect of A was important on ASSD. The sharper a curve was, the shorter the ASSD was.

Color legend represents K_v/R . The influence of the crest curve parameter depended on the algebraic difference on grades. On sharper curves, ASSD was proportional to the ratio K_v/R . On the contrary, a higher K_v/R produced a lower ASSD on flatter curves.

CONCLUSIONS AND RECOMMENDATIONS

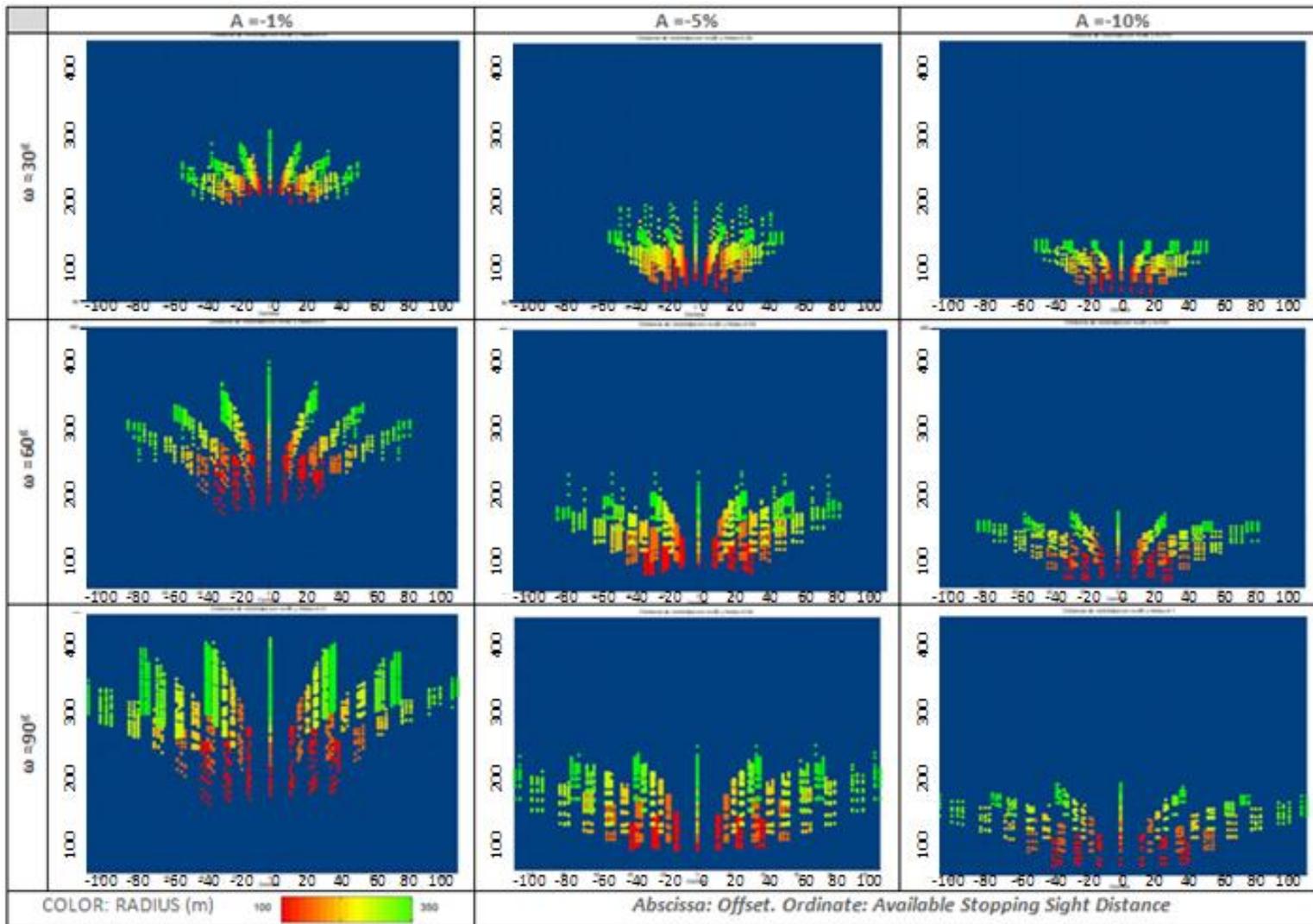
The objective of this study was to maximize the available stopping sight distance at vertical crest curves overlapped with horizontal curves in two-lane roads. This paper presents a finite element method to calculate the stopping sight distance and specific criteria on overlapping horizontal and vertical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

A software application in Matlab was developed based on finite element method to calculate the 3D minimum available sight distance of a vertical crest curve overlapped with a horizontal curve, as well as the sight distance profile.

The results of the software application are presented in tables where the available stopping sight distance depends on four parameters. A conclusion of the research is that the ratio between the vertical crest curve parameter (K_v) and the horizontal radius (R) affects the available stopping sight distance. The optimal proportion of K_v/R that maximizes the available sight distance is generally in the interval [0.05, 0.15] m. It was found that the values of K_v , that maximize the sight distance, are sometimes lower than the minimal values established in the Spanish guidelines. Therefore, a suitable sight distance can be achieved when good alignment coordination is carried out even with lower K_v than the recommended ones. Furthermore, increasing the crest curve parameter may reduce the available stopping sight distance when algebraic differences between consecutive grades are less than 3%. On the other hand, only a weak impact of the offset between the horizontal and vertical vertices on the available sight distance has been concluded, where the optimal is set within the interval [-12, 6] m. Finally, the effect of the approach grade is important even if the algebraic difference of vertical grades is kept fixed, founding the optimal between 0 and 3 %.

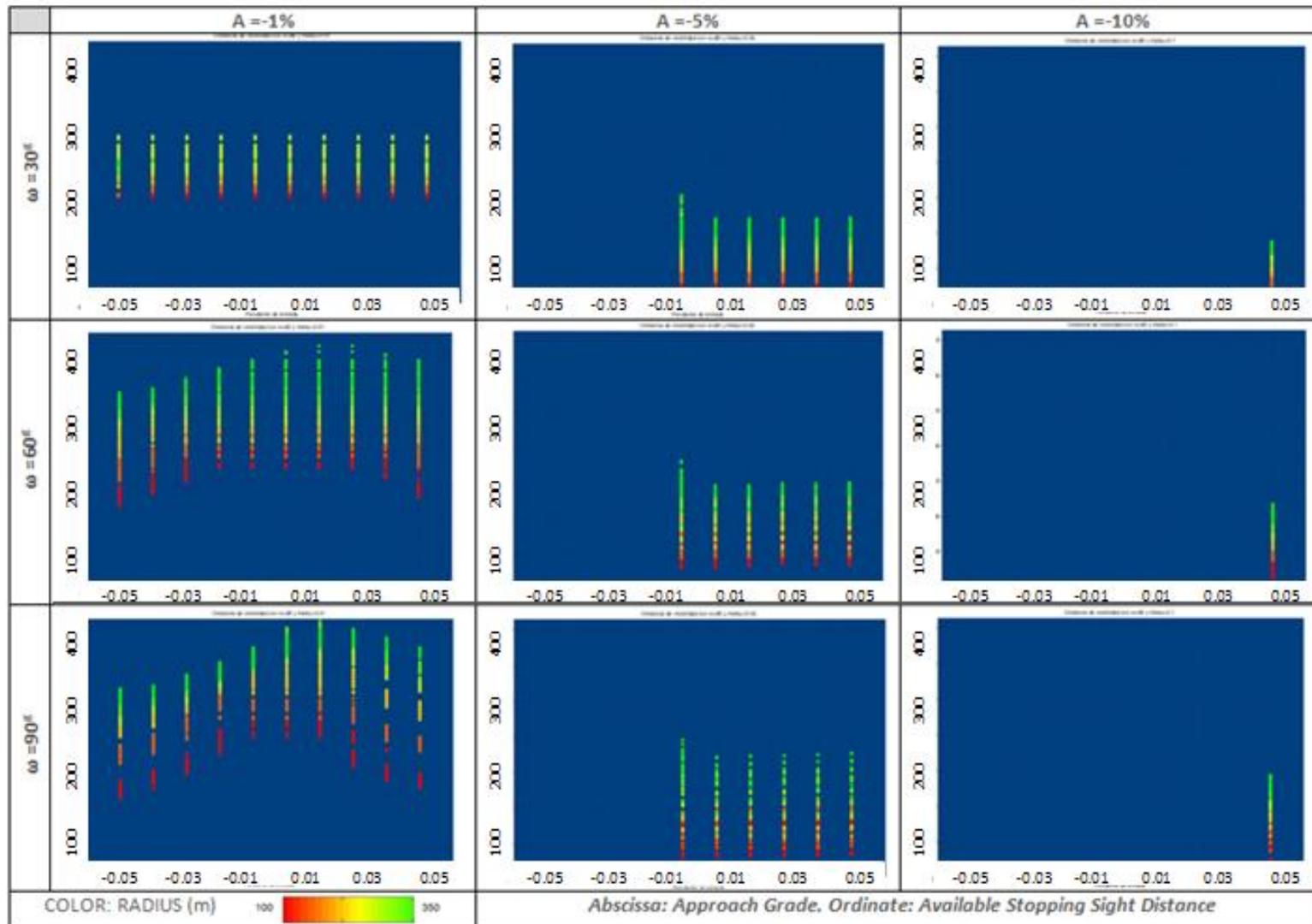
The three dimensional effect of the road has been analyzed by the sight distance profile. It was observed that the layout visibility gets principally lost in the superelevation transition point of the exterior side of the curve, specifically, in the point where the superelevation changes its sign. Thus, the vertical midpoint is not the point with the highest available sight distance.

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.



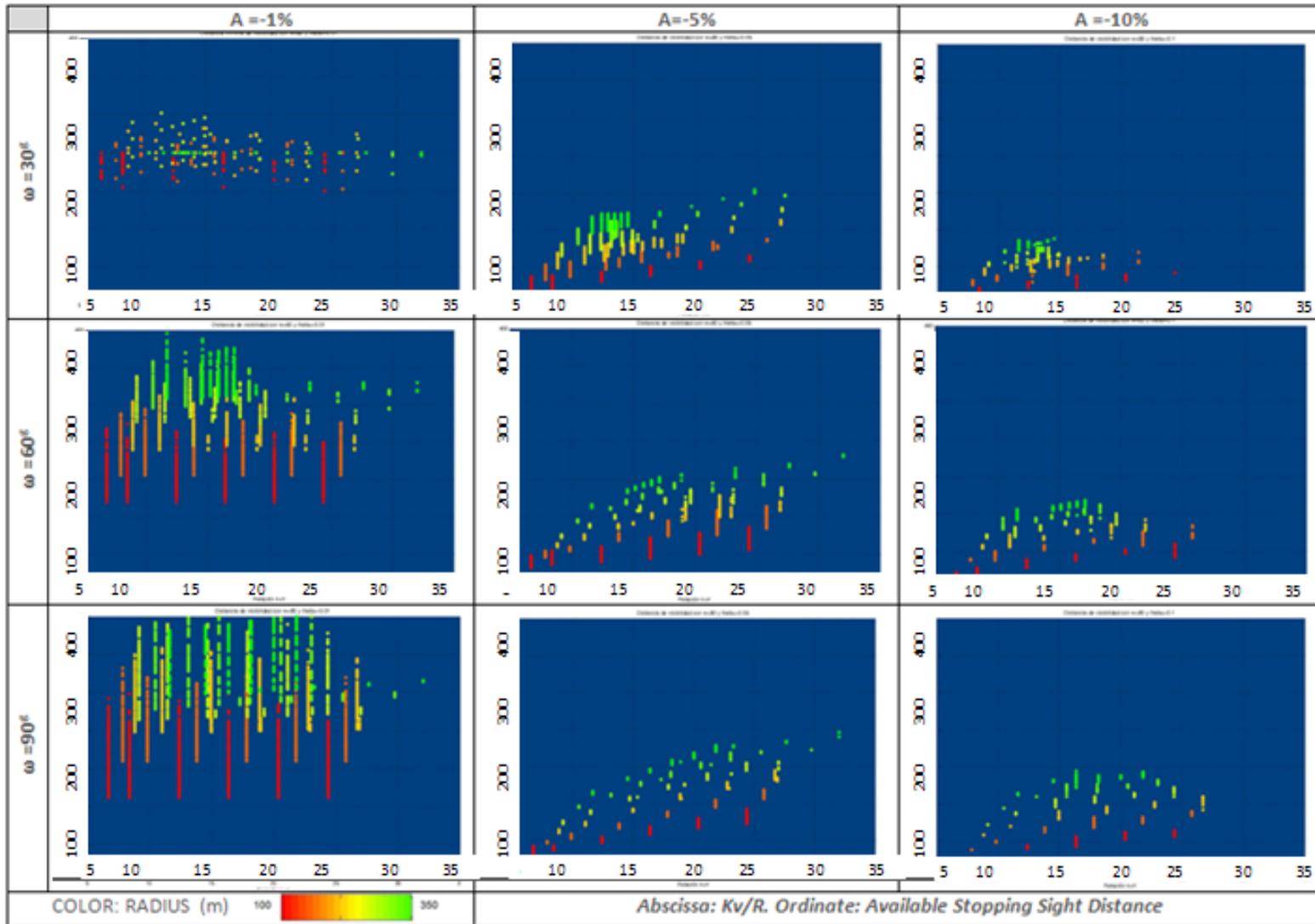
1
2
3

FIGURE 9 Offset Effect on ASSD.



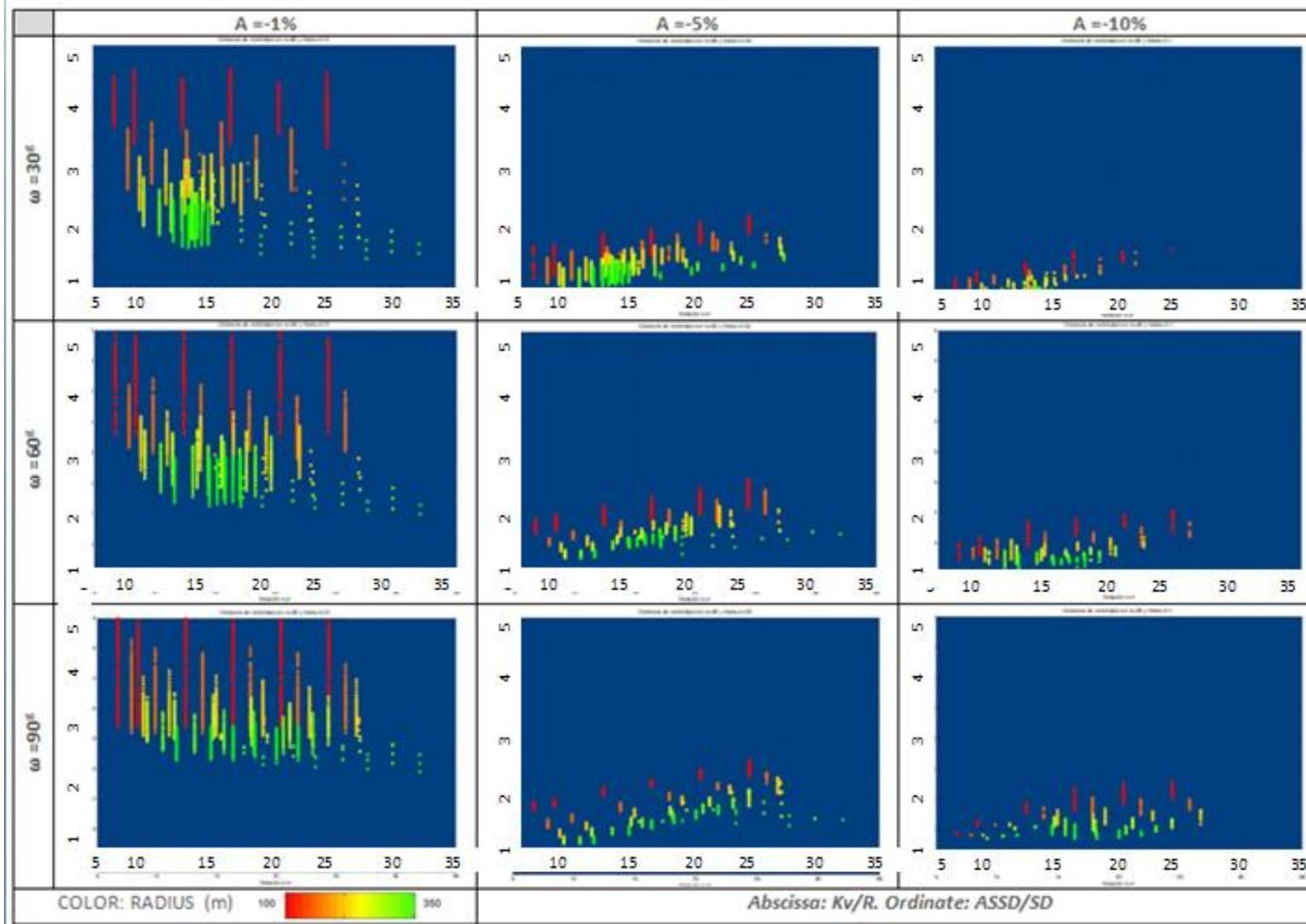
1
2
3
4

FIGURE 10 Approach Grade Effect on ASSD.

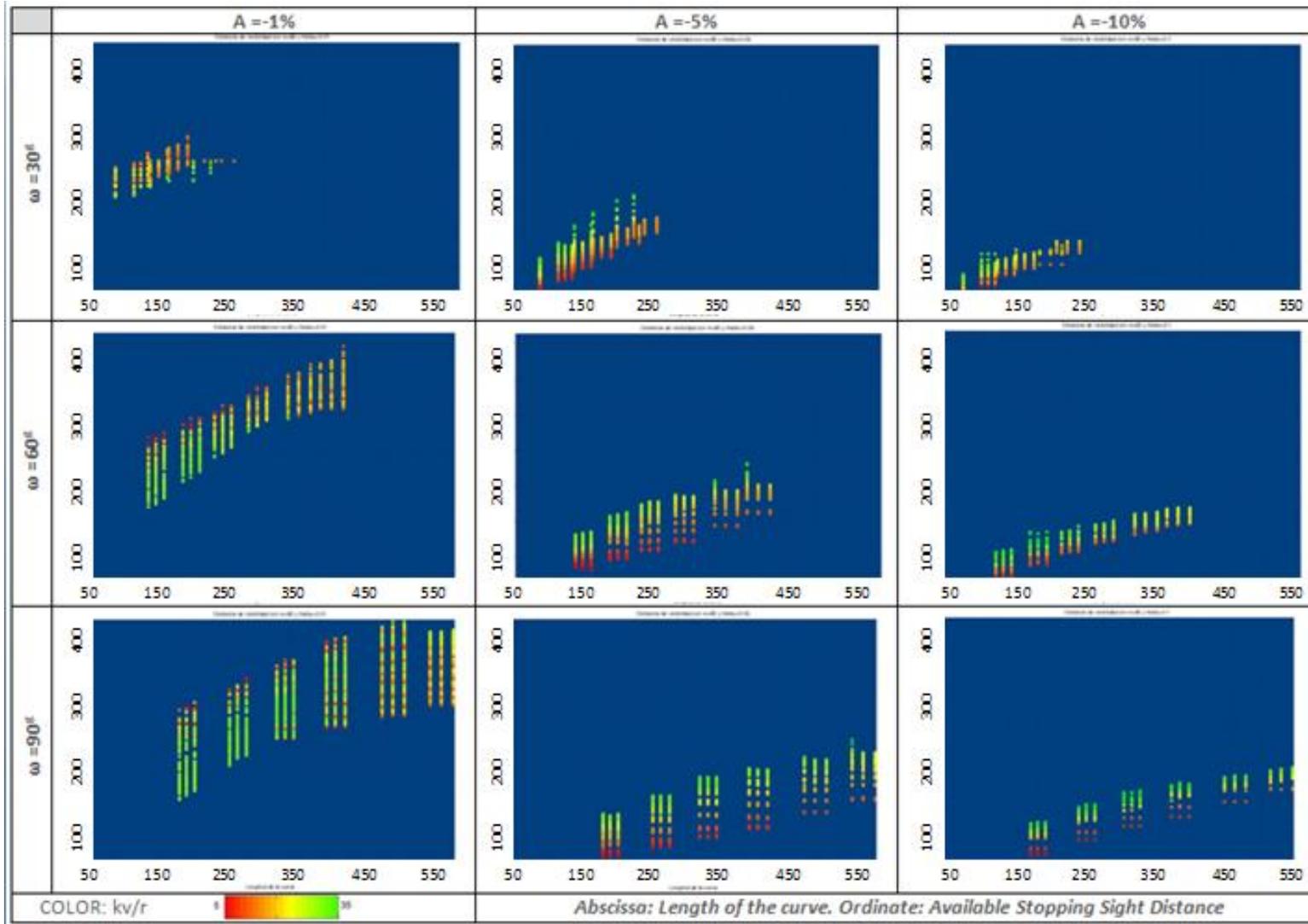


1
2
3
4

FIGURE 11 Ratio between the Crest Curve Parameter and the Radius Effect on ASSD.



1
2
3 **FIGURE 12 Ratio Kv/R Effect on Ratio ASSD/SSD.**



1
2
3 **FIGURE 13 Length of the Curve Effect on ASSD.**

1 REFERENCES

- 2 1. Hassan, Y., Easa, S.M., and A.O. Abd El Halim. Design considerations for combined highway
3 alignments. *Journal of Transportation Engineering*, 1997, Vol 123, No. 1, pp 60-68.
- 4 2. Sanchez, E. A 3-dimensional analysis of sight distance on interchange connectors. . In *Transportation*
5 *Research Record: Journal of the Transportation Research Board*, No. 1445, Transportation Research
6 Board of the National Academies, Washington D.C., 1994, pp. 101-108.
- 7 3. Hassan, Y., Easa, S.M., and A.O. Abd El Halim. Analytical model for sight distance analysis on three-
8 dimensional highway alignments. . In *Transportation Research Record: Journal of the Transportation*
9 *Research Board*, No. 1523, Transportation Research Board of the National Academies, Washington
10 D.C., 1996, pp. 1-10.
- 11 4. Hassan, Y., and S.M. Easa. Design considerations of sight distance red zones on crest curves. *Journal*
12 *of Transportation Engineering*, 1998, Vol. 124, No. 4, pp 343-352.
- 13 5. García, A. Optimal vertical alignment analysis for highway design – Discussion. *Journal of*
14 *Transportation Engineering*, 2004, Vol. 130, Issue 1, pp 138.
- 15 6. García, A., and M.A. Romero. 3D Calculation of Stopping-Sight Distance from GPS Data –
16 Discussion. *Journal of Transportation Engineering*, 2007, Vol. 133, Issue 11, pp. 645-646.
- 17 7. Romero, M.A., and A. García. Optimal overlapping of horizontal and vertical curves maximizing sight
18 distance by genetic algorithms. Presented at 86th Annual Meeting of the Transportation Research
19 Board, Washington, D.C., 2007.
- 20 8. Yan, X., Radwan, E., Zhang, F., and J.C. Parker. Evaluation of dynamic passing sight distance
21 problem using a finite-element model. *Journal of Transportation Engineering*, 2008, Vol. 134, No.6,
22 pp. 225-235.
- 23 9. Lovell, D., Jong, J.C., and P. Chang. Improvements to sight distance algorithm. *Journal of*
24 *Transportation Engineering*, 2001, Vol. 127, No.4, pp. 283-288.
- 25 10. Ismail, K., and T. Sayed. New algorithm for calculating 3D available sight distance. *Journal of*
26 *Transportation Engineering*, 2007, Vol. 133, No.10, pp. 572-581.
- 27 11. Hassan, Y., and S.M. Easa. Modeling of required preview sight distance. *Journal of Transportation*
28 *Engineering*, 2000, Vol. 126, No.1, pp. 13-20.
- 29 12. American Association of State Highway and Transportation Officials (AASHTO). *A policy on*
30 *geometric design of highways and streets*, Washington, D.C., 2004.
- 31 13. Ministerio de Fomento, *Instrucción de Carreteras, Norma 3.1 – IC “Trazado”*, Madrid, 2000.
- 32 14. Hassan, Y. Improved design of vertical curves with sight distance profiles. In *Transportation Research*
33 *Record: Journal of the Transportation Research Board*, No. 1851, Transportation Research Board of
34 the National Academies, Washington D.C., 2003, pp. 13-24.
- 35 15. Taiganidis, I. Aspects of stopping-sight distance on crest vertical curves, *Journal of Transportation*
36 *Engineering*, 1998, Vol. 124, No. 4, pp. 335-342.