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## Sight distance analysis of highways using GIS tools

María Castro<sup>a,\*</sup>, Luis Iglesias<sup>b</sup>, José A. Sánchez<sup>c</sup>, Luis Ambrosio<sup>d</sup>

<sup>a</sup> Dept. Transportes, E.T.S.I.C.C.P., Universidad Politécnica de Madrid, Prof. Aranguren s/n, 28040 Madrid, Spain

<sup>b</sup> Dept. Explotación de Recursos Minerales y Obras Subterráneas, E.T.S.I.M., Universidad Politécnica de Madrid, Ríos Rosas, 21, 28003 Madrid, Spain

<sup>c</sup> Dept. Ingeniería Civil: Hidráulica y Energética, E.T.S.I.C.C.P., Universidad Politécnica de Madrid, Prof. Aranguren s/n, 28040 Madrid, Spain

<sup>d</sup> Dept. Economía y Ciencias Sociales Agrarias, E.T.S.I.A., Universidad Politécnica de Madrid, Avd. Complutense s/n, 28040 Madrid, Spain

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### ABSTRACT

Analyzing the distance visible to a driver on the highway is important for traffic safety, especially in maneuvers such as emergency stops, when passing another vehicle or when vehicles cross at intersections. This analysis is necessary not only in the design phase of highways, but also when they are in service. For its use in this last phase, a procedure supported by a Geographic Information System (GIS) has been implemented that determines the highway distances visible to the driver. The use of a GIS allows the sight distance analysis to be integrated with other analyses related to traffic safety, such as crash and design consistency analyses. In this way, more complete analyses could be made and costs shared. Additionally, with the procedure proposed it is possible to use data regarding the trajectory of a vehicle obtained on a highway with a Global Positioning System (GPS) device. This application is very useful when highway design data are not available. The procedure developed and its application in a case study are presented in this article.

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## 1. Introduction

The driver's line of sight on horizontal curves may be obstructed by lateral obstacles such as cut side-slopes, trees, and buildings. On crest vertical curves, the line of sight may be obstructed by the vertical curve itself. Also, nighttime sight distance on sag vertical curves may be limited to the farthest point covered by the vehicle headlights. The analysis of the distance visible to a driver on the highway is important for traffic safety. Standards in different countries recognize this importance, including minimum sight distance values for maneuvers like emergency stops, passing another vehicle or vehicles crossing at intersections, (AASHTO, 2004; Ministerio de Fomento, 2000). To aid designers, current design guides offer 2-D analytical models to analyze the available sight distance (AASHTO, 2004; Ministerio de Fomento, 2000) and there is highway design software that includes tools for calculating available sight distance to ensure it complies with regulations. Hassan et al. (1998a,b) have proposed doing 3-D (three dimensional) sight distance analysis.

Highway design software uses a Digital Terrain Model (DTM), characteristics of the cross-section, and an alignment, defined by means of tangents, circular curves, spirals and vertical curves, to make highway sight distance calculations. When a new highway is designed the alignment is known (it is in the design) and sight distance is easily calculated with highway design software. However, if this sight distance analysis is done on existing highways the alignment data may not be available and, thus, sight distance analysis cannot be done using this type of software. Another drawback of highway design software is its use of Digital Terrain Models that, unlike Digital Surface Models, do not take into account side obstacles, like trees or buildings, which could greatly reduce driver sight distance.

\* Corresponding author. Tel.: +34 91 3366653; fax: +34 91 3366654.

E-mail address: [maria.castro@upm.es](mailto:maria.castro@upm.es) (M. Castro).

On the other hand, Geographic Information Systems (GISs) have been applied in different areas of transportation since the 1980s (Thill, 2000; Lang, 1999). The potential of GIS for analysis and the increasing number of highway inventories supported by a GIS make these techniques very useful tools to facilitate and improve studies of road safety (Lamm et al., 1995; Cafiso, 2000; Steenberghen et al., 2004; Castro et al., 2008). The viewshed calculation tools implemented in GISs have been used in different applications in fields such as architecture, land use planning, or simulations (Fisher, 1996; Izraelevitz, 2003).

The use of GISs in highway sight distance studies would allow the use of data sources that, besides the terrain, include obstacles like trees or buildings that could reduce driver sight distance. These data sources could be, for example, Light Detection and Ranging (LIDAR) images (source of Digital Surface Models) or Digital Terrain Models including vector cartography (buildings and other obstacles). In this way, Khattak and Shamayleh (2005) use LIDAR data, orthophotos and a GIS to create 3D models of a two-lane rural highway, then, through visual inspection of these 3D models, identify 10 possible sight distance obstructions. These possible sight distance obstructions were analyzed using the GIS and validated with field observations.

The main aim of this research is to develop and validate a procedure to perform sight distance analysis of existing highways where project data is either not available or not reliable. The availability of a GIS-based procedure to obtain information on sight distance would also allow this analysis to be combined with other traffic safety analyses, such as crash and design consistency. In this way, more comprehensive studies can be carried out and costs shared.

In the first part of this paper the procedure for calculating sight distances using a GIS is shown in detail. Close attention has been paid to validating the procedure in the second part of the paper. To this end, sight distance results obtained using the GIS in a two-lane rural highway located in Madrid (Spain) were compared with the results obtained using a highway design software package. The results of the comparison were analyzed using a Kolmogorov–Smirnov test for two samples and a Wilcoxon signed-rank test for paired samples.

If highway alignment data were not available, the use of a Global Positioning System (GPS) device for collecting highway geometry data (centerline) is a reliable alternative (Federal US Highway Administration, 2000, 2005; Transportation Research Board, 2002; Ben-Arieh et al., 2004; Chang, 2004; Imran et al., 2006; Castro et al., 2006; Campbell et al., 2007). Thus, in the last part of this paper, data from a vehicle trajectory, taken with a GPS device, are used to estimate the highway alignment. Using these GPS-obtained points, the procedure proposed has been applied to calculate sight distance. As in the previous case, the results obtained with the GIS and GPS were compared with the results obtained using a highway design software package. A comparative analysis of results was performed using a Kolmogorov–Smirnov test for two samples and a Mann–Whitney U test for independent samples.

## 2. Sight distance with GIS

Most GIS algorithms calculate profiles from the desired viewpoint to each point on the grid. Subsequently, intervisibility analysis is performed between points, considering land elevations along each profile (De Floriani and Magillo, 1994; Franklin et al., 1994; Wang et al., 2000; Izraelevitz, 2003; McGlone, 2008). If the land surface rises above the line-of-sight then the target is out of sight, otherwise it is in sight (Fisher, 1996).

In this section, the procedure for computing the sight distance from a point on a highway is presented. The following data are needed: the theoretical trajectory that the vehicle would follow, the coordinates ( $x, y$ ) of the point from which it is desired to compute the sight distance (position of the driver's eyes), and the Digital Terrain Model (DTM). ArcMap tools (ESRI, 2007, 2008) have been used to determine viewsheds and calculate distances (ESRI, 2009a,b). The viewshed calculation tool allows all points that are visible from a specific point to be determined, considering a Digital Terrain Model.

The process used is outlined in Fig. 1. Using the GIS tools the zones visible from the calculation point are determined. These zones intersect with the highway, and the distance along the section next to the point being considered is computed.

The procedure is implemented through standard GIS tools (ArcGis) and consists of:

1. Defining the sight distance calculation parameters (OFFSET, AZIMUTH, VERTICAL angle and RADIUS) for the points (defined in Fig. 2)
2. Selection of the point from which sight distance will be calculated.
3. Calculation of the viewshed, i.e., determination of the points in the Digital Terrain Model that are visible from the considered point.
4. Transformation of the raster file of visible zones to a polygon type file. The polygons of visible and invisible zones are thus obtained.
5. Calculation of the geometric intersection of the visible zones with the line defining the vehicle trajectory.
6. Calculation of the length of the path between the point under consideration and the intersection of the vehicle trajectory with the visible zone. This distance is the sight distance. If there are multiple intersections, the nearest one is the sight distance.

Taking the resolution of the raster file obtained in the process of calculating the viewsheds as  $a$ , which coincides with the resolution of the DTM, the sight distance obtained should be rounded to the nearest multiple of  $a$ , but must be less than the

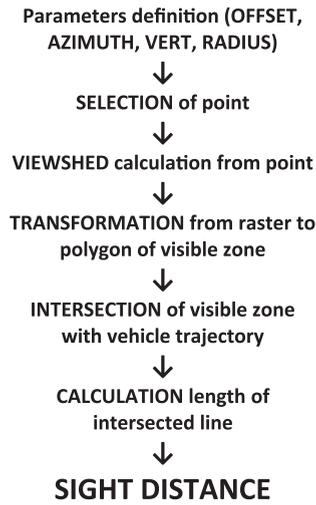


Fig. 1. Sight distance calculation scheme.

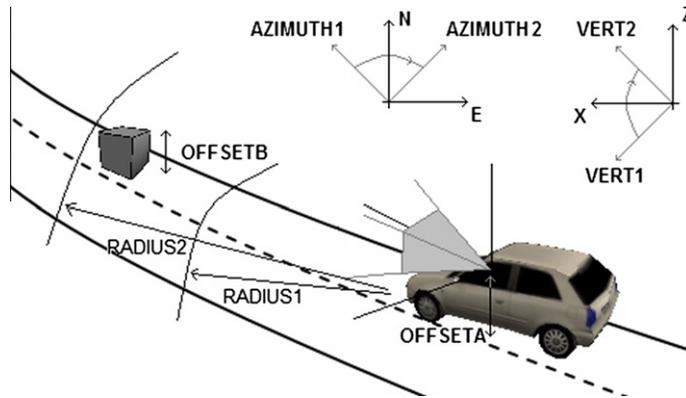


Fig. 2. Sight distance calculation parameters.

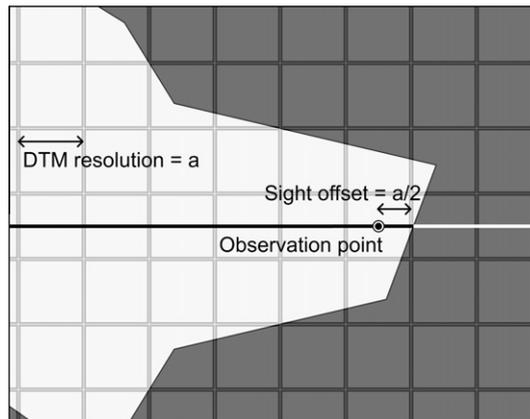


Fig. 3. Excess in sight distance calculation due to raster files resolution.

length obtained by the intersection, since the resolution of the procedure used to measure the sight distance is  $a$ . The sight distances obtained are therefore multiples of  $a$ .

As the theoretical point from which sight distance is computed corresponds with the center of a pixel, and the distance obtained when intersecting the trajectory with a polygon is calculated from the edge of a pixel, the computed distance exceeds the real distance at each end by  $a/2$  (half of the pixel resolution) (Fig. 3).

On the other hand, the transformation process from a raster to a vector model (polygon) could produce small polygons within the visible zone. These polygons, when intersected with the vehicle trajectory, could produce sections without visibility whose length is less than the resolution of the digital model ( $a$ ), as shown in Fig. 4. This deficiency implies that the calculated sight distance would be significantly reduced if at least one of these sections exists. In order to avoid these problems, a buffer on the original polygons with a distance equal to the resolution of the DTM has been introduced to obtain new polygons. As a result, zones with a calculated sight distance lower than the resolution of the DTM disappear, but the new calculated distance is increased by  $a$  at both ends. Therefore, the total distance calculated must be reduced by  $3a$  ( $1.5a = a + a/2$  at each end).

### 3. Case study and procedure validation

The procedure has been applied to the M-607 highway, a two-lane rural highway with a design speed of 100 km/h. It was built in 1996 and is located in Madrid (Spain). The section considered is a 12 km section that runs from East to West. The elevation of the area varies from approximately 835 m, in the middle of the section, to 950 m at the ends. According to the American Design Standard (AASHTO, 2004) this highway could be considered as located on rolling terrain.

Models need the relative position of the driver's eyes: distance to the edge of the road and height above the road surface (Fig. 2). Usually, these values vary from one country to another and over time within the same country. For example, the present Spanish standard (Ministerio de Fomento, 2000) assumes 1.1 m as the height above the road surface, whereas 40 years ago it was 1.2 m. In the same way the present AASHTO guide (2004) takes the height to be 1.08 m, while some years ago it was 1.3 m. Regarding the horizontal position, the Spanish standard (Ministerio de Fomento, 2000) indicates that the trajectory of the vehicle is such that the position of the driver will be 1.5 m from the edge and the American guide (AASHTO, 2004) assumes that the driver is in the centerline of the inside lane. So, as the width of each lane is 3.50 m, according to the Spanish standard (Ministerio de Fomento, 2000) the trajectory of the vehicle will be 2 m away from the highway centerline. In accordance with the Spanish standard (Ministerio de Fomento, 2000), the value of OFFSETA is 1.1 m, because it represents the height at which the driver eyes are located, and so, it is the point from which sight distance is calculated. The value of OFFSETB is 0.2 m, because it represents the theoretical height of the observed object (Ministerio de Fomento, 2000). In Table 1 the values used for sight distance calculation using a GIS are summarized.

In order to estimate grid spacing requirements, an error analysis of the geometric determination of available sight distance on horizontal curves was performed. In these curves, the distance between the nearest visual obstruction and the inner side of the roadway (clearance) is:

$$F = R - (R - b) \cdot \left[ \frac{VD}{2 \cdot (R + b)} \right] \quad (1)$$

where  $R$  is curve radius,  $F$  is clearance,  $b$  is horizontal distance between the driver's eyes and the side of the roadway,  $VD$  is available sight distance and  $\cos$  is cosine. From this equation, the increment in clearance versus an increment in the available sight distance could be expressed as:

$$\Delta F = \frac{\Delta VD}{2} \cdot \sin \left[ \frac{VD}{2 \cdot (R + b)} \right] \quad (2)$$

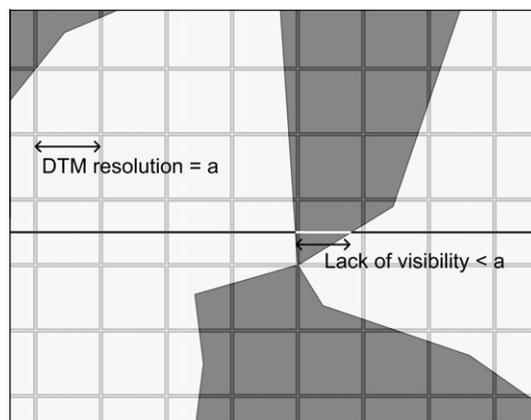


Fig. 4. Loss of visibility in sections shorter than the resolution of the DTM.

**Table 1**

Values used for sight distance calculation with GIS.

OFFSETA (m)	OFFSETB (m)	AZIMUTH 1 (°)	AZIMUTH2 (°)	VERT1 (°)	VERT2 (°)	RADIUS1 (m)	RADIUS2 (m)
1.1	0.2	180	0	90	−90	0	2000

According to the Spanish Standard (Ministerio de Fomento, 2000) the minimum radius allowed on this highway is 450 m and the required sight distance is 180 m. A horizontal error (clearance increment) of 5 m thus corresponds to an available sight distance error of 50 m and a grid spacing of 5 m is therefore used in the DTM.

Regarding the vertical accuracy of the DTM, an estimate of its required accuracy has been made from an error analysis of the geometric determination of available sight distance on crest vertical curves. In these curves, the minimum available sight distance could be calculated using the following formula:

$$VD = \sqrt{-2 \cdot K_v \cdot (\sqrt{h_1} + \sqrt{h_2})} \quad (3)$$

where  $K_v$  is the parameter of the vertical curve and  $h_1, h_2$  are the heights of the driver's eyes and the obstacle respectively. From this equation, the increment in sight distance due to an error in height could be expressed as:

$$\Delta VD = \frac{DD}{\sqrt{h_1 \cdot h_2}} \cdot \frac{\Delta h}{2} \quad (4)$$

where DD is the required sight distance. Using the heights (1.1 and 0.2 m respectively) and the required sight distance (180 m) specified by the Spanish Standard (Ministerio de Fomento, 2000), a height error of 0.26 m corresponds to a sight distance error of 50 m. The vertical accuracy of the DTM used is 0.25 m.

As explained in the previous section, in the calculation of the points visible from a given point, using the Digital Terrain Model (DTM), the spatial resolution of the output raster file coincides with the resolution of the Digital Terrain Model. In addition, since the resolution of the DTM used is 5 m, and the separation between the points considered is also 5 m, the sight distance obtained has been rounded off to a multiple of 5 and all the sight distances obtained are multiples of 5. Because of the resulting problems when transforming models from raster to vector mentioned in the previous section, the total distance must be reduced by 15 m ( $7.5 \text{ m} = 5 \text{ m} + 2.5 \text{ m}$  at each end).

In order to validate the procedure, the GIS calculated sight distances have been compared with those calculated by highway design software (TRIVIUM) (Puy, 2008). This software computes sight distances using a Digital Terrain Model (DTM), the horizontal and vertical characteristics of the alignment (tangents, spirals, circular and vertical curves) and the characteristics of the cross-section. Both procedures use the same DTM, calculation points and parameters (the relative position of the driver's eyes and the height of the observed object).

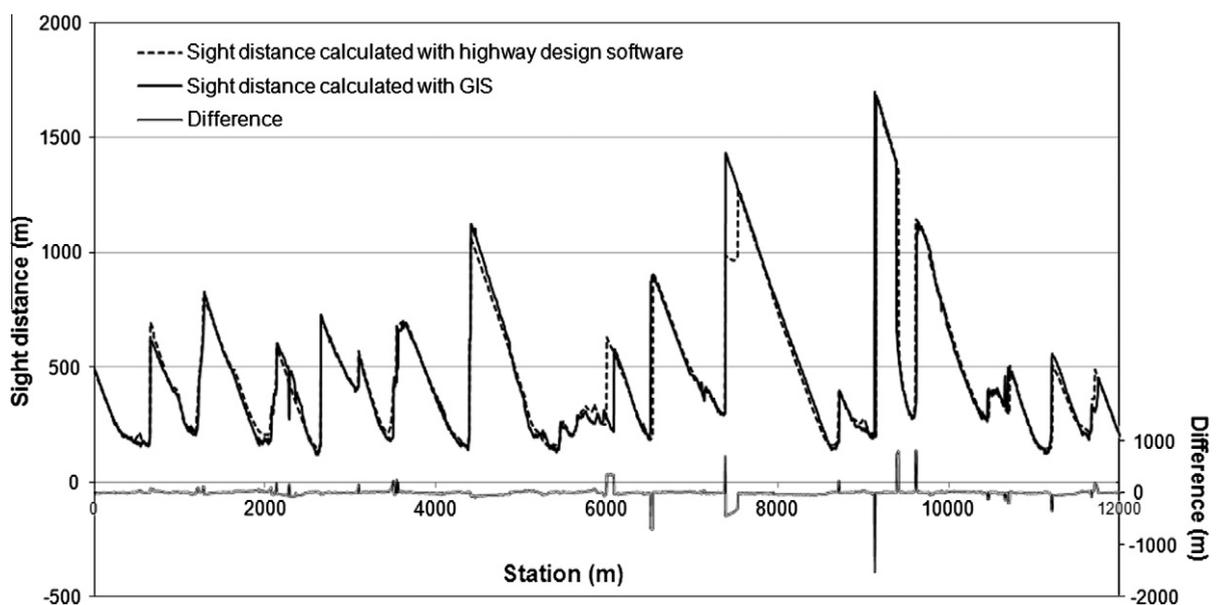


Fig. 5. Comparison between sight distances calculated by both methods considered. (Highway design software versus GIS.)

In Fig. 5 the comparison between sight distances obtained by the proposed method and those obtained using the highway design software is shown. Larger differences between the values calculated by the two methods appear in the vicinity of points where abrupt variations in sight distances take place. However, similar values are obtained by both methods a few meters away (between 30 and 40 m) from the points at which these discrepancies occur.

There are only two zones where the distances calculated by the two methods differ in a relatively long section, in an 80 m long section from kilometer 6.000 to 6.080, in which the sight distance obtained by the highway design software is greater than the distance obtained by the proposed GIS method. As can be seen in Fig. 6, there is a small elevation in this zone (in the Figure the DTM of the zone has been emphasized with a circle), and the lines of sight drawn from the calculation points could thus be blocked. This possible blocking may mean that the proposed method could detect zones without visibility that are not detected by the highway design software.

Similarly, in the section between kilometer 7.385 and 7.535, there is a 150 m long section where sight distances calculated with the proposed GIS procedure are greater than those obtained with the highway design software. As can be seen in Fig. 7, the highway geometry has an “S” design in this zone, where the elevation increases relatively quickly, the highway being above the mean elevation. It is possible that this higher elevation of the highway could be an obstacle to the lines of sight drawn by the highway design software, and this obstacle could explain the lower distances calculated by it.

In order to make a formal validation of the proposed procedure simple statistics for both methods (GIS and highway design software) are determined. They can be seen in Table 2. The comparison between the results of both methods is made in two steps. First, a Kolmogorov–Smirnov test is made to verify that the sight distances calculated using both methods have the same distribution. The result obtained is 0.3567, greater than 0.05. Therefore, both samples come from the same continuous distribution with a 95% confidence interval. Secondly, since the sight distances calculated by both methods have been obtained using the same DTM and at the same points located on the theoretical trajectory of the vehicle, the two samples could be considered as dependent and paired, i.e. there is a correspondence between the samples in each observation. Therefore, a Wilcoxon signed rank test is performed to compare both medians. The result obtained is 0.456469, greater than 0.05. There are thus no significant differences, at 95% confidence interval, between the two methods.

As the Spanish Standard (Ministerio de Fomento, 2000) establishes required sight distances in 50 m increments, calculated sight distances must have an error of less than 20 m. As the difference between the means (1.6 m) is less than the resolution of the DTM (5 m) and less than the resolution established for distance calculation (20 m), it may be concluded that both means are equal and, therefore, the proposed method for computing sight distances can be considered as valid as the method used by highway design software.

On the other hand, the use of GISs in highway sight distance studies has several advantages. Firstly, data sources (such as LIDAR images) that, in addition to terrain, include other obstacles, such as trees or buildings, can be used. Secondly, the use of a GIS allows integrating this sight distance analysis with other analyses related to traffic safety. In this way, more complete analyses could be done and the costs shared. Fig. 8 shows a detail of the analysis done in the case study. By means of the GIS, crashes, design consistency and sight distance have been analyzed. Design consistency refers to the condition in which roadway geometry does not violate driver expectations. Until now, the most frequently used methods to evaluate consistency have been based on operating speed profile analysis. These methods estimate the operating speed at which a typical vehicle can travel along the segment being studied, establishing comparisons with defined criteria. The 85th percentile of a sample of speeds is accepted as a standard estimate for the operating speed at a specific location. Fig. 8 shows two criteria of consistency: the difference in  $V_{85}$  between successive elements (shown with flags) and the difference between  $V_{85}$  and design speed ( $V_d$ ) (shown with different linetypes). In Fig. 8 a zone with several crashes and reduced sight distance has been detected.

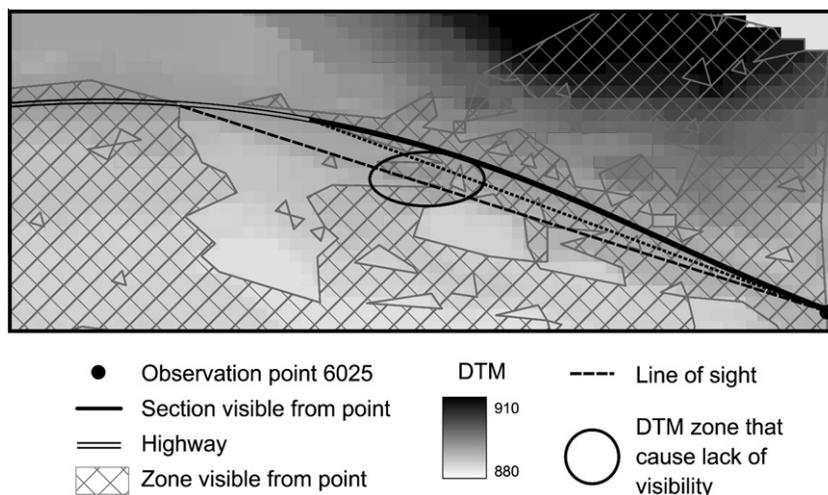


Fig. 6. Zone 1 with different sight distance results depending on the procedure used for calculation. (Highway design software versus GIS.)

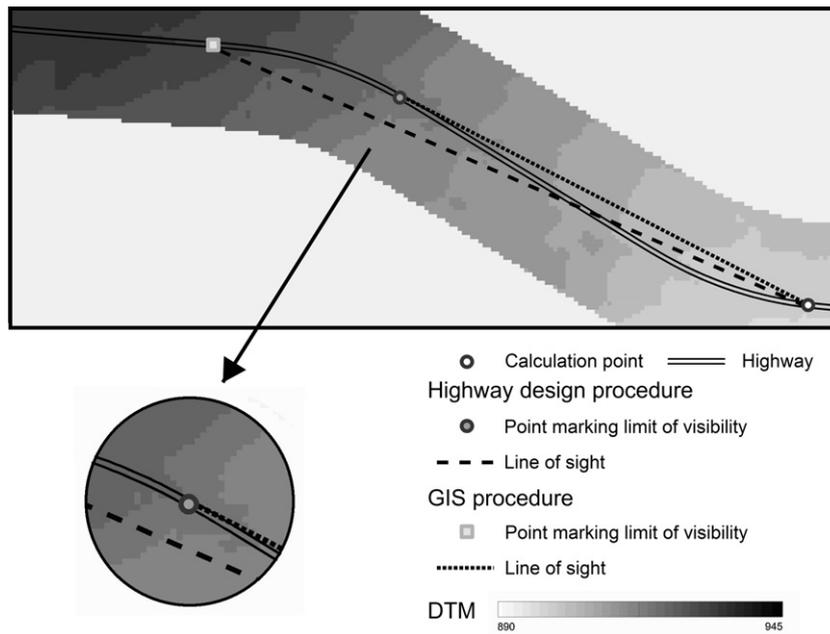


Fig. 7. Zone 2 with different sight distance results depending on the procedure used for calculation. (Highway design software versus GIS.)

Table 2

Simple statistics of the sight distances calculated.

	Highway design software	GIS	Sight distance obtained with GIS at points determined by GPS
Number of observations	2401	2401	597
Mean	471.037	472.638	460.268
Variance	83900.424	92245.004	86731.220
Standard deviation	289.655	303.719	294.502
Mean standard error	5.911	6.198	12.053
Maximum value	1680	1700	1675
Median	395	390	385
Mode	160	210	290
Minimum value	145	120	115

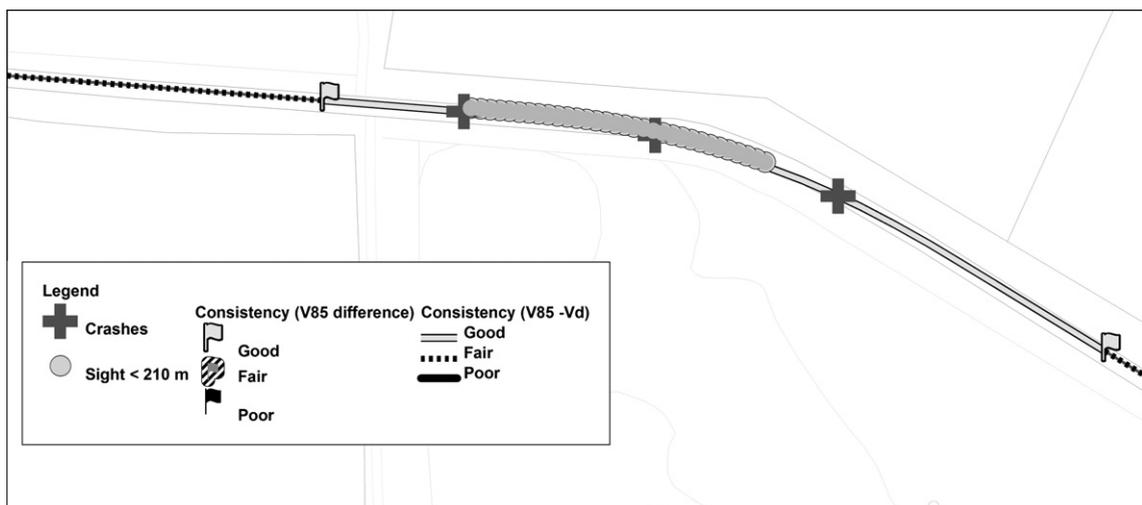


Fig. 8. Detail of the GIS case study. Zone with short sight distance and crashes.

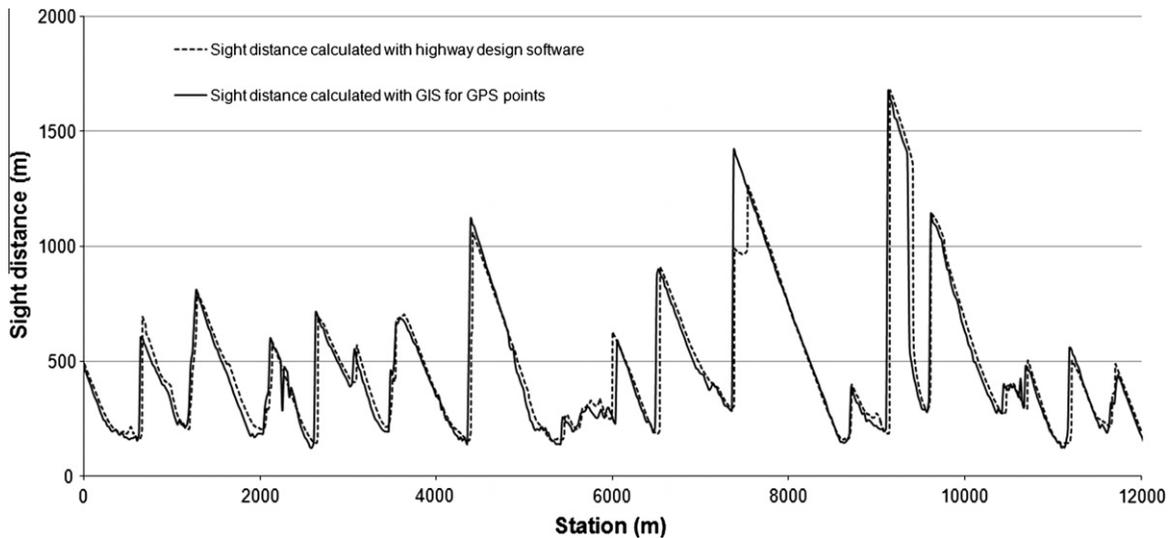


Fig. 9. Comparison between sight distances calculated by the highway design software and, at the points determined by GPS, by the method proposed.

#### 4. Analysis of sight distances without project information

The proposed method could also be used to calculate sight distances in highways where design information (characteristics of tangents, spirals, circular and vertical curves) is not available or is not up to date, as for example in many already built highways.

Castro et al. (2006) have proposed a method to obtain a highway centerline using GPS data, which also provides an estimate of the accuracy of the highway centerline obtained. This method has been applied to the highway under study to estimate the highway centerline and, from it, the points needed to make the sight distance analysis.

Data was gathered with a Leica System 500 GPS from a vehicle traveling at an approximate speed of 80 km/h, so points recorded with the GPS receiver are, approximately, 20 m apart from each other. The nameplate mean square error of this device with post processing of L1 code is 30 cm. The measurement technique applied was kinematic mode after a static known point initialization (KPI). C/A code and full-wave carrier phase were processed with no loss of lock. The PDOP value was between 6.9 and 2.1 with an average value of 4.8. The number of satellites available during observation was between 8 and 9. The obtained highway centerline has an accuracy of 0.68 m.

In order to calculate sight distances from the GPS-determined points, they have been placed on the Digital Terrain Model (using only the horizontal information provided by the GPS). Next, the proposed procedure (GIS based) has been applied to these points. For this purpose, both the driver's eyes and the obstacle are placed, following the Spanish standard (Ministerio de Fomento, 2000), in the same relative position (Fig. 2) as in the previous case presented, OFFSETA = 1.1 and OFFSETB = 0.2 m respectively. In Table 2, simple statistics for the sight distances calculated with the proposed method at these GPS-determined points are shown.

Fig. 9 shows the results obtained with the highway design software and with the proposed GIS method using GPS defined points. In order to analyze the usefulness of the proposed method when highway design data are not available, a comparison has been made between the results of sight distance analysis using this method and using highway design software. As in the previous case, the comparison between the results of both methods is made in two steps. First, a Kolmogorov–Smirnov test is made to verify that the sight distances calculated using both methods have the same distribution. The result obtained is 0.0997, greater than 0.05. Therefore, both samples come from the same continuous distribution at 95% confidence interval.

As the calculation points used are not the same in both methods, a Mann–Whitney  $U$  test for independent samples has been performed. As can be observed, the difference of the medians (10 m) is greater (two times) than the resolution of the MDT (5 m) but less than the resolution established for distance calculation (50 m following the Spanish Standard). The  $U$  value obtained is 0.158578, greater than 0.05. Thus, there are no statistically significant differences, at 95% confidence interval, between both medians. Therefore, the proposed method could also be considered valid to estimate sight distances using information on the trajectory of a vehicle obtained by a GPS device and a Digital Terrain Model with an appropriate resolution.

#### 5. Conclusions

Sight distance estimation using a GIS has proved its viability. The distances obtained using this approach and the classic approach, through highway design software, are statistically the same.

In the case of existing highways, the proposed procedure has an advantage over highway design software since it could be integrated with other road safety analyses. In this way, more comprehensive studies could be easily carried out. Specifically, joint analyses of sight distance, crashes and design consistency have demonstrated synergies.

In addition, this method could be applied using GPS data instead of highway design data. Therefore, sight distance analysis, could be made not only for new highways whose design data were readily available but also in highways that are in service regardless of the availability and quality of their design data.

Moreover, if digital surface models, which take into account side obstacles not considered by highway design software, are available, the proposed procedure could produce more realistic results than highway design software. These digital surface models could be obtained using sensors such as LIDAR (Light Detection and Ranging).

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