Spatial analysis of geometric design consistency and road sight distance

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Because of the high number of crashes occurring on highways, it is necessary to intensify the search for new tools that help in understanding their causes. This research explores the use of a geographic information system (GIS) for an integrated analysis, taking into account two accident-related factors: design consistency (DC) (based on vehicle speed) and available sight distance (ASD) (based on visibility). Both factors require specific GIS software add-ins, which are explained. Digital terrain models (DTMs), vehicle paths, road centerlines, a speed prediction model, and crash data are integrated in the GIS. The usefulness of this approach has been assessed through a study of more than 500 crashes. From a regularly spaced grid, the terrain (bare ground) has been modeled through a triangulated irregular network (TIN). The length of the roads analyzed is greater than 100 km. Results have shown that DC and ASD could be related to crashes in approximately 4% of cases. In order to illustrate the potential of GIS, two crashes are fully analyzed: a car rollover after running off road on the right side and a rear-end collision of two moving vehicles. Although this procedure uses two software add-ins that are available only for ArcGIS, the study gives a practical demonstration of the suitability of GIS for conducting integrated studies of road safety.

Keywords: geographic information systems; spatial analysis; visibility analysis; digital elevation or terrain models; global positioning

1. Introduction

Because of the high number of crashes occurring on roads, it is necessary to intensify the search for new tools that help in understanding their causes. In recent years, many researchers have focused their attention on geometric design consistency (DC), which is defined as the relationship between the geometric characteristics of a highway and those that the driver expects to encounter. In their perception of such characteristics of the road, drivers are influenced, on the one hand, by the experience of what they have found in the road section they have just travelled, and, on the other, by the accumulated experience gained in previous trips with similar characteristics to the current drive. Since motorists adapt the way they drive to the geometric conditions they encounter, good DC reduces the likelihood of errors and unsafe maneuvering while driving. For example, a long tangent followed by a sharp curve in a road placed on level terrain does not match drivers' expectations, which could be a dangerous situation. Several studies have shown that lack of consistency is related to traffic accidents (Voigt 1996, Wu *et al.* 2013, Oña *et al.* 2014).
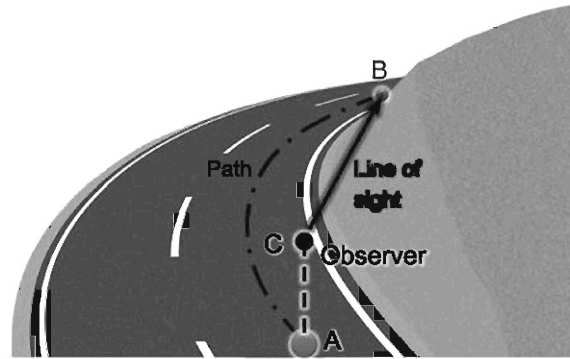
Figure 1. 3D view of ASD (arc AB, along the road), LOS (segment CB) from observer's eyes to the object, height of observer's eyes (segment AC).

Another cause of traffic accidents is related to available sight distance (ASD). ASD is defined as the distance that the driver can see along the vehicle path on the road (arc AB in Figure 1). This distance allows drivers to obtain information about the driving environment in real time, adapting the way they drive to the circumstances of the road and its surroundings. Segment AB is a vertical offset which represents observer height. Segment CB is the line of sight (LOS) and goes from the observer (driver's eye) to the road surface. Note that ASD (arc AB in Figure 1) and LOS (segment CB in Figure 1) are related, but different, concepts. ASD is of major importance when hazardous maneuvers must be performed, such as overtaking or emergency braking. Several studies have shown the existence of a direct link between accident rate and insufficient ASD (Sparks 1968, Silyanov 1973, Urbanik *et al.* 1989, Steinauer *et al.* 2002). Since the 1990s, geographic information system (GIS) researchers have developed algorithms for determining visibility and viewsheds (the area which is visible from a particular viewing location) (Fisher 1993, De Floriani and Magillo 1994, Wu *et al.* 2007, Tabik *et al.* 2013, Zhao *et al.* 2013). Several topics related to visibility have been studied, such as the effects of digital elevation model (DEM) resolution or vegetation on viewsheds (Fisher 1996, Ruiz 1997, Berry and Kidner 2005, Llobera 2007, Murgoitio *et al.* 2013). While ASD (arc AB in Figure 1) and visibility are related, they are different concepts, and for geometric road design, it is important to know ASD. For instance, if there is an object in the roadway (dead animal, rock), drivers should see it from a distance (arc AB in Figure 1) greater than the stopping distance. Also, in case of several viewsheds from a particular viewing location, ASD only corresponds to the nearest viewshed to the driver. For instance, Figures 2a–2c show the case of a sight-hidden dip. There are two viewsheds separated by a hidden section and ASD is the distance AB (not the distance AD). This case, in which drivers see a road section followed by a hidden section and a second visible section, is potentially dangerous for road safety. To study cases like this, it is necessary to know the lengths of the sections involved (AB, BC, and CD in Figures 2a–2c). Viewsheds are not relevant for these analyses. Only recently have ASD calculations using GIS been considered (Castro *et al.* 2011, 2014). The development of Castro *et al.* (2014) is computationally more efficient and complete than the 2011 version. It has, for example, a specific tool for studying sight-hidden dips based on analysis of the sight distance diagram (Figure 2d).
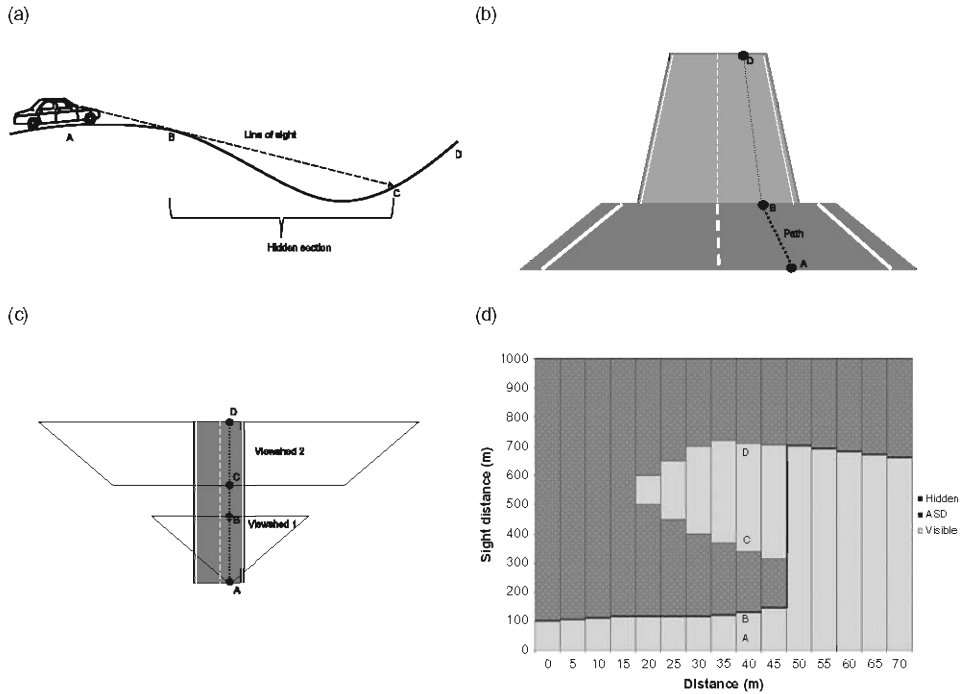
Figure 2. Sight-hidden dip: (a) profile view: road hidden section (BC); (b) 3D view of the sight-hidden dip; (c) plan view showing two different viewsheds; (d) sight-distance diagram showing visible section AB, hidden section BC, and the distant visible section CD.

The potential of GISs in spatial analyses and the increasing number of road inventories supported by a GIS, including traffic data and crash rates, suggest that the GISs can be a useful tool for safety studies (Steenberghen *et al.* 2004, Mountrakis and Gunson 2009, Mohaymany *et al.* 2013, Quddus 2013). However, these safety studies based on GISs do not usually consider DC or ASD. This may be due to the fact that the efficient calculation of DC and ASD requires specific tools. The aim of this research is to explore the use of GISs for integrated analysis, taking into account crashes and factors related to geometric road design, such as DC and ASD. In this way, the possible connection between a crash and poor DC and/or not enough ASD can be more easily studied.

The first part of this paper summarizes the whole procedure and how DC and ASD were calculated with GIS (through two software add-ins). The next part describes the experimental study. More than 100 km of roads and 500 crashes were analyzed. The results show that DC and ASD could be related to crashes in approximately 4% of cases. The potential of GISs is highlighted through the analysis of two crashes: a car rollover after running off road on the right side and a rear-end collision of two moving vehicles. Finally, conclusions and some ideas for future work are presented.

2. Procedure

An integrated analysis of different aspects linked to traffic safety (crash occurrence, ASD, and DC) was performed using ArcGIS 10 (ESRI, Redlands, CA, USA). Figure 3 (flow-chart) describes the whole procedure. A GIS of the study area is built. A digital terrain
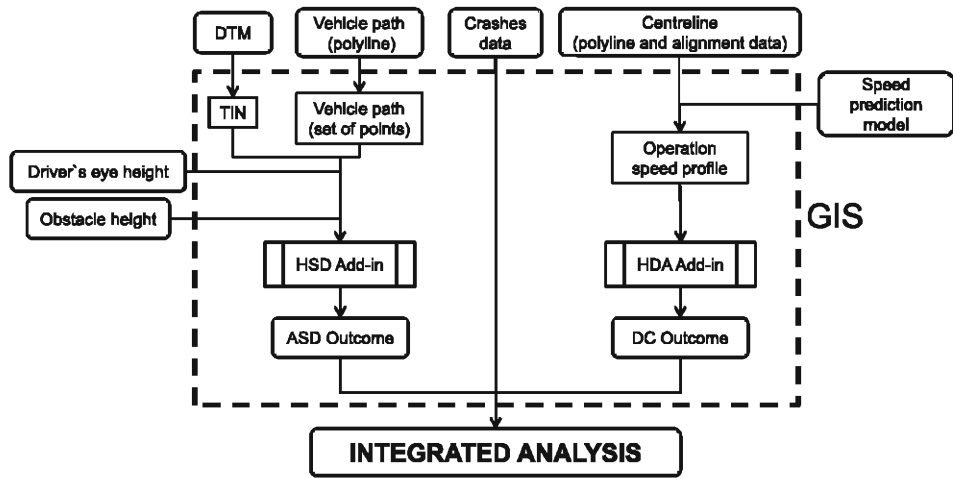
Figure 3.   Procedure flowchart for road safety analysis integrating ASD, DC, and crashes.

model (DTM) (bare ground), a vehicle path (polyline), a road centerline (polyline and alignment data), and crash data (location and characteristics) are integrated in the GIS. From the DTM, a triangulated irregular network (TIN) is generated using the 'Create TIN' tool from the TIN management Toolset in ArcToolBox/3D Analyst. From the polyline that represents the vehicle path, a set of points is extracted using the standard shapefile editor available in ArcGIS. ASD is calculated using the software add-in, Highway Sight Distance (HSD), implemented in ArcGIS (Castro *et al.* 2014). This calculation uses the following data: the TIN, points of vehicle path, driver height, and obstacle height. The add-in allows either 2D (x, y) or 3D (x, y, z) points to be used for the vehicle path. Users must indicate whether they are 2D or 3D points. If they are 2D points, the add-in takes as z-coordinate the corresponding coordinate on the TIN surface using the 'Surface Spot' tool from the Functional Surface Toolset in ArcToolBox/3D Analyst. After performing the calculations, several shapefiles and graphs are generated. The DC study was performed using the Highway Design Analysis (HDA) software add-in implemented in ArcGIS (Castro *et al.* 2008b). The DC study consists of three stages: speed profile calculation, evaluation of consistency, and representation of consistency (shapefiles). In order to get a speed profile, a speed prediction model is needed. Crash data are also stored in a database and displayed as shapefiles. Finally, as the analyses of all data and the results previously commented are on the same software platform, an integrated analysis is carried out. In what follows, a more detailed explanation of how the DC and ASD studies are performed is provided.

The DC study was based on speed profile analysis. This methodology was chosen as it is the most widely used (Krammes *et al.* 1995). The speed profile (Figure 4) represents the operating speed that most vehicles would not exceed when travelling. The 85th percentile of a sample of speeds is accepted as a standard estimate for the operating speed at a specific location (AASHTO 2011). Figure 4 shows a speed profile (V_{85}) which corresponds to a road section comprising a tangent followed by a curve with radius R_1, another tangent thereafter, then a curve with radius R_2, and finally a third tangent. Assuming that vehicles travel along the first tangent (speed $V_{\text{tangent 1}}$), before reaching the first curve, the drivers will reduce speed (deceleration line in Figure 4), driving at speed V_{curve1} and, just after leaving curve 1, they will accelerate (acceleration line in Figure 4).
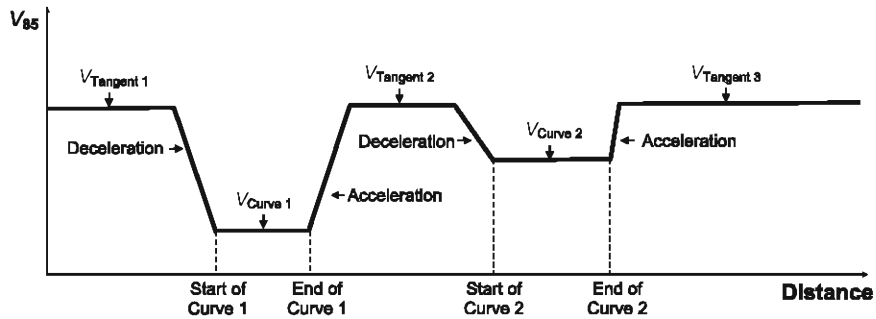
Figure 4.   Operating speed profile showing V_{85} along a road section.

There are several criteria to evaluate DC through speed profile analysis. The most widely used criterion, supported by road traffic accident studies, evaluates DC between successive elements (tangents and curves) (Lamm *et al.* 1995):

- good design: if the difference in V_{85} between successive elements is ≤10 km/h;
- fair design: 10 km/h < difference in V_{85} ≤ 20 km/h; and
- poor design: 20 km/h < difference in V_{85}.

Another very extensively used criterion to evaluate DC is the comparison between the operating speed and the design speed (used for road design) (V_d) (Lamm *et al.* 1988):

- good design: if the difference between V_{85} and V_d is ≤10 km/h
- fair design: 10 km/h < ($V_{85} - V_d$) ≤ 20 km/h
- Poor design: 20 km/h < ($V_{85} - V_d$)

The DC study was performed using the HDA software add-in implemented in ArcGIS (Castro *et al.* 2008b). The procedure followed several stages. First, the speed profile was determined (i.e. the variation of V_{85} along the section studied). For this purpose, alignment data as well as an operational speed model including the values of basic parameters involved in the model are required. The software enables users to define a formula for speed prediction (e.g. $V_{85} = A - B/R$, R being the radius of circular curves, and A and B are constants). In addition, the HDA user must define other basic parameters (several speeds, in km/h, and an acceleration and deceleration rate, in m/s^2) to fully determine the speed model:

- Minimum speed: This is a lower threshold required to avoid unrealistically low values for speed. The threshold depends on the type of road, design speed, and user criteria.
- Maximum speed: This is an upper threshold value to avoid unlikely high-speed values. It is frequently assumed that this speed equals posted speed. This value depends on the type of road, the design speed, and user criteria as well.
- Initial and final speed: These speed values are the most likely speed at which the driver starts or ends the section. For instance, they predict speed when the vehicle either comes from or encounters an urban crossing or a roundabout.

- Acceleration and deceleration rates: These are defined to link horizontal alignment elements with different V_{85} (between a tangent and a curve or between curves of different radii).
- Desired speed (V_{des}): It is the speed the driver aims to achieve in long tangents. When the model formula is of the type $V_{85} = A - B/R$, R being the radius of circular curves, and A and B constants, by default, the software takes $V_{des} = A$.
- Design speed (V_d).

Once the speed profile has been defined, DC is evaluated according to the aforementioned criteria: criterion 1, the difference between V_{85} and design speed, and criterion 2, the difference between speeds of successive alignment elements. According to criterion 1, the results are presented on the road centerline, by means of a color code. In the case of criterion 2, flags are depicted on each curve or tangent using the same color code.

The ASD study has been performed using the HSD software add-in developed for ArcGIS (Castro *et al.* 2014). Sight distance is calculated by determining the first point on the path (2D or 3D points), which is not visible from the location of the driver. The algorithm uses the 'GetLineOfSight' extension of ArcGIS '3D Analyst'. To carry out sight distance calculation with GIS, the vehicle path (AB in Figure 1 and AD in Figure 2) and a TIN are needed. The vehicle path along the roadway can be estimated assuming that the vehicle is at a fixed distance from the shoulder or from the road centerline. Also, the true path of the vehicle can be used, provided it is obtained by means of Global Positioning System (GPS) devices. Throughout this set of 3D points, a polyline was obtained using the 'Make polylines from points' tool from the Xtools Pro extension for ArcGIS. From the polyline that represents the vehicle path, a discrete path comprising stations spaced 5 m apart is extracted using the standard shapefile editor available in ArcGIS. The height of the driver's eye and the height of the target obstacle are also required. ASD calculation is made through two loops. The outer loop places a virtual observer (at the height of the driver's eye) at each station of the path. The inner loop launches lines of sight towards the stations (at the height of the target obstacle) ahead of each position of the virtual observer. Each LOS retrieves a Boolean value (seen or unseen), which is stored. When the first invisible station is reached from a particular position of the observer, ASD has been determined and equals the curvilinear distance between these two stations.

Sight distance outcome is depicted in a chart called sight-distance diagram. The horizontal axis provides information about the stations where the driver is placed, whilst the vertical axis shows the distance ahead from each station along the vehicle path. Within the chart seen stations and unseen stations are shown in different colors (Figure 2d: seen stations in light gray and unseen stations in dark gray). Additionally, this chart is capable of highlighting a common geometric design shortcoming called sight-hidden dips. They occur when a driver is able to perceive simultaneously two separate sections of the road, yet not the one in between (Figures 2a and 2b). This perspective defect may come from either a sequence of a crest and a sag curve in the vertical alignment (profile view) or from a string of curves in the horizontal alignment (plan view) where the inner roadside is flanked by obstacles, such as cut-side slopes, vegetation, walls, or buildings.

A different approach for considering sight distance in the analysis is the inverse sight distance or target-seen distance (i.e., the farthest distance along the vehicle path from which a target is seen by the driver). This target-seen distance is very useful when studying the possible causes of an accident, since crash databases usually contain information about where the crash occurred. This datum is particularly interesting whenever a crash between vehicles takes place on the roadway.

3. Experimental results and discussion

An integrated analysis of different aspects linked to traffic safety (crash occurrence, ASD, and DC) was performed in two-lane rural roads located in the Madrid region (Spain). Several roads were chosen, featuring different geometric design parameters, different traffic flows, and located within flat, rolling, or hilly terrains. The study area comprises around 200 km^2. The maximum altitude is 1524 m and the minimum 530 m. It includes river valleys and mountains. The design speed of the roads ranges from 40 km/h to 100 km/h, the roadway widths were 4.7 m and 7 m, radii ranged from 8 m to 4600 m, whilst vertical gradients reached a maximum of 10% (one case). The length of road analyzed was 112 km. All calculations and analysis were carried out with GIS.

For this study, data was compiled on crashes occurring over a 13-year period (between 1998 and 2011) on the aforementioned roads. A total of 585 cases were studied, for which the relevant reports drawn up by traffic police were available. These reports contain information of the circumstances involved in each case (daytime or nighttime, number of vehicles involved, meteorological conditions, etc.), as well as the location, and they form the crash database in the GIS.

The DC study was performed using the HDA software add-in, implemented on ArcGIS (Castro *et al.* 2008b). For the speed model, a Spanish model developed within the same zone has been utilized (Castro *et al.* 2008a) (Equation (1)):

$$V_{85} = 120.16 - 5596.72 \, / \, R \tag{1}$$

where R is the radius of the circular curves of the horizontal alignment (plan view) and V_{85} is the operation speed for each curve.

The ASD study was performed using the HSD software add-in developed for ArcGIS (Castro *et al.* 2014). Vehicle path was based on data collected by a GPS mounted in a vehicle travelling along the highway. The receiver antenna was mounted on the top of the vehicle, threaded into a robust magnetic base. Throughout this set of 3D points, a polyline was obtained using Xtools Pro extension for ArcGIS, as previously described. From the polyline that represents the vehicle path, a discrete path comprised of stations spaced 5 m apart was extracted using the standard shapefile editor available in ArcGIS. Also, DTMs defined by a regular grid, spaced 1 m or 2 m apart, were utilized, building up a surface defined by the TIN through the 'Create TIN' tool from the TIN management Toolset in ArcToolBox/3D Analyst. As previously mentioned, the add-in allows the use of 2D or 3D points. In this study, although 3D points were taken with a GPS, their z-coordinate was ignored (i.e., they were used as 2D). In order to achieve a better understanding, several orthophotos of the study area were included in the GIS. According to Spanish geometric design guidelines, ASD calculation was performed assuming the height of the driver's eye to be 1.1 m and the height of the target obstacle to be 0.2 m (Ministerio de Fomento 2000).

By means of GIS, a spatial analysis was performed, determining which accidents in the database occurred in segments where either DC is classified as poor or visibility conditions are deficient. After this preliminary analysis, the number of cases to be considered fell to 109 crashes. Next, the concurrent circumstances in each case were studied, as well as the type of crash, resulting in 18 cases where the authors consider deficient visibility may have been one of the factors involved in the collision, 8 cases in

which poor DC could be a factor, and one more case in which both factors might have influenced the crash. These represent 4.3% of the whole sample considered.

In this section, two cases will be fully analyzed as illustrative examples:

- Case A: Car rollover after running off the road on the right side
- Case B: Rear-end collision of two moving vehicles

3.1. Case A: car rollover after running off the road on the right side

Figure 5a shows a section of road where an accident took place, at station 12,850 m eastbound. After driving along a tangent of 770 m, the car tips over onto its roof on the right roadside of a curve. The position of the crash is highlighted by a cross in Figure 5a. The speed profile determined by HDA software indicates that operative speed along the
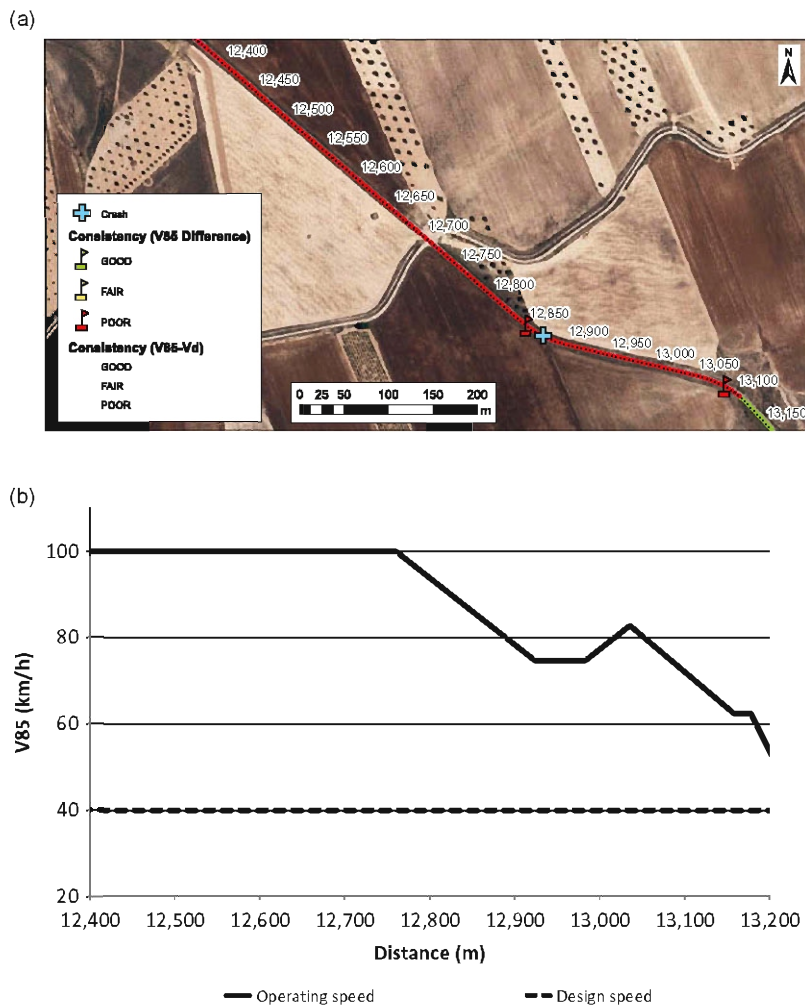

Figure 5. DC analysis of case A: (a) plan view showing crash location and the results of DC analysis; (b) speed profile used for DC analysis.

tangent reaches 100 km/h, whilst the speed for the circular curve was 75 km/h (Figure 5b). Since the speed gap is greater than 20 km/h, DC is 'poor' according to criterion 1. Therefore, in Figure 5a, there is a dark gray (red in online version) flag between the first tangent and the beginning of the curve. On the other hand, the speed reached along the tangent (100 km/h) is much higher than the design speed of the road (40 km/h), which shows that DC is also 'poor' according to criterion 2. Within the GIS map, element classification is linearly depicted on the centerline according to the second criterion, and the dark gray (red in online version) segments indicate elements where differences in speed are greater than 20 km/h (Figure 5a).

Given that the results of ASD calculation are available within the GIS, the integrated analysis is simple and effortless. As can be seen in Figure 6a, the vehicle travelling eastbound first runs along a tangent where ASD is greater than 200 m, illustrated by the light gray (green in on-line version) segment on the road centerline. ASD drops gradually below 100 m (depicted in dark gray (red in online version)) as the driver approaches the first curve, and it rises again afterwards. Neither the sight distance diagram (Figure 6b) nor the vertical alignment (profile view of the section) (Figure 6c) evidences the existence of sight-hidden dips. Although ASD decreases in the vicinity of the curve, the type of
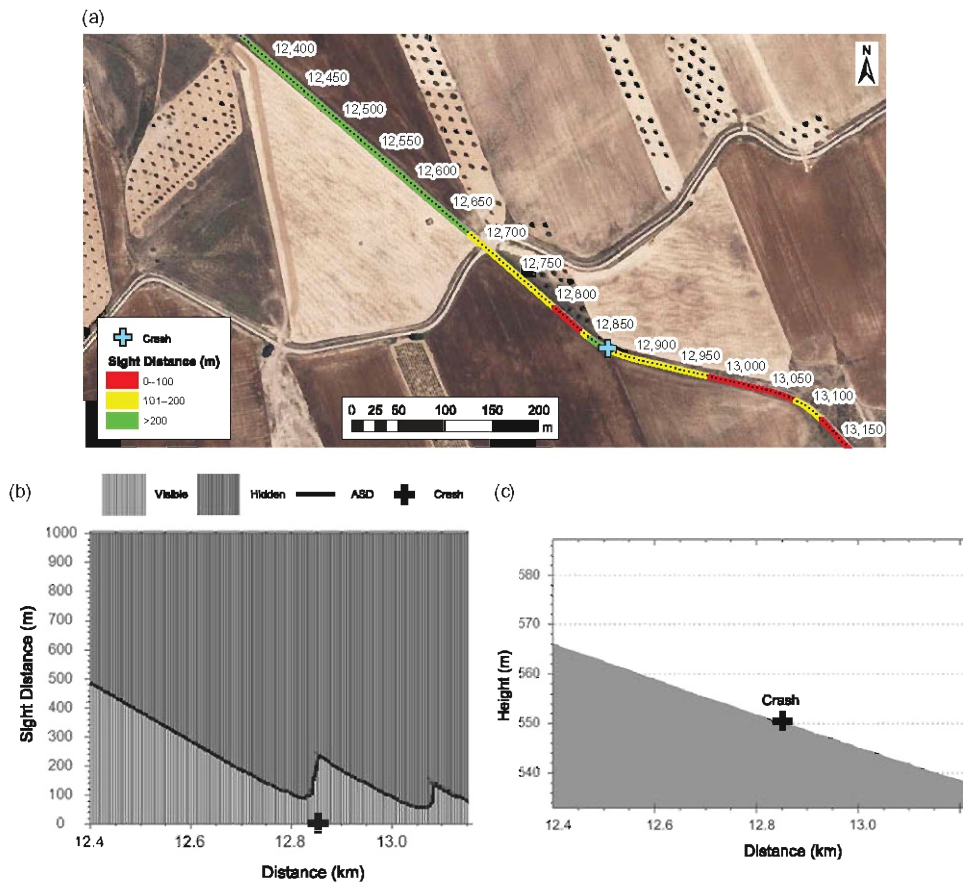

Figure 6.   ASD analysis of case A, showing crash location: (a) results of ASD analysis over a plan view; (b) sight-distance diagram; (c) road vertical alignment (profile view).

crash (rollover after running off the road on the right side) would allow one to dismiss the possibility that poor visibility conditions might have influenced the accident.

3.2.   Case B: rear-end collision of two moving vehicles

A collision which occurred between two moving vehicles is now analyzed. They were both travelling eastbound (Figure 7), and the crash took place within their own lane. It happened in the vicinity of a very large radius (3000 m) curve at a time when the road surface was dry and clean. Since the accident location was station 1270 m, the section between stations 900 m and 1400 m was analyzed.

Figure 7 shows the outcome of DC analysis of the section involved. The difference between the speed profile and design speed is within the interval 10 to 20 km/h; therefore, DC is classified as 'fair' according to criterion 1 (i.e. medium gray (yellow in online version) strip on the road centerline). The difference between speeds in adjacent elements is smaller than 10 km/h, which is symbolized by means of the light gray (green in online) flags (DC is 'good' according to criterion 2). Figure 7 shows the exact position of the collision by a cross between two light gray (green in online version) flags.

Figure 8a shows the sight-distance diagram of the section. The shape of the seen area indicates the existence of a sight-hidden dip. This phenomenon is first perceived from station 965 m and vanishes at station 1000 m. At the beginning, the driver sees a section of 155 m (ASD), which is followed by a hidden section of 330 m and another seen section thereafter. The hidden section is highlighted in the vertical alignment (profile view) of Figure 8b. As the driver moves forward, the hidden section becomes shorter, until it is finally fully visible for the driver at station 1000 m. The accident location is also emphasized using a cross (Figures 8a and 8b, station 1270 m). When the rearmost vehicle reaches station 965 m, the driver is not able to see the section between stations 1120 m and 1450 m; hence, they could not see part of the traffic travelling in the same direction. Figure 8b demonstrates that the collision took place within the hidden section.

With the help of the speed prediction model (Equation (1)), GIS is able to estimate that the speed at which the driver travels in the curve (radius 3000 m) is
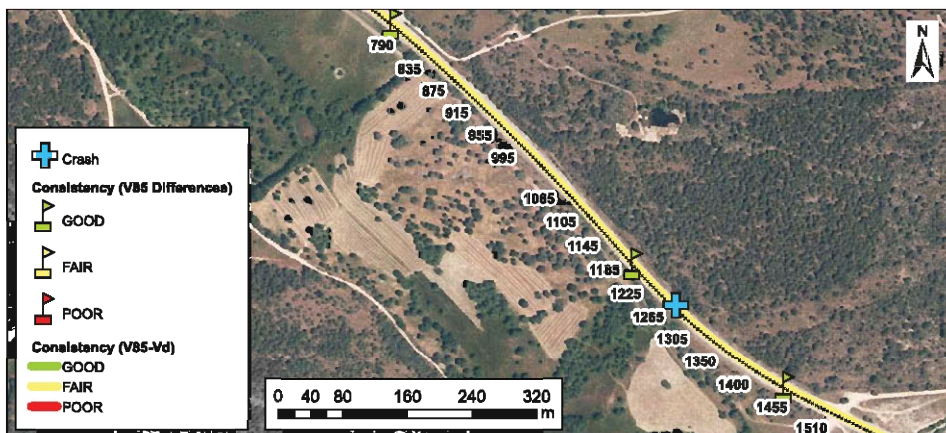

Figure 7.   Case B: plan view showing crash location and the results of DC analysis.
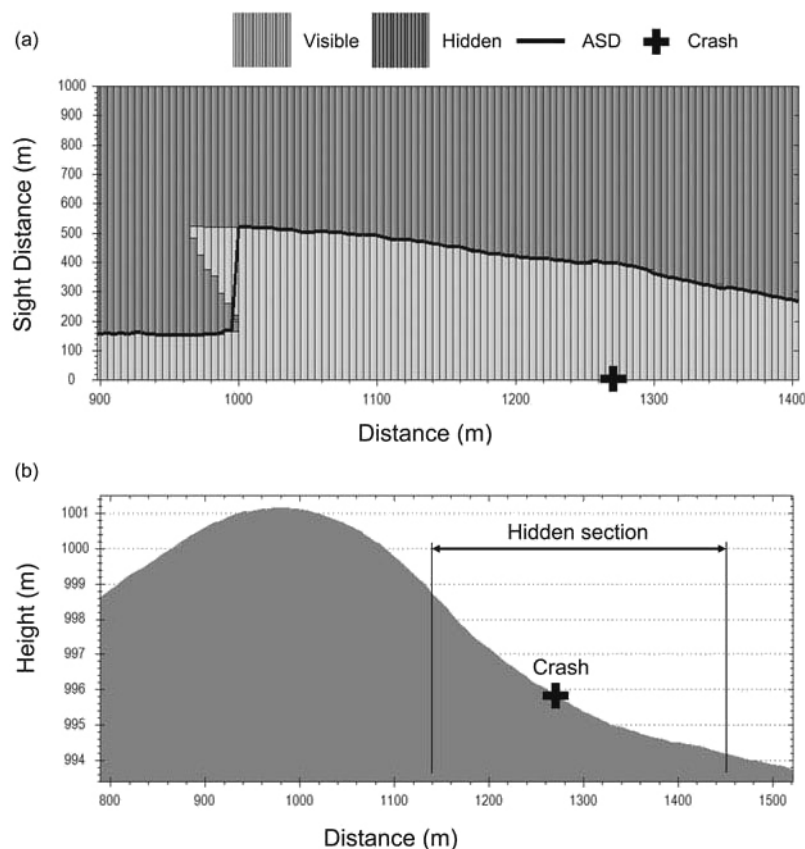
Figure 8. ASD analysis of case B showing crash location: (a) sight-distance diagram; (b) road vertical alignment (profile view) showing the hidden section.

118 km/h. It is also known that the maximum vertical gradient in this section is 2.7%, and stopping sight distance is 273 m (Ministerio de Fomento 2000). In the sight distance diagram (Figure 8a), a continuous black line depicts ASD in each position. When the driver experiences the phenomenon of a sight-hidden dip, (i.e. between stations 965 m and 1000 m), ASD is approximately 150 m, well below the distance needed to perform an emergency stop safely (273 m). As a result, the sight-hidden dip area may be hazardous, because if there were an unexpected obstacle in it, there would not be enough ASD to stop before colliding with such an obstacle. Before station 1000 m, the driver does not see the section where the accident took place, which is actually hidden (Figure 8b).

As mentioned above, the HSD software add-in is also capable of analyzing target-seen distance. In this case, station 1270 m, where the crash took place, is seen from 270 m away, i.e. from station 1000 m (Figure 9). When the driver reaches station 1000 m, they can see a vehicle placed at station 1270 m, but even so, the distance between both vehicles would not be sufficient to carry out an emergency stop safely. Bearing in mind that the consistency analysis revealed that DC is not 'poor', the study suggests that the cause of the accident could be, in some way, related to low ASD.
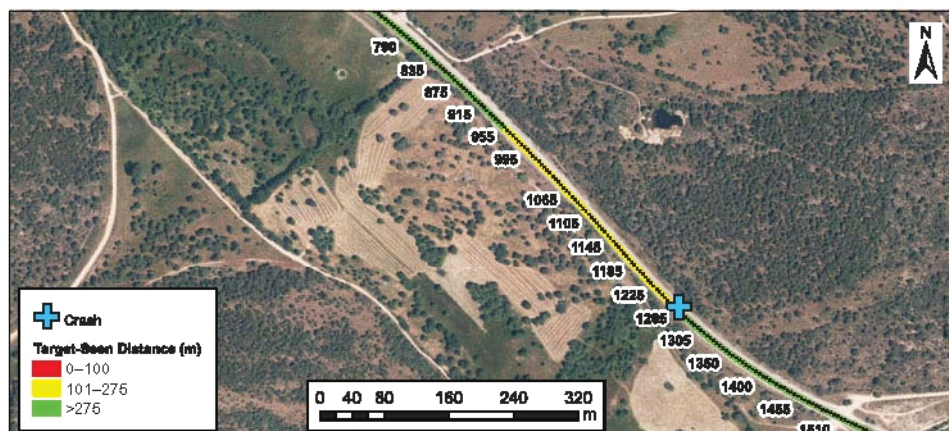
Figure 9. ASD analysis of case B showing crash location and distance from which target point is seen.

4. Conclusions

Geometric DC and sight distance studies can be directly performed using specific tools (HDA and HSD) installed on a single GIS platform. This fact has several advantages. First, the use of the same computing platform simplifies calculation and ensures compatibility of output formats. Furthermore, subsequent analyses of the alignment data and other spatial variables (operation speed profile, DC, ASD, and accidents) are simplified, because they can be performed using the same platform. In addition, the analysis of results is enhanced, since the researcher is provided with a unique spatial system where data are complementary. Thus. the analysis of complex problems is improved, as in those related to the geometric design of roads and traffic accidents. Looking ahead, the fact that all the information is on a single platform simplifies data management and updating. However, this procedure uses two add-ins that are available for ArcGIS only.

This research has shown that several variables useful for traffic safety studies could be determined: speed profile, difference between speeds of adjacent elements, ASD, lengths of road sections that can (and cannot) be seen from each position, and the distance from which a particular position of the road is seen. A detailed study of these variables, in the vicinity of the accidents recorded, has shown that they could be related to crashes in approximately 4% of cases. The study has provided a practical demonstration of the suitability of GIS for conducting integrated studies of road safety. Road network administrators may benefit from this methodology to address the problem of traffic safety caused by possibly poor geometric design. Future research will focus on larger accident and road network databases as well as on the influence of diverse aspects, such as DTM resolution, vegetation, and DSM in sight distance calculations. An enhancement of add-in functionality will also be considered.

Funding

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