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# Sight distance studies on roads: influence of digital elevation models and roadside elements

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## Abstract

Sight distance plays an important role in road traffic safety. Two types of Digital Elevation Models (DEMs) are utilized for the estimation of available sight distance in roads: Digital Terrain Models (DTMs) and Digital Surface Models (DSMs). DTMs, which represent the bare ground surface, are commonly used to determine available sight distance at the design stage. Additionally, the use of DSMs provides further information about elements by the roadsides such as trees, buildings, walls or even traffic signals which may reduce available sight distance.

This document analyses the influence of three classes of DEMs in available sight distance estimation. For this purpose, diverse roads within the Region of Madrid (Spain) have been studied using software based on geographic information systems. The study evidences the influence of using each DEM in the outcome as well as the pros and cons of using each model.

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*Keywords:* Geometric design; Alignment; Digital elevation model; Geographic information system; Sight distance; Traffic safety.

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## 1. Introduction

Drivers ought to have a sufficient available sight distance, among other factors, if succeeding at any possible manoeuver involved in driving is targeted. Different manoeuvers inherent in driving such as emergency stops,

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evasive manoeuvers, passing or merging, require certain room to be carried out effectively and safely. In response to this, guidelines for geometric design of roads in different countries set minimum sight distance threshold values for each of these manoeuvers, depending on design speed (Ministerio de Fomento, 2000; AASHTO, 2004; FGSV, 2012).

Due to its close relationship with traffic safety, available sight distance studies should not take place exclusively at the design stage, but also during exploitation since conditions either of the road itself or by the roadsides might have varied. On certain occasions, in fact, available information about the geometry of the road either does not exist or it is not reliable because such roads have not been executed exactly according to project specifications or due to alterations in the geometry of the road. Moreover, elements by the roadsides might have arisen, such as trees or buildings, after the road was completed, which may obstruct the driver's vision. In addition, roadside equipment (i.e. signals and barriers) could also influence visibility.

In order to calculate available sight distance, which is measured along the theoretical path travelled by a vehicle, two data sets are needed: the vehicle path itself and a model which represents the pavement surface as well as the roadsides. In addition, the height of the driver's eye and the target object height are two fundamental parameters that must be defined.

The aim of this document is to analyze the influence of each type of DEMs for sight distance studies, comparing the output data produced by each.

## 2. Background

In order to facilitate the geometric design of roads, the Spanish guidelines for geometric design of roads (Ministerio de Fomento, 2000), among others, proposes a two-dimensional analytical methodology for available sight distance estimation. Nevertheless, these procedures are not practical since they consider separately horizontal and vertical alignment, which may lead to over- or underestimate actual available sight distance (Hassan, Easa & Abd El Halim, 1997). It is more common instead, to use DEMs and algorithms based on line-of-sight loops to perform this task, using though a 3-D approach. Such procedures retrieve the cross-sectional terrain profile below the line of sight, between observer and target location, identifying any possible obstruction. Besides algorithms based on line-of-sight loops, procedures based on viewsheds have been considered to study available sight distance of roads (Castro, Iglesias, Sánchez & Ambrosio, 2011; Jha, Karri & Kühn, 2011). Concerning the relationship between the presence of elements by the roadsides and visibility, Ismail and Sayed (2007) studied the influence of median barriers on available sight distance.

Computer-aided applications for road design estimate available sight distances and compare them against distances required to carry out specific manoeuvers. They also have visualization tools that simulate the driver's perspective while travelling along the section involved (Kühn, Volker & Kubik, 2011; Castro, 2012). Such visualization tools are utilized to supervise proper 3-D alignment coordination, yet it requires this checking procedure is performed by experienced engineers (Larocca, da Cruz, Quintanilha & Kabbach, 2011).

Moreover, methods based on line-of-sight loops permit to create sight distance diagrams. These charts represent the stations where the driver is sequentially placed on the horizontal axis, and visibility characterization of stations ahead from each position on the vertical axis (Kühn & Jha, 2011; Castro, Anta, Iglesias & Sánchez, 2014). Sight distance studies along vehicle path using such charts have been used not only to compare available and required sight distances but also to evaluate 3-D alignment coordination (Roos & Zimmermann 2004; Jha, Karri & Kühn, 2011; Castro et al., 2014) and to assess geometric design consistency (Altamira, Marcet, Graffigna & Gómez, 2010). The German Road and Transportation Research Association has drawn up guidelines in order to provide recommendations both for virtual image generation and sight-distance diagrams (FGSV, 2008).

Several authors have researched about the effects of insufficient available sight distance on traffic safety (Olson, Cleveland, Fancher & Kostyniuk, 1984; Fink & Krammes, 1995; Fambro, Fitzpatrick & Koppa, 1997; Andueza 2000; Caliendo, Guida & Parisi, 2007). Crash frequency has been observed to be negatively correlated to available sight distance (Sparks, 1968; Sylianov, 1973; Urbanik II, Hinshaw & Fambro, 1989).

DEMs, which are 3-D depictions of the earth surface, are increasingly derived using Light Detection And Ranging (LIDAR) techniques to capture points from such surface. Two classes of DEMs can be distinguished: digital terrain models (DTMs) and digital surface models (DSMs). DTMs, which represent the bare ground surface, are employed at the design stage not only for earthwork estimation and hydrological studies but also for available sight distance estimation, whilst DSMs have been commonly used in landscape modelling, fitting into the road and its environment in principle, better than DTMs do. DSMs provide, in fact, further information about elements by the roadsides which could diminish available sight distance. However, the intrinsic features of DSMs make difficult such sight distance analysis when using entities that do not enable two points on its surface to have the same plan projection while their heights are different. This fact hinders a reliable representation of cantilevered features, which is particularly awkward when they are partially located above the road, as occurs for tree crowns or gantry signs.

Khattak and Shamayleh (2005) have utilized DSMs to estimate available sight distance in roads. In addition, data acquisition using LIDAR to derive DSMs can be done using two different techniques: through airborne LIDAR (Fig. 1) or by travelling along the road in a vehicle, also provided with LIDAR devices.

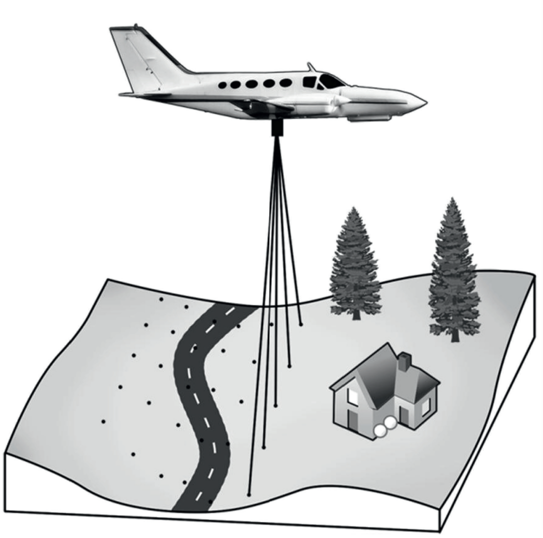

Fig. 1. Sketch of data collecting using airborne LIDAR.

A DEM is represented, when handled within GIS, as a triangulated irregular network (TIN) that satisfies Delaunay triangulation criteria in the horizontal projection (Esri, 2008). First, only the horizontal projection of points is deemed in TIN building; later heights are assigned to each point, creating vertices to build the surface up. This way, an open polyhedral surface is created, consisting of non-overlapped adjacent triangles in such a way that two points on the surface cannot have the same horizontal projection while their heights are different. Although the problem of Delaunay can always be successfully solved in two dimensions, the corresponding problem in three dimensions has not been fully treated (George & Borouchaki, 1998). Hanusch (2010) refers to these sight distance analysis techniques using DEMs as 2.5-D. As an alternative to algorithms that study cross-sectional terrain profiles, Hanusch (2010) proposes a 3-D methodology to study visibility by analyzing triangle overlapping within a surface, and distinguishing which parts of them are viewed and which ones are not.

## 3. Materials and methods

### 3.1. Digital elevation models

Three different types of DEMs have been utilized for this study. First, a DTM derived from a set of points captured through airborne LIDAR. It consists of an evenly spaced grid. Second, a DSM also derived from airborne LIDAR and constant grid spacing. Finally, a DSM obtained through a LIDAR device mounted on a car travelling along the road, whose set of points is irregularly distributed, called Mobile Mapping System (MMS). The models obtained with the set of points captured by airborne LIDAR were not specially scheduled for this study, but they are somewhat available for any purpose. In many of the roads involved in the study, DTMs and DSMs consist of a 1-meter spaced grid, created by the Spanish Geographic Institute within the National Plan of Aerial Othophotography (PNOA) (Ministerio de Fomento, 2010). The models whose grid was derived from airborne LIDAR data for the remaining road have a constant spacing of 2.5 meters.

The set of points used to create MMS DSMs differs from the two others since it was derived from the Mobile Mapping System IPS2-Compact of Topcon (Topcon, 2010). This equipment captures the position of 3-D points from its environment. Such devices are mounted on the vehicle so that the laser beam scopes the roadway and most roadside area: two sideward-oriented laser devices and a third one downward oriented, all of them installed at vehicle rear. Other components of the equipment are used for locating and orientating the survey. The GNSS device provides geospatial position, IMU device provides orientation and odometer the distance travelled, speed and angle of rotation of the vehicle wheels. Vehicle speed during data collection was circa 50 km/h; consequently, the set of points is arranged in 15-centimetre spaced cross sections. Crosswise to the centerline, the set of points is laid out so that points are in close proximity and regularly spread where nearer the scanner, whilst the grid is more irregular and dispersed as the distance to the device increases. As a result, such derived model has a higher density of points and is most highly detailed than a DEM derived from airborne LIDAR.

Due to the different features of each type of DEM, the output after sight distance calculation may result significantly different for the same road. DSMs provide additional information about the shape of the roadside, whose influence in sight distance is to be studied. Therefore, items such as trees, buildings, walls or even road signs are considered in this analysis. However, DSMs inner characteristics entangle the output understanding, hence making sight distance analysis more cumbersome.

As mentioned in previous section, MDS are unable to depict the actual shape of certain elements properly, in particular, items containing through-hole shapes or cantilevered parts, which are especially problematic when located partially above the roadway, as occurs for tree crowns or gantries. In such cases, the set of points had to be edited, filtering points out or modifying the height value for all those points whose horizontal projection falls within the roadway but its height is notoriously higher than the pavement surface. As MMS DSMs are high-resolution models, there are many surveyed elements that should be filtered out. This applies, for example, to overhead power lines, vehicles travelling during the survey or even birds. Such noise can be generally eliminated by deleting these points without entailing a substantial loss of information, due to the high resolution of these models. Nevertheless, as the scanning devices are on the road, the cloud of points could not be dense enough for areas slightly off vehicle track, or certain elements by roadsides could create shadow areas behind them.

### *3.2. Studied roads*

Available sight distance has been analyzed for four sections of 2-lane rural roads located within the region of Madrid (Spain), totaling a length of 56 km. Table 1 shows DEM used to study sight distances in each road. Moreover, sight distance calculation was performed on either direction of each road. Three of these roads are located on rolling terrain, whilst the remaining one traverses hilly terrain. Another important feature is roadway width, which is different for each.

The four road sections evaluated are characterized by having abundant items by the roadsides, which may have influence on sight distance. In these sections, singular zones in terms of sight distance have been found, caused by elements by the roadsides.

Table 1. DEMs used to study available sight distance in each road.

| Road denomination | DTM | DSM | MMS DSM |
|---|---|---|---|
| M-221 | DTM01 IGN | | IPS2 |
| M-325 | DTM01 IGN | DSM01 IGN | IPS2 |
| M-607 | DTM2.5 SC | DSM2.5 SC | |
| M-629 | DTM01 IGN | | |

### 3.3. Software

The analysis of available sight distance of the aforementioned roads was made using geographic information systems (GIS). For this purpose, a specific software application based on line-of-sight loops, which operates embedded in a GIS, was developed (Castro et al., 2014). The input data sets required by the application are basically two: a DEM and vehicle path along the section (de Santos, Anta, Castro & Paréns, 2013). It is also necessary to set values for both the height of driver's eye and the height of target obstacle. According to the Spanish geometric design guidelines (Ministerio de Fomento, 2000), the values of these parameters were 1.1 meters for driver's eye height, and 0.2 meters for obstacle's height.

In order to employ an algorithm based on line-of-sight loops, vehicle path must be deemed discretely, thus 5-metre spaced stations were set along such path, where driver and target are successively placed while performing the loop. From each of those stations where the driver's eye is located the application checks whether a target located in the stations ahead is actually seen or, on the contrary, the line of sight is intercepted by the DEM surface. Since human visual acuity is limited, stations up to 1000 meters far were checked only.

## 4. Results and discussion

First, it was found that the influence of DEMs on available sight distance is negligible within straight sections. This fact was identified in the study of road M-325, where all available DEMs were utilized.

### 4.1. Influence of vegetation

Trees and plants by the roadsides have been found to be the features that reduce available sight distances the most, especially when it comes to forests and densely wooded areas. Roads M-325 and M-629 actually run through a pine forest area, and it is within these zones where editing the points of tree crowns cantilevered above the roadway is essential. Since the horizontal projection of tree crowns overlaps the roadway, the computational procedure builds up a Delaunay triangulation so that a bulge hindering the roadway is created in the DSM resulting therefrom, distorting sight distance estimation in that zone. Hence it is necessary to modify the height value of these points, lowering them down to the pavement height. Comparing the output obtained by using different DEMs, abnormally low sight distances in these critical zones before data processing, are amended after editing the cloud of points.

A section of road M-607 near a mound, which is covered with trees and bushes, is another remarkable study area. Fig. 2 shows the real aspect of the scene, where both the mound and the roadway section seen beyond are pointed. In this case, there is no cantilevered items projected over the roadway, hence a DSM performs a more accurate representation of the scene. According to the study using a DTM, the mound causes an interruption of visibility of circa 40 meters length that ranges along 720 meters. This fact can be observed in Fig. 3, represented by the slim diagonal strip spanning between letters 'a' and 'b', shaded in light grey. Nevertheless, in the study carried out using a DSM, as it takes vegetation into account, hidden section is proved to be larger whilst visible section beyond is much less noticed, a fact more tied in with reality. As it can be seen in Fig. 3, in this section the differences in the results obtained using different MDE are significant not only for available sight distances, but also in the length of the hidden and re-emerged sections where they occur.

### 4.2. Influence of roadside equipment

Roadside equipment items such as signals or barriers located by the roadsides also have influence on available sight distance. In general, these items are fundamentally vertical; therefore they are not detected by airborne LIDAR surveys. Except for considerably large devices, geospatial data of roadside equipment is captured when surveying with terrestrial equipment only (IPS2).

As an exception, it is worth mentioning the case of a single-leg gantry located on road M-607 (Fig. 4). Due to its large size, the DSM derived from LIDAR survey does depict it. In this case, a bulge is created within the DSM due to the Delaunay triangulation constraints, as occurred for tree crowns or overhead power lines, obstructing visibility. Fig. 6 shows how available sight distance falls to 0 as the virtual driver approaches to the gantry in the non-edited DSM (dotted line). As this makes no sense compared to the output using a DTM (dashed line) within the same section, it is essential to process data, editing heights of 3-D points projected on the roadway as explained. Once processed the DSM, available sight distance is represented by the black line in Fig. 5. This is a more realistic output since values for the DSM and the DTM practically coincide.

Fig. 2. Mound causing a hidden section and visible roadway section beyond in M-607.

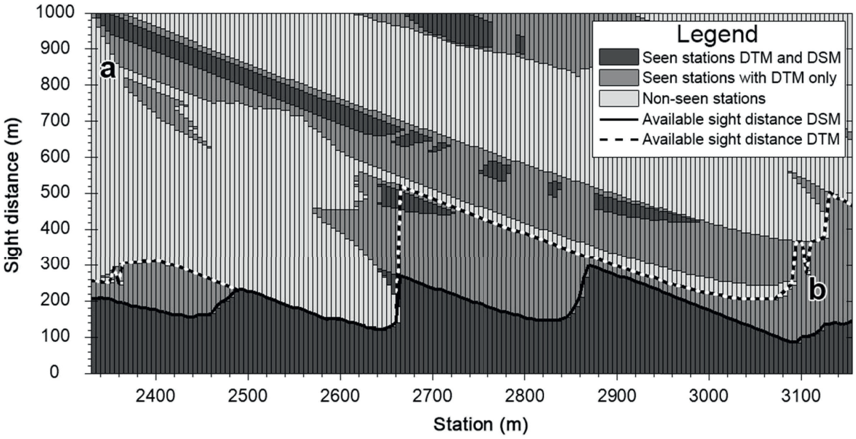

Fig. 3. Sight distance diagram comparison between the outputs of studies using a DTM and a DSM in M-607.

Route confirmation signs and other large traffic signs existing by roadsides have effects on sight distance outcome as well, although these items cause merely small hidden sections (from 5 to 10 meters long). Its influence is more noticeable when they are located at the inner side of a rightward curve and/or just before a sag vertical curve. This fact is ascertained in sections of road M-221 with such equipment, when the sight distance analysis was carried out using a MMS DSM. Several signalization panels are located before a crest curve, having a null footprint on the sight distance diagram. On the contrary, those set at the beginning of a sag curve do produce that some stations ahead cannot be seen from driver's position. Yet not only do large signs have influence on visibility. Also, road signs such as the speed limitation sign depicted on Fig. 6 produces the vertical row of non-seen stations while a driver is around station 440, in the diagram shown on Fig. 7 (marked as 'a').

Fig. 4. Single-leg gantry signal in M-607.

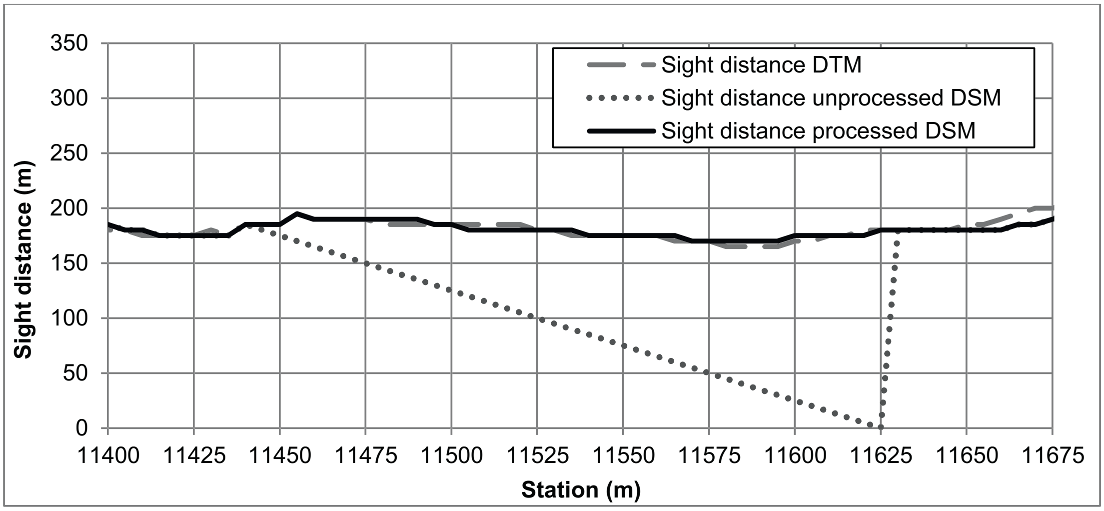

Fig. 5. Results of sight distance calculation near the gantry in M-607.

Another example of roadside equipment that influence on sight distance outcome is safety barriers. Since the height of this item is slightly higher that the target height fixed for the calculation, it is common that, in sections previous to horizontal curves, sight distance drops when using a MMS DSM in comparison with results derived from the DTM. This fact is proved in several sections of road M-221, where the majority of the route is equipped with guard rails. Safety barrier marked in Fig. 6 produces a significant reduction of available sight distance. This is seen by the cavity shaded in medium grey marked with 'b' in Fig. 7. Sight distance hence falls 160 meters along a section of 135 meters (from station 380 to 515). This gap in sight distance come, in one hand, from the fact that the height of barriers is slightly higher than the fixed target to be seen and, on the other hand, from the length of section where such safety device is installed. As a result, safety barriers have a significant influence on sight distance, yet it is highly sensitive to initial parameters since if a higher target height had been set, sight distance decrease would have been lower.

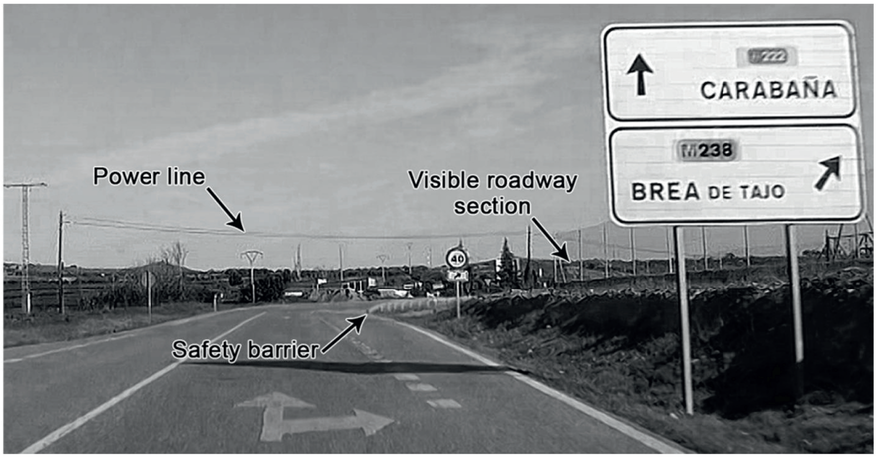

Fig. 6. Items by the roadsides that influence on visibility in M-221.

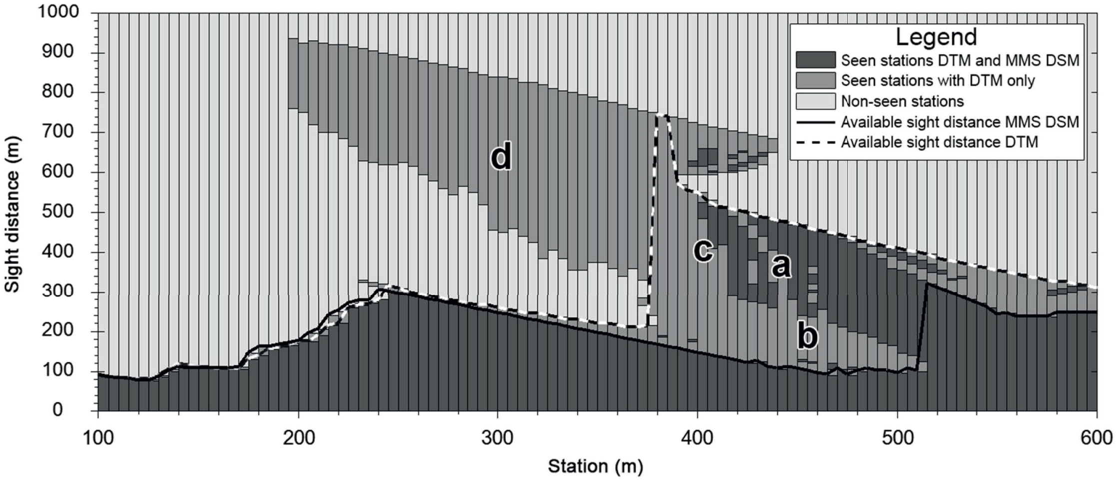

Fig. 7. Sight distance diagram comparison between outputs using a DTM and a MMS DSM in M-221.

### *4.3. Influence of other elements by the roadsides*

Items by the roadsides other than roadside equipment and plants also affect available sight distance. As an example, a wire fence arises within same section of road M-221 discussed in previous section, observable in Fig. 6, was studied. IPS2 data acquisition devices recognized 3-D points of such fence due to its high sensitivity. As a result, the Delaunay triangulation was built up in such a way that the surface of the MMS DSM depicts an opaque wall. In addition, the wire fence is placed at the inner roadside of a horizontal curve, making a section of roadway actually visible (Highlighted in Fig. 6) to be hidden behind the “wall” when calculating sight distance using a MMS DSM (Fig. 7). From station 400 on, in Fig. 7 (letter ‘c’), a section of road is seen beyond available sight distance, which corresponds to the station where a driver would have left the wire fence behind. Such section of road, which is visible after passing the the fenced zone only, according to the sight distance calculation output, is actually seen through the wired fence much before. This fact is supported by the results obtained using a DTM for the same section (area shaded in medium grey marked as ‘d’ on Fig. 7).

Moreover, the overhead power line highlighted on Fig. 6 was also detected by the terrestrial survey using IPS2 equipment. Therefore, the cloud of points was edited in order to prevent an “opaque wall” crossing the road in the MMS DSM.

## 5. Conclusions

The influence of elements by the roadsides in sight distance of roads, depending on the DEM employed, has been studied, highlighting the strengths and weaknesses of each. When the road analyzed is straight, it is simpler to use a DTM, not only because the results are identical, but also because the cloud of points does not have to be edited to delete noise. Such analysis using a DTM is sufficiently reliable if no trees or other cantilevered elements affecting sight distance are above the roadway. However, in sections with curves, where the lines of sight are projected out of the pavement surface, differences between the models studied are evident. In such cases, the outcome is more tied in with reality if any of the DSMs is utilized. Thus, the use of DTMs is not recommended where the alignment is sinuous in the horizontal projection and dense vegetation or other perceivable elements arise by the roadsides. In general, DSMs are more suitable for available sight distance estimation and other studies such as 3-D alignment coordination because results obtained using a DSM are usually more realistic. For DSM derived from airborne LIDAR in particular, as these models do not deem roadside equipment, data require much less processing and the interpretation of the output is easier. However, analyzing sight distance in this way is entangled by the impossibility of representing the surface of the scene due to Delaunay triangulation limitations.

MMS MDSs allow maximum accuracy compared to other models derived from aerial LIDAR, since it reproduces the road and its environment in much more realistic way. However, the high sensitivity of IPS2 technology, leads to deem points of elements by the roadside, even small ones, creating significant problems in both preprocessing the cloud of points as well as the study of issues related to alignment coordination. The use of these models requires a much more thorough analysis to discern whether the cause of insufficient sight distance is road geometry and landform (cut-side slopes), or conversely is due to an item by the roadsides. The use of models derived from MMS MDS is recommended to study actual sight distance conditions more accurately for very specific cases, in absence of circumstances that may cause some of the problems inherent in the use of Delaunay triangulations explained in this document. In addition, the influence of road equipment such as safety barriers in these models has been demonstrated. Although in this particular case, the result is very sensitive to parameters to be set, as the height of target obstacle. Also, it is recommended to identify elements by the roadside that could lead to misleading results, such as fences, to interpret the results appropriately.

It is necessary to improve existing techniques and to develop new other techniques capable to avoid such difficulties, exploiting the potential of MMS DSMs in the study of available sight distance, so as to enable study more realistic sight distance studies also in sections where there are cantilevered elements above the road, overpasses or even tunnels.

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