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Original

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3D modelling of highway guardrails for sight distance assessment

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26 **Abstract**

27 Safety barriers limit the severe consequences to occupants of vehicles leaving the roadway from
28 colliding with obstacles, yet they may significantly reduce the available sight distance (*ASD*). A
29 procedure was devised to accurately recreate highway guardrails in three dimensions (3D), fitting the
30 barriers onto the curve roadsides. The effect of these devices on the reduction of the *ASD* was thus
31 evaluated in a set of case studies comprising different curve radii overlapped with different vertical
32 alignments and combined each with two safety barriers in two-lane rural roads. The 3D models of
33 highway curves with the selected guardrails were created in a Geographic Information System. Then,
34 a geoprocessing model was used to compute the *ASD*. The results made possible to quantify the *ASD*
35 reduction produced by the barrier with higher containment level in relation to the highway design
36 parameters, which can assist authorities in developing more comprehensive safety device standards.

37

38 **Keywords**

39 Guardrails, Highways, Sight distance, Road safety, 3D modelling

40 Introduction

41 Road restraint systems are safety devices aimed at protecting drivers and occupants from the
42 consequences of vehicle departure from the carriageway, absorbing the impact energy. Since they
43 contain out-of-control vehicles within the road, the even more serious consequences resulting from
44 an impact against roadside fixed objects or the vehicle rollover are avoided (AASHTO 2018).

45 Road restraint systems are installed along medians and roadsides, so they limit the driver's
46 ability to see the roadway ahead (Wang et al. 2017). Steinauer and Mayer (1999) observed that on
47 left-hand curves on German motorways crashes are more frequent than on the counterpart right-
48 hand curves due to the sight-distance reduction caused by the median barriers. The limitation of the
49 available sight distance (*ASD*) is often in contrast with the need to guarantee a sufficiently long visible
50 portion of the road ahead where to complete manoeuvres safely. As a result, road designers must
51 satisfy both needs adopting adequate barriers and geometric characteristics preserving a minimum
52 *ASD* from potential conflict points and/or obstacles along the driving path (AASHTO 2018; Ministerio
53 de Fomento 2016; Ministero delle Infrastrutture e dei Trasporti 2001). Sight distance is one of the
54 most important elements not only in the road design but also in the road management to the aim of
55 traffic safety (Castro et al. 2016). Montella (2001) advocated cost-benefit analyses to choose the most
56 appropriate traffic containment device in terms of safety performance. Consequently, given the
57 effects of safety barriers on the *ASD*, it must be included in such analyses (De Santos-Berbel et al.
58 2018).

59 The installation and performance requirements of safety barriers in European countries are
60 regulated by European and national standards. As stated by European standards (CEN 2002, CEN
61 2011a; b, CEN 2012), barriers are classified according to several containment levels, the entity of the
62 deflection of the system and classes of dissipated impact energy. However, each Member State
63 imposes different minimum requirements based on the road characteristics and operating traffic
64 conditions (Ministerio de Fomento 2009, 2014; Ministero delle Infrastrutture e dei Trasporti 2004).
65 Hence, in similar roads operating under similar traffic conditions, barriers of different characteristics

66 may be installed in the same European country, as well as among countries. In this sense, barriers that
67 oversize the minimum standard requirements may be selected in a precautionary way while
68 significantly altering sight-distance conditions.

69 The selection of roadside barriers for new construction or safety upgrading involves
70 contemplating the combined effect of highway geometrics with limited sight distance (AASHTO 2011).
71 Sarhan and Hassan (2012) investigated the effect of different concrete barriers on the *ASD* for the
72 stopping maneuver. Nevertheless, studies addressing the impact and consequences in terms of sight
73 distance of installing different guardrails, which have a more complex three-dimensional (3D) shape
74 than concrete barriers, have not been found in the literature. Furthermore, it has been evidenced that
75 small differences in accuracy of 3D road items might produce significant variations in the *ASD*
76 estimation (Bassani et al. 2019; Iglesias et al. 2019). As a consequence, the 3D modelling of road
77 barriers must be carried out with the highest accuracy and precision.

78 This research aims to devise an advanced procedure to accurately recreate highway sections
79 with guardrails in 3D. Moreover, the procedure was tested for evaluating the effect of two different
80 guardrails on the *ASD* on curves in relation to the highway design parameters.

81 The paper is divided into five sections. The introduction is followed by a review of the current
82 state of the art. A subsequent section outlines the procedure devised to recreate the guardrails and
83 describes the organization of the case studies. The next section summarizes and discusses the results
84 obtained from the study. Conclusions and brief considerations about future research are presented in
85 the last section.

86

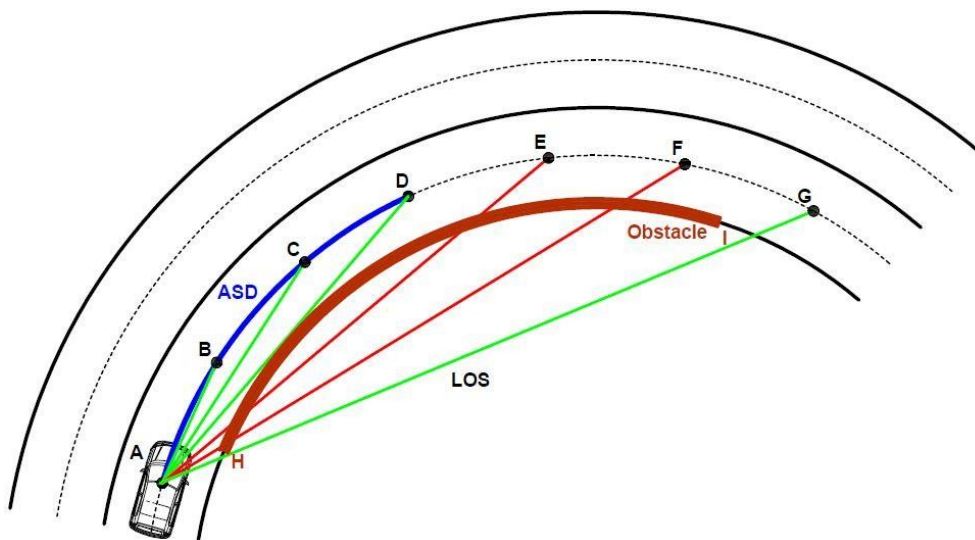
87 **Related works**

88 The *ASD* is the maximum length of the road stretch ahead measured along the future path that the
89 driver can see in the presence of sight obstructions, i.e. elements of the roadway and/or the roadside
90 (Castro et al. 2016). **Figure 1** illustrates how the *ASD* is measured along the vehicle trajectory as the
91 distance between the farthest point visible (D), detected from the intersection between the line of

92 sight – LOS – and the trajectory itself) and the point of view (A). From the point of view A, straight
93 lines may be built to link target points along the future path (B, C, D, ...G); lines AB, AC, ..., and AG are
94 sight lines from the driver's eyes. Since the lines AE and AF intersect the sight obstruction (the HI
95 element), the driver cannot see the road stretch from E to F. Hence, he/she can only see the sections
96 from A to D and from G: the ASD is, therefore, the arc length from A to D.

97 For safety reasons, the ASD must be greater than the distance used to stop the vehicle before
98 hitting an unexpected object along the lane (i.e., the stopping sight distance, SSD). Consequently, the
99 ASD may be considered in the evaluation of safe speed limits. The comparison between ASD and SSD
100 allowed assessing the influence of sight distance on road safety. Ibrahim and Sayed (2011)
101 incorporated stochastic risk measures due to insufficient sight distance to a crash prediction model to
102 evaluate the potential impact of horizontal curve design on the collision frequency. By analysing top
103 crash-prone segments, Gargoum and El-Basyouny (2020) showed that the crash frequency is 2 to 3
104 times higher where the required SSD is not met.

105



106

107 **Figure 1.** Graphical definition of the available sight distance (ASD).

108

109 For the ASD analysis, Spanish and Italian highway design standards (Ministerio de Fomento
110 2016; Ministero delle Infrastrutture e dei Trasporti 2001) provide values for the height of the driver's

111 eye and the height of a possible obstacle, with the driver's head position located at 1.1 m above the
112 pavement surface. Different obstacle heights are assumed in the assessment of *ASD* to check the
113 compliance with the *SSD* requirements: 0.1 m with the Italian standard, and 0.5 m with the Spanish
114 one. For research purposes, the heights of target may be differentiated from the standard values.
115 De Santos-Berbel and Castro (2018) set the driver's eye heights at 1.5 m and 2.0 m to simulate sight-
116 distance scenarios with heavy vehicles in the vicinity of underpasses, producing relevant variations in
117 the *ASD* outputs.

118 The *ASD* depends on cross-section elements, roadside features, and horizontal and vertical
119 alignment (Ismail and Sayed 2007). On existing roads, reduced sight distance may be caused by
120 inadequate geometric design, changes in the initial roadside conditions due to natural or human
121 actions, or both (De Santos-Berbel et al. 2013).

122 Although most current design policies contemplate the two-dimensional (2D) approach to
123 evaluate the *ASD*, the literature suggests that a 3D approach is much more reliable to avoid
124 overestimation or underestimation of the *ASD* (Castro et al. 2017). De Santos-Berbel et al. (2018)
125 studied and compared the differences between the output of 2D and 3D *ASD* analyses produced by
126 concrete barriers on curves on existing highways. The results found significant differences between
127 both procedures. Particularly, the superelevation, the effect of which could be included in the 3D
128 procedure, was found to affect the results. Papadimitriou et al. (2018) highlighted the need to consider
129 the combined effect of 3D alignments alloys and the presence of containment devices.

130 Many methods and algorithms have been developed and validated for the evaluation of the
131 *ASD*. Several authors have proposed *ASD* estimation procedures based on modelling the surface of
132 the roadway and roadside features to recreate the highway and its environment (Castro et al. 2014;
133 Ismail and Sayed 2007). Liu (2013) developed an analytical method to determine the available sight
134 distance on combinations of vertical and horizontal curves in the presence of roadside barriers. These
135 procedures have shown limitations to represent overhanging features in the road environment.
136 Alternatively, Campoy-Ungría (2015) suggested an *ASD* estimation method based on prismatic line-of-

137 sight buffers launched directly on a high-density LiDAR cloud of points, not requiring any terrain
138 surface. More recently, fully 3D methods have been developed and validated to obtain reliable *ASD*
139 results (Gargoum et al. 2018; Ma et al. 2018; De Santos-Berbel and Castro 2018).

140 Some recent investigations have been focused on the use of mobile laser scanning (MLS) data
141 to obtain point clouds to be used to accurately create 3D models of real driving scenarios along road
142 sections (Alcón Gil et al. 2021; Bassani et al. 2015; Ma et al. 2018; Shalkamy et al. 2020) and
143 intersections (Jung et al. 2018). The difficulties inherent in the use of MLS techniques stem, on the one
144 hand, from the strong dependence of the *ASD* analysis on the accuracy of the objects modelled in the
145 near environment and its modelling procedure to subsequently obtain realistic *ASD* values. Hence, a
146 dense cloud of points is required to enable a proper modelling of the shape of elements that may
147 represent a sight obstruction (Bassani et al. 2019; Iglesias et al. 2019). As a result, a significant amount
148 of data and storage capacity are necessary, with a significant share of data points that are not
149 effectively necessary for the analysis (i.e., inefficient). On the other hand, the use of MLS is, in
150 principle, limited to real scenarios and is not suitable to be used in road design scenarios.
151 Nevertheless, the procedure utilized in this study is capable of incorporating 3D features derived from
152 MLS surveys along with virtual new elements to recreate different scenarios (Alcón Gil et al. 2021; De
153 Santos-Berbel and Castro 2018).

154 To lighten the computational burden and related costs to carry out sight distance calculation,
155 Ma et al. (2019) have introduced the use of a convolutional neural network that enables the
156 estimation of the *ASD* using far fewer points. This algorithm improves the above reported
157 inefficiencies related to the use of large databases from MLS, partially solving the former of the two
158 issues abovementioned.

159 Spatial analysis and environment modelling capabilities of geographic information systems (GIS)
160 have led to the development of *ASD* estimation procedures (Khattak and Shamayleh 2005). Castro et
161 al. (2011) provided a 3D approach based on viewsheds to evaluate *ASD* by using GIS tools. Later on,
162 Castro et al. (2014) provided a more efficient procedure based on algorithms that iterated lines of

163 sight. Bassani et al. (2016, 2019) evaluated the *ASD* in an urban road scenario where several sight
164 obstruction types are present, intending to highlight and compare the computational efficiency,
165 advantages and drawbacks of GIS and numerical computing codes.

166 The use of a GIS in highway sight distance studies can help solve part of the difficulties in the
167 use of traditional design software because it can be employed to carry out other geometric and safety
168 analyses. For example, consistency and safety analyses are carried out overlapping with GIS the
169 information coming from crash counts, operating speeds, traffic data, road features, and geometric
170 characteristics of a highway (Castro and De Santos-Berbel 2015; Iglesias et al. 2016). Furthermore, the
171 detection of shortcomings and hidden dips in the 3D alignment can also be carried out in the GIS
172 environment (Castro et al. 2017; Castro and De Santos-Berbel 2015). Road design standards and
173 guides can be used in a GIS to generate realistic 3D road models starting from 2D data including
174 centreline and basic cross-sectional information (Wang et al. 2014). Current GIS applications are
175 robust enough to model road elements and obtaining results comparable to those coming from sight
176 inspections. Finally, GIS is a flexible tool that can also overcome the limitation of MLS based techniques
177 because it can easily include 3D sight obstructions, e.g. objects in the roadside like poles, installations,
178 and safety barriers.

179

180 **Methodology and materials**

181 This section outlines the procedure to build up the 3D model of the horizontal curves with the selected
182 guardrails for the assessment of the *ASD*. The computer software used to analyse the 3D models is
183 also described.

184

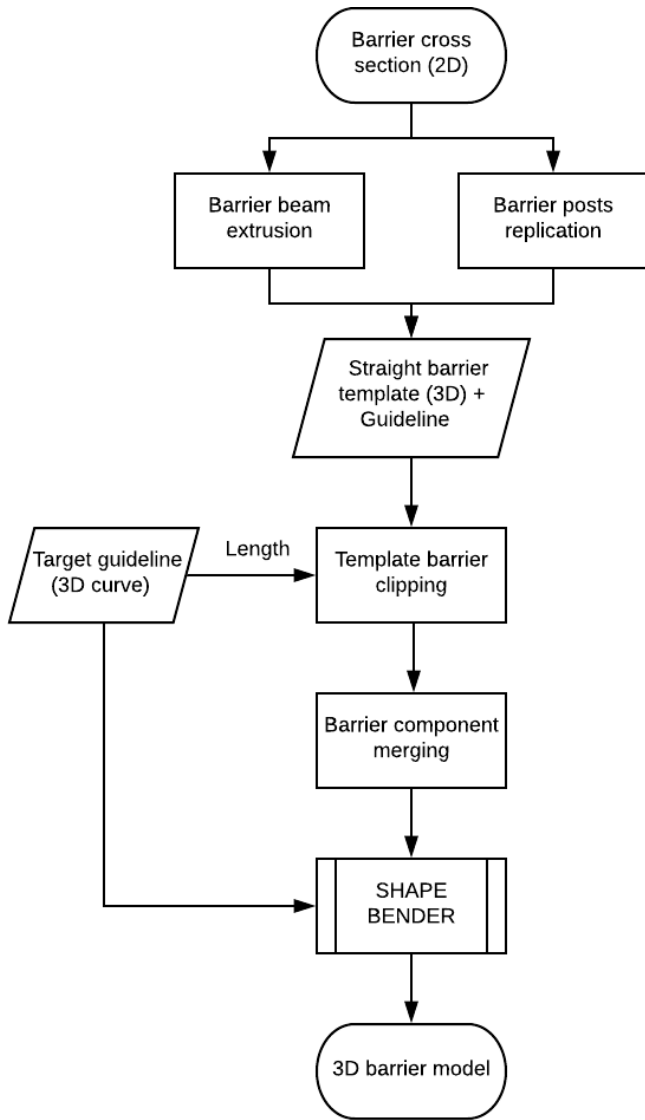
185 ***3D modelling: barrier design***

186 The importance of accurately and precisely modelling the road and its environment in 3D, guardrails
187 included, stems from obtaining reliable results from the analysis. In this sense, these devices must be
188 accurately recreated and adapted to the roadside for any given highway alignment layout. The

189 assessment of the ASD contemplated two different types of guardrails. The first one is a 2-wave
190 N2-type guardrail, which reflects the guardrail typically installed on Spanish two-lane rural highways.
191 The second one is a 3-wave H2-type guardrail, widely used in Italy on the same road type. The process
192 devised to create the 3D barrier models is illustrated in **Figure 2**. All the relevant components of their
193 profile were drawn on computer-aided design software. It is worth noting that the considering
194 elements must be represented with closed lines to facilitate the operations in 3D drawing software
195 used later.

196 The cross-section drawings displayed in **Figure 3** were imported into SketchUp Pro to create the
197 3D models. Then, the barrier beam was extruded along a straight guideline perpendicular to the plane
198 containing the beam cross-section. This guideline, represented by the red dotted line in **Figure 4**,
199 serves in turn as the reference line for the installation of the barrier since it is located at the same
200 height as the base of the posts and in the same vertical position as the generating line of the beam
201 closest to the road centreline. Next, the barrier posts were replicated and inserted at the specified
202 fixed distances throughout the barrier (4 m for the N2 type, 2 m for the H2 type), thus obtaining the
203 3D model of the guardrails displayed in **Figure 4**.

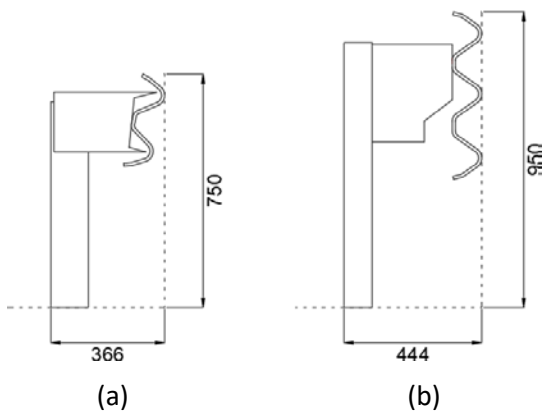
204 The straight barrier displayed in **Figure 4** serves as a template to create the required barrier
205 models for any highway alignment. SketchUp Pro was selected to take advantage of the CLF Shape
206 Bender extension, which makes it possible to adapt a given shape, not necessarily with a
207 homogeneous cross-section, to a 3D curve given a guideline for the original shape and another
208 guideline for the target shape (Trimble 2013).



209

210 **Figure 2.** Flowchart of the 3D barrier model creation process.

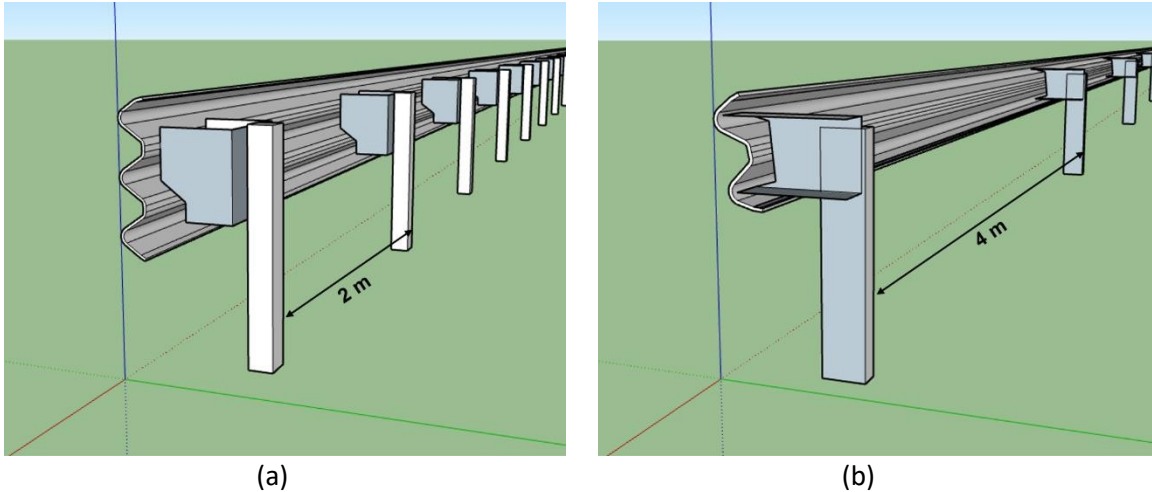
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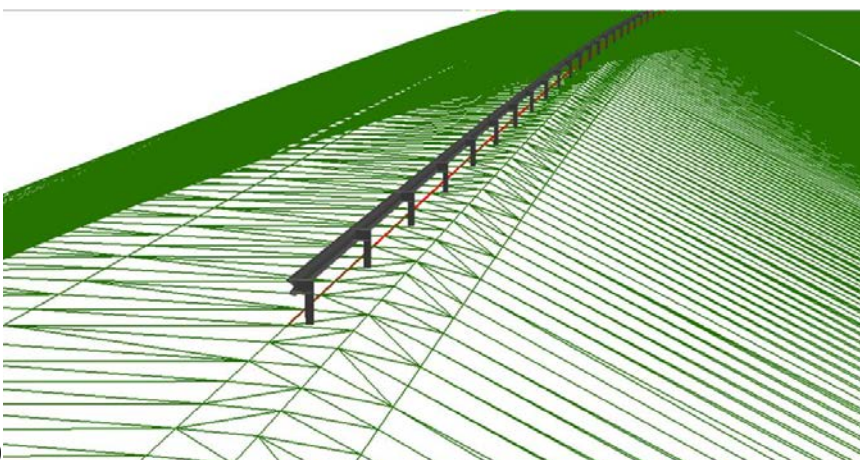
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214 **Figure 3.** Cross-sections of N2 (a) and H2 (b) metallic barriers (unit of measurement: mm).



215
216
217 **Figure 4.** 3D view of N2 (a) and H2 (b) selected guardrails in SketchUp Pro.
218

219 To create a barrier that suits the highway curve in 3D, the 3D curve featuring the roadway inner
220 edge was imported into SketchUp. Next, for producing a barrier without longitudinal distortion, the
221 straight barrier template and its guideline were clipped with length equal to that of the target
222 guideline. Then, all the resulting guardrail components were merged into a single object as required
223 to launch the Shape Bender extension. The 3D guardrail models thus produced were exported as
224 Collaborative Design Activity (COLLADA) format and then imported into a multipatch feature in
225 ArcScene (3D GIS environment), where they were placed in their final position (**Figure 5**). A multipatch
226 feature is a GIS entity whose specific data represent the outer surface of an object, which occupies a
227 volume in the 3D space (ESRI 2008).



229
230 **Figure 5.** 3D view in ArcScene of N2 guardrail inserted on the TIN model and fitted to the roadside
231 (red line).

232 ***Geoprocessing model***

233 Whereas the feature classes representing different types of barriers as visual obstructions that
234 comprise the 3D model were laid out in the 3D environment of ArcScene, the evaluation of the ASD
235 was run in ArcMap 10.3. This allowed boosting computation performance while maintaining the 3D
236 nature of the highway model. Numerical results were obtained by using a GIS geoprocessing model
237 developed and validated by the authors (Iglesias et al. 2016; De Santos-Berbel and Castro 2018). This
238 geoprocessing model is based on tools from the 3D Analyst extension of ArcMap and it permits to
239 consider 3D visual obstacles. First, “Construct sight lines”, which connects the positions in space of the
240 driver’s eye point and the target points (ESRI 2021a). Then a sequential automatic selection of the
241 generated line feature class input the “line of sight” tool along with the elevation model and the
242 multipatch feature class (ESRI 2021b). It evaluated whether each line of sight is obstructed by any of
243 the model features and, if so, returns a new point feature class containing the exact position in space
244 where the lines of sight were obstructed. In addition, the geoprocessing model outputs the sight
245 distance evaluation results from which the ASD values are retrieved.

246 The data required to execute this geoprocessing model includes the theoretical path followed
247 by a vehicle (with stations spaced 5 m apart) and the elevation model which recreates the highway
248 and its roadsides. In general, two types of elevation models are available: digital terrain models (DTM)
249 and digital surface models (DSM). A DTM is a 3D representation of the terrain surface which includes
250 exclusively the elevation of the bare ground, without vegetation, traffic signs, or buildings. On the
251 other hand, DSMs consider the structures on the surface, also detecting overhanging features.
252 Nevertheless, when overhanging features are present by the roadsides (as in the case of safety
253 barriers), the intrinsic features of DSMs do not support two points on its surface having the same
254 horizontal projection and different elevation values (Iglesias et al. 2016; De Santos-Berbel and Castro
255 2018). To overcome this problem, the highway 3D model was built up combining a DTM and fully-3D
256 modelled landscape features. The former was built up in GIS from a cloud point created using CLIP
257 version 1.29 road design software (TOOL S.A. 2013). The point cloud was created from the most

258 relevant points of road cross-sections spaced 1 meter apart. Next, a triangular irregular network (TIN)
259 (surface defined by the mesh in **Figure 5**) was built considering the point cloud as the node set. The
260 later comprises the multipatch feature classes modelling the guardrail as a sight obstruction. The
261 procedure allows to include mass standardized constructive elements into the highway 3D model in
262 the GIS environment. Therefore, the method hereby presented provides reliable results thanks to the
263 incorporation of lifelike-modelled 3D objects.

264 It must be noted that guardrails do not constitute a simple continuous obstacle like vertical
265 surfaces (e.g., walls, rigid concrete barriers), but they might enable the driver to perceive the road
266 ahead through the spaces between posts beneath the barrier beam. In this sense, the capability of the
267 geoprocessing model to return the 3D position of the visual obstruction and identify the visual
268 obstacle that obstructed each line of sight made it possible to accurately assess the *ASD* in the
269 presence of guardrails contemplating its complex 3D shape.

270 Furthermore, the driver's eye height and the target height are two required input parameters
271 of the geoprocessing model. Their values were taken according to the Spanish highway design
272 standard, as 1.1 and 0.5 m, respectively (Ministerio de Fomento 2016).

273 The algorithm first launches sightlines connecting the driver's point of view and targets located
274 along the vehicle path ahead, up to a prespecified maximum distance. Next, it checks whether the
275 sightlines are obstructed or not by either the DTM or the inserted multipatch features and retrieves
276 the *ASD* values.

277

278 ***Experimental design***

279 To test the procedure for building up 3D models, a set of highway alignments was created. Nine
280 horizontal curves were designed with different radius, each one connected to spirals at both ends.
281 Two alternative vertical profiles were designed for each curve: a flat-grade profile and a profile with
282 vertical curves overlapped to each horizontal curve according to the alignment coordination principles
283 (Ministerio de Fomento 2016; Ministero delle Infrastrutture e dei Trasporti 2001). The cross-section

284 consists of a 7-m wide travelled way with two lanes (3.50 m each), one per driving direction, and 0.5
285 m-wide shoulders. Since the guardrail was placed in such a way that the horizontal projection of the
286 innermost generatrix of the beam coincides with the outer edge of the shoulder, the lateral offset
287 with respect to the travelled way was 0.5 m. In terms of design speeds, radii, and superelevation of
288 curves, two categories of roads can be distinguished, the so-called *Group 2* and *Group 3* according to
289 the Spanish standard denomination for undivided highways (Ministerio de Fomento 2016).

290 The geometric features of the horizontal curves are provided in Table 1. The length of each
291 curve has been laid out to ensure that the ends of the lines of sight that determine the minimum *ASD*
292 associated to the curve lie within the bounds of the circular arc of the curve on both travelling
293 directions. Table 1 also includes the parameter K_V (equation 1) of the overlapped vertical curve.
294 Negative K_V values correspond to vertical crest curves while positive ones correspond to vertical sag
295 curves. Design speeds in *Group 2* range from 120 to 80 km/h at intervals of 10 km/h. In *Group 3*, design
296 speeds range from 80 to 50 km/h. The design speed values are associated to the minimum radius
297 allowed in a highway segment as indicated in Table 1.

$$298 \qquad \qquad \qquad K_V = 100 \cdot L/\theta \qquad \qquad \qquad \text{Eq. 1}$$

299
300 where K_V is the vertical curve parameter in m, L is the length of vertical curves in m, and θ is the
301 absolute value of the algebraic difference between the outbound i_2 and inbound i_1 grades in %.

302 To carry out the sight-distance analysis using the geoprocessing model, either guardrail model
303 was set by the inner roadside of each curve. The *ASD* estimation was repeated for both travelling
304 directions.

305

306
307

Table 1. Geometric characteristics of the horizontal curves. The negative value of K_V indicates a crest vertical curve (group 2), a positive value represents a sag vertical curve (group 3).

Group	Section	Horizontal radius (m)	Design speed (km/h)	K_V (m)	Superelevation (%)	SSD (m)
2	Curve 1	700	120	- 38467.98	8	261.49
	Curve 2	550	110	- 30218.00		216.79
	Curve 3	450	100	- 24718.02		178.59
	Curve 4	350	90	- 19218.05		145.48
	Curve 5	250	80	- 13718.10		116.85
3	Curve 6	265	80	+ 14617.94	7	116.85
	Curve 7	190	70	+ 9515.16		91.17
	Curve 8	130	60	+ 6750.37		69.67
	Curve 9	85	50	+ 4198.36		51.73

308

309

As previously stated, the *ASD* along a highway section must meet the distance needed for vehicles to stop (i.e., $ASD \geq SSD$). *SSD* is measured from the driver's position at the time when the obstruction appears and justifies the braking. It includes two contributions: the distance covered by the vehicle from the instant the driver perceives the obstacle to the instant the brake is applied (i.e., the perception and reaction distance) and the distance needed to stop from the instant the braking maneuver begins (i.e., the braking distance). *SSD* in m is evaluated according to Equation 2:

315

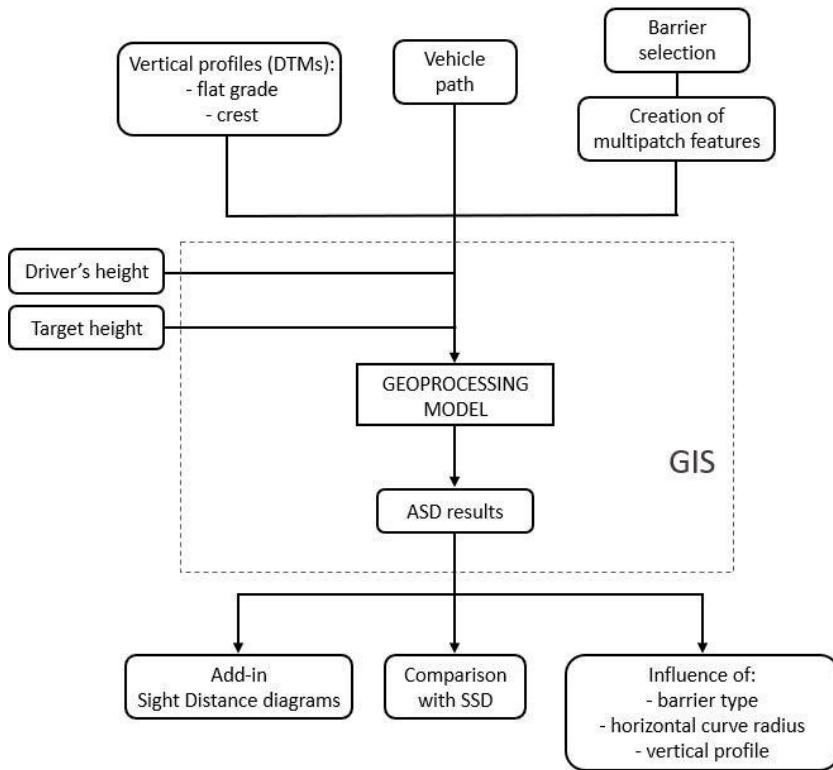
$$SSD = \frac{V \cdot t}{3.6} + \frac{V^2}{254 \cdot (f_I + i)} \quad \text{Eq. 2}$$

316

317

where V is the design speed in km/h, t is the perception and reaction time (2 s, according to the Spanish standard (Ministerio de Fomento 2016)), f_i is the longitudinal friction coefficient (as a function of the design speed), and i is the longitudinal grade in %. Table 1 provides *SSD* values for this experiment. In this assessment, the longitudinal grade was neglected due to its small values. **Figure 6** gives the flow chart of the sight distance analysis.

322



323

324 **Figure 6.** Flow chart of the research study.

325

326 By setting the vehicle trajectory and the roadside features, the geoprocessing model elaborated
 327 the sight distance diagrams with both profiles. Once the *ASD* values had been extracted, the impact
 328 of the barrier type on the *ASD* in function of the horizontal curve radius and the vertical profile was
 329 determined.

330

331 **Results and discussion**

332 The minimum *ASD* values obtained for each alignment on either travelling direction combined
 333 in turn with either guardrail model have been extracted. The aforementioned capability of the
 334 geoprocessing model to identify the position and the visual obstacle at which lines of sight are
 335 intercepted made it possible to assert that in the case studies the *ASD* limitation was produced by the
 336 barrier beam. Although lines of sight might pass through the gap between the barrier posts, it was
 337 checked that these lines did not affect the *ASD* output since the limiting feature was found to be the
 338 barrier beam in all cases.

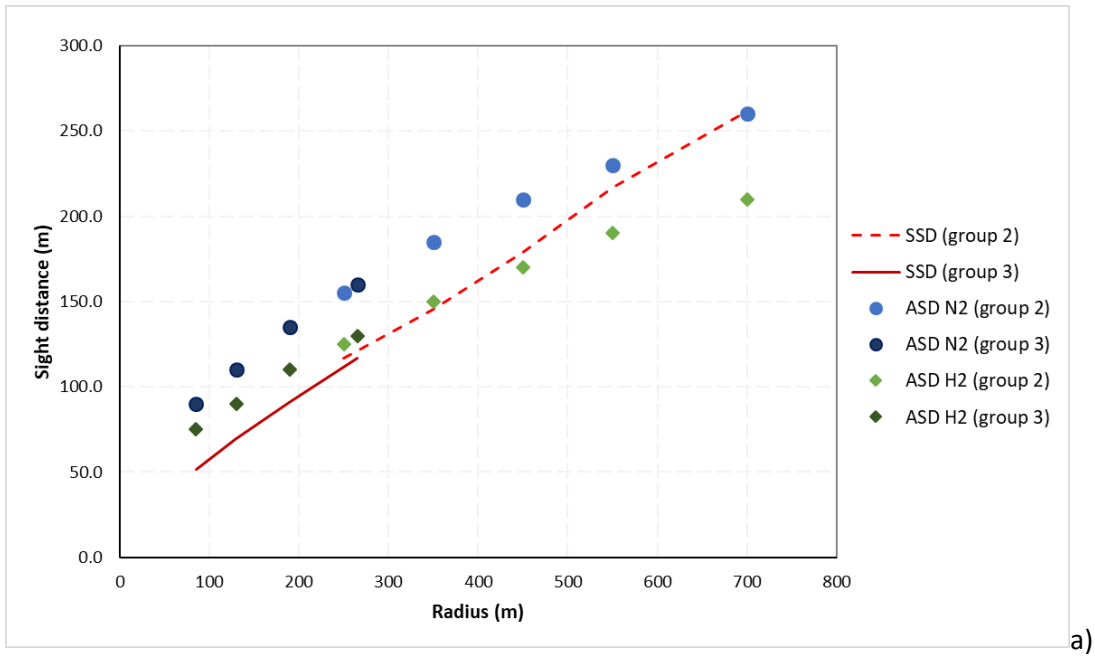
339 First, horizontal curves overlapped with the flat-grade profile were analyzed with either barrier,
340 discerning between left-hand and right-hand curves (**Figure 7**). Considering that in the absence of
341 visual obstructions the *ASD* would be unlimited, a reduction of the *ASD* is observed in all the curves
342 due to the presence of barriers.

343 On left-hand curves overlapped with flat-grade profile (**Figure 7a**), the *ASD* is greater than the
344 required *SSD* in all group 3 curves (those with smaller radius) with both barrier types. A greater
345 decrease of the *ASD* with the H2 guardrail due to its higher size is evident. This reduction in *ASD*
346 increases as the radius of the curve increases too. For curves of Group 2, the *ASD* met the required
347 *SSD* in the presence of the 2-wave N2 barrier, except for the curve with $R = 700$ m ($ASD = 260$ m vs.
348 $SSD = 216.8$ m). The 3-wave H2 barrier does not allow the *ASD* to meet the required *SSD* in curves with
349 a larger radius (e.g. $ASD = 210$ m vs. $SSD = 261.5$ m for $R = 700$ m).

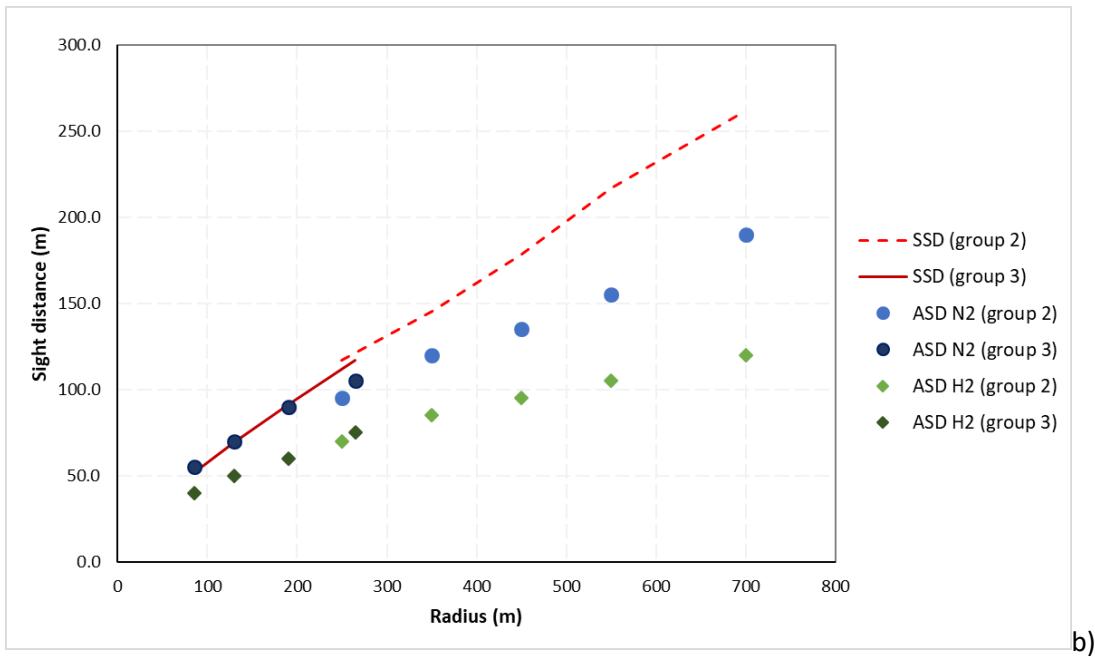
350 In right-hand curves (**Figure 7b**), barriers do not guarantee the required *SSD* in almost all the
351 analysed cases, with a greater obstruction given by the 3-wave H2 barrier. The greatest sight distance
352 deficits are observed for the largest radii: with the H2 barrier, the *ASD* values are lower than half of
353 the required *SSD* (e.g. $ASD = 120$ m vs. $SSD = 261.5$ m for $R = 700$ m). The N2 guardrail provides *ASD*
354 always larger than *SSD* only curves of smaller radius (e.g. group 3, $ASD = 55$ m vs. $SSD = 51.7$ m for
355 $R = 85$ m).

356 As expected, results depict that the installation of 2-waves guardrails is less unfavorable than
357 the installation of 3-waves ones in terms of sight distance. All else being equal, the *ASD* is greater in
358 left-hand bends, while in right-hand curves it is more difficult to guarantee it, especially in curves with
359 larger radii.

360 Since there are two different cases for vertical profiles (flat-grade and with vertical curves), it is
361 possible to compare the effect of the same barrier in different vertical alignments. Figure 8 shows the
362 analyses for N2 barrier, while Figure 9 those for H2 guardrail.



363



364

365 **Figure 7.** Sight distance analysis as a function of the radius on horizontal curves overlapped with flat
 366 grade: a) left-hand curves, b) right-hand curves.

367

368 Considering the N2 barrier in left-hand curves (Figure 8a), the ASD is greater than the required

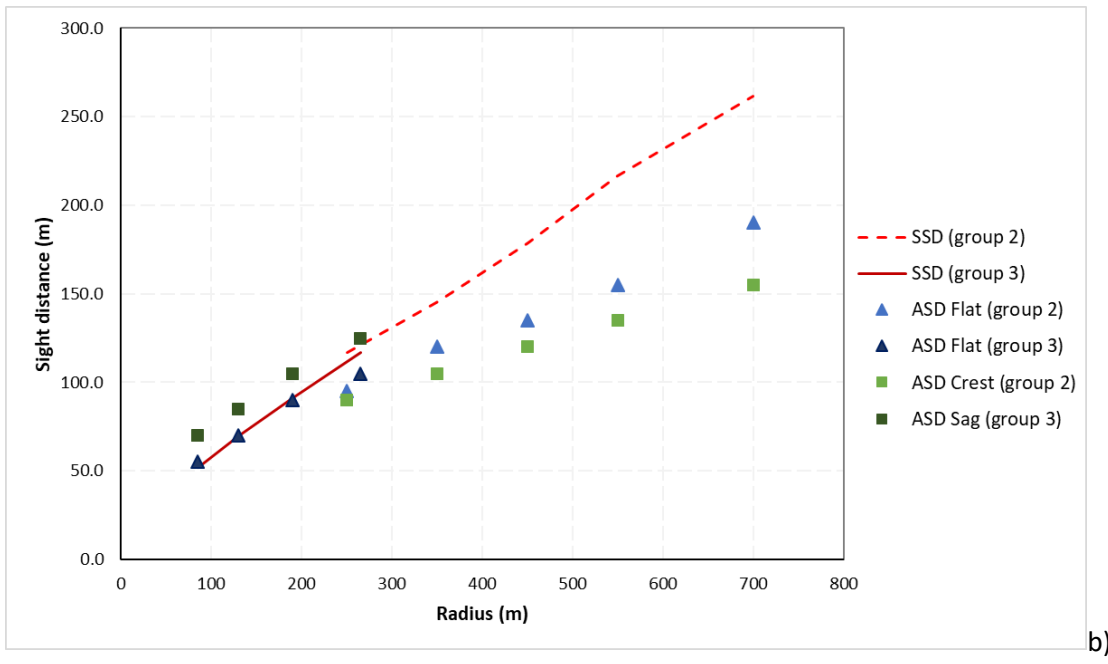
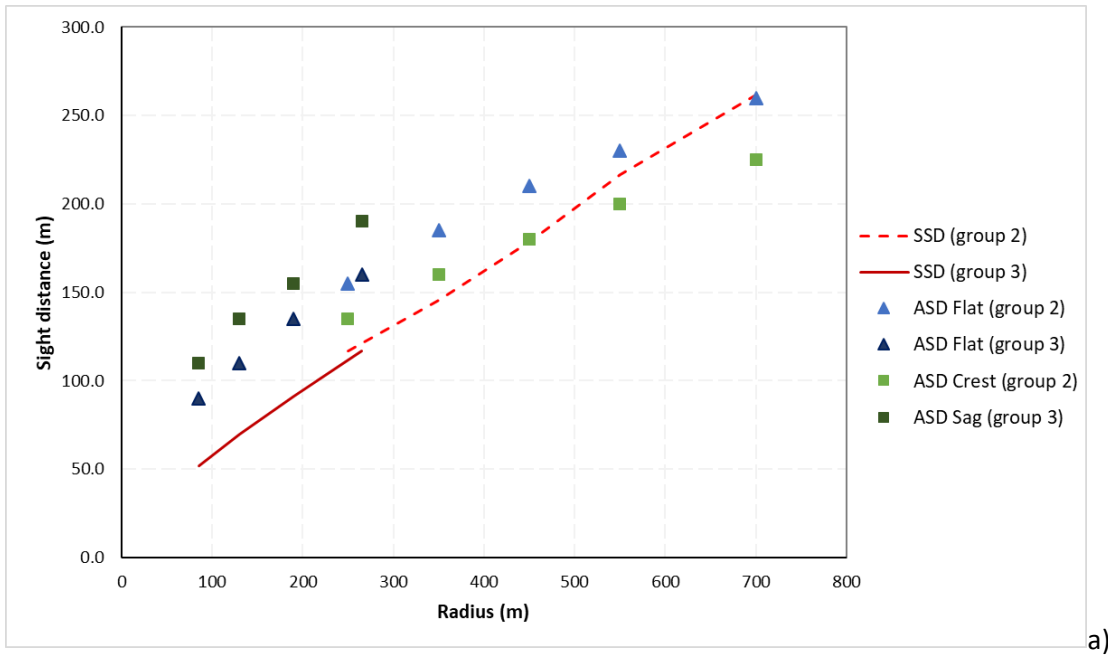
369 SSD in all group 3 curves for both types of vertical profiles (flat and sag). The greatest ASD values are

370 reached in the non-flat profile, with sag vertical curves. For group 2 curves the SSD is always

371 guaranteed in the flat-grade terrain. However, the vertical profile with crest curves does not allow the

372 ASD to meet the required SSD in curves with a larger radius (e.g. $ASD = 225$ m vs. $SSD = 261.5$ m for

373 $R = 700$ m).



376 **Figure 8.** Sight distance analysis in function of the radius on horizontal curves overlapped with N2
 377 barrier: a) left-hand curves, b) right-hand curves.

378

379 Even considering two different vertical profiles, the situation in terms of ASD is critical for
 380 right-hand curves (Figure 8b). For group 3 curves, the sag vertical profile guarantees $ASD > SSD$ in all
 381 curves; ASD values are lower than the required SSD for the group 2 curves, with both vertical profiles,
 382 especially with the flat-grade terrain.

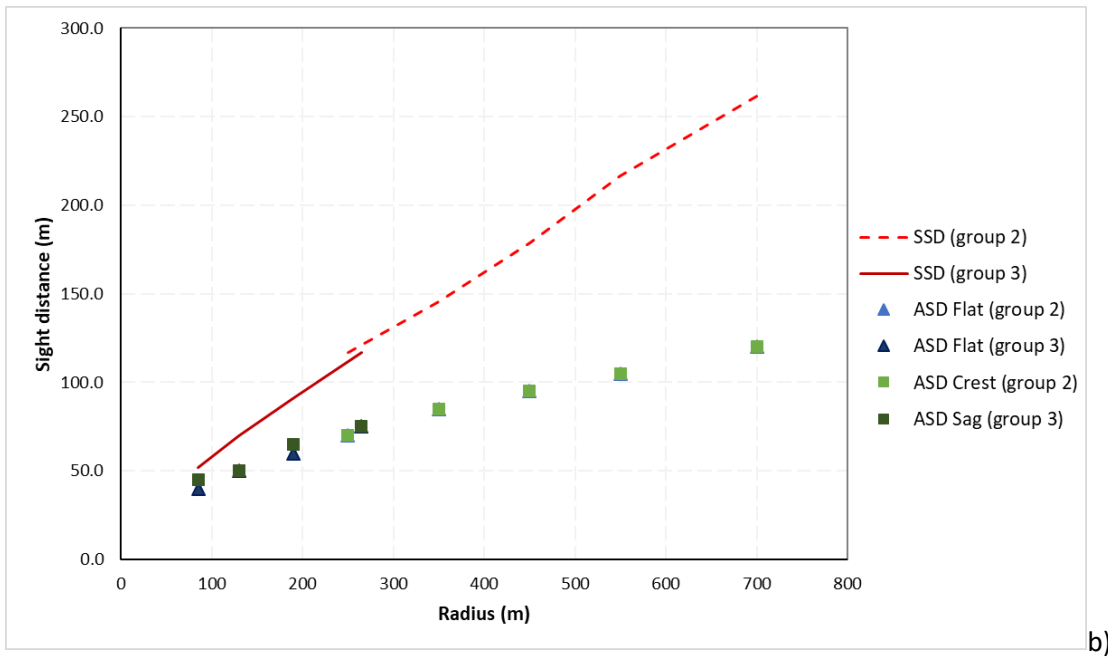
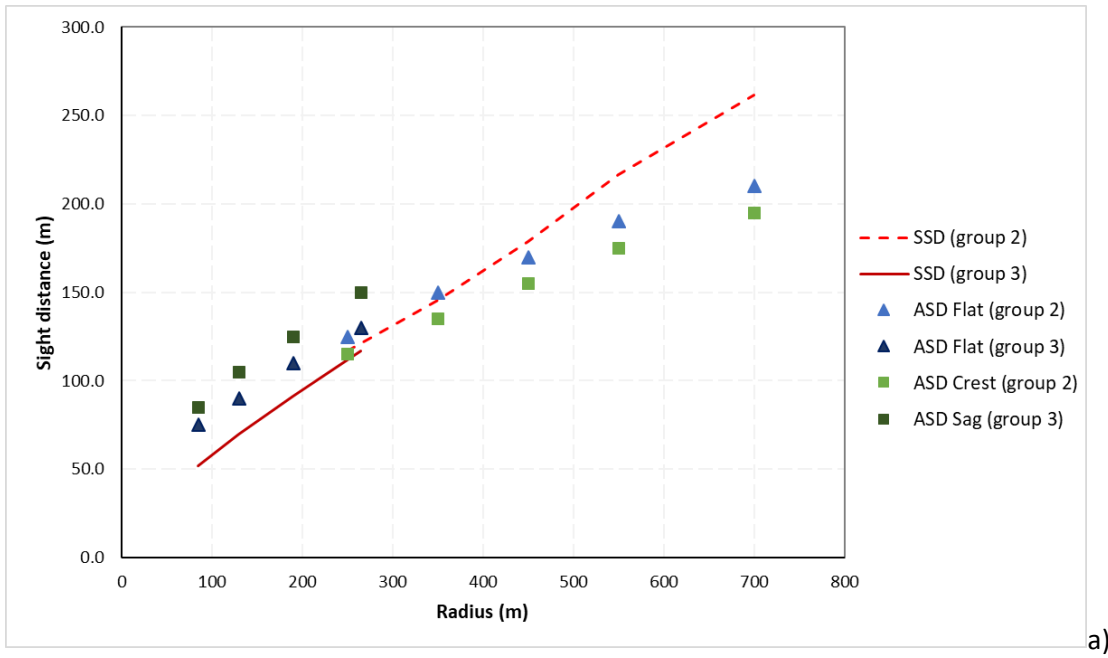
383 By setting the H2 barrier in left-hand curves (Figure 9a), the ASD values exceeded the required
 384 SSD in all group 3 curves with both types of vertical profiles (flat and sag). In this case, sag vertical

385 curves provide better sight conditions as well. A different situation occurs for group 2 curves, where
386 the *ASD* meets the required *SSD* just in the flat-grade terrain in the smallest curvature radii of the
387 category (e.g. *ASD* = 125 m vs. *SSD* = 116.8 m for $R = 250$ m). This trend is again justified by the vertical
388 profile: if the sag vertical curve provides a better sight distance, the crest one decreases the length of
389 the road visible from the driver point of view.

390 In right-hand curves (Figure 9b), sight conditions do not comply with safety requirements in the
391 presence of H2 guardrail, and the difference between *ASD* and *SSD* increases as the curve radius
392 increases. *ASD* values for the flat-grade terrain and crest curve vertical profile are almost identical; in
393 particular, in group 2, they coincide. This is attributable to the smaller distance between the driver
394 and the sight obstruction (i.e., the guardrail), with the result that the same sight line is obtained for
395 both cases (i.e., flat-grade and crest).

396 By analysing the *ASD* values for the two different vertical profiles, it can be observed that the
397 presence of vertical curves impacts the sight distance: *ASD* increases in presence of sag curves (from
398 $ASD(N2) = 90$ m and $ASD(H2) = 75$ m for “flat” profile to $ASD(N2) = 110$ m and $ASD(H2) = 85$ m for “sag”
399 profile, for $R = 85$ m, left-hand curve; from $ASD(N2) = 110$ m and $ASD(H2) = 90$ m for “flat” profile to
400 $ASD(N2) = 135$ m and $ASD(H2) = 105$ m for “sag” profile, for $R = 130$ m, left-hand-curve). Although
401 safety conditions are usually met in the left-hand curves, it is clear that crest vertical curves decrease
402 the *ASD* values (from $ASD(N2) = 210$ m and $ASD(H2) = 170$ m for “flat” profile to $ASD(N2) = 180$ m and
403 $ASD(H2) = 155$ m for “crest” profile, for $R = 450$ m, left-hand curve).

404 The results documented in this manuscript are consistent with those obtained by Sarhan and
405 Hassan (2012), where they found that crests provide reduced *ASD* values, while sags increase the *ASD*
406 in comparison to the flat-grade terrain case in the presence of concrete barriers. In particular, as the
407 absolute value of K_V decreases, *ASD* increases on sag curves and decreases on crests. Reduced lateral
408 offsets were also found to affect negatively sight distance conditions. In this sense, the research results
409 are also in line with preliminary results of the authors on existing highways in the presence of concrete
410 barriers (De Santos-Berbel et al. 2018).



413 **Figure 9.** Sight distance analysis as a function of the horizontal radius on curves overlapped with H2
 414 barrier: a) left-hand curves, b) right-hand curves.

415

416 **Conclusions**

417 **Research contribution**

418 Previous studies demonstrated that GIS is a useful tool to carry out sight distance analyses on 3D
 419 models developed on existing road segments as well as on road projects. At present, no other
 420 modelling technique can provide reliable and fast results on road design scenarios. This study intended

421 to assess the variations of *ASD* due to different safety barrier types (i.e., their height) which can result
422 from a difference in the design decision or cross-country difference in road standards. To this aim, the
423 Shape Bender extension in the SketchUp Pro 2019 environment was used to adapt barriers to terrain
424 models depicting different combinations of horizontal and vertical alignment. This tool greatly
425 facilitates the 3D design, and it is particularly useful for roads and infrastructures.

426 GIS tools are useful to understand the effects of two different guardrail models on the *ASD* in
427 curves. The use of multipatch features allows considering in the analysis sight obstruction previously
428 modelled through 3D drawing software. As in this case, a faithful 3D reproduction of the guardrails
429 allows to obtain reliable results, with a minimum of error, compared to other methods that may be
430 more lacking.

431

432 ***Implications***

433 Road designers should be aware of the impact of safety barriers on the *ASD* when considering the
434 installation of barriers. The presence of taller barriers, even though they can provide greater
435 containment levels, offer a reduced *ASD* value: in particular, worse visibility conditions detect in the
436 presence of the 3-waves barrier (H2 guardrail) compared to the N2 type. Given that the N2 barrier has
437 a lower height, it enabled greater *ASD*.

438 As the radius of the horizontal curve increases, it becomes more difficult to ensure *ASD* values
439 that allow safe braking manoeuvres. It is demonstrated in group 2 curves (those with larger radii of
440 curvature): as the radius increases, the difference between *SSD* and *ASD* increases too. This result is
441 consistent with expectations because of the link between curve radii and design speed values (the
442 higher the radius, the higher the design speed).

443 The worst sight conditions are certainly detected on right-hand curves. Comparing the curves,
444 the *ASD* values are greater in the left-hand bends than in the right-hand ones. Again, this is consistent
445 with expectations because of the dependence of *ASD* from the distance of the observer from the sight
446 obstruction (the smaller the distance, the smaller the *ASD*).

447 From different comparisons involving the vertical profile and the dimensions of the curves, it is
448 possible to see how the vertical profile affects the sight distance. Sag vertical curves increase *ASD*
449 values, while the presence of horizontal curves overlapped with crest vertical curves worsens the sight
450 conditions compared to a flat-grade terrain, especially in left-hand curves.

451

452 ***Limitations and future research needs***

453 This work is limited to the specific road type and the two guardrails considered. Other analysis should
454 be carried out with the aim of extend the results to different road and barrier typologies. Furthermore,
455 the position for the barrier in the roadside (or in the median) is another factor that affects the *ASD*
456 and that deserve specific analysis. The comparison between rigid and guardrails with different heights
457 and shapes will provide other insight on the effects of these road furniture on the *ASD*.

458 As future lines of research, the authors are working on a driving simulator study to check
459 whether the driver perceives and adapt their behavior to the different sight distance condition along
460 curves treated with the two different barriers.

461

462 **Data Availability Statement**

463 Some or all data, models, or code that support the findings of this study are available from the
464 corresponding author upon reasonable request.

465

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