INFLUENCE OF HEADLAMP LIGHTING PARAMETERS ON NIGHTTIME SIGHT DISTANCE

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Abstract: Despite the higher accident rates during night driving compared to those in daylight, little research has been conducted on nighttime highway safety. Nighttime sight distance is one of the most relevant factors in night driving. Current design guides provide two dimensional models to study nighttime sight distance in order to design sag vertical curves. These models may, nonetheless, underestimate or overestimate the available sight distance because they do not take account of possible combinations with horizontal alignment nor the actual roadside obstructions. It is therefore necessary to develop a three-dimensional (3D) procedure capable of analyzing the available sight distance under nighttime conditions. This way, it is possible to set the basis of nighttime driving safety research. Thus the study of nighttime sight distance could help in determining whether highway geometric design or headlamp features may influence accident-prone locations. The aim of this study is to analyze the influence of the headlamp lighting parameters on real highways and compare the nighttime sight distance outcome to that in daylight. A GIS-based application for sight-distance studies with a specific tool for nighttime sight distance has been used. The headlamp parameters studied were beam range, headlamp height, upward divergence angle and horizontal spread angle. The analysis has been carried out on different real highways, which enabled the study of the influence of each parameter on different 3D alignments.

Keywords: road safety, nighttime sight distance, headlamp.

1. Introduction

Despite the higher accident rates during nighttime driving compared to those in daylight, little research has been conducted on nighttime highway safety. Nighttime sight distance is one of the most relevant factors in night driving. Studies demonstrated the need for use 3D methods to estimate daytime available sight distance. This fact may also be applied to nighttime available sight distance. Moreover, not only has the combined effect of horizontal and vertical alignments to be known, but also the influence of adjacent alignments is relevant.
When a vehicle traverses a sag vertical curve at night, the stretch of highway illuminated ahead depends on the position of the headlights and the direction of the light beam. Current design guides provide two dimensional models to study nighttime sight distance to design sag vertical curves. However, the diversity of headlight features and layouts has not been properly incorporated in geometric design neither their impact on the visibility conditions produced.
The procedure presented hereby is an extension of the GIS-based daytime sight distance application developed by the authors (Castro et al., 2014). This paper analyzes the effect of headlamp lighting parameters on unlit rural highways under nighttime conditions through the study of an in-service highway.

2. Background

Statistics indicate that nighttime accidents are more frequent than those occurred at daytime even though the traffic volume registered during the night is significantly lower (AASHTO, 2011). In fact, 32 % of fatalities occurred on highways in 2013 in Spain were at dusk or nighttime and 61 % of pedestrians killed befell on rural highways (DGT, 2014). It is therefore necessary to intensify the research on nighttime highway safety.
The enhancement of highway design has produced evident benefits for safety and comfort. However, generous alignments might have also created potential challenges by enabling higher speeds (Dell'Acqua, 2015). On the one hand, Rockwell et al. (1970) reported that drivers adopt higher speeds at nighttime as the available sight distance increases. Limited sight distance under nighttime conditions, on the other hand, reduces reaction chances to road users (Adler et al., 1973).
Design guides propose two-dimensional (2D) analytical methods to device alignments that enable sufficient visibility conditions both on daytime and nighttime conditions (AASHTO, 2011; Ministerio de Fomento, 2016). Recently, the prescriptions for sag curve design were reviewed (Gibbons et al., 2012). It was observed that a static object on the roadway was detected by drivers from distances significantly shorter than those assumed on stopping sight distance models, regardless of the vertical element type. It follows that the limiting factor is often the lighting conditions rather than the highway geometry.
To apply sight distance as design criterion, guides consider separately highway plan and profile. Such practices may nonetheless lead to underestimate or overestimate the actual sight distance yielded as they ignore the combined effect of alignments and roadsides in three dimensions (3D) (Hassan et al., 1997). Ekrias et al. (2008) measured and analyzed traffic lighting features to simulate automobile headlights. Hassan et al. (1997) developed a procedure to compute the available sight distance in 3D on theoretical alignments. Horizontal and vertical curves overlapped were studied. It was

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observed that a wider horizontal spread angle enhances visibility up to an extent that depends on the highway geometric design. It was also confirmed that supererelevation improves visibility. Sivak et al. (1998) evaluated the effects of a variety of factors on the photometric performance of low-beam headlamps.

AASHTO (2011) assumes a headlight mounting height of 0.60 m and a 1 degree as the upward divergence of the light beam from the longitudinal axle of the vehicle. This height value is at odds with that recommended by the Spanish design standard (Ministerio de Fomento, 2016) or the Portuguese one (JAE, 1994), which set the headlight height at 0.75 m. As might be expected, assuming a lower headlight height lays on the safe side. Thus, it is necessary to provide insight on the influence of this height value. For example, the headlight height values of the 11 most sold vehicles (by far compared to the 12th one) in 2015 in Spain, the average is 0.731 m, ranging between 0.658 and 0.858 m. It is important as well to know the effect of the other variables on nighttime sight distance.

Headlamp regulations around the world are not homogeneous even if vehicles put on market are mostly the same. For example, the American standard (ANSI, 2010) is compulsory in the United States and allowed in Canada and Mexico, while the European counterparts (ECE, 1995) required or allowed in most every other country in the world. Whereas European standards are more concerned about headlight glare avoidance with lower beam, which may penalize lighting performance, American standards encourage high headlight performance, at the expense of other users' visual comfort.

An additional issue in nighttime driving is headlight glare. McLaughlin et al. (2005) evaluated discomfort glare experienced by drivers at night. Glare avoidance is primarily considered by standards and automobile manufacturers. In order to reduce the chances of headlight glare, successive regulations diminished the illuminance permitted above the plane defined by the beam axes for the inner headlamp (Gibbons et al., 2012). Current headlamps provide less illuminance above that plane. Thus Hawkins and Gogula (2008) proposed to reduce the upward divergence angle considered for headlight sight distance estimation from 1 degree to a value between 0.75 and 0.9 degrees.

According to the American Federal Motor Vehicle Safety Standards (1991), headlights may be located at a height between 560 mm and 1370 mm. Likewise, the European standard (ECE, 1995) sets the minimum and maximum height at 500 mm and 1200 mm respectively. In line with this, the Italian standard (Ministero delle Intrastrutture, 2001) sets the headlight height at 0.5 m. However, parameters in highway design guides are usually based on outdated vehicle dimensions. Hence Fitzpatrick et al. (1998) characterized modern vehicle headlight heights for their use in geometric design.

The distance to the farthest point covered by light beam depends upon several factors. The first consideration concerns low beam and high beam. Also, the amount of light to consider a point as lit is essential. This implies the analysis of a more complex problem dealing with human vision and perception, affecting as well other two parameters whose influence are hereby analyzed: horizontal spread angle and upward divergence angle. Although many values may be proposed, in general, a range of 70 to 90 m assuming 3 lx as threshold illuminance for low beam could be considered headlamps according to lighting patterns (Boyce, 2009).

Fig. 1 shows the headlights geometric variables and the layout of vehicle headlights in relation to the driver position. The beam axle is parallel to the roadway grade and its heading angle equals that of the vehicle at each station. The upward divergence angle β is measured from the beam axle. The horizontal spread angle α is the angle symmetrically subtended sideward from the beam axle in both headlamps. Distances d_1, d_2 and d_3 define the location of headlamps in relation to the driver. The value d_1 is determined by the distance between the horizontal projection of the driver's eye and the projection of the straight line joining both headlamps. The d_2 is the distance between headlamps and d_3 outlines the lateral offset of the left headlamp relative to the driver, assuming right-hand traffic.

3. Materials and methods

The GIS-based application Road sight distance was utilized to compute the available sight distance (Castro et al., 2014). It has a specific module for nighttime sight distance computation. The algorithm launches lines of sight along a set of stations placed on the driver's path on the highway, evaluating whether those stations are seen from the driver's position. The nighttime module sets a further condition: the target must lie within the light beam. Such light beam comprises the two beams produced by each headlamp which are delimited by the planes defined by the horizontal spread angle, the upward divergence angle and the headlamp range (Fig. 1).

Stations are set all along the theoretical vehicle path spaced 5 meters apart. In this study, the driver's eye height and the target height were set at 1.1 and 0.5 m respectively, in conformity with the Spanish geometric design standard (Ministerio de Fomento, 2016). Likewise, the stations where driver is placed are at an offset of 1.5 m from the outer edge of lane. The beam axle is assumed to be parallel to the gradient of the vehicle travelling on the pavement all the way, which was retrieved from the vertical alignment of the highway. The slope between two successive stations can be taken from the terrain model on the roadway as surrogate value if it is precise enough. Distances d_1, d_2 and d_3 shown in Fig.1 were taken from the average values of the 11 most sold vehicles in Spain: 1.775 m, 1.345 m and 0.32 m respectively.
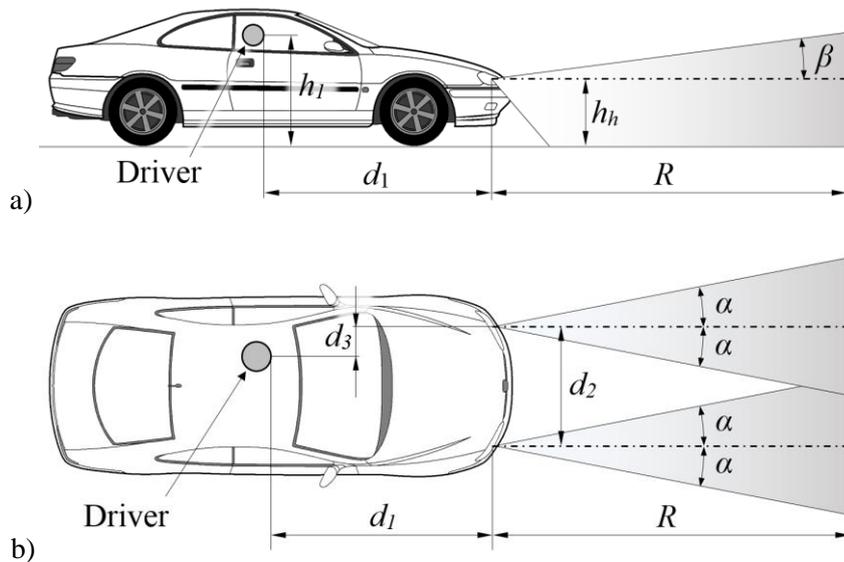
Fig. 1.
Headlamps position in relation to the driver and headlight parameters: a) profile; and b) horizontal projection

The four headlamp parameters to be studied were beam range, headlamp height, beam upward divergence and horizontal spread angle. All values considered in this study for each vehicle headlight parameter are shown in Table 1 which were taken in consistency with the above review of standards and current values. Thus, a total of 900 sets of nighttime sight distance were produced.

Table 1
Headlamp parameters and values studied

Parameters	Values
Beam range	80 m / 100 m / 150 m / 200 m / 300 m
Headlamp height	0.65 m / 0.70 m / 0.75 m / 0.80 m / 0.85 m / 0.90 m
Beam upward divergence	0.7° / 0.8° / 0.9° / 1° / 1.1°
Beam horizontal spread angle	2.5° / 3° / 3.5° / 4° / 4.5° / 5°

A two-lane rural highway was chosen for this study (M-104), which is located in the Region of Madrid (Spain). The length of the section spans 11 km. Its alignment is winding on both the horizontal and the vertical projection, and the design speed is assumed to be 60 km/h. The cross section comprises the roadway of 6.5-meter wide, and 1.25-meter hard shoulder on either side. According to the Spanish geometric design standard (Ministerio de Fomento, 2016), the corresponding stopping sight distance would be 70 m on flat grades. However, the steepest grade reaches 8% on few segments, which means that the stopping sight distance would range from 63 m, when driving uphill, to 79 m, while grade is downhill. The minimum beam range in Table 1 was chosen after this.

4. Results and discussion

First, the consistency of results was analyzed. According to what can be expected, the higher the parameter value is, the longer the nighttime sight distance results for all parameters. Moreover, performing a paired comparison between cases, where all variables remain the same except one, the median results equal or higher in the sample where the variable modified takes a higher value, whatever the variable considered is.

The Wilcoxon signed-rank test for paired samples was performed to determine whether daytime available sight distance and nighttime sight distance come from the same distribution. In all nighttime sets, the p-value resulted less than 0.0001 when compared to the daytime counterparts. It can therefore be rejected at the 99% confidence interval that nighttime sight distance and daytime available sight distance come from the same distribution. The same test was carried out between three relevant headlights cases simulated. Such datasets are those produced by the most favorable parameters (highest input values) , the standard values (beam range 200 m, headlight height 0.75 m, upward divergence 1 degree and horizontal spread 3 degrees), and the most unfavorable parameters (lowest input values). The cumulative frequency graph of these results can also be seen on Fig.2. Even in these cases, the p-value resulted also less than 0.001. Consequently, it can therefore be rejected at the 99% confidence interval that any of these four datasets come from the same distribution.
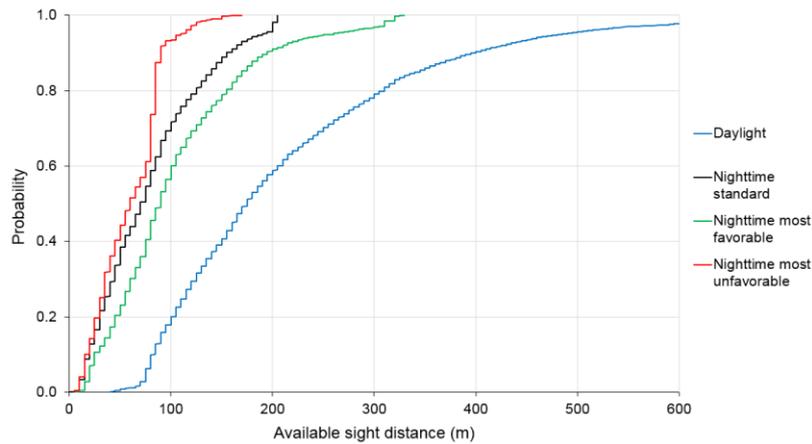
Fig. 2.
Cumulative frequency graph of four relevant available sight distance datasets

It has to be borne in mind that the available sight distance is measured along the vehicle trajectory on the roadway. Conversely, the headlamp range is a straight-line distance. This means that on a winding stretch, the available sight distance outcome may exceed the nominal headlamp range. This fact can be noticed on Fig. 2, where the beam range for nighttime sight distance of the most unfavorable case is 80 m and values over that threshold arose. The same applies to nighttime sight distance in the standard case (beam range: 200 m) and most favorable (beam range: 300 m).

The reader must keep in mind that the lighting range provides the driver with information, among others of the alignment, traffic signs and possible obstacles on the roadway. Notwithstanding the foregoing, the daytime sight distance is still useful in nighttime driving since the field of vision allowed by the roadway and roadside features enable the driver to see other users' headlights and taillights, especially with regard to passing sight distance.

To study the influence of the headlamp range, three series of headlight datasets results were considered, where all parameters are fixed except the beam range. Once again, the first series of results corresponds to the maximum of those values studied (most favorable), the second one set fixes the values at their standard values (headlight height 0.75 m, upward divergence 1 degree and horizontal spread 3 degrees) and the last one takes the most unfavorable ones (minimum values). Fig. 3 shows the share of the overall length where the available sight distance is limited by the headlamp range. While the three series take similar values and show a sharp decrease of sight distance limited for the shortest ranges, the standard and the most unfavorable series present a very low decrease at the highest range around 82 and 85% respectively. Only the most favorable series continues reducing the limitation of the light beam at a moderate rate below 75%. This fact would prove that the rest of parameters are those which enhance visibility conditions to create the evident gap between the most favorable series and the two others. However, if sections with limited sight distance (below values recommended by Spanish standard) are considered exclusively, the influence of headlamp range is null since range is assumed to be no shorter than 80 m.

It is also remarkable that in the case of the winding highway considered in this study, even in the best case, the nighttime sight distance is limited by the light beam along three quarters of the track. Although the geometric design of the highway determines indeed how much of the section ahead is illuminated, it is not the only restrictive factor. It would be interesting to test different roadway scenarios with diverse clearances to study the influence of alignment and roadsides.
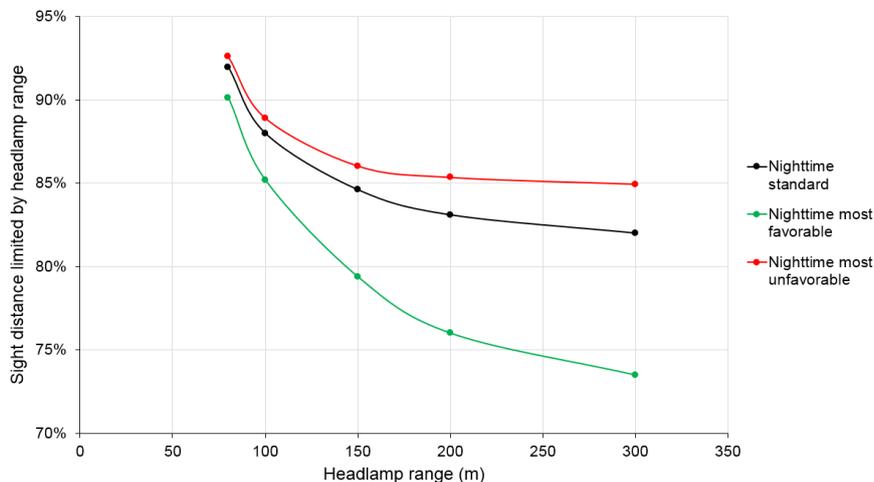
Fig. 3.
Share of nighttime sight distance limited by headlamp range

Next, the influence of headlight height was studied. Likewise, three series of datasets were considered. On each, all the headlight height are considered for the most favorable (maximum values for the other parameters), the standard and the most unfavorable (maximum values for the other parameters). The median of each dataset and the percentage below the available sight distance enforced by the Spanish standard (79 m) were studied to evaluate the influence of this parameter. The median is considered instead of the mean value since the sight distance take discrete values. The consideration of the share of sight distance above the standards permits the study of the influence of this parameter in the lowest tail of the samples, i.e. the zones where the hazard is higher. The results shown in Fig. 4 indicate that this influence is low regardless of the series considered. While the share of sight distance above the stopping sight distance rises slowly, the median values jump just one step (5 meters) in the most favorable and most unfavorable series.
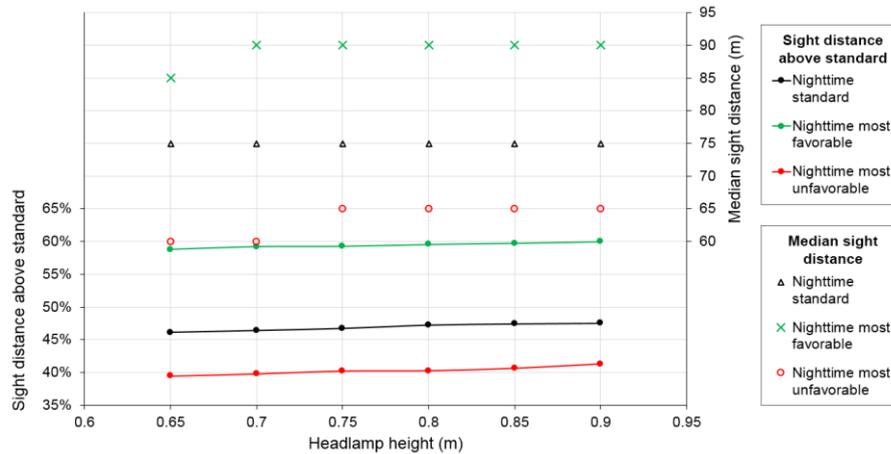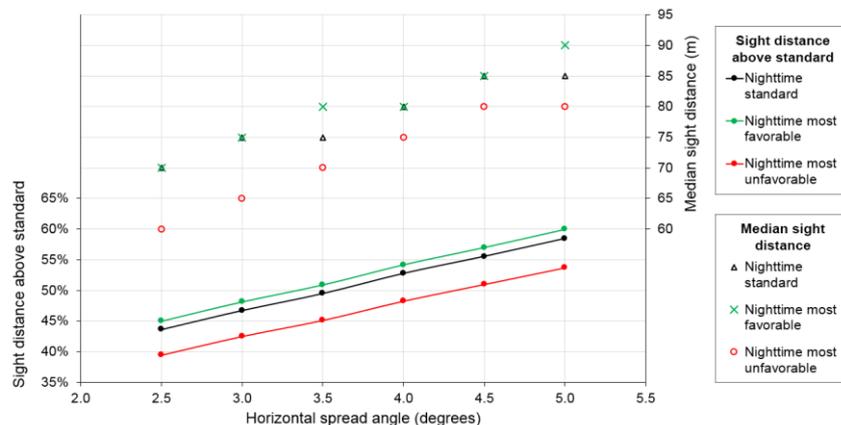

Fig. 4.

Influence of headlamp height on the share of nighttime sight distance above stopping sight distance and median nighttime sight distance

The analysis that follows corresponds to the influence of the beam horizontal spread angle. The usual three series of datasets were considered, varying the value of the horizontal spread angle: the most favorable combination of the parameters, the other standard parameters and the most unfavorable combination of them. The influence of the horizontal angle is significantly higher than in the case of the headlight height because it increases steadily on the three series of data, at a rate of around 5% per degree (Fig. 5). Also, almost every increment of the spread angle entails an increment on the sight distance median. However, the enhancement of the visual field at night as the horizontal spread angle increases is counteracted in terms of safety by the possibility of producing glare to other road users.

Finally, the influence of the upward divergence angle is addressed. As for the previous parameters, the usual three series of datasets were considered while the vertical angle above the beam axle is varied: most favorable, standard and most unfavorable. The results are shown in Fig. 6. Firstly, the variation of the share of sight distance above standard is less close to be linear since a discontinuity around 0.9 degrees is observed for the three series. While the improvement in results is noticeable as the upward divergence changes from 0.8 to 0.9 degrees, it is barely perceptible when the angle is increased to 1 degree. Although the range of the upward divergence at stake is smaller than that of the horizontal spread, the influence of the vertical one is greater per degree. The divergence angle above the beam axle is also hazardous with regard to headlight glare.

Fig. 5.

Influence of beam horizontal spread angle on the share of nighttime sight distance above stopping sight distance and median nighttime sight distance
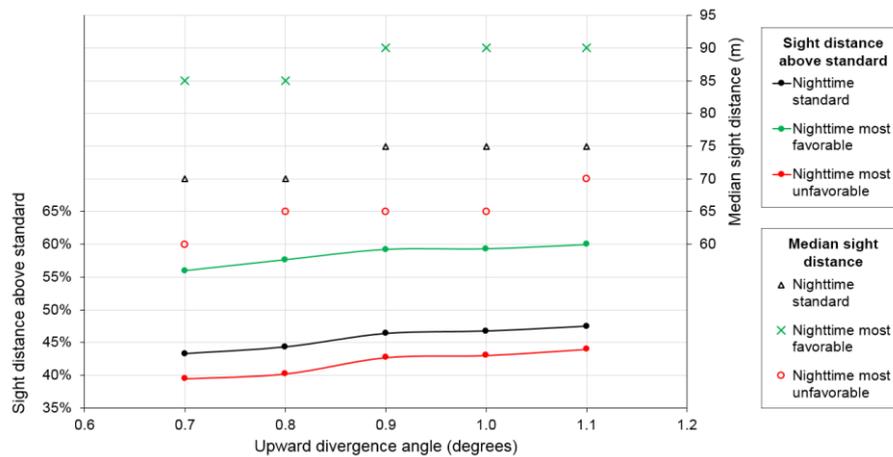
Fig. 6.
Influence of beam upward divergence angle on the share of nighttime sight distance above stopping sight distance and median nighttime sight distance

5. Conclusions

The influence of four vehicle headlight parameters has been studied: headlamp height, beam range, horizontal spread and upward divergence angle. This methodology also sets the basis of nighttime sight distance on driving safety research.

The expected qualitative effect of each parameter was produced in the results, i.e. the nighttime sight distance increased as the parameter values did so. However, the numerical influence of each one was different. It was found that the most influencing parameter was the upward divergence angle, particularly when sight distance are below those recommended by guides. In this case study, the results show that an angle of 0.9 degrees produces nighttime visibility conditions as satisfactory as for the widespread standard value of 1 degree. Also, the influence of the horizontal spread angle is close in importance to the vertical angle above the beam axle. The beam range is nonetheless useful for little in the case of a winding highway such as the case herein addressed.

Although the Spanish standard takes a relatively high headlamp height to study nighttime sight distance, especially when compared to the American one, the results evidenced that the influence of this parameter is very little and the dependences seem much greater for the other parameters. It can be concluded from this that the safety implications of this assumption are not significant. In further studies, the effect of directional headlights on nighttime sight distance is to be analyzed. In addition, different scenarios may be set up in order to test how effective this novel technique results depending on the clearance available in curves.

Acknowledgements

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