Night-time visibility as a function of headlamp beam pattern and pavement reflection properties

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Abstract: The visibility level (VL) approach is often applied to assess the performance of vehicle lighting systems. After describing the details of the VL computational model, we review how it is ordinarily implemented for assessing night-time visibility in driving conditions. Then we present an evolution of the VL approach which consists in evaluating visible edges instead of visible objects, thereby solving the problem of non-uniform luminance at the considered target and at its background. And finally, we present a night-time visibility meter tool for road operators to characterize the contribution of the pavement to the visibility under headlight illumination, with a potential application in AFS.

Keywords: Visibility, contrast, headlamp, pavement, photometry, small target, edges

1. Introduction

Road accidents at night are disproportionately high in numbers and severity compared to day, and the major factor contributing to this problem is darkness because of its great influence on the driver's behaviour and ability. To provide visibility to the driver in unlit areas, vehicles are equipped with headlamps which illuminate the road ahead. But in the presence of oncoming traffic, using low beam is compulsory to minimize headlight glare. Hence, designing headlamps which maximize roadway visibility for the driver and minimize the nuisance to other road users at the same time is a challenge.

There are at least two different approaches to evaluate the performance of front-lighting systems. Those who design and manufacture headlamps use standard criteria which are directly related to the headlamp beam pattern. Some of these criteria are related to safety, such as the 3-lux line, and others are related to comfort, such as the beam spread. Those who use the headlamps (or their representatives) prefer criteria which are directly based on visibility range. They tend to focus on specific targets which are critical in terms of safety, namely pedestrians, pavement markings and signs. Implementing the latter, driver-oriented approach involves conventional traffic scenarios, which actually form the basis of the standard criteria of the former, vehicle-oriented approach.

Visibility Level (VL) is the index which is most often used to assess the performance of lighting systems in a driver-oriented approach, not only for vehicle lighting systems, but for road lighting systems as well. The VL is the ratio between the actual contrast of a target and the threshold contrast which is needed to detect the target. The threshold is usually computed by means of an empirical vision model based on laboratory data, and the operational viewing conditions are accounted for by means of a field factor based on road tests.

After reviewing the VL-based approaches to evaluate lighting systems, we present two VL-based tools to evaluate visibility in night-time driving conditions: first an image processing technique for the comparative analysis of headlamp beam patterns, then a visibility meter system to evaluate the contribution of road pavement to headlight visibility along highways.

2. Night-time visibility assessment

2.1 Visibility Level (VL)

For a given driver with a given acuity and a given contrast sensitivity, the ability to detect a given achromatic object in a given traffic situation mainly depends on three parameters: object luminance, background luminance and adaptation luminance. To put it simply, the luminance difference required to detect an object on its background increases with the overall light level to which the driver is adapted.

The luminance difference threshold was investigated by Blackwell in the 1940's in laboratory conditions, with uniform discs on uniform backgrounds [1]. The results of his experiments, based on an extensive number of individual observations, now constitute a reference. He later proposed to use the ratio between actual contrast and threshold contrast as a visibility descriptor, and this so-called Visibility Level (VL) was adopted by the CIE to evaluate lighting design in terms of visual performance [2]:

$$V = \frac{C}{C_{\text{th}}} = \frac{(L - L_{\text{b}})/L_{\text{b}}}{(L_{\text{th}} - L_{\text{b}})/L_{\text{b}}} = \frac{\Delta L}{\Delta L_{\text{th}}} \qquad (1)$$

where C is the actual contrast and C_{th} the threshold contrast, L is the actual object luminance and L_{th} the object luminance at threshold contrast, L_{b} is the background luminance, ΔL is the actual luminance difference and ΔL_{th} the threshold luminance difference.

2.2 Calculation of threshold contrast

Given all the parameters, the most accurate way to calculate the threshold contrast for a particular situation is to interpolate from Blackwell's laboratory data, but a more convenient method is to use analytic functions fitted to the laboratory data [3]. Several such empirical models have been introduced in the past [4]. One of the most popular was proposed by Adrian in the 1980's for targets subtending less than 60 minutes of arc [5]:

$$\Delta L_{th} = (\phi^{½} / \alpha + L^{½})^2 \qquad (2)$$

where $\phi^{½}$ and $L^{½}$ are defined in three ranges of the background luminance:

• if $L_b \geq 0.6$ cd.m^{-2}

$\phi^{½} = \log(4.1925\, L_b^{0.1556}) + 0.1684\, L_b^{0.5867}$

$L^{½} = 0.05946\, L_b^{0.466}$

• if 0.00418 cd.m^{-2} < L_b < 0.6 cd.m^{-2}

$\log \phi^{½} = -0.072 + 0.3372 \log L_b + 0.0866 (\log L_b)^2$

$\log L^{½} = -1.256 + 0.319 \log L_b$

• if $L_b \leq 0.00418$ cd.m^{-2}

$\log \phi^{½} = 0.028 + 0.173 \log L_b$

$\log L^{½} = -0.891 + 0.5275 \log L_b + 0.0227 (\log L_b)^2$

Equation 2 only applies for long exposure times (2 s or more), positive contrast, young observers (in their 20's), and a 50% detection probability, but it can be extended to account for other sets of these important parameters by means of several multiplying factors for which Adrian also introduced analytic expressions [5]. The time factor F_t accounts for an exposure time e shorter than 2 s:

$$F_t = 1 + a(\alpha, L_b) / e \qquad (3)$$

where:

• $a(\alpha, L_b) = (a(\alpha)^2 + a(L_b)^2)^{½} / 2.1$

• $a(\alpha) = 0.36 - 0.0972\, b(\alpha)^2 / (b(\alpha)^2 - 2.513\, b(\alpha) + 2.7895)$ with $b(\alpha) = \log \alpha + 0.523$

• $a(L_b) = 0.355 - 0.1217\, b(L_b)^2 / (b(L_b)^2 - 10.4\, b(L_b) + 52.28)$ with $b(L_b) = \log L_b + 6$

The polarity factor F_n accounts for a negative contrast (target darker than the background):

$$F_n = 1 - m\, \alpha^{-\beta} / (2.4\, \Delta L_{th}) \qquad (4)$$

where $\beta = 0.6\, L_b^{-0.1488}$ and:

• if $L_b \geq 0.1$ cd.m^{-2}

$\log(-\log m) = -0.125 (\log L_b + 1)^2 - 0.0245$

• if 0.004 cd.m^{-2} < L_b < 0.1 cd.m^{-2}

$\log(-\log m) = -0.075 (\log L_b + 1)^2 - 0.0245$

The age factor F_a accounts for the age A of the observer. It is defined in two ranges:

• if 23 y < A < 64 y

$$F_a = (A - 19)^2 / 2160 + 0.99 \qquad (5a)$$

• if 64 y < A < 75 y

$$F_a = (A - 56.6)^2 / 116.3 + 1.43 \qquad (5b)$$

Finally, the probability factor F_p accounts for a probability of detection p higher than 50% [6]:

$$F_p = (\ln(1-p) / \ln(0.5))^{1/2.532} \qquad (6)$$

The general expression for the threshold luminance difference is obtained by multiplying Equation 2 by the factors of Equations 3 to 6.

2.3 VL in night-time driving conditions

At night without street lighting, the illumination comes from the headlamps alone. The effect of headlight on visibility has been thoroughly investigated in the past decades [7][8], and still is with the development and standardization of adaptive front-lighting systems [9]. There are some who believe that the primary purpose of the headlamps is to light the roadway, not necessarily objects on the roadway (as noted by Kosmatka [10]). It may be true for comfort or acceptance, but obviously not for safety. As a consequence, headlamp performance descriptors based on illuminance alone, such the 1-lux line, may be very handy to compare beam patterns [11][12], but they are insufficient to predict visibility distance [13]. Like visibility under street lighting conditions, visibility under headlight conditions must be evaluated in terms of luminance. But unlike a street lighting installation, headlamps cannot be optimized for a particular road configuration.

The luminance needed to calculate the VL results from the illuminance generated by the headlamps, and from the reflective properties of the illuminated surface. Because contrast determines visibility, two surfaces must be considered for the purpose of evaluating visibility distance: that of the object to detect, and that of the background. There are two types of objects of interest for traffic safety: pavement markings for lane keeping and obstacles for collision avoidance. Markings are specifically designed to maximize reflection in the direction of the headlamps, close to the direction of the driver, which results in high contrast with the non-retro-reflective pavement [14]. As for obstacles (projecting above the road), pedestrians hold a particular stake, and particular efforts were devoted to study their visibility, because they are the most probable object on the road and because they are even more at risk than the drivers. But pedestrians are "tall" objects, so the surfaces behind the upper part of their body are further away from the headlamps than their lower background. Under high beam illumination, this results in higher VL at torso level than at leg level, as can be seen in Ising's analysis of field measurements [15]. Under low beam illumination, it may happen that the bottom part of the pedestrian silhouette has a higher VL because of the cut-off in the beam pattern. In that case, the visibility of the pedestrian is similar to the visibility of any small object on the pavement. Detecting small targets may not be the only aspect of the visual task of a driver, but it is generally assumed that if headlamps are capable of disclosing the most difficult objects to see at sufficient distance, they will certainly provide reasonably safe visibility of practically all other hazardous obstacles [7], which explains why small target visibility (STV) is agreed upon as a relevant criterion for assessing the performance of lighting systems, both for street lighting and front-lighting. Adrian proposed to consider a 20 cm x 20 cm object, arguing that a car could just clear such an object when rolling over it [6]. Despite Lecocq's demonstration that a spherical target would be more relevant [16], Adrian's small square target remains a standard. Targets with fancy shapes are often dealt with by computing some equivalent area [14][15], but it must be noted that a square object is more difficult to see than a rectangular object [18], which is contrary to the ordinary assumption that target shape is of minor importance [17].

Under headlamps illumination, the relevant parameter to characterize the reflective properties of a vertical object (when its surface is not specular of retro-reflective) is the diffuse reflection factor ρ:

$$L = \frac{\rho}{\pi} E = \frac{\rho}{\pi} \frac{I \cos\theta}{d^2} \tag{7}$$

where L is the target luminance, E is the illuminance generated by the headlamps on the object, I is the intensity of the headlamps in the direction of the object, θ is the lighting angle from the normal to the object surface, and d is the distance between the headlamps and the object. In headlamp visibility studies, the targets are usually considered dark, with reflection factor values between 5% and 10%, though values up to 25% are sometimes considered [13][19]. Horizontal objects (markings) and the pavement are best characterized by means of the retro-reflected luminance coefficient for headlight illumination R_L (cd.m^{-2}.lx^{-1}):

$$L = R_L \, E_\perp = R_L \, \frac{I}{d^2} \tag{8}$$

where $E_\perp$ is the illuminance generated by the headlamps on a surface perpendicular to the lighting direction at the position of the target. The R_L of the pavement depends on the relative illumination / observation geometry, but for a given vehicle, it has been shown to be independent of the distance beyond a few tens of meters, with values ranging between 5 and 30 mcd.m^{-2}.lx^{-1} for dry pavements [20][21]. It should be noted that using the reflection factor to characterize the pavement under headlight illumination may result in a significant underestimation of the calculated road luminance.

With the previous information, it is theoretically possible to calculate the luminance of a small target on the road illuminated by headlamps, as well as the luminance of the pavement. But a problem arises when trying to calculate the resulting VL: the pavement, which constitutes the background of the small target, is not uniform. This is usually dealt with in two ways: either the background luminance is set to the average luminance inside a "small" region around the target [13], or it is set to the luminance of the pavement at one of the borders of the target [19][22]. Blackwell and Bixel tend to validate the second approach, stating that the visibility of targets in target-background complexes of non-uniform luminance can probably be best understood in terms of the contrast made by the target with respect to its background at the target border, and that it is not meaningful to describe target contrast in terms of the average luminance of the background [23].

The last variable needed to calculate the VL is the target exposure time. Based on observations of eye movements while driving, the exposure interval is almost always set to 200 ms [6][17].

The question which remains to be settled in order to apply the VL approach is whether the driver is adapted to the background luminance L_b, or if the adaptation luminance L_a should be substituted for L_b as proposed by Adrian [5]. In headlight visibility studies, the adaptation luminance is usually set to the background luminance, although it is sometimes set to the average luminance around the object or over some region at the center of the driver's field of view [22][24]. Practically, the adaptation luminance in headlight illumination conditions is generally unknown [25], although a couple of methods have been proposed to estimate it [19][26].

2.4 Field factor

The previous section describes all the parameters that must be taken into account to implement the VL approach in night-time driving conditions. Theoretically, an object with VL = 1 is just noticeable. However, threshold contrasts measured in operational conditions are always higher than the threshold contrasts predicted from laboratory data because of the driving task demand [15][17][27]. This is dealt with by yet another multiplier called the field factor, which can also be interpreted as a threshold VL for visibility in actual traffic situations as opposed to laboratory conditions.

With a theoretical analysis on how to set a value for the field factor, Dunipace *et al* suggest that VL = 15 should be an adequate visual requirement for highway driving when combined with a factor Fp = 2 to set the detection probability to 99% [17]. They also argue that the field factor is smaller in the case of road tests, mostly because of the controlled test procedures. The experimental analysis by Ising *et al* gives compatible conclusions, with required visibility levels of 1 to 23 for alerted drivers [15]. These field factor values corroborate those proposed by Adrian [6]: 15 to 20 for night-time driving, with 6 or 7 as a strict minimum for safety, considering a detection probability over 99.9%.

3. Effect of headlamp beam pattern by contrast ratioing at visible edges

3.1 Objective

Assessing headlight visibility range by means of the VL approach ordinarily consists in setting small targets (or other objects) at different distances in front of the studied headlamps, and then using a photometer to measure the target luminance and the background luminance, in order to calculate the VL and compare it with some field factor or human observations [19][22]. Since the early 1990's, the use of imaging photometers has progressively developed, allowing measuring both the target and the background in just one shot [28]. However, processing the measured luminance distribution, or luminance map, is not as straightforward as it may seem: the image region of the evaluated object and that of its background must be selected, and their luminance must be computed even though they are not uniform. Assuming that objects are visible from their edges and contours, we claim that assessing the visibility of these features is enough to compare the performance of different headlamps, and we propose an image processing framework to compute relative VL maps [29].

3.2 Image processing framework

The technique to compute a relative VL map from a luminance map is based on an image binarization technique which detects the locally most contrasted contours [30]. This technique was implemented and optimized in order to compute the local contrast at the detected edges in the image [31]. Basically, we consider that features in the image are visible from the contrast at their borders, so we find these borders and compute the luminance difference there. The result is a luminance difference map.

Let us now consider two similar lighting systems (such as two vehicle headlights) A and B providing two different luminance maps L_A and L_B when illuminating a particular road scene. Assuming the adaptation luminance is the same, a relative VL map can be computed by taking the ratio of the luminance difference ΔL_A and ΔL_B at the local edges found with the previous image processing technique:

$$V_{A/B} = \frac{\Delta L_A}{\Delta L_B} = \frac{\Delta L_A / \Delta L_{th}}{\Delta L_B / \Delta L_{th}} = \frac{V_A}{V_B} = \frac{1}{V_{B/A}} \qquad (9)$$

where V_A and V_B are the VL values respectively produced by systems A and B. Edges where $V_{A/B} > 1$ are arguably easier to see with lighting system A than with lighting system B.

3.3 Sample results

The presented technique was applied to compare two high beam headlights, A and B, with respect to the visibility of dark small targets (the reflection factor of the targets is 6%) at three standard positions on the road ahead [32]. A synthetic road scene was simulated with diffuse surfaces (the reflection factor of the pavement is 20%) to render the luminance map generated by each lighting system, as shown in Figure 1. Both luminance maps were processed to compute the luminance difference maps shown in Figure 2. The resulting relative VL maps comparing A/B and B/A are shown in Figure 3.

One cannot tell which lighting system provides the best visibility for the targets by simply looking at the

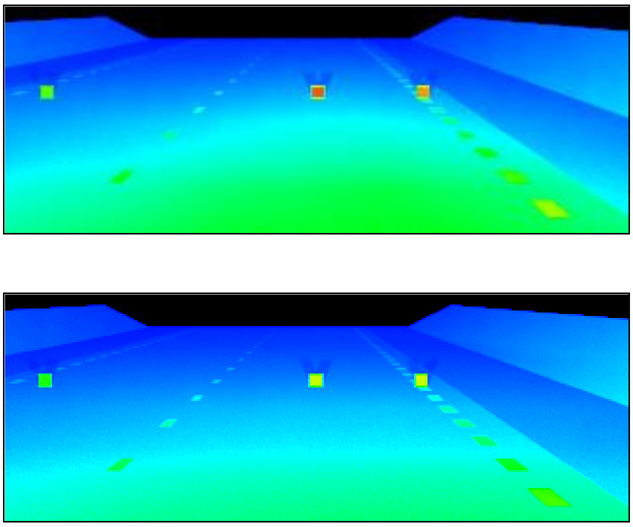

Figure 1: Simulated luminance maps generated by high beams A (top) and B (bottom).

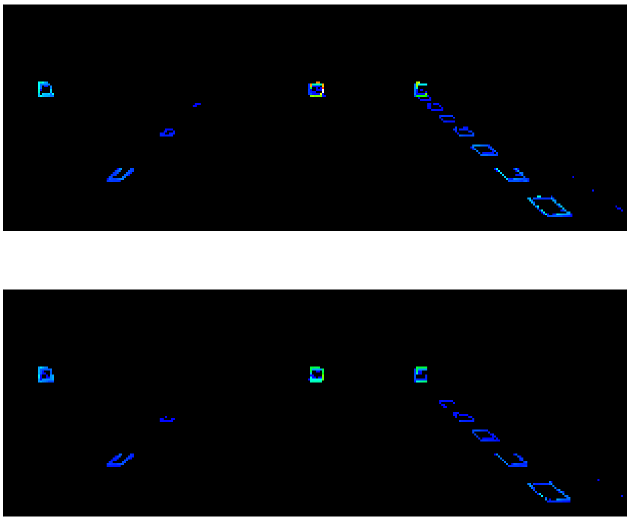

Figure 2: Luminance difference at edges under illumination of high beams A (top) and B (bottom).

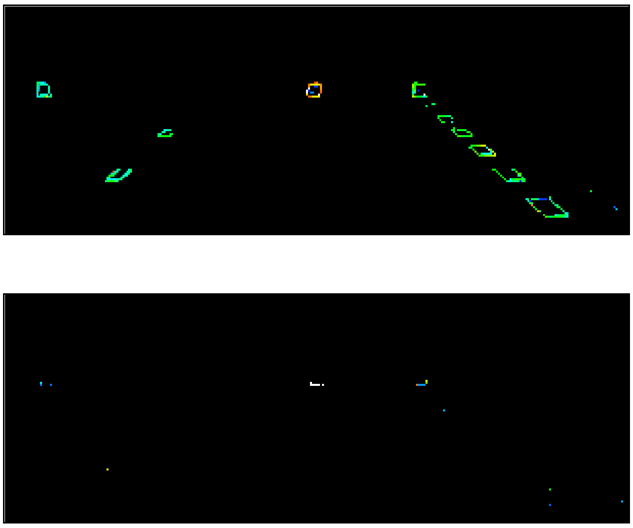

Figure 3: VL ratio A/B (top) and B/A (bottom).

luminance maps (Figure 1), and the non uniform background makes it difficult to evaluate the background luminance to compute the VL. The luminance difference maps (Figure 2) are more informative, but the relative VL maps (Figure 3) are even easier to interpret, clearly designating A as the lighting system which allows for the best small target visibility in that particular configuration.

3.4 Discussion

As illustrated in the previous example, relative VL maps provide a solution to the problem of analyzing complex luminance maps grabbed with imaging photometers. One application is the comparison of the beam patterns of various headlamps with that of a "reference" headlamp, highly rated by experts, in standard driving scenarios [33]. Overall indicators such as those proposed by Hautière *et al* [34] could be calculated from the relative VL map for the purpose of objectively rating the performance of vehicle lighting systems.

One should keep in mind that the relationship between contrast ratio and VL ratio (Equation 9) relied on the assumption that the compared lighting systems generate the same state of visual adaptation for the driver. The validity of this hypothesis can only be investigated when a method has been developed to estimate the adaptation luminance in spatially complex road scenes. Nevertheless, relative VL maps provide a conventional tool for comparing the performance of similar lighting systems.

It should also be noted that the image processing technique which finds local edges in the luminance map is dependent of the resolution. Introducing a frequency contrast sensitivity model instead of the just noticeable difference model should remove that dependency. It might also solve the problem of the size dependency which prevents us to compute absolute VL maps because the size parameter, which impacts the luminance difference threshold (Equations 1 and 2), is undetermined for contours.

4. Effect of pavement reflection properties by night-time visibility metering

4.1 Objective

The VL approach is mostly applied to assess the performance of both street lighting and headlight systems, and it is also applied to assess the performance of signs and markings. But it seems that it has never been applied to assess how the pavement contributes to the visibility under headlight illumination. We hereby propose a conventional method to measure the night-time visibility distance along rural roads devoid of street lighting, to help road operators locate poor visibility sections of their network, and decide where to implement countermeasures [35].

4.2 Computational model

The model underlying the night-time visibility meter tool is inspired from the conventional method to design street lighting systems and evaluate their performance [36]. The idea is to predict the VL of a small object on the roadway at any point along the road under headlight illumination, based on the measured retro-reflected luminance coefficient R_L of the pavement.

The pavement R_L can be measured with a mobile retroreflectometer called ECODYN (Figure 4): it is normally used by road operators to monitor the performance of pavement markings, but it is also capable of measuring low values because it was design to measure the contrast between the markings and the pavement [37].

Figure 4: The ECODYN (mlpc®) system was developped for the continuous measurement of the retro-reflected luminance of pavement markings.

The scenario is that of a car driver on a rural road without traffic, hence using high beams. Except for the pavement R_L, all geometric and photometric parameters are set conventionally: the eyes of the driver are 1.5 m above the ground, the headlamps mounting height is 0.65 m, the small target is a gray 0.18 m side square with a reflection factor of 6%, and the headlamps beam pattern is the average European high beam from UMTRI [38].

The VL of the target is calculated using Adrian's model, as detailed in Section 2. The background luminance is arbitrarily set to the luminance of the pavement at the distance of the target, to account for the combined problems of the unknown adaptation luminance and of the non-uniform background.

The target visibility distance is defined as the distance at which the target VL, computed with a detection probability of 99.96% (F_p = 2.6), is equal to the field factor, which we set to the value 7 recommended in France for street lighting [39]. Since Adrian's model cannot be inversed to calculate a distance from a VL value, the visibility distance is obtained iteratively by setting the target closer and closer to the headlamps, starting at 150 m, until the VL reaches the adopted threshold value (this method is described in [14]). The obtained night-time visibility distance D_N is a conventional index.

4.3 Sample results

The proposed method was implemented on a section of a highway where part of the pavement had recently been renovated (the transition between the old and new pavement can be seen in Figure 5). The resulting visibility profile is shown in Figure 6.

The renovated section appears clearly between 1.5 and 2.8 km, with D_N close to 85 m, whereas it is under 70 m before and after that section. This is due to the fact that the new pavement surface is darker, with R_L values as low as 4 mcd.m^{-2}.lx^{-1}.

The conventional visibility distance is meant as a relative indicator of poor night-time visibility, but it can be compared to a conventional safety distance D_S, like the distance driven at legal speed in the regulatory 2 second headway, which is 50 m at 90 km/h. Assuming that this is the distance needed for the driver to react and stop the car, then $D_N < D_S$ means that the driver will not be able to avoid collision. This situation occurs at 1.1 km and after 3.3 km on the road section where the method was tested (Figure 6).

Figure 1: Darker pavement improves nighttime visibility distance under headlight illumination.

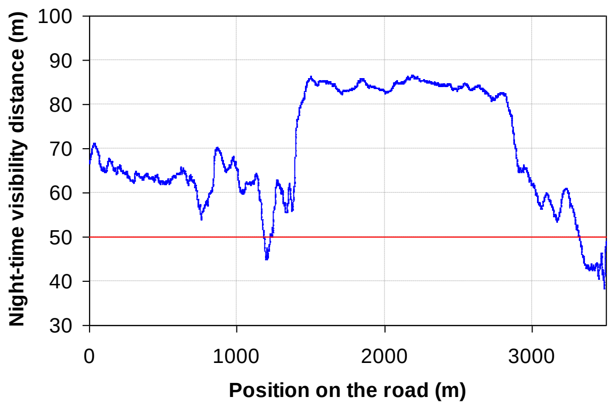

Figure 2: Visibility distance of a small target along a road section under high beam illumination, computed from measured pavement R_L considering a field factor of 7 for the VL.

4.4 Discussion

The proposed night-time visibility meter tool is in fact a mobile pavement retroreflectometer combined with a VL-based computational model which predicts the visibility distance of a potential obstacle along the road under high beam illumination. It will allow the road operators to detect sections of their network where the visibility is relatively poor, but the field factor, or threshold VL, still needs to be calibrated by road tests before it can be used to assess absolute visibility distances.

Considering the situation of on-coming headlights would be a useful complement. It can be done by adapting the computational method to use average low beams instead of high beams, and to account for disability glare by adding the glare veiling luminance (which can be computed with the CIE standard equations [40]) to the luminance of the target and that of the background.

The relevance of the proposed night-time visibility meter tool would also be improved by taking the geometry of the road (radius and slope) into account.

5. Conclusions

Night-time visibility, taken as the largest distance at which a driver detects a small target on the roadway under headlight illumination, obviously depends on the beam pattern of the headlamps. For that matter, and given the development of imaging photometers, the edge-based VL approach holds a high potential as an evolution of the object-based VL approach for assessing the performance of vehicle lighting.

Nevertheless, since visibility is a matter of contrast between the target and the pavement, the road surface also plays a part, and one which is seldom considered when assessing headlight visibility range. But with the development of AFS [9] and infrastructure-vehicle integration [41], there may come a time when the headlamps will be capable of adapting their pattern according to information about the pavement provided by the road operator, in order to optimize the visibility distance.

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7. Glossary

AFS: Adaptive Front-lighting Systems
CIE: Commission Internationale de l'Eclairage
STV: Small Target Visibility
VL: Visibility Level