A conventional approach to nighttime visibility in adverse weather conditions

Romain Gallen, Eric Dumont and Nicolas Hautière

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1 Introduction

This paper presents a conventional approach for assessing highway visibility at night in foggy weather, based on the Visibility Level (VL) concept. The method is adapted from a nighttime visibility assessment method published earlier. First, we recall the basics of the VL concept and the associated target visibility computation model. We also recall the conventional obstacle collision scenario which serves to estimate the nighttime visibility distance as a function of pavement retroreflectivity for a given headlamp beam pattern, using the basic laws of photometry. Then we introduce the visibility impairing effects of fog. The first effect is the exponential attenuation of luminance with distance, described by Beer-Lambert law. The second effect is the veiling luminance generated by the backscattering of headlight, for which we propose an empirical model based on physically-based simulations. We apply the presented approach to low-beam and high-beam patterns in different fog conditions, and we bring quantitative proof for the need to dip the headlamps in dense fog. Finally, we discuss the potential benefits of the presented approach for road operation as well as for automotive front-lighting and advanced driver aiding system design.

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 size and luminance, background luminance and adaptation luminance. 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 [1]. The results of his experiments 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]:

$$\mathrm{VL} = \frac{C}{C_{\mathrm{th}}} = \frac{(L - L_{\mathrm{b}})/L_{\mathrm{b}}}{(L_{\mathrm{th}} - L_{\mathrm{b}})/L_{\mathrm{b}}} = \frac{\Delta L}{\Delta L_{\mathrm{th}}} \tag{1}$$

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

The most convenient method to calculate the threshold contrast is to use analytic functions fitted to Blackwell's laboratory data. One of the most popular among such empirical models was proposed by Adrian in the 1980's for targets subtending less than 60 minutes of arc [5]:

$$\Delta L_{\mathrm{th}} = \left(\frac{\varphi^{1/2}}{\alpha} + L^{1/2} \right)^2 \cdot F_{\mathrm{p}} \cdot F_{\mathrm{c}} \cdot F_{\mathrm{t}} \cdot F_{\mathrm{a}} \tag{2}$$

with ϕ and L functions depending of the background luminance given by Adrian, α the angular size of the target (in arcmin), F_p depending on the detection rate needed (1 for 50%, 2.6 for 99.9%),. F_c, F_t and F_a are correction factors computed applied to take into account the contrast polarity, the presentation time and the age of the observer. Adrian's photometric model is still the most commonly used for assessing the visual performance for object detection, despite its caveats [6]. Adrian provided some threshold VL values accounting for field conditions (as opposed to laboratory conditions) [7]: 15 to 20 for night-time driving, with 6 or 7 as a strict minimum for safety, considering a detection probability over 99.9%.

2.3 VL in night-time driving conditions

At night without road lighting, illumination comes from the headlamps alone. The effect of headlight on visibility has been thoroughly investigated in the past decades [8][9], and still is with the development and standardization of adaptive front-lighting systems [10].

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-retroreflective pavement [11]. As for obstacles (projecting above the road), 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 revealing the most difficult objects to see at sufficient distance, they will certainly provide reasonably safe visibility of practically all other hazardous obstacles [8], which explains why small target visibility (STV) is agreed upon as a relevant criterion for assessing the performance of lighting systems. We can estimate the illuminance E that reaches a target at distance d given a pair of headlamps for which we know the luminous intensities I_L and I_R emitted toward the target:

$$E = E_L + E_R \approx \frac{I_1 + I_2}{d^2} \qquad (3)$$

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

$$L \approx \frac{\rho \cdot E}{\pi} \approx \frac{\rho}{\pi} \cdot \frac{I_1 + I_2}{d^2} \qquad (4)$$

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, 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 [12]. Horizontal objects (markings) and the pavement are characterized by means of the retro-reflected luminance coefficient for headlight illumination R_L (cd.m^{-2}.lx^{-1}):

$$L = R_L E_\perp \approx R_L \cdot \frac{I_1 + I_2}{d^2} \tag{5}$$

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 illumination and observation geometry, but 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 [13].

With the previous information, it is possible to calculate the luminance of a small target on the road illuminated by headlamps, as well as the luminance of the pavement at the base of the target, which serves for both the background luminance and the adaptation luminance [14]. As usual for headlamp evaluation; the exposure interval is set to 200 ms, and a young driver is considered (age 25). These settings can be used to assess the photometric visibility distance as a function of pavement reflectivity and headlamp beam pattern [15].

2.5 Impact of fog on apparent luminance

The effects of fog on light propagation at night are illustrated in Fig. 1. Two major effects should be accounted for when the only source of illumination is the front-lighting system of the observer's vehicle: attenuation and back-scattering.

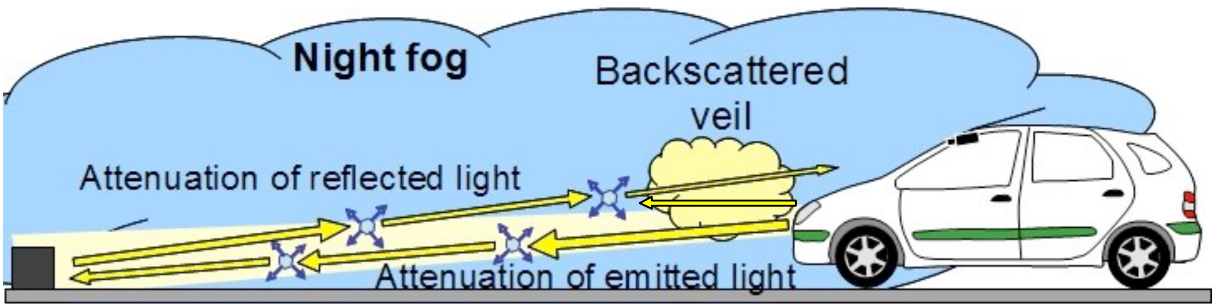

Figure 1: The different effects of fog on light propagation in a driving scene

We estimate the attenuation of light along its path from the headlamps to the target and back to the driver using classical models of light scattering in disperse media. Then we estimate the luminance of the backscattered veil with an empirical model based on Monte Carlo simulations.

2.5.1 Scattering of light depending on the distance

Fog is a dispersed media that contains water droplets formed around condensation nuclei and non-active sub-micron particles, but the latter have relatively little effect on light propagation. Therefore, fog is ordinarily assumed to contain spherical water droplets in different numbers and sizes [24].

Fog is known for its effects on visibility. The droplets composing the fog scatter light in all directions with proportions depending on the size and number of particles per unit volume. Multiple studies have described its effects on the luminance of surfaces and signals. The simpler models describe the effects of fog on perceived luminance based solely on the extinction coefficient k of Beer-Lambert exponential attenuation law while more complex model take into account the distribution of droplet sizes [18]. Beer-Lambert law describes the amount of a light beam transmitted through a slab of fog of depth d and extinction coefficient k such that :

$$L = L_0 \cdot e^{-kd} \tag{6}$$

Considering the visibility of a black object against the sky, the CIE has related the extinction coefficient k to the meteorological visibility distance V_{met}:

$$V_{met} = \frac{3}{k} \tag{7}$$

Knowing the contrast threshold necessary for the detection of a target with Adrian's model and the attenuation of contrast due to a fog of given extinction coefficient, we are able to compute the distance at which this minimal contrast is still perceived, thus the photometric visibility distance in fog.

Fog induces a double attenuation of light for night driving conditions: Beer-Lambert law applies first on the path from the vehicle headlamps to a surface in the scene, and then from the target to the driver's eyes. We can compose Eq. (4) and (5) with Eq. (6) in order to model this phenomenon:

$$L \approx \left(R \cdot \left(\frac{I_L + I_R}{d^2} e^{-kd} \right) \right) \cdot e^{-kd} = R \cdot \frac{I_L + I_R}{d^2} e^{-2kd} \tag{8}$$

with the reflectance R being equal to R_L or ρ/π depending if we consider the pavement or the target.

2.5.2 Back-scattered veil from headlight

Another phenomenon that contributes to the loss of contrast in the scene is linked to back-scattered headlight. Although most energy is scattered forward, some is scattered backwards toward the driver, thus generating a permanent veiling effect in front of the car.

The luminance of the backscattered veil L_v has been studied with a Monte Carlo light tracing software [19]. It has been shown to depend on both fog type (radiation or advection) and meteorological visibility distance, and to follow the following model (Fig. 2):

$$L_V = \frac{1}{aV_{met} + b} \tag{9}$$

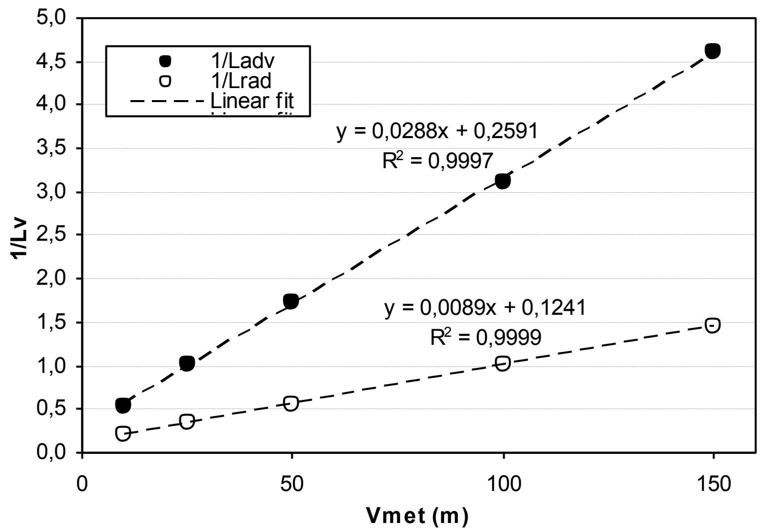

Figure 2: Headlight backscattered veil luminance as a function of meteorological visibility distance for two types of fog (radiation and advection).

Parameters (a,b) depend on fog type: (0.0089,0.1241) for radiation fog, (0.0288,0.2591) for advection fog.

This luminance is over imposed on the driving scene, setting the driver's visual adaptation and increasing the apparent luminance of all surfaces, Eq. 8 becomes:

$$L = R\frac{I_R + I_L}{d^2}e^{-2kd} + L_V \tag{10}$$

3 VL computation

We propose to adapt the nighttime visibility metering tool proposed earlier [15] in order to estimate photometric visibility distance in nighttime fog. 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 beam pattern, pavement retroreflectivity and the fog parameters.

3.1 Tools

The model underlying the night-time visibility meter tool is inspired from the conventional method to design street lighting systems and evaluate their performance [22].

The pavement R_L can be measured with a mobile retroreflectometer such as ECODYN (Fig. 3). Usually used by road operators to monitor the performance of pavement markings, this device is also capable of measuring low values because it was designed to measure the contrast between the markings and the pavement [17].

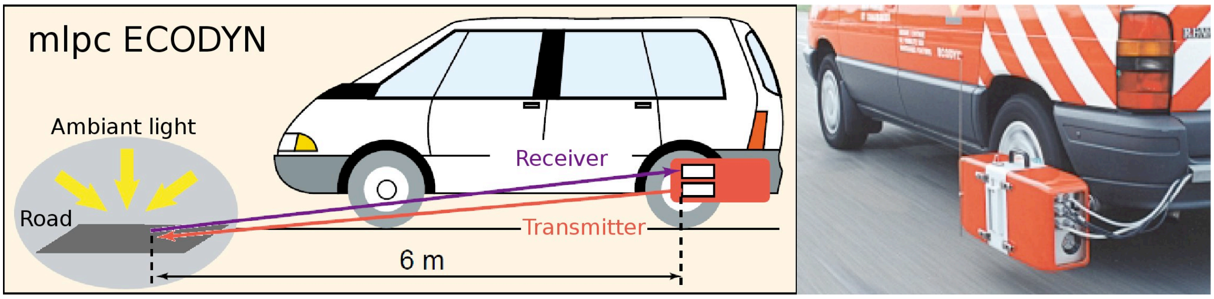

Figure 3: Retro-reflection measuring device ECODYN (mlpc®).

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 [20].

The VL of the target is calculated using Adrian's model, as detailed in Section 2. Since Adrian's model cannot be inversed to compute 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 7, the adopted threshold value.

3.2 Results

The previous method was implemented on a 3-km highway section on which the pavement retroreflected luminance profile had been measured, using UMTRI beam patterns with different nighttime fog conditions. Results for radiation fog are shown in Fig. 4.

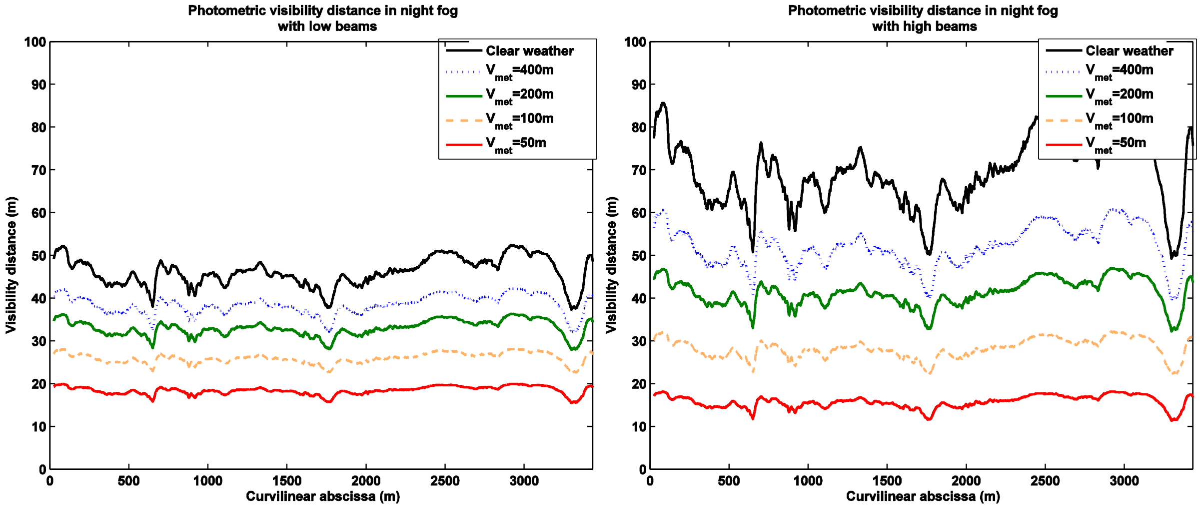

Figure 4: Photometric visibility distance in nighttime advection fog using low beams (left) and high beams (right) depending on meteorological visibility distance.

We can see that the photometric visibility distance is strongly reduced in presence of radiation fog. It is worth noting that in dense fog (Vmet = 50 m), high beams provide less visibility than low beams because of the backscattered veil. This effect is even stronger in radiation fog, as the backscattered veil is stronger. It confirms the legal recommendations that in dense fogs, one should use low beams rather than high beams.

3.2 Conclusion

The assessment of the nighttime visibility distance can be combined with the notion of atmospheric visibility in order to predict the visibility range when driving in different fog conditions at night. This has been done by simulating typical headlights in a standard scenario. By working at high rate and by using modulated light, the ECODYN acquisition device can be used up to 120 km.h^{-1} by daytime as well as by nighttime, which allows for a fast characterization of the reflecting properties of a whole network. Our simulation tool would then allow for a logical prioritization of sections lacking for nighttime visibility.

Recent evolutions in the regulations concerning automotive lighting systems such as [21] have lead to proposals such as [22] tending to a more common use of “highbeams type“ lighting systems. This interesting proposal should nonetheless be investigated knowing that in certain meteorological conditions the appropriate answer may be elsewhere as we showed it for dense fogs. Knowing the impact of the illuminance distribution of headlights on nighttime visibility could help standardizing the beam patterns and knowing the impact of fog conditions may help to define guiding rules for future adaptive lighting by a combination with embedded fog detection systems such as proposed in [23] in order to adapt to lighting conditions as well as to local meteorological conditions.

The visibility metering tool may also be used to help road operators anticipate visibility reduction depending on the weather, and thus adapt posted speed limits dynamically (by means of changeable message signs or with future cooperative systems).

Finally, the issue of seeing the road at night in absence of public lighting is a general problem, but moreover for some populations such as older people. Knowing this is a parameter of Adrian’s model, this tool could be helpful to characterize the distribution and deviation of visibility supply on a road network among drivers and take safety measures or adapting lighting systems to these problems.

3.2 Bibliography

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