Extended Photometric Model of Fog Effects on Road Vision

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ABSTRACT

The road environment casts a luminance distribution into the eyes of the driver. In the presence of fog, the resulting visual signal is disturbed due to light scattering by airborne water droplets. This phenomenon has three major effects which cause an overall visibility loss: attenuation, halo and veiling. Koschmieder’s law is widely used to describe how fog modifies the visual signal, but it only applies when observing non-luminous objects in daytime. In night-time and/or with self-luminous objects, luminance from scattered light can no longer be neglected. In the present paper, the optical mechanisms underlying the visual effects of fog are first analyzed. Koschmieder’s law is then extended in order to account for halos and back-scattered veil in the disturbed visual signal. The utility and validity of the resulting photometric model are discussed, and an example is provided which illustrates how it can be used to predict the image of a foggy road environment as seen by a driver. Despite its complexity, the presented model should find many applications, such as driving simulation or aiding device design.

INTRODUCTION

Fog is a traffic hazard (*1*). Dense fog can drastically impair visibility, taking away visual clues that are crucial for a safe driving. Such adverse visibility conditions dramatically increase the risk of chain reaction accidents. Therefore, it is important to comprehend the visual effects of fog, in order to improve road safety by designing adapted in-vehicle and roadside solutions.

But fog is a rather unpredictable meteorological phenomenon. Experimental studies are therefore very difficult to set up in natural outdoor situations, not knowing when and where fog will occur. Artificial fog facilities make it possible to ensure better control over important parameters, yet they are limited by size and technology. Simulation can be used as a complementary tool to overcome these problems: not only does it provide fine controllability, but also reproducibility, as well as security when it comes to the study of human performances. But to simulate a phenomenon such as visibility impairment by fog, a photometric model is needed. As the photometric effects of fog have now been thoroughly described, it is possible to develop such a model.

In the present paper, the mechanisms underlying visibility impairment in fog are first analyzed, and then a model based on Koschmieder's law is proposed to describe the various effects of fog on the photometric image of the road environment perceived by the driver.

FOG, LIGHT AND VISION

Fog microstructure

Fog is a thick cloud of microscopic water droplets suspended at ground level. It can be described by its particle size distribution (from a few tenth to several tens of micrometers in size) and its concentration. It often occurs in the evening when the cooling ground brings the air temperature down to dew point, and vanishes in the morning with the heat of the sun.

Light scattering

When light propagating in fog encounters a droplet, the luminous flux is scattered in all directions. The spatial distribution of scattered energy depends both on the size of the droplet and on the wavelength. For visible light (wavelengths between 380 and 780 nm) and fog, this distribution, described by the phase function, can be computed using Mie's electromagnetic equations, and absorption can be considered negligible. Light goes under multiple scattering along its path in fog. The energy loss is described by the extinction coefficient k [m^{-1}], which depends on the droplet size distribution and the concentration. According to Beer-Lambert law, the transmissivity T of a slab of fog is

$$T = \mathrm{e}^{-\tau} \qquad \text{(Equation 1)}$$

where $\tau = kd$ defines the optical density, d [m] being the width of the slab.

Visibility impairment

The driver mainly relies on visual information to keep his vehicle within a safe trajectory. The effect of light scattering in the presence of fog is to modify this information by an overall reduction of contrasts as a function of distance. This effect is generally described by the meteorological visibility V_m [m], defined as the greatest distance at which a black object of suitable dimensions (*sic*) can be recognized by day against the horizon sky (*2*). Using the expression of transmissivity in Equation 1 with a threshold contrast of 5% yields the following approximate relation between the visibility V_m and the previously defined extinction coefficient k:

$$V_\mathrm{m} \approx \frac{3}{k} \qquad \text{(Equation 2)}$$

This way of describing fog visual effects is somehow limited, because the microphysical nature of the fog is not taken into account, although previous experiments have shown that the particle size distribution does affect visibility in fog (*3*). Therefore, the meteorological visibility should only be used as an intuitive equivalent to the extinction coefficient.

FOG PHOTOMETRIC EFFECTS

In order to propose a more adequate characterization of the visual effects of fog, the physical mechanisms underlying these effects were analyzed. Due to the total lack of control over important parameters when experimenting in natural fog, this work was mostly based on simulations. A semi-Monte Carlo light tracing technique was designed to simulate luminance measurements (*4*), considering the fact that the distribution of luminance throughout the environment constitutes the “visual signal”, which is analyzed by the visual system to infer higher order information such as shapes or distances.

Composition of the visual signal

The visual signal can be decomposed into primary and secondary zones. A primary zone corresponds to luminance coming directly from a light source. A secondary zone corresponds to luminance coming from an illuminated surface, which receives its energy from the various natural (sky) and artificial (headlamps, public lighting) light sources in the environment. In the case of primary zones, light follows a single path from the source to the observer, whereas in the case of secondary zones, light follows at least two paths: one from each source to the surface, and then one from the surface to the eye. This is illustrated by Figure 1. Fog effects on the visual signal are caused by the scattering that occurs along these paths.

Attenuation effect

In daytime, the sky is the main source of luminous energy. It generates a generally uniform illuminance throughout the environment, which depends on time, geographical and meteorological conditions. Depending on the optical properties of the surfaces, part of this energy is re-emitted toward the observer, generating an intrinsic luminance L_0 (luminance at a close range) for each surface element.

In night-time, only artificial light sources are responsible for the intrinsic luminance of the surfaces. In clear weather conditions, each light source would contribute to the intrinsic luminance of each surface element. But in the presence of fog, scattering causes this contribution to be attenuated by a factor equal to the transmissivity $\exp(-kd_s)$, where d_s is the distance between the light source and the surface element, and k is the extinction coefficient of the fog.

The intrinsic luminance of a surface element in the direction of the observer is the sum of all intrinsic luminances generated by natural and artificial illuminations. Again, part of this energy is scattered by fog on the distance d between the surface and the observer, causing the transmitted luminance to be attenuated by a factor equal to $\exp(-kd)$.

Halo effect

Fog alters the primary zones of the visual signal by scattering the luminous energy along its path from the light sources. Part of the energy is scattered back toward the eye off-axis, adding a halo of scattered light around the transmitted signal. This effect was shown to be equivalent to a convolution (*5*). Therefore, by analogy with an optical filter, a slab of fog can be characterized with its Modulation Transfer Function (MTF), equal to the module of the Fourier transform of its Point Spread Function (PSF).

It was found that the MTF M_0 of a given homogeneous microstructure, when specified for a given optical density τ_0, could be generalized to compute the MTF M for a different optical density τ using the following property in the Fourier domain:

$$M = M_0^{\tau/\tau_0} \qquad \text{(Equation 3)}$$

Consequently, the Frequential Contrast Operator (FCO) was defined as the MTF of a slab of unit optical density. This operator can be used to characterize almost any slab of fog (at least for $\tau < 6$) for a particular microstructure.

It was also confirmed that the FCO varies with the size of the fog droplets, as shown in Figure 2: bigger droplets yield higher transmission of contrast in low spatial frequencies. In the visual signal, it means that bigger droplets yield stronger halos. However, the scattered halo remains secondary compared to the transmitted luminance.

Veiling effects

Veil from atmosphere

In daytime fog, the droplets in the air between the observer and the elements of the road environment also contribute to the apparent luminance by scattering toward the eye some of the energy it receives from the sky (single scattering) and from other droplets (multiple scattering). The resulting atmospheric veiling luminance L_a increases exponentially with distance (*6*):

$$L_a = \left(1 - e^{-kd}\right) L_f \qquad \text{(Equation 4)}$$

where L_f is the luminance of the fog at the horizon.

Veil from back-scattering

When the observer is in fact driving in fog, the low-beam headlamps of his vehicle ought to be turned on. Fog droplets in front of the vehicle interact with this luminous flux, scattering a part of it back into the eyes of the driver in a non-uniform distribution. The back-scattered veiling luminance L_b was found to be at least two orders of magnitude smaller than the atmospheric veiling luminance in daytime. Yet it contributes to the loss of visibility in night-time conditions (*7*), and therefore should be taken into account.

MODELING FOG VISUAL EFFECTS

The major effects of fog on road vision – attenuation, halo and atmospheric veiling – all depend on the distance. Therefore, the two-dimensional distance distribution in the observer's field of view needs to be taken into account. Based on the geometrical and photometrical description of the road environment, a formalization of the perturbations generated by fog in the visual signal was tried, in order to predict the image seen by the driver in foggy conditions.

Koschmieder's law

As reported in (*6*), Koschmieder conducted detailed calculations on the illuminance of a cone of air receiving light from the atmosphere, the sky and the ground, and came out with a simple expression of the apparent luminance of an object of intrinsic luminance L_0 observed from a distance d against the horizon:

$$L = e^{-kd} L_0 + \left(1 - e^{-kd}\right) L_f \qquad \text{(Equation 5)}$$

where L_f is the fog luminance at the horizon, and k is the extinction coefficient of the fog. Duntley later found a similar expression for non-horizontal visibility.

This elegant expression however relies on certain hypotheses concerning the conditions of observation. In particular, Koschmieder's law can only be applied to non-luminous objects observed in daytime. This is quite limiting when it comes to road vision, for two main reasons: fog often occurs at night, and the visibility of rear lamps or traffic signals is an important matter of study.

For night vision, Allard's law provides a basic equation relating the illuminance generated by a point source of light to the transmissivity of the atmosphere (*6*). Yet this theory is only a direct application of Beer-Lambert exponential law of attenuation, and does not account for the halo effect caused by forward scattering.

Extended model

Starting from Koschmieder's law, and based on the analysis of the mechanisms underlying visibility impairment, an extended model for the effects of fog on the visual signal can be proposed. The model takes the two-dimensional distribution of range and intrinsic luminance in the field of view as input. The extinction coefficient k (or the meteorological visibility) and the FCO F of the fog must also be specified. The perturbed visual signal is computed in three steps: attenuation, convolution and veiling.

The first step concerns secondary zones. The intrinsic luminance of visible surfaces is decomposed in two parts: L_0 coming from daylight, and $\Sigma\, L_s$ coming from artificial light sources. The transmitted luminance L_2 is computed by applying Beer-Lambert attenuation factor, first to the paths of lengths d_s from every light sources to the surface, and then to the path of length d from the surface to the observer:

$$L_2 = e^{-kd} \left(L_0 + \sum e^{-kd_s} L_s\right) \qquad \text{(Equation 6)}$$

The second step concerns primary zones. The intrinsic luminance L_i of visible light sources is attenuated and spread onto the neighboring zones using the range dependent PSF of fog as a convolution kernel..

The PSF is obtained by taking the inverse Fourier transform of the MTF of the slab of length d separating each light source from the observer. The MTF is derived from the specified FCO F using Equation 3. Thus, the transmitted luminance L_1 of primary zones can be expressed as follows:

$$L_1 = L_\mathrm{i} * \mathbf{F}^{-1}\left\{F^{kd}\right\} \qquad \text{(Equation 7)}$$

In the third and final step, atmospheric and back-scattered veiling luminances are added to the result of the two previous steps, and yield the apparent luminance:

$$L = L_{\{1|2\}} + \left(1 - \mathrm{e}^{-kd}\right)L_\mathrm{f} + L_\mathrm{b} \qquad \text{(Equation 8)}$$

where $L_{\{1|2\}}$ is either L_1 for primary zones or L_2 for secondary zones in the visual signal.

Implementation

This model was implemented in order to compute bidimensional luminance maps in arbitrary foggy road environments. The program needs rather complex information as input:

- intrinsic luminance map due to each light source: $L_0(x,y)$, $L_s(x,y)$ and $L_\mathrm{i}(x,y)$;
- range map from the observer and from each light source: $d(x,y)$ and $d_s(x,y)$;
- fog FCO, meteorological visibility and luminance: F, V_m and L_f;
- back-scattered luminance map: $L_\mathrm{b}(x,y)$;

where (x,y) represents a direction within the observer's field of view.

As an example, a simple rural road scene was modeled, containing two straight marked lanes and a crossroad sign set 50 m ahead of the simulated driver. Three cars were set in the scene: the driver's vehicle with its headlights in low-beam position, a vehicle going the same way 75 m ahead with its rear-lights on (the one on the right is supposed to be a rear fog light, and so is brighter), and a vehicle coming the other way 150 m ahead with its headlights on in low-beam position. The same simulation code as the one which served to study frequential filtering of contrast by fog was used to compute intrinsic luminance maps and distance maps, as well as the back-scattered luminance map which corresponds to the driver's vehicle headlights. The model was then applied to compute the photometric images of the scene perceived by the driver in the presence of a fog (formed of droplets around 10 µm in diameter, with meteorological visibility $V_\mathrm{m} = 100$ m), both in daytime (with fog luminance $L_\mathrm{f} = 500$ cd.m^{-2}) and in night-time. The results are shown as iso-luminance maps respectively in Figure 3 and Figure 4.

DISCUSSION

Pros and cons

With the presented model, one can predict how fog affects road vision for a driver at any time of day or night (even in intermediate crepuscular situations), for both self-luminous and reflective objects. This should prove quite useful to people concerned with road safety in low visibility conditions. It has already been adapted in order to be implemented into the visual loop of a driving simulator (*8*).

On the other hand, very detailed photometric and geometric information is needed, although the model can be simplified in particular situations. And some limitations remain. One of the major limiting hypothesis is the spatially uniform fog, when natural fog usually comes in banks. Spatial uniformity of fog luminance may also be objected to. Then the FCO can only be used to predict the halo effect around light sources emitting isotropically toward the observer, which is acceptable for rear-lights or active signs, but not for public lights or headlights. And hidden light sources cannot be processed, though their halo may actually be visible. Finally, the scattered energy from the light sources is not taken into account in the intrinsic luminance of the surfaces. But getting past these limitations would require global illumination calculations, which are far less versatile than the presented image processing approach.

Validation

A validation of the model was attempted with psychologists, by assessing the effect of dense fog on the perception of distance (*10*). Previous experiments had been conducted in artificial fog facilities, where observers had been asked to estimate the distance which separated them from the rear of a vehicle whose rear fog-lights were on, both in daytime and night-time; the fog had to be very dense (meteorological visibility under 15 m) for the limits of the facilities to remain invisible. These experiments were reproduced using a driving simulator, inside which images generated with the photometric model of fog visual effects were displayed (the video projecting system had been calibrated). The results proved reasonably satisfactory, though the limited luminance dynamic range of the display system was found to be problematic, especially for the restitution of the night-time conditions. Sample images of this experiment are presented in Figure 5.

Future research

Having characterized and modeled the photometric effects of fog on road vision, experiments and research should now be undertaken to assess its perceptive effects, in terms of visibility levels (*9*) for instance. The presented model can be used to synthesize test images of markings, signs, signals or targets, in order to investigate drivers' visual needs and produce recommendations for road and highway operations.

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LIST OF FIGURES

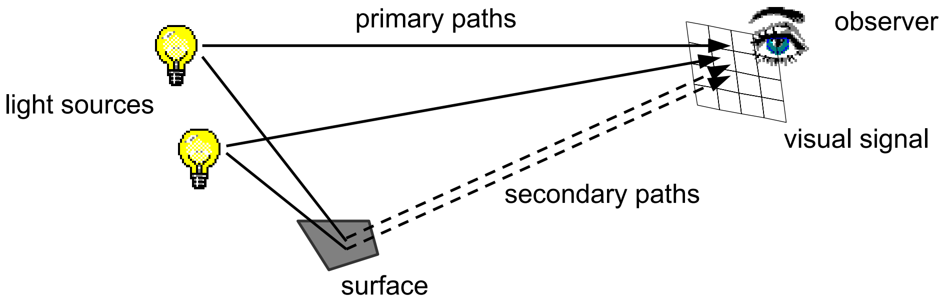


FIGURE 1. Composition of the visual signal.

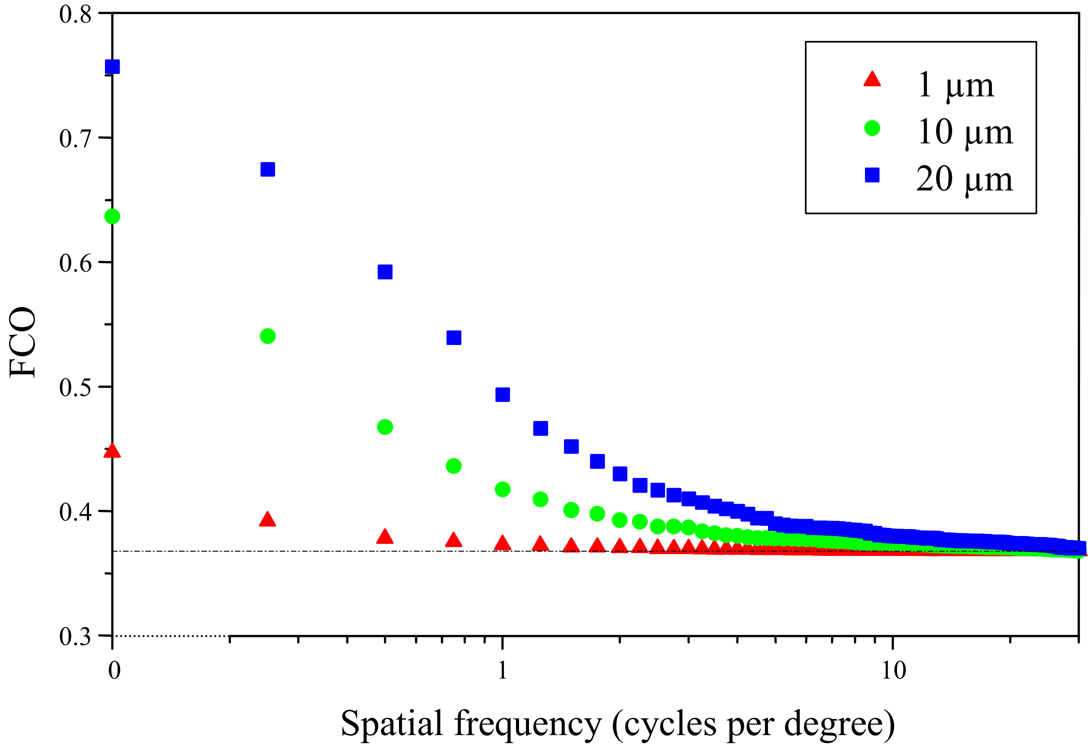


FIGURE 2. Frequential Contrast Operator plot comparing fogs with different droplet size distribution modes.

FIGURE 3. Example of iso-luminance map computed with the presented model for daytime fog: V_m = 100 m, L_f = 500 cd.m^{-2} (the horizontal field of view is 20°).

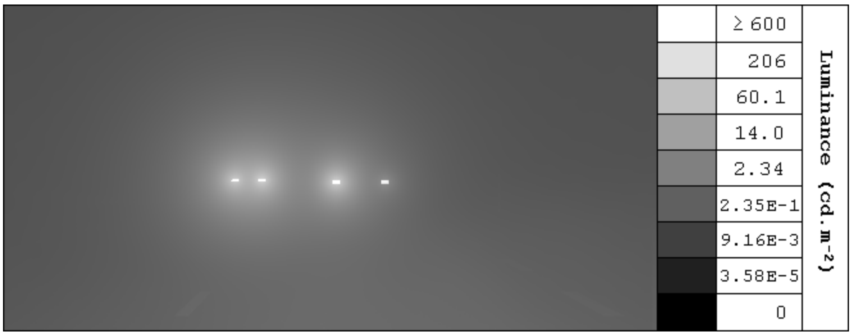
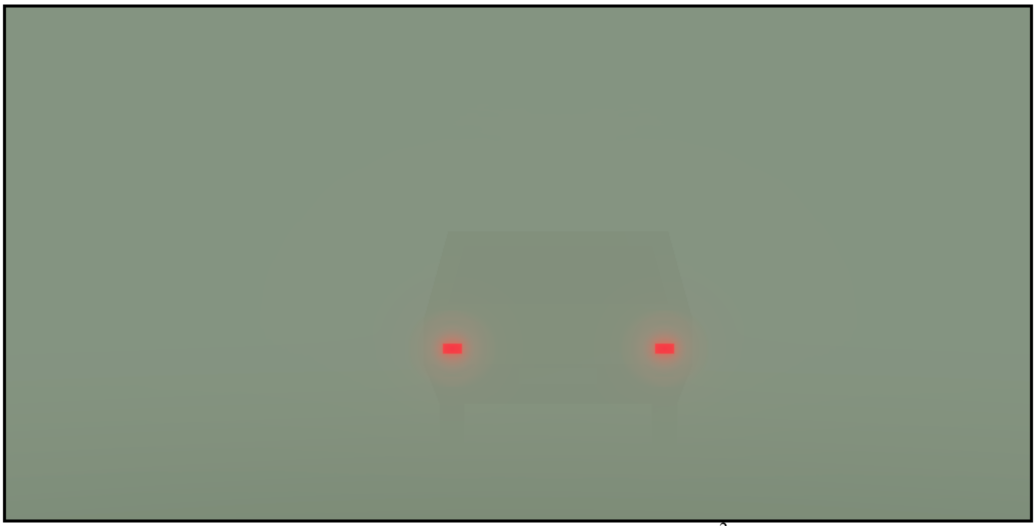


FIGURE 4. Example of iso-luminance map computed with the presented model for night-time fog: V_m = 100 m, L_f = 0 cd.m^{-2} (the horizontal field of view is 20°).



(a) $V_m = 8$ m, $d = 7$ m, $L_f = 1600$ cd.m^{-2}

(b) $V_m = 6$ m, $d = 13$ m, $L_f = 0$ cd.m^{-2}

FIGURE 5. Sample images generated with the presented model for validation experiments, which consisted in comparing distance estimation in real and simulated dense fog situations, both for (a) daytime and (b) night-time conditions (the horizontal field of view is 50°).