Review of the Mechanisms of Visibility Reduction by Rain and Wet Road

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1 Introduction

Rain drastically modifies the visual environment of road users, particularly at night. It changes visibility through its effects on headlights, windshield, pavement and markings. Rain lessens the performance of headlamps and other light sources by filtering part of their luminous power, thus reducing the illuminance on the roadway ahead of the vehicle. Rain affects the capacity of the driver to see through the windshield. Rain also affects visibility by changing the amount of headlight retro-reflected by the road surface toward the driver. The film of water on the pavement makes delineation and pedestrian crossing markings almost invisible by cancelling the retroreflective properties of the beads in the painting materials. The same physical phenomenon makes the pavement appear darker than in dry conditions.

This is a brief list of commonplace facts on the visual effects of rain [10]. In the following, we seek to explicit the physical and psychophysical ground of these facts, based on scientific references when available.

The outline of the paper is as follows: in the first section, we study the visual effects of the falling rain; in the second section, we tackle the visual effects of sprayed water; in the third section, we list the properties of wet materials, specially pavement markings; finally, we propose synthetic diagrams describing the effects of rain on roadway visibility.

2 Visual effects of the falling rain

2.1 The nature and microstructure of rain

Rain is a population of water droplets falling, interacting with each other and with the environment. While falling, a rain drop undergoes rapid shape distortions. This shape is size-dependent. Small drops are usually spherical, but as their size

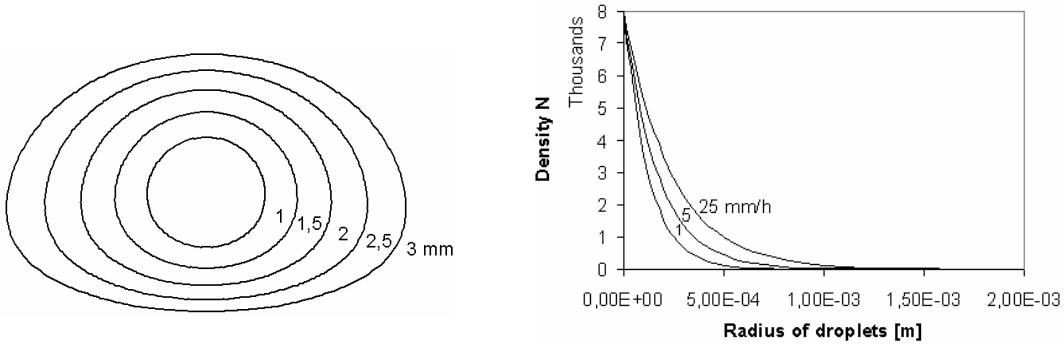
grows, they tend to a spherical oblate shape. The shape of a rain drop is described in [2] as the cosine distortion of a sphere at the tenth order:

$$r(\theta) = a\left(1 + \sum_{n=1}^{10} c_n \cos(n\theta)\right) \quad (1)$$

where a is the radius of the undistorted sphere, $c_{1,\ldots,10}$ are coefficients which depend on the radius of the drop, and θ is the elevation polar angle. θ=0 corresponds to the direction of the rain. Shapes of various sized drops are presented in Figure 1a. Rain drops come in a wide range of sizes. Their size distribution is often modeled using Marshall-Palmer distribution [16]:

$$N(a) = N_0 e^{-\Lambda a} \quad (2)$$

where a is the radius of a drop, $N(a)$ the number of drops per volume unit with sizes between a and a+da, N_0=0.08 cm^{-4}, Λ=82$R^{-0.21}$ and R is the rain density in mm.h^{-1}. This distribution is plotted in Figure 1b.



(a) *(b)*

Figure 1: (a) shapes of rain drops. (b) Marshall-Palmer rain drop size distribution.

Rain drops fall at a constant speed called the terminal velocity. An empirical study is presented in [11] on the terminal velocity of rain drops for different drop sizes. This data are approximated in [27] with the following function:

$$V_{term} = 9{,}4\left(1 - e^{-1{,}57\times10^{3} a^{1{,}15}}\right) \quad (3)$$

2.2 Light scattering in rain

Some experiments were conducted in an attempt to relate optical extinction on a long distance to rain density. [26] reports the results from five other investigations, and concludes that the optical depth τ obtained from the measurements corresponds within 25% to the value computed on the basis of different rain drop distributions. The optical depth is computed by integrating the extinction coefficient k_s along the optical path L as follows:

$$\tau = \int_0^L k_s dz \tag{4}$$

The general relation found between the extinction coefficient k_s (m^{-1}) and rain intensity R ($mm.h^{-1}$) is the following:

$$k_s = aR^{\gamma} \tag{5}$$

where a and γ differ with respect to the location and the optical devices used in the experiments. Experimental curves are plotted in Figure 2.

Finally, [21] measured the back-scattering of a light source in rain. Based on these measurements, they proposed an empirical model. However, the relevance of this model was not tested since.

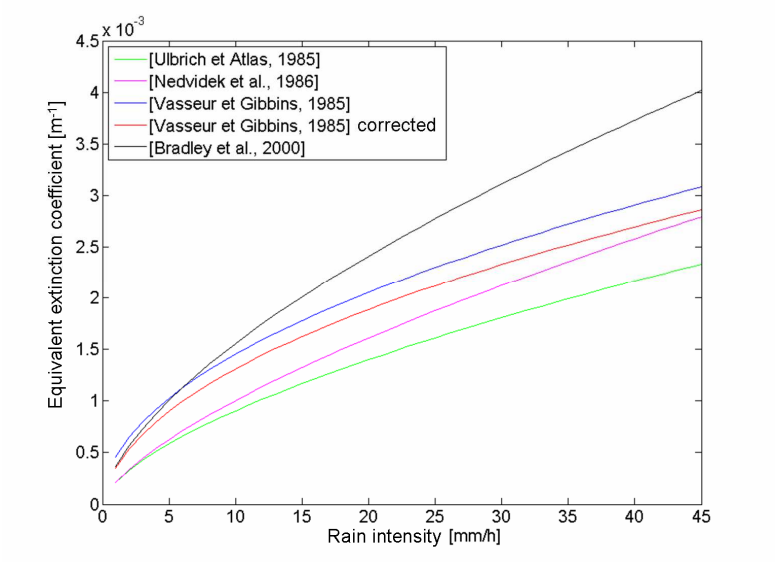


Figure 2: Different experimental curves relating the atmospheric extinction coefficient and the intensity of the rain.

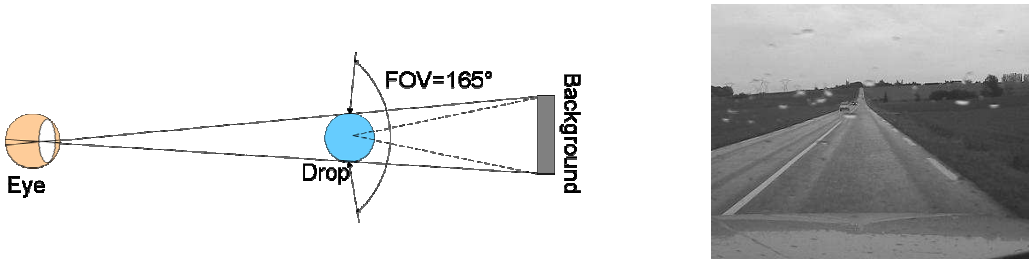
2.3 Consequences on roadway visibility

Light scattering in rain is rather limited. Using an analogy with the visual effects of fog, the effects of scattering in rain can be a problem for driving when the meteorological visibility ($V_{met}=3/k_s$) falls below 400 m, which is equivalent to a 300 $mm.h^{-1}$ rain according to Eq. (5). Such levels of precipitation are seldom observed.

3 Visual effects of sprayed water

3.1 Visual effects of rain on the windshield

To the best of our knowledge, there is no analytic model for the overall reduction of visibility induced by rain on the windshield. [9] focus on the appearance of rain drops. They show that the field of view refracted by a spherical drop is about 165°, and assimilate the drop with a fish-eye lens. The corresponding optical diagram is presented in Figure 3a.



(a) *(b)*

Figure 3: Optical diagram illustrating the fish-eye lens effect created by a rain drop.

One can assume rain drops on the windshield to have a similar effect, save for the deformation of the spherical drops on the windshield. The drops on the windshield roughly reflect the road environment, which is illustrated in Figure 3b.
On the other hand, several experimental studies on wiper usage focused on object visibility and seeing distance. Some driver visibility studies were restricted to stationary vehicles in artificial rain [13][18]. Other studies were conducted in actual rain. They showed that wipers do not interfere with the perception of the road scene with respect to saccadic eye movements [6]. Moreover, seeing distances are significantly reduced when rain intensity increases [3][12][17]. In particular, [3] investigated the visibility distance of target vehicles under natural downpours. The observers were onboard a vehicle, and notified when they detected a target car while their wipers were engaged or recently stopped. These experiments showed that detection distances decrease significantly with ambient lighting and that visibility distance decreases as rain intensity increases. Visibility distance was found to be lower for observers onboard a moving vehicle (vs. stationary) because of the higher concentration of water on the windshield. Based on these experiments, a model was proposed for the visibility distance of cars through the windshield in rain condition in daytime condition. This model can be simplified by:

$$D = c_0 (rt)^{-c_1} e^{c_2 L_b} \quad (6)$$

where c_0, c_1, c_2 are strictly positive constant values, rt characterizes the accumulation of rain water on the windshield, r being the intensity of the rain and t the time between wiper movements, and L_b the background luminance.

3.2 Visual effects of water sprayed by other vehicles

The water sprayed by vehicles has undeniable effects on visibility. [8] studied these effects. Unfortunately, no model came out of it, because of several experimental difficulties which impeded the identification of prevailing parameters. Other studies showed that splash and spray is reduced by 95% on porous asphalt compared to other ordinary pavement surfaces. Figure 4, taken from [20], shows a heavy vehicle on a road section with and without porous asphalt. However, such a figure is dubious since it is not backed up with a measurement protocol. The most rigorous works have been conducted for the development of heavy vehicle spray reduction devices. Even though these researches do not directly address driver visibility, the metering systems which were used to study such devices might be used to investigate this particular problem. A synthesis of the works conducted before 2000 is proposed in [15].

Figure 4: Water sprayed by a heavy vehicle on ordinary and porous asphalt [20].

4 Light reflections on wet materials

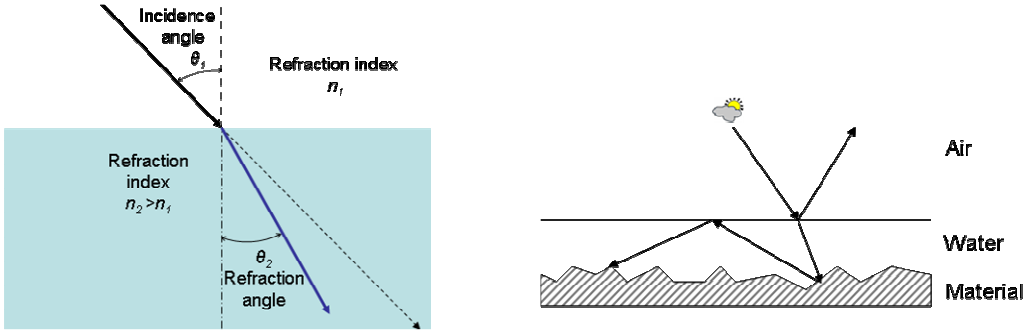
4.1 Water at the surface

The water on a surface (e.g. a puddle on the pavement) makes it specular because of the smooth air-water interface. Optical interactions on such a surface are governed by Fresnel equation for dielectric materials:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad (5)$$

A film of water on a Lambertian surface can also make the surface appear darker [14]. This is mainly caused by internal reflections at the water-air interface.

Part of the light reflected by the Lambertian surface is reflected back when it hits the water-air interface. This light is again subject to absorption by the material of the surface before being reflected again. This leads to a sequence of absorptions which darkens the surface.



(a) *(b)*

Figure 5: Illustration of the Fresnel equation: a material with a layer of water on its surface reflects less light because of internal reflections at the water-air interface.

4.2 Water underneath the surface

The presence of water underneath a surface is another important factor influencing the appearance of the material. In the case of pulverulent materials, (sand or limestone), water can penetrate inside holes formerly filled with air. This modifies the reflection properties of the material, favoring forward scattering [25]. The main reason is that the refraction index of water is higher than the index of the air, and usually closer to the index of the material. This means that a ray of light entering the material is less refracted because the refraction index is more homogeneous when the material is wet. As illustrated in Figure 6, the consequence is that the ray undergoes more scattering before leaving the surface. This increases the total amount of absorbed light, and the overall effect is a material with reduced reflectivity.

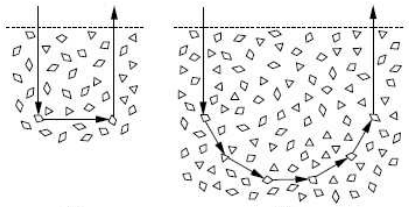


Figure 6: Shortest path for a ray of light to enter and exit the material with (left) a 90°mean scattering angle and (right) a 30°mean scattering angle.

4.3 Consequences on roadway visibility

Rain changes the visual aspect of the road. The road surface appears more specular or darker, depending on the observation angle. This can be dazzling for the driver, especially in daytime with the sun at grazing angles, or at night with opposing headlights. With visual performance impaired by glare, it is more difficult for the driver to detect hazards. The visibility of retro-reflective road markings is also particularly impaired. These markings are designed to send headlight back toward the vehicle. They are usually made of a painting onto which glass beads with a high refraction index (between 1.5 and 2.5) are encrusted (Figure 7a). The optical properties of the beads are described in more details in [29] and [23]. In daytime, on wet roads, retroreflective materials reflect sunlight, and sometimes appear darker than the pavement. At night, when the road is slightly wet, the retroreflective efficiency of the beads is reduced, as illustrated in Figure 7b. When the road is wet and the water layer is higher than the size of the beads, headlight is mostly reflected at the air-water interface (Figure 7c), so markings may disappear. This is why all weather markings were developed. A nice introduction to this particular issue is proposed in [5].

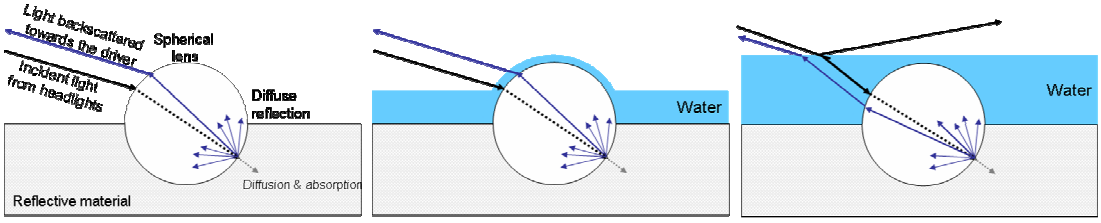


Figure 7: Optical mechanisms governing retroreflection on pavement markings with encrusted beads in (a) dry, (b) humid and (c) wet conditions.

5 Conclusion

In this paper, we have provided physical explanations for the effects of rain on roadway visibility. These explanations are based on either optical or psychophysical models. We have classified the visual effects of rain into three main categories. The first category concerns light scattering by rain drops. The second category concerns splash and spray. It encompasses both rain falling on the windshield and water splashed by other vehicles. The third category concerns wet road surfaces, especially road markings, whose appearance is modified by the water layer.

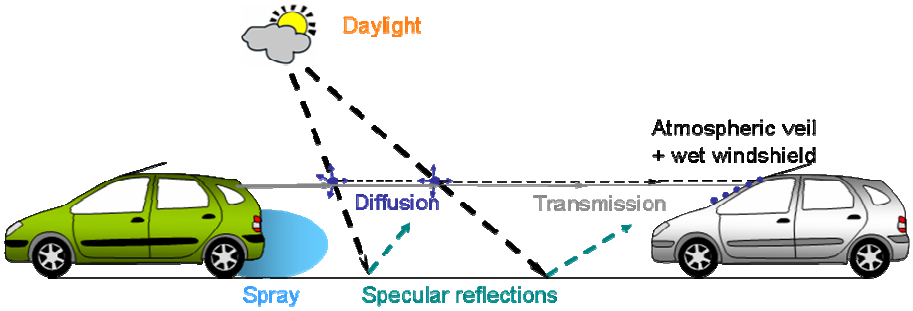
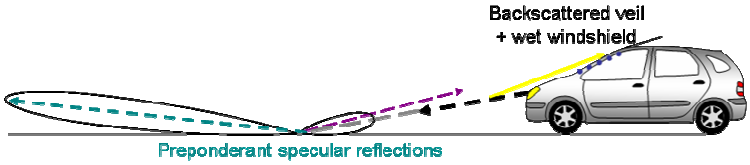


Figure 8: Visual effects of rain in daytime

In the end, the reduction of visibility caused by rain and sprayed water results from a combination of these three categories of effects. We can estimate a priori that the effects of the second and third categories have the highest impact on visibility, scattering effects being negligible for common intensity downpours. To give a schematic view of these effects, we propose two diagrams. Figure 8 shows the various effects of rain on daytime visibility: reduced transmission, atmospheric veil, wet windshield, spray and specular reflections. Figure 9 shows the nighttime rain situation, with the same effects as in daytime plus specular reflection overcoming retroreflection on the pavement.

From this review of the literature, we have seen that the mechanisms of visibility reduction by rain and wet road are numerous. The technical solutions to enhance the perception of the driver in rainy weather are thus also numerous: adaptive wipers, adaptive headlights, anti-splash and spray devices, porous pavement, retroreflective markings… A next step should be to focus on headlights. The quantitative visibility models should enable to define scenarios and to compute the necessary power to compensate for the visibility loss, or to find alternative strategies to compensate for the backscattering of light.

(a)



(b)

Figure 9: Nighttime visibility (a) in clear weather (b) in rainy weather.

6 References

[1] W. Bachman, T. Wingert, and C. Bassi. Driver contrast sensitivity and reaction times measured through a salt-covered windshield. *Optometry - Journal of the American Optometric Association*, 77(2):67–70, 2006.

[2] K. V. Beard and C. Chuang. A new model for the equilibrium shape of raindrops. *Journal of the Atmospheric Sciences*, 44(11):1509–1524, June 1987.

[3] V. Bhise, J. Meldrum, L. Forbes, T. Rockwell, and E. McDowell. Predicting driver seeing distance in natural rainfall. *Human Factors*, 23(6):667–682, 1981.

[4] S. G. Bradley, C. D. Stow, and C. A. Lyuch-Blosse. Measurements of rainfall properties using long optical path imaging. *Journal of Atmospheric and Oceanic Technology*, 17(6):761–772, June 2000.

[5] D. Burns, T. Hedblom, and Miller T. Modern pavement marking systems: the relationship between optics and nighttime visibility. In *18th Biennal Transportation Research Board Visibility Symposium*, 2007.

[6] A. Cohen and H. Fischer. Does the windshield wiper impede a driver's vision? *International Journal of Vehicle Design*, 9(4-5):533–541, 1988.

[7] E. Dumont. Caractérisation, modélisation et simulation des effets visuels du brouillard pour l'usager de la route. PhD thesis, Université Paris V, Novembre 2002.

[8] F. Fournela. Visualisation des projections d'eau sur route mouillée. In *Journées des Sciences de l'ingénieur*, Dourdan, France, 2003.

[9] K. Garg and S. Nayar. Vision and rain. *International Journal of Computer Vision*, 75(1):3–27, October 2007.

[10] M. Green, M. Allen, B. Abrams, and L. weintraub. *Forensic vision with application to highway safety*, third edition. Lawyers & Judges Publishing Company, 2008.

[11] R. Gunn and G. D. Kinzer. Terminal velocity for water droplet in stagnant air. *Journal of Meteorology*, 6:243–248, 1949.

[12] D. Ivey, E. Lehtipuu, and J. Button. Rainfall and visibility – the view from behind the wheel. Technical Report 135-2, College Station, TX: Texas Transportation Institute, 1975.

[13] T. Kurahashi, Y. Fukatsu, and K. Matsui. Method of evaluating visibility provided by windshield wipers in rainy conditions. In *SAE Technical Paper Series*, number 851636, 1985.

[14] J. Lekner and M. Dorf. Why some things are darker when wet. *Applied Optics*, 27(7):1278–1280, 1988.

[15] C. MacAdam. Update on the status of splash and spray suppression technology for large trucks. Technical report, NHTSA, 2000.

[16] J.S. Marshall and W.M.K. Palmer. The distribution of raindrops with sizes. *Journal of Meteorology*, 5:165–166, 1948.

[17] R. Morris, J. Mounce, J. Button, and N. Walton. Field study of driver visual performance during rainfall. Technical Report DOT-HS-5-01172, College Station, TX: Texas Transportation Institute, 1977.

[18] R. Morris, J. Mounce, J. Button, and N. Walton. Visual performance of drivers during rainfall. *Transportation Research Record*, 628:19–25, 1977.

[19] F. Nedvidek, C. Schneider, and E. Kucerovsky, Brannen. Near-infrared extinction in rain measured using a single detector system. *Journal of atmospheric and oceanic technology*, 3:391–399, 1986.

[20] J. Nicholls. Review of UK porous asphalt trials. Technical Report 264, TRL, 1997.

[21] D. B. Rensch and R. K. Long. Comparative studies of extinction and backscattering by aerosols, fog, and rain at 10.6 μm and 0.63μm. *Applied Optics*, 9(7):1563–1573, July 1970.

[22] R. Rogers, M. Lamoureux, L. Bissonnette, and R. Peters. Quantitative interpretation of laser ceilometer intensity profiles. *Journal of atmospheric and oceanic technology*, 14:396–411, 1997.

[23] M. Stoudt and K. Verdam. Retroreflection from sperical glass beads in highway pavement markings 1: Specular reflection. *Applied Optics*, 17(12):1855–1858, 1998.

[24] C. Stow, G. Bradley, K. Paulson, and L. Couper. The simultaneous measurement of rainfall intensity, drop-size distribution, and the scattering of visible light. *Journal of Applied Meteorology*, 30:1422–1435, 1991.

[25] S. Twomey, C. Bohren, and J. Mergenthaler. Reflectance and albedo differences between wet and dry surfaces. *Applied Optics*, 25(3):431–435, 1986.

[26] C. W. Ulbrich and D. Atlas. Extinction of visible and infrared radiation in rain: Comparison of theory and experiment. *Journal of atmospheric and oceanic technology*, 2:331–339, 1985.

[27] F. J. R. Van Mook. Driving rain on building envelopes. Technical report, Faculty of Architecture, Planning and Building of the Eindhoven University of Technology, 2002.

[28] H. Vasseur and C. J. Gibbins. Prediction of apparent extinction for optical transmission through rain. *Applied Optics*, 35(36):7144–7150, December 1996.

[29] K. Verdam and M. Stoudt. Retroreflection from sperical glass beads in highway pavement markings 2: Diffuse reflection (a first approximation calculation). *Applied Optics*, 17(12):1859–1869, 1998.

[30] H. Zwahlen. Driver eye scanning behavior in rain and during an unexpected windshield wiper failure. *Zeitschrift für Verkehrssicherheit*, 26:148–155, 1980.