THE SCATTER OF LIGHT OF DIFFERENT COLOUR IN THE ATMOSPHERE

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1. INTRODUCTION

It is often claimed (Devaux, 1956, 1970) that yellow light is superior to white light for vehicle headlamps. This claim is supported by evidence of physical, physiological and psychological nature. In most cases, it turns out that the advantages of yellow light are small, and can usually be neglected particularly when a comparison is made between yellow (filtered) and white (unfiltered) light for incandescent sources. (Schreuder, 1975).

Our particular argument is related to the scatter in the atmosphere, notably in haze and fog. The present study gives a survey of the literature as far as relevant to this specific question.

2. THEORY

When electro-magnetic waves impinge upon a material medium they are attenuated. This has the following causes: reflection at the interfaces, absorption by the medium itself and scattering by the particles in the medium. Only the last of these will be discussed.

Scattering of light by objects in its path is a subject which theoretical physicists have long investigated with great interest: for instance, the research by Stokes, Rayleigh, Mie and many others. More recent compilations and reviews have been given by Van de Hulst (1957) and Deirmendjian (1969).

A central position in the matter under consideration has Rayleigh's law.
For particules very much smaller than the wavelength λ:

$$S = 24\pi^3 \left(\frac{n^2 - 1}{n^2 + 1}\right)^2 \frac{Nv^2}{\lambda^4}$$

in which S is the scattering per unit of volume, N the number of particules per unit of volume, n the refractive index and v the volume of the particles. Rayleigh's law has been given in different forms. This form comes from Monnier & Mouton (1939, p. 90).

In its form give, multiple scattering is not included. This effect is treated in detail by Harris (1951).

The formula means that, for constant n and N, the scattering of blue light is much stronger than of long-wave light. If, however, the particles are not very small compared with the wavelength, the dispersion of scattering is much less. This relationship still applies well to particles smaller than 0.1λ.
Angström's approximation $S= c/\lambda^a$ is often given for this. (Devaux, 1970, wrongly attributes this formula to Boutarie). For a = 4 we again have the original Rayleigh formula. With increasing particle dimensions a, however, decreases. With particles of the same order

of magnitude as the wavelength, a is about zero, and hence the scattering does not depend on the wavelength. With particles larger than the wavelength, a approaches -1. This is the limiting value for large discs; the case of pure diffraction. The scattering described here often is called "Rayleigh scattering". Before Rayleigh had elaborated the theory, Tyndall had been experimenting in this field. Thus, reference is somtimes made - rather confusingly - to the Tyndall effect: for instance Le Grand (1956) and Adrian (1961). See Longhurst,(1964, p. 413).

The particle sizes important in practice will be discussed further on. Firstly, it will be briefly shown why visual observation is impeded by the scattering of light.

With very strong scattering all objects have the same colour and luminance. This of course means that the objects are no longer distinguishable individually and are thus invisible. Scattering of light plays the following part in this. The light from a bright object (for instance a light source) that would strike the eye without scattering, is partly scattered and therefore does not enter the eye; this causes a reduction in the object's "apparent luminance".
Note: Actually such phenomena cannot be described at all with the usual concepts of photometry. Use has to be made of terms such as apparent and intrinsic luminances, which are nonsense really. Intrinsic luminance is the luminance and apparent luminance is not luminance at all. A system that is fundamentally correct and is usable in practice has been proposed by Moon. The notion of luminance is dropped; it is superseded by the "helios",which is in fact defined for scattering media. Unfortunately, this system did not find favour in the eyes of the CIE. We will not go into this, but refer readers to the literature. See Moon (1961, Introduction) and also Moon (1942), Gershun (1939).

The reduction of "apparent" luminance proceeds until the light source has become invisible. In the case of pure scattering this light is not absorbed. Part may (after having been scattered one or more times) reach the eye from a direction in which there is some dark object. This object apparently becomes lighter. These two effects proceed so far until complete equivalence is reached. A good description of this is given by Middleton (1952, p. 72). A theoretical discussion of this phenomenon is given by Fry et al (1947).

Of greater practical important is the case in which the equality is not yet reached. In view of the foregoing , this is characterised by a reduction in the "apparent" luminance of light sources, and an increase in the "apparent" luminance of relatively darker objects and therefore a reduction in contrasts. This will be appreciated if the scattered light is described as a veil with a luminance of L_s. This veil covers both the object with luminance L_o and the background with luminance L_b. The (intrinsic) contrast without scattering C becomes the ("apparent") contrast with scattering C^1. Now C is always greater than C^1 because:

$$C = \frac{L_b - L_o}{L_b} \quad \text{and} \quad C^1 = \frac{(L_b + L_s) - (L_o + L_s)}{L_b + L_s} = \frac{L_b - L_o}{L_b + L_s}$$

The conclusion is clear: each L_s reduces all contrasts and hence always has a negative effect on the possibilities of visual observation. Below we shall examine the conditions in which this negative effect is noticeable, and those in which the effect depends on the colour of the light.

3. SCATTERING OF LIGHT IN THE ATMOSPHERE: MIST AND HAZE

In this and the next paragraph we shall first deal with some physical and meteorological aspects of mist and fog. Then, as far as necessary, the theory of scattering of light will be enlarged upon, and lastly the effect of all this on the usefulness of various colours of light will be discussed.

The earth's atmosphere is never completely clear. Apart from the molecules themselves there are always dust particles and, in most places, water vapour. Where these is a lot of motor traffic there are also contaminants from exhaust gases and road and vehicle wear. Data on the composition of the atmosphere and many of the frequent contaminants can be found in the documentation on air pollution, for instance Magill et al., (1956), Anon (1970, pp. 95 and 100); Sherwood & Bowers (1970).

Contaminants requiring special attention are silicon (sand) and carbon (soot). These absorb light and also scatter it. Rarely, and then only rather locally, is their concentration so high that car drivers are inconvenienced by visibility being too poor. See e.g. OECD 1975. In this functional approach, the driver's task is treated as primary (Griep, 1971; Schreuder, 1971). Any other air pollution effects, however, important they may be, such as poisoning, stench, etc. are specifically disregarded. The resulting clouds of dust and vapour may of course be very noticeable. Their particles are often small. Magill et al., (1956) state that exhaust gas particles have dimensions of about 0.1μ (quoted by Schreuder, 1964).It may thus be advisable to illuminate tunnels and other places where very high exhaust gas concentrations occur with yellow light (preferably monochromatic sodium light). A better solution is, of course, to prevent such particle clouds from forming, for instance by proper ventilation. See Schreuder (1964, pp. 24 and 53). Simular effects can be prevalent in open roads. Again here, reference is made to the comprehensive study published by OECD (1975).

In the temperate countries of e.g. Western Europe this is all of minor importance. Clouds of such particles will not become so dense as to inconvenience traffic, because long before that another phenomenon has occurred. That is to say, condensation. As this is primarily of importance in denser fog, it is gone into further in para. 4. Only a few comments will be made at present.
It is known that water does not directly condense from water vapour in the open air. It is quite possible for highly supersaturated water vapour to exist without condensation, since this needs condensation nuclei. Unlike sublimation nuclei, which must be symmetrical six ways, most particles can act as condensation nuclei. These often consist of salt (sodium chloride) from the sea. Condensation usually proceeds so far that relative humidity comes very close to 100%. Only if there are very many condensation nuclei,
can condensation still occur at a relatively humidity
under 100%. See e.g. Monnier & Mouton (1939, p. 94). The droplets then usually stay small; see para 4. Lastly, the effect of sunlight (U.V.) on certain aerosols may cause a reaction leading to a very rapid growth of fog. Of these the first and third are of importance in a country with the climate and anti-pollution concern of Western Europe, i.e. an atmosphere with few (condensed) water drops but rather a lot of dust and water vapour, and an atmosphere with rather many water drops. Meteorologically, such conditions are described as haze and mist or fog. (By definition meteorological visibility in haze is greater than 1000 m, and in fog less than 1000 m.)

We therefore have to deal with two distinct cases, which we shall discuss separately.

Haze, as stated, is caused by small particles in the atmosphere, small compared with the wavelength, so that scattering of light can be expected to de dependent upon the wavelength. On the other hand, the scattering can be expected to be largely isotropic. See, for instance, Minnaert (1942, p. 247).With increasing particle size, scattering is less colour-related and more directed. The theory of these phenomena is fairly complicated. For this, reference is made to the classical research by Mie (1908) and text books such as Van de Hulst (1957). Summaries of this can be found in Middleton (1952), Byers (1965) and many other meteorological handbooks, and in Monnier & Mouton (1939, pp. 92 et seq.).

The advocates of yellow light for vehicle headlamps base their preference mainly on atmospheric disturbances through small particles. Devaux (1970, p. 569) states that Rayleigh's formula always applies with an exponent of 2.5, but especially in clear weather. This differs greatly from the 1.3 stated by Middleton (1952, p. 42) as the result of a large number of measurements (which, however, he does not describe in detail). This applies to haze even if meteorological visibility is up to 30 km. With visibility of 90 km the exponent was only 1.6 (Middleton, 1935). Lastly, Middleton (1952, p. 45) gives an equation by Löhle (1944):$a = 0.06\ V^{1/3}$; V = visibility in meters; applies to $V > 1000$ m.

Devaux (1956, p. 38),one of the most fervent advocates of yellow headlamps, claims that the biggest advantages of yellow light are in a dusty and somewhat misty atmosphere. This advantage has been claimed earlier (CIE, 1939c). Based on the theory and the convincing evidence quoted by Middleton (1952), it is indeed likely that blue light is scattered more than red light in small-particle haze, This view is substantiated by Monnier & Mouton (1939), who firstly go through many published material (op.cit. pp. 113 et seq.; largely the same material quoted by Middleton) and secondly quote their own measurements (op.cit. p. 129). Two remarks have to be made: firstly, it cannot be stated easily how much of this advantage remains when the slight difference between the light of incandescent lamps with and without a yellow filter is considered. Secondly, Devaux does not state that in the conditions quoted by him meteorological visibility is so great that road traffic is not inconvenienced at all by it. Since Devaux provides no further information on the tests on which he bases his conclusions, it is indeed impossible to refute these and other claims on a quantative basis. The apparently very stringent evidence advanced by Monnier & Mouton (1939) also fails in this respect: upon closer examination many results relating to clear atmosphere ("limpide") prove to be stated as if they were decisive for haze or even fog.

However, it should be noted that the very detailed study by Monnier and Mouton certainly deserves more attention than it usually receives in the literature.

It should be stressed, however, that no one has even claimed that yellow light is inferior to white as regards scattering in haze. It has, though, been claimed that the advantages of yellow light are hardly demonstrable either theoretically or practically and are, moreover of very minor significance to road traffic (Stiles, 1966). It may be added that psychological rather than physical phenomena presumably play a part in this. (Schreuder, 1975)

When one considers possible advantages of yellow light for vehicle headlamps as regards the atmospheric scatter, it is interesting to note that, for example Luckiesh (1921, p. 148) states that the range of a white light $R = 1.53\sqrt{I}$ and of a red light $R = 1.5\sqrt{I}$ (R in miles and I in cd). There are, however, no further details of the measuring methods, spectral distribution etc. Walsh (1965, p. 79) also states that (at least foveally) the "range" does not depend on the wavelength.

In signalling practice, especially at sea, the selectivity is apparently regarded as negligible: all current considerations on the range of signal lights in clear and "approximately " clear weather are expressed as light intensities without any indication of the colour. It can be inferred from this that colour does not matter in practice. See, for example, Middleton (1952, Chapter 7) and Adrian (1962). This must not, however, be confused with the fact that visual perceptibility may depend on colour, especially in situations supra- threshold conditions.

4. SCATTERING OF LIGHT IN THE ATMOSPHERE: FOG

As to scattering of light there is a big difference between haze (and mist) on the one hand and fog on the other. If the dust particle concentration exceeds a particular value and if relative humidity increases, condensation of water on these particles commences, with the particles acting as condensation nuclei.

The process is fairly complicated. With very small droplets (of pure water for instance), the surface tension is much lower than with a flat surface. This means that in order to maintain a small droplet a certain supersaturation is needed. Supersaturation is usually caused by adiabatic cooling. This means that with gradual cooling very minute droplets are first formed. If cooling continues (despite the release of the heat of condensation) the droplets first remain small, until a given critical situation is exceeded. When some of the droplets have exceeded a given size (for instance through coagulation) they will rapidly grow until the relatively humidity is reduced to just above 100%. In this latter part of the process the remaining small droplets are no longer stable; they evaporate and increase humidity again. The final result is that the big drops grow at the expense of the small ones. This means that when saturation and/or concentration of condensation nuclei has passed a certain limit the resulting droplets will all be of a certain minimum size. It depends on the absolute humidity, temperature and concentration of nuclei how many droplets there will be; their dimensions, however, will always be of the same order. The processes involved have been described in detail by Byers (1965, pp. 32-35). Figure 1 is taken from this. It shows the relationship between relative humidity and radius of water droplets in equilibrium with vapour. The parameter is the volume of NaCl per water droplet. It is striking that the curves for various volumes of NaCl straighten out only for a few micron's radius close to 100% relative humidity. It is also important to note that the pure water curve has no maximum, but falls monotonously. This means that condensation nuclei are still needed; individual water molecules apparently cannot function in this way (Byers, 1965, p. 40). Besides the salt crystals described, other nuclei may be: ions, dust, sand and soot particles, etc. A detailed discussion of this can be found in Amelin (1967).

At a high absolute humidity, there may be very many droplets. Once they are of a certain size they begin to fall noticeably; see Byers (1965, p. 75) and Middleton (1952, p. 53), who quotes Stokes' well-known formula. They then strike other droplets and coagulate. This process may continue until large droplets, raindrops - several mm in diameter - are formed.

The relative frequency of droplets with different diameters may thus vary very greatly; small droplets, however, do not occur as long as large drops exist. Large in this sense means a diameter of at least 2 to 5μ. This agrees excellently with the frequency of particle size in fog as found in practice. New fog (radiation fog) still contains a fair amount of small particles, but if there is time for coagulation, the maximum frequency occurs at a diameter between 4 to 10μ (advectional fog, clouds). Figure 2 shows a compilation of results from Pedersen & Todsen (1960) as quoted by Byers (1965). Similar distributions have been found by many other research workers. See, for example, Middleton (1952, pp. 52 et seq.). He gives the following empirical formula: $V = C.\exp.\left[(a-a_m)^2/b\right]$, in which V is the frequency of droplets of radius a; C a constant for the cloud in question and a_m the radius for the maximum frequency. This formula is taken from Bricard (1940). Foitzik (1950) suggests a variant.

Middleton (op. cit.) says in this context that there are no very small radius droplets and attributes this to an error in collecting techniques, an opinion that is shared by Münster (1938). In view of the foreoging , this view is presumably incorrect; very small droplets are unstable. Houghton's results (1939) are also quoted; indicating very large drops, especially in coasted fog. The smallest are 10μ, the biggest 100μ, and the modus is at 45μ ! Lastly, Dessens' measurements (1947) are quoted, and can be used as a further substantiation of the theory. Dessens (using a very elegant method which did allow him to record very minute droplets unlike most other workers) found the maximum frequency at a radius of 0.4μ with relative humidity 78%. This situation thus apparently corresponds to the left-hand, rising part of Figure 1. As stated, these conditions are prevalent in haze, but not fog. Finally, it may be noted that Dessens indeed did measure the expected wavelength relationship (Middleton, 1952, p. 50).

Jiusto (1964) gives comparable droplet-size values. Here again (op.cit. p. 11) smaller droplets are found for radiation fog than for advective fog; the smallest are about 2 to 3μ in diameter, the biggest are 25 and 35μ respectively. This applies to the underside of the fog At the top there are larger droplets (op.cit. p. 12). Juisto does not state the frequency, but the contribution which a given size of droplets makes to total water content. These values are calculated from a formula given by Best (1951), analogously to Bricard's (1940) equation above. Values measured by Jiusto are also given (op.cit.p. 8). The characteristic values of radiation fog and advectional fog (also called land fog and coastal fog) are given as: mean droplet sizes 10μ and 20μ respectively, and range of droplet sizes 5 - 35μ and 7 - 65μ respectively. Estimated and measured values correspond well if the difference between bottom and top of the fog are taken into account. (The difference between the distributions for low and high fog are related to the difference in absolute humidity; Jiusto, 1964, pp. 2 and 9).

Pilié (1966) describes measurements of advective and frontal fog (not radiation fog). The smallest droplet diameters found averaged 6μ and 4μ : the maximum diameters 63μ and 52μ respectively. The median averaged 21μ . It is suspected, however, that the method applied measured the big drops in particular. Kocmond & Jiusto (1968) finally give some values for radiation fog: average radius 5μ and range of radii 2 - 18μ (Note: radius and not diameter!). Furthermore, Kocmond & Perchonok (1970) report similar values, and add that there is a very big-inter-droplet space.

Similar values (minimum about 2μ, maximum 30 - 50μ) are given by Wolff (1938) based on Houghton's (1932) data, for which a large number of other measurements, partly mentioned above, are also quoted.

It can safely be concluded from all these measurements that fog does not contain droplets smaller than 1 to 2μ in diameter. This therefore means that the exponent of Angströms'approximation is always negative. Hence, if there were a wavelength-relationship for scattering, this would mean that red is scattered more than blue. This selective scattering, however, is not noticeable in practice: (a) because of the relatively small number of droplets and (b) because the exponent still always remains close to 0.
Some interesting information on this has been put in a figure by Middleton (1952, figure 3.10). We have converted the data to meteorological visibility and given them in Figure 3. The data originate from Foitzik (1938). They clearly show that with very great meteorological visibility there is considerable selectivity; below a given value, selectivity fairly suddenly drops to nil. Middleton (1952, p. 44) quotes further research by Foitzik (1938) showing that this fully agrees with Mie's theory.

Some measurements have been quoted showing that droplet size in fog is usually several tens of microns. Now there appears to be a fairly general relationship (at least for fog consisting of spherical droplets of pure water) between meteorologcial visibility and droplet-size distribution. The relationship between the relative frequency and the median value of the diameter has already been indicated above (Bricard, 1940). The relationship between meteorological visibility V and average droplet size $\bar{r}$ is governed by Trabert's (1901) equation: $V_m = 2.6\ k\bar{r}/\omega$ (quoted by Kocmond & Perchonok, 1970), in which k is a parameter of the order of unity related to droplet-size distribution (bearing in mind Bricard's equation no major differences appear to be likely) and ω is the volume of the liquid water in fog (Kocmond & Perchonok do not say what units these are expressed in!). Combining Bricard's and Trabert's equations indicated a connection between particle-size distribution and meteorological visibility could be derived.

Finally, a remark on droplet size measurement. It was long uncertain whether the lack of droplets smaller than 1 to 2μ was not due solely to the difficulty of catching such droplets and determining their diameters. It is true that many older methods have a lower limit of about 2µ, with the exception of Dessens' neat method (1947). Middleton (1952, para. 3.4.) discusses a number of the older measuring methods. If microscopic aids are used, the reading equipment itself sets a limit of about 1µ. But this can be remedied with modern equipment; it is indeed so that droplets smaller than 1 to 2µ hardly occur (Kocmond, 1971).

Monnier & Mouton (1939) describe a microscopic droplet-size measuring method, though without giving quantitative results (pp. 96 ... 102).

Based on the theoretical considerations already mentioned it can thus be assumed that fog scatters light roughly aselectively, in view of its droplet sizes. This is confirmed by a number of research workers, though they do not always explicitly state their sources. Hence, Devaux (1956) says that dense fog equally disperses all colours. Luckiesh (1953) doubts the value of fog lamps. Schober (1967) says that yellow light is not an improvement. This is also established in CIE (1948), quoting Boelter & Ryder (1940). Middleton (1952), lastly, again quotes a number of workers who found no significant different, i.e. Luckiesh & Holladay (1941), Born et al. (1933). On the other hand he quotes Stuart (1934) who does find a pronounced difference. Since Middleton gives no details of this research a completely satisfactory opinion is not possible. Kocmond & Perchonok (1970) also decide there is a wavelength-relation on the basis of papers by Arnulf & Bricard (1957). Harris's (1951) exhaustive study makes, however, no reference to any influence of light colour.

Monnier & Mouton (1939, pp. 110 et seq.) give a number of rather conflicting results. They quote Rudolph (1904) who finds that dense simulated fog transmits green and yellow light better than orange and yellow. But Rudolph apparently also claimed that moderate natural fog transmits red better than blue. Houghton (1931), Utterback (1919) and Born & Franz (1933, 1935) are also quoted. It is stated that, according to Houghton, fog with 2 to 3µ droplets has the greatest transmission of light with a wavelength of 490 nm (blue green). According to Utterback, the maximum is 560 nm (yellow green); no further details of the fog are indicated. Born & Franz state that with simulated fog containing approx. 6μ droplets, red light shows more pronounced scattering than the other colours, which do not differ much.

Measurements with simulated fog should, however, be used with caution; simulated fog is mostly generated by atomising water and not by condensation like natural fog. Simulated fog is usually much denser, while it has been suggested that its droplet size have a much narrower dispersion. This might explain why the various investigations gave a maximum (and sometimes a minimum) transmission and why this maximum or minimum is at different wavelengths.

Monnier & Mouton (1939, pp. 113 et seq.) also quote a number of investigations into natural fog. According to Granath & Hulburt (1929), light with a wavelength of 450 nm (blue) in a dense fog is reduced to 1/100 of its value after 800 m and to 1/1000 after 1200 m. For red (650 nm), this happens after 925 and 1400 metres respectively. These values mut not be generalised; in dense fog the absorption (!) of blue light is more pronounced than in mist. All told, a somewhat unclear statement! Unspecified measurements by Foitzik are quoted, and it is stated that in fog with visibility of less than 800 m, transmission does not depend on light colour, but that over 1000 m blue light is always transmitted more than red light - even up to 30% more. This is followed immediately by a statement by Foitzik that blue is scattered in mist more than red, Finally, Born et al. (1933) are quoted; they say that in fog with 300 m visibility the transmission of 483 nm light is 5% to 6%. greater than of 657 nm (greenish yellow and deep red respectively).

It is remarkable to note in this connection that an international body like the CIE after a first denying the value of coloured light, later for a long time recommended using yellow light, particularly in fog (CIE, 1935, 1939b). An intermediate position is taken by the ECE (1969) which allows both white and yellow light. The remarkable thing, however, is that if yellow light is used for fog lamps, farily strict standards are prescribed for their colour.

5. CONCLUSIONS

The considerations advanced here, lead to the following conclusions:
(a) natural mist and haze are selective to some extent since short-wave light is scattered more;
(b) clouds of dust and vapour originating from traffic and industry may have a fairly strong absorption;
(c) haze, mist and dust clouds are rarely so dense as to inconvenience road traffic;
(d) fog so dense as to inconvenience road traffic shows a scattering of light not noticeably related to the wavelength of the light.
Sincere the droplets are always large compared with the wavelength, long-wave light would be scattered more than short-wave if there were any appreciable scattering.

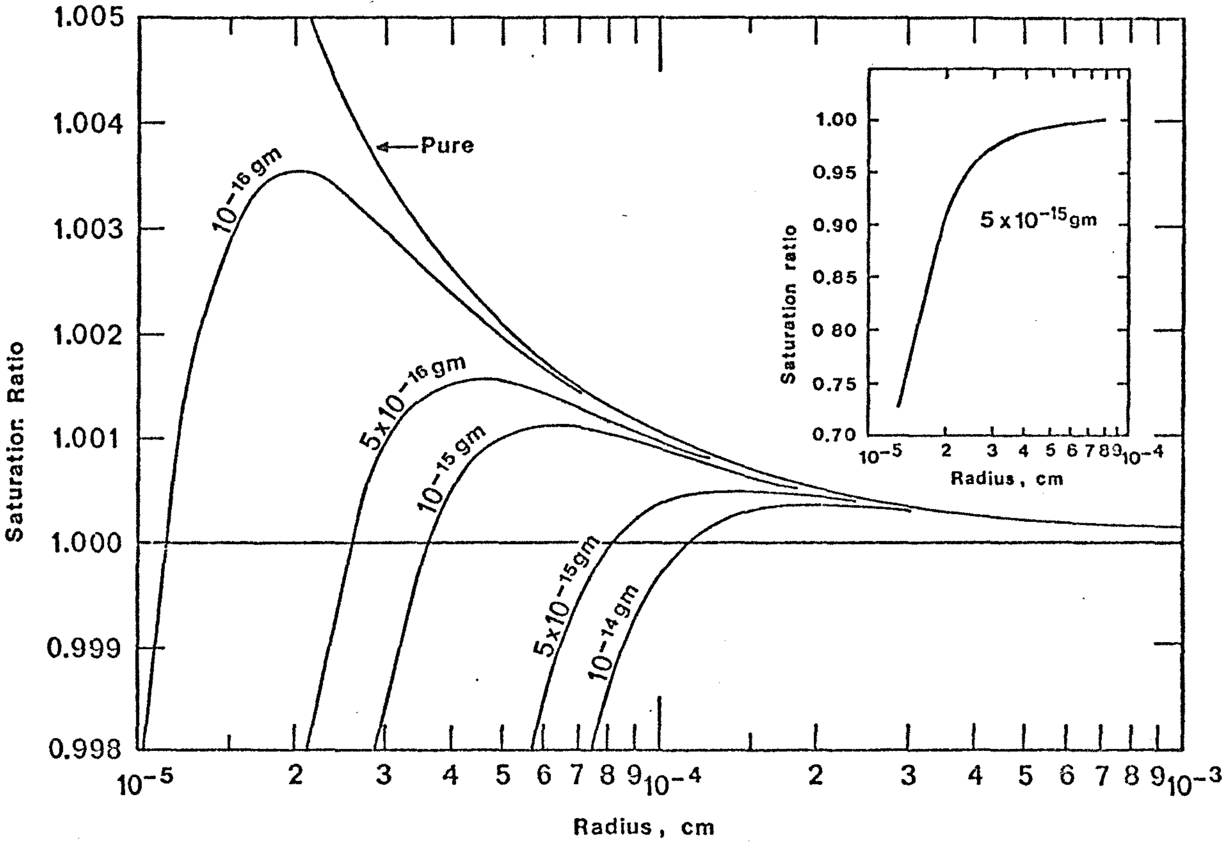
To sum up therefore: no practical benefit is to be expected as regards transmission through the atmosphere by using yellow (filtered) incandescent lamp light for car headlamps.

Subscripts of figures

Fig. 1 Curves of equilibrium saturation ratio of water droplets containing the stated mass of sodium chloride compared with Kelvin curve for pure water droplets. Inset: curve for 5 X 10^{-15}g NaCl on a compressed scale extended to the droplet size at which the given amount of NaCl would form a saturated salt solution in the droplet. All computations are made for a temperature of 25° C, but the values are very nearly the same at other atmospheric temperatures.
This graph is quoted from Vyers (1965) figure 2.4.

Fig. 2 Size distribution of droplets in fog and non-precipitating stratus clouds. Based on measurements of Pedersen & Todsen (1960) as quoted by Byers (1965) fig. 6.1 and 6.2.

Fig. 3 Mean values of relative extinction coefficient as a function of the mean coefficient for the three colours. Adapted from Foitzik (1938). This figure is quoted from Middleton (1952) figure 3.10. The visibility scale is calculated according to Best (1951).



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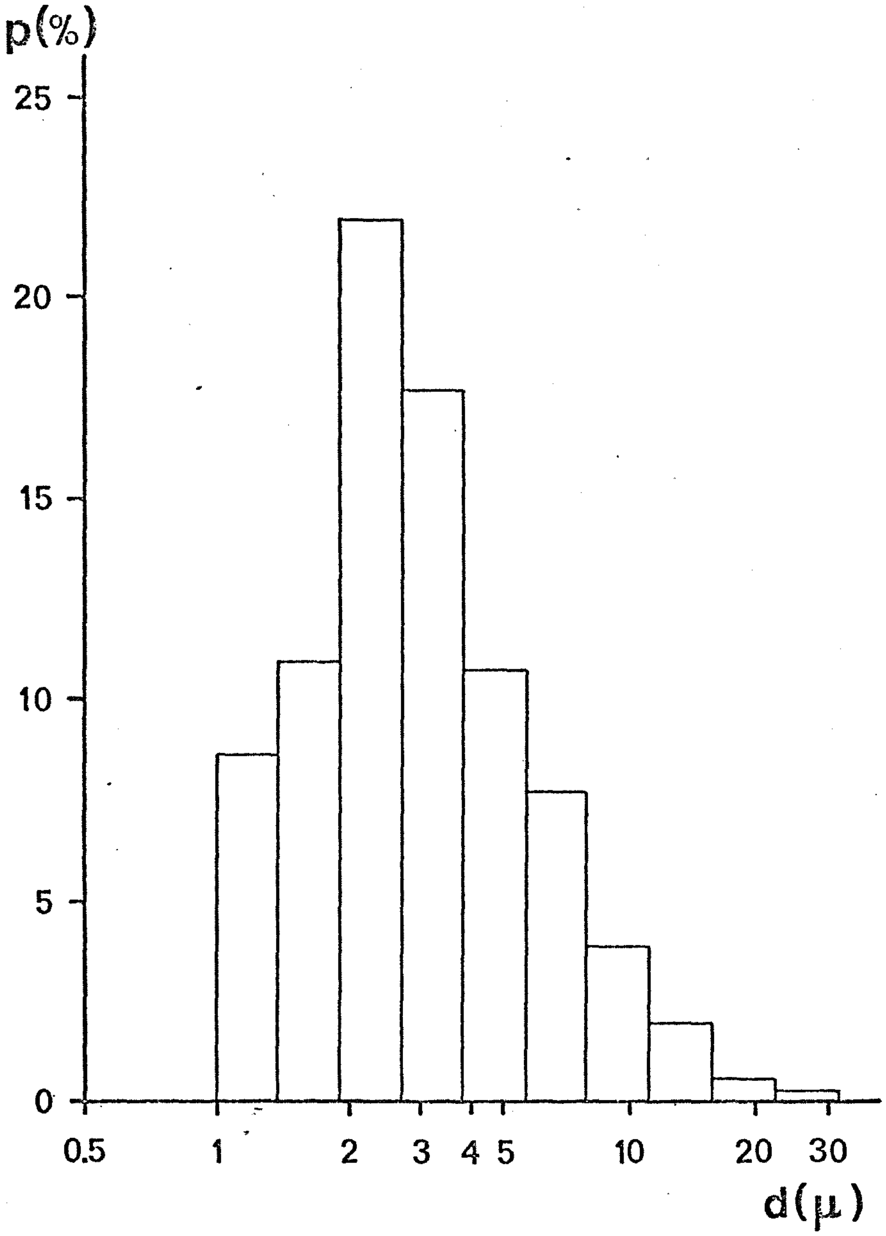

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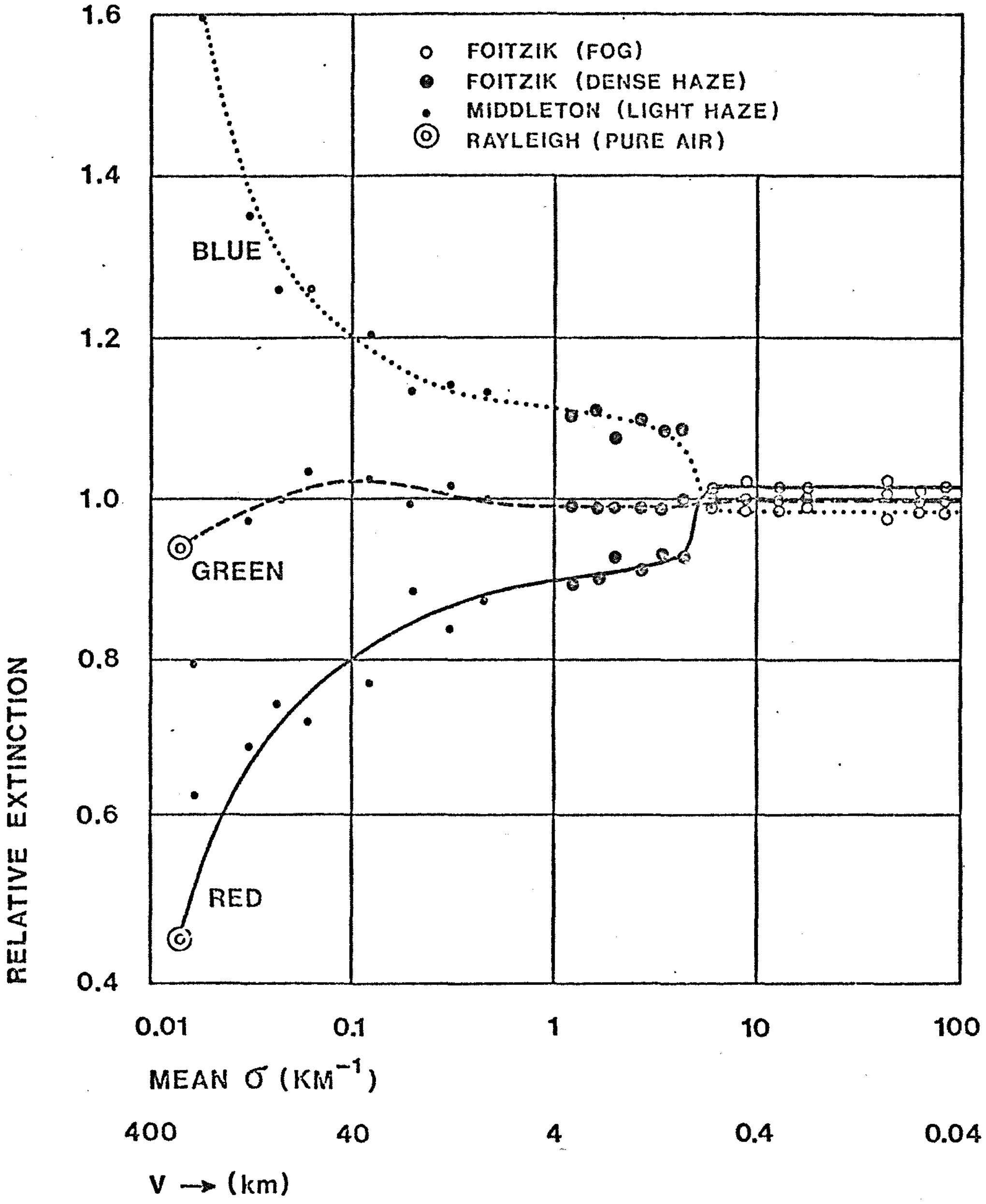

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