MOTORWAY LIGHTING UNDER FOG CONDITIONS

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MOTORWAY LIGHTING UNDER FOG CONDITIONS: ABSTRACT

Physical and meteorological aspects of fog

Fog is a meteorological condition where a large number of very small droplets of water float in the atmosphere. The resulting dispersion of light reduces the visibility. More in particular, the light from a "glare" source will form a haze that stretches over the complete field of view. This will result in a contrast reduction, and therefore often to a reduction in the visibility of the object. Because the droplets are very small, the light is either scattered over large angles or not scattered at all. This means that the contrasts are reduced, but not the "sharpness" of the edges and lines in the field of view. Furthermore, as fog droplets usually are of the same order of magnitude as the wavelength of the (visible) light, fog is colourless (white or gray): the light is scattered independently of the wavelength. And finally, water is a clear fluid that absorbs no light.
The daytime meteorological visibility (v) is defined as the distance at which a black object forms a contrast of 2% to the horizon sky. At night the visual range is used, the range over which a specific light is just visible. The definition of the visibility is related to the visual threshold. This means that all practical objects cease to be adequately visible at a distance much shorter than the meteorological visibility. The practical visibility distance for real objects is about one-third of v.

Fog is formed by condensation. For this, there must be enough water in the atmosphere, the temperature must be low enough for the relative humidity to be 100%, and there must be enough condensation nuclei. The droplet size and its distribution do not differ very much for different fogs. Fogs may differ greatly, however, in respect to the number of droplets per unit of volume, resulting in large differences in visibility. Fog droplets therefore show an almost perfect spherical shape. As the average size of the droplets is of the same order of magnitude as the wavelength of the light, the dispersion primarily results from diffraction "around" the droplets. The dispersion does not depend in any appreciable way on the wavelength.

The consequences for practice are very important. First, it does not make any sense at all to use coloured light for illumination in fog, like e.g. low-pressure sodium lights.

These lamps may have a number of advantages also in fog (as a result of their relative large dimensions) but not as a result of the colour of their light.

Fog does not scatter the light in all directions equally strong. The "forward" scatter (along the direction of the light) is by far the strongest; the backward scatter ("back scatter") is less strong, but still quite remarkable. And the scatter in crosswise directions ("side scatter") is by far the weakest. In practice this means that the angle between observation and light incidence should be as close to 90 degrees as possible. This is a major advantage of the application of catenary lighting in fog-prone regions.

Fog is formed when the temperature of water-carrying air is reduced. The temperature drop can be the result of a migration of the air.
The most common type of fog of this sort is the advective fog. Moist air is moved by the general circulation towards an area where the temperature is lower. Advective fog is more common in the winter than in the summer. As the overall temperature is low, and thus the absolute humidity, advective fog usually is not very dense, but usually it is very extended.
Another type of fog is the mountain fog. The droplets form as a result of a drop in air temperature, as the air is pressed uphill. The fog may be very dense. Mountain fog is restricted to hilly or mountainous regions. It can form in any season. The fog usually is not very extensive, nor very patchy.
The third important fog type is the radiation fog, which forms when in stationary air the temperature drops, e.g. from nocturnal radiation. Radiation fog will form only at night, and particularly at the end of the night when temperatures are lowest. Radiation fog is formed usually in the summer. Radiation fog can be extremely patchy, and extremely dense.

Visibility aspects of fog

The main effect of fog on road traffic is the contrast reduction as a result of the "veil" that extends over the field of view.

When driving a car, it is possible only to arrive at sensible decisions regarding the "near future" when the driver can be certain that there will be nothing sudden, unexpected or hazardous. The required preview depends on the manoeuvre to be executed. The smaller manoeuvres such as making small corrections to the cross-wise position within the driving lane or to the driving speed are related to the actual handling of the vehicle, require only a preview of about 3 seconds. For "higher" manoeuvres like changing driving lanes the preview must be about 7 to 10 seconds. For still "higher" manoeuvres like coming to a stop, overtaking a preceding vehicle on a two-lane two-way road, or passing a priority intersection, a preview of some 20 to 40 seconds may be required.

The next question is, what elements should be regarded as visually critical. The following elements seem to be of special importance:
- for keeping the lateral position in the traffic lane: the lane markings and the (horizontal) general road markings, and the border of the pavement itself;
- for keeping the distance to the preceding traffic: obviously the preceding vehicle itself, and more in particular its markings (lamps and retroreflectors);
- for the emergency manoeuvres: a wide variety of objects, like signals (lights and other) on vehicles, pedestrians and cyclists on or near the road and obstacles like rocks and boxes.

It is not enough that the visually critical elements are visible; it is necessary that there is a fair chance that they are effectively detected.

The role of artificial lighting

It is generally accepted that fog is a considerable road-safety hazard. In most countries, the percentage of fog accidents is between 1 and 3%, with peaks in both directions.

The function of artificial light in fog is essentially the same as the function for clear atmosphere. It is to make the visually critical elements (better) visible. Studies point out that the accident risk in the dark is 50% to 100% higher that during daytime. However, during rain or fog at night, the accident risk can increase to the ten-fold of the risk in dry, clear daytime. It is therefore recommended to install general purpose road lighting on motorways that run through noted fog-prone areas.

Requirements for motorway lighting in fog

When lane changings at high speeds and/or overtaking manoeuvres at low speeds are deemed necessary, the visibility should be at least 700 m; when the visibility is 300 m, corrections to the lateral position within the driving lane are still possible at high speeds (120 km/h), and lane changings at low speeds (50 km/h), but overtaking is out of the question, even at 50 km/h.

This points to an aspect of road safety in fog that is often overlooked or not understood. Many people drive at high speeds in clear air - say 120 km/h. Under these conditions they can perform safely almost all relevant motorway manoeuvres. When fog begins, they reduce speed, and may consider themselves as real safe drivers: they slow down to - say - 90 km/h. What they do not realise is that for many manoeuvres, particularly involving other traffic participants, this speed is far too high for safe driving even under moderate fog. A speed of maybe 50 km/h would be called for.

As regards road lighting, in order to be able to perform the manoeuvres like corrections in speed or position, the road, the limits of the road, the road markings and any small object on the road must be visible up to 200 to 300 meters in order to permit safe, fast traffic. Normal general purpose road lighting of adequate standards will be able to provide the required information. More precise, the requirements as given in the CIE (and similar) recommendations suffice in almost all cases. These recommendations are for motorways: a luminance level L of 1 to 1.5 cd/m^2, a uniformity U_o better than 0.7 and regarding the glare restriction a TI of less than 15%. For moderate fog (v not less than some 300 m) the same requirements are valid. For more complicated manoeuvres, like lane changes, the preview requirements are much higher. Here, the visibility of the road itself is often not sufficient, due to the foreshortening of the road in the perspective view. For high speed traffic, additional information is needed. Usually, this information is provided by delineators. These delineators are equipped with retroreflectors, which are less effective in fog, as a result of the fact that the light has to traverse twice the fog layer between the delineator and the driver - once travelling from the lamp to the delineator, and once more on the way back. In fog, road lighting lanterns are indispensable. For still more complicated manoeuvres, the preview is still larger. The required information relates primarily to the run of the road. Here, the information requires both in clear air as in fog the presence of road lighting lanterns.

In this respect, three further remarks must be made. First, it should be noted - as has been indicated earlier - that the visual range from light sources is larger than the visibility as measured from the contrast threshold. A diffusely reflecting object cannot be seen as far as a light source. This means that for a medium- or long-range preview, light sources are much to be preferred, particularly in fog conditions.
The second remark has to do with the same facts. During the day, road lighting lanterns are just (small) diffusely reflecting objects, but at night they emit light. This is the ground for the well-known phenomenon that the visual guidance at night can be much better than at day, provided the road carries a road lighting installation.
The third remark is again related to the first and the second: in spite of the fact that disability glare is a negative factor in road lighting, that should be restricted as far as possible, the lanterns should be constructed in such a way that the light distributions are not completely of the "cut-off" type, particularly in fog conditions. Severe glare should be avoided, of course, but in this respect the TI-value of 15% as quoted above from the CIE-Recommendations gives a good result in fog. The open cut-off lanterns that were popular on the continent of Europe several decades ago, showing a TI of 5% or even less, are to be avoided for fog conditions.

Installation characteristics for motorway lighting in fog

If the lighting is supposed to be particularly effective in fog, it should be adapted in all cases to the specific characteristics of light scatter and light transmission in fog. The scatter is not equally strong in all directions: side scatter is lowest; back scatter is more pronounced, and forward scatter is strongest. And as the major disturbance of fog is caused by the veil that results from the scatter of light, it is clear that road lighting is most beneficial in fog when the light is emitted crosswise in respect to the direction of view. This refers particularly to those manoeuvres that require a short-range preview. The best results are found with lighting systems that emit the light perpendicular to the road axis, like e.g. catenary lighting. Cut-off lanterns, where in spite of the symmetric light distribution, the light emitted along the road axis in the same direction as the traffic is predominant, are less beneficial as the back scatter is more disturbing than the side scatter. And non-cut-off lanterns, where the light emitted along the road axis against the traffic dominates, are not suitable at all during fog.

Luminaires that emit much light against the traffic may have a large visual range, but they cause an intense light veil as the result of the forward scatter. Practice indicates that the normal catenary lighting lanterns give the best compromise: they remain visible in most fog situations; only in the densest of fogs they are clearly less visible than non-cut-off lanterns; however, under such conditions road traffic is hardly possible at all. Catenary lighting has another advantage: the rather short interdistance between the lanterns (usually between 15 and 30 m) support the view regarding the run of the road at intermediate distances. This is already a marked advantage in clear weather, but even more so in fog. Catenary lighting is therefore recommended for general purpose lighting in fog-prone areas.

Contrary to what is often stated, natural (clean) fog scatters all visible light equally strong. However, the scatter is influenced to a certain degree by the (intrinsic) luminance of the light sources. Therefore, large lamps show a certain advantage over concentrated sources. This favours low-pressure sodium lamps and fluorescent tubes over high-pressure sodium or mercury lamps. In view of the lumen output per unit, the low-pressure sodium lamps are to be preferred for motorway lighting, particularly because the monochromatic light is not a draw-back at all for lighting roads exclusively for motorized traffic.

In conclusion, length-wise mounted catenary lighting systems equipped with low-pressure sodium lamps are recommended for general purpose lighting for motorways in fog-prone areas.

CONTENTS

1. INTRODUCTION

Fog is a meteorological condition where a large number of very small droplets of water flow in the atmosphere, forming an aerosol. As the droplets are of the same order of magnitude as the wavelength of (visible) light, the light is dispersed by the fog. This dispersion reduces the visibility. Firstly, light from the objects to be seen is dispersed, it is propagated into other directions, it will not reach the eye of the observer, and therefore cannot contribute to the visual perception. Secondly, light originating from other parts of the field of view, that is emitted into a direction different from the eye of the observer will be dispersed as well and may in part reach the eye of the observer, where it cannot contribute to the perception - in contrary, it will cause disturbance. More in particular, if the light originates from a strong "glare" source, the scattered light will form a haze that stretches over the complete field of view. The luminance of this haze must be added to the luminances of the object and its direct surround - the parts of the field of view that are relevant for the perception. This will result in a contrast reduction, and therefore often to a reduction in the visibility of the object.

This can bee seen as follows. Traditionally, the contrast (the intrinsic contrast) is defined a follows:

$$C = \frac{L_1 - L_2}{L_2} \qquad [1]$$

where L_1 is the luminance of the object, and L_2 the luminance of the surround (both in cd/m^2). When a haze (usually called a "veil") with luminance of L_v (in cd/m^2) is spread over the field of view, both L_1 and L_2 are increased by L_v. The contrast (the visible contrast) C' becomes:

$$C' = \frac{(L_1 + L_v) - (L_2 + L_v)}{(L_2 + L_v)} = \frac{L_1 - L_2}{L_2 + L_v} \qquad [2]$$

Comparing [1] and [2] shows directly that the nominator is the same, but the denominator is increased. So C' is always smaller than C.

Three important notes should be made: First, the droplets are very small, so the light is either scattered over large angles or not scattered at all. This means that the contrasts are reduced, but not the "sharpness" of the edges and lines in the field of view. Secondly, as fog droplets usually are of the same order of magnitude as the wavelength of the (visible) light, fog is colourless (white or gray): the light is scattered independently of the wavelength. In this respect, fog differs from haze. And thirdly, water is a clear fluid that absorbs no light. Also this results in a colourless fog, different from smoke or smog. In the latter, the colour of the aerosol particles (e.g. sulphur) may give a distinct colour to the clouds.

2. METEOROLOGICAL ASPECTS OF FOG AND FOG FORMATION

2.1. Meteorological visibility

Fog is defined in the meteorological practice as an aerosol primarily consisting of water, in a density that the horizontal meteorological visibility (v) is reduced to 1000 meter or less. When v is between 1000 and 2000 meter, meteorologists speak of "haze"; when v is over 2000 meter, there is no standardized term, although for a person outdoors the scene might look quite "hazy"

The meteorological visibility is defined as the distance at which a black object (with zero reflectance) forms a contrast of 2% to the horizon sky. The precise definition is given in Douglas & Booker (1977). This definition cannot be used directly. Firstly, it cannot be measured directly; secondly, the horizon sky usually cannot be defined, and thirdly, zero reflectance does not exist in reality. Traditionally, the visibility is assessed by judging whether specific landmarks are still just visible. At day, these landmarks are church spires, chimneys etc.
The night-time visibility is defined differently. In fact, at night the more relevant measure is the visual range, the range over which a light of a specified luminous intensity is (just) visible. Again, the precise definition is given in Douglas & Booker (1977). At night the visual range was estimated in practice by assessing the visibility of a number of fixed, known lights near the observational site. Usually they were red obstacle lights.

As data regarding the visibility were used mostly in aviation, and because one could only fly when there was good visibility, these empirical assessments did suffice for many decades. When radio beacon and radar assisted bad-weather flying became feasible (theoretical down to zero visibility) the traditional assessment was not accurate enough. Furthermore, it could not be accepted any longer that it was not possible to relate the day-time and the night-time visibility in any reasonable way. Since about twenty years the visual assessment of the visibility has been replaced - at least at the major meteorological stations - by the measurement of the atmospheric transmission. Standard tables were set up to convert transmission data into visibility data. These tables exist both for day-time conditions (contrast thresholds) as for night-time conditions (visual range of lights). However, these two cannot be converted to one another in a simple way. An example is given in Figure 1 where the values, both calculated, are plotted in a relation to the atmospheric transmission. We have transformed the data from this figure in a table: see Table 1. We will come back to these data in para. 5.5 when discussing motorway lighting systems for fog conditions.

One should realize that the definition of the visibility is related to a situation that almost coincides with the visual threshold. This means that all practical objects cease to be adequately visible at a distance much shorter than v. When the meteorological visibility is e.g. 1000 meter, most practical objects like trees, houses and cars cannot be seen properly when they are more than maybe 300 - 400 meter away. Some data are given in Table 2. It seems to be at the safe side to consider the practical day-to-day visibility distance for real objects that are relevant for road traffic to be about one-third of v.

It is proposed here to introduce an additional visibility concept: the practical visibility (v_p). Provisionally, v_p is considered as being 0.33 v (one third of the meteorological visibility). Obviously, additional measurements are required to define vp more precisely.

As long as flying was done exclusively by vision, the meteorological data were not interesting for road traffic, even when the practical visibility v_p was taken into account. Flying was stopped at visual conditions that were still so good that the road traffic was not disturbed. However, as the ranges in which the aviation became interested were lower, the measurement of the visibility became useful for road traffic. At the same time, one realized that fog could be a real road-traffic safety hazard. From then on, assessment of v became a standard information aspect for road traffic as well.

These aspects of meteorological visibility are well-documented in the literature. Two classical standard works are Middleton (1952) and Douglas & Booker (1977).

2.2. The physics of fog formation and dissipation

Fog is an aerosol, consisting of water droplets. These droplets can come into the atmosphere only because they originate there, the relevant process being condensation. For this, the situation has to fulfill a number of requirements. The major requirements are: there must be enough water in the atmosphere, the temperature must be low enough for the relative humidity to be 100%, and there must be an ample supply of condensation nuclei. The first requirements is obvious: no water, no fog. The second means that the atmosphere contains all the water it can contain under the circumstances. The relative humidity designates the fraction of the maximum of the water vapour that is present. The corresponding temperature where the relative humidity reaches 100% is often called the "dewpoint".

Although it seems to be a contradiction, under specific circumstances the relative humidity can be more than 100%. Water can condensate only around condensation nuclei. These nuclei can be any object; preferably they should have a crystal structure that is similar to that of water. Thus, silicon (sand) and ice (snow) are suitable condensation nuclei. When the condensation has started, it will continue until the relative humidity falls to 100%.

In almost all situations there are enough condensation nuclei, particularly near the surface of the earth - where fog is the most interesting for road traffic.

Details of fog formation and the physical phenomena related to it can be found in the standard meteorological textbooks (e.g. Byers, 1959) and also in Kocmond & Perchonok (1970).

As water is colourless, fog usually is colourless as well, even when the nuclei are coloured, because the total volume of the nuclei is small compared to the total water volume in the fog. In some extreme cases, however, the nuclei are so abundant that the fog is coloured as well. A notorious example is the fog that used to harass London: the "pea-soup" was yellow as a result of the colour of the sulphur that originated from the coal burners.

When considering the London fog (which has not occurred after 1958, the year the coal burners were banished), one should realize that fog is not the only aerosol that may reduce visibility. A comprehensive overview is given in OECD (1976) where, apart from fog, also the other causes for the reduction of the visibility are discussed: rain, snow, air pollution, smoke and dust. For the road traffic the fog is the most general problem: the reduction of v in rain is usually negligible (expect in tropical downpours, but then road traffic is obstructed for other reasons); snow usually is a traffic-safety hazard much more as a result of reduced skidding resistance than of reduced visibility; air pollution is man-made and can therefore precisely localized in place and in time - and needs to be avoided for other reasons in the first place. Smoke and dust are only in rare occasions a traffic hazard. This report will therefore restrict itself to (natural; "clean") fog.

2.3. Characteristics of fog

Fog is an aerosol consisting predominantly of water. This means that fog consists of small droplets of water that float around in the atmosphere. There is no strict distinction between fog and clouds. In spite of the fact that there are considerable differences in practice, these will be disregarded here as they have only little consequence for road traffic. For the report here, clouds can be regarded as dense fog.

An important factor of fog is the droplet size, and the distribution of the droplet size. The fact that the water droplets float in the atmosphere restrict the upper limit of the droplets. When the droplets have a diameter of over 0.1 mm, they cannot float for any considerable time in the absence of vertical air currents - they will precipitate as rain or drizzle, and the fog dissolves. The lower limit for stable droplets is given by the evaporation. Traditionally, the relative vapour pressure of water is defined for a flat surface - a sphere with infinite diameter. The water surface is stable only if the relative humidity near the surface is 100%. If it is lower, the water evaporates; if its is higher, water condenses. When the water surface has a considerable curvature, this equilibrium between evaporation and condensation shifts toward the evaporation. The (virtual) relative humidity near surfaces with a considerable curvature is lower than in reality. This means that small droplets tend to evaporate, and the faster the smaller the droplets are. When the diameter of the droplets is under 0,005 mm, the curvature is so great that the droplets evaporate rapidly. The excess water vapour condenses again, mainly on the larger droplets. In the long run, there is a water migration from the small towards the large droplets. This goes on until the droplets are so large that they start to fall. According to this process, all fog tends to precipitate within about one or two days. Of course, it is possible to have longer fog periods if "new" fog is formed.

The droplet size distribution can be calculated on the basis of the thermodynamic properties of water and air. A survey is given in Jiusto (1964). It is, however, difficult to measure the droplet size distribution in real fog. The reason is that the droplets have to be "caught", and catching very small droplets proves to be exceedingly difficult. So the measured distributions will be biased as the smallest droplets are under-represented; it is hard to establish by how much they are under-represented.

The droplet size and its distribution do not differ very much for different fogs. Fogs may differ greatly, however, in respect to the number of droplets per unit of volume. For obvious reasons, fog requires a relative humidity of the air of 100%. If the humidity is below 100% the water droplets evaporate and the fog disappears; a humidity of more that 100% is usually not stable. However, the absolute humidity (the amount of water per volume unit of air) can vary very much indeed. This amount depends directly on the temperature. From Table 3 (after Hütte, 1919) it follows that e.g. at 25 degrees the absolute humidity is seven times as high as at -5 degrees. As the size and the size distribution do not vary very much, the number of droplets per volume unit is directly proportional to the water content. And because the visibility is directly related to the number of droplets per volume unit, warmer fog usually results in lower visibility.

2.4. Light scatter and light absorption in fog

Light scatter in turbid media has been a subject of study for theoretical and experimental physicists. Broadly speaking, one may discern three areas of interest, divided by the size of the bodies that cause the dispersion. When the bodies are small in respect to the wavelength of the light, one speaks of "Raleigh"-scattering; when they are large the dispersion is caused by traditional (optical) diffraction, and the area in between is the "Mie"-scatter. Atmospheric scatter is prevalent in all three areas, but for fog the Mie-scattering is the most important. Diffraction occurs in rain, and Raleigh scatter in haze, but in neither case the scatter is enough to seriously impede the road traffic.

The water droplets that float in the atmosphere in fog move only at a very small speed in respect to the surrounding air. This means that there is no force acting on them causing a distortion of their shape. Fog droplets therefore show an almost perfect spherical shape (See Kocmond & Perchonok, 1970). This permits a rigorous mathematical treatment of the light dispersion by the droplets. As the average size of the droplets is of the same order of magnitude as the wavelength of the light, the dispersion primarily results from diffraction "around" the droplets; refraction "in" the droplets contributes only little to the dispersion.

The mathematics of the dispersion of light by many droplets are treated in full by Mie in the beginning of the century (See Douglas & Booker, 1977, and Van de Hulst, 1957). The rigorous treatment is possible for many spherical droplets of the same dimension and for one wavelength. When the real droplet size distribution and the wavelength distribution of "white" light are introduced, the dispersion cannot be calculated analytically. Several authors presented approximations of the results (See Middleton, 1952). Probably the best-known approximation is the phenomenological (Koschieder's) "law"; a clear survey of this matter is given by Kocmond & Perchonok (1970). There is a reasonable correspondence between the calculations and the measurements; as we have explained in para. 2.3, one difficulty is the fact that the droplet size cannot be measured precisely.

Because in almost all natural "clean" fogs the droplet size is of the same order of magnitude as the wavelength of visible light, the dispersion does not depend in any appreciable way on the wavelength. This can be observed directly: fog - and clouds for that matter - are white or gray, but never coloured, signifying that the wavelength distribution of the scattered light is identical to that of the incumbent light (Schreuder, 1976). This is not the fact for smoke or haze, as their composing objects are much smaller - much smaller than the wavelength of the light. Thus, in haze and smoke, Raleigh scattering predominates, resulting in the fact that smoke looks blue-ish when illuminated from the side, and reddish when the light source is viewed through the smoke. As is indicated in the OECD study (OECD, 1976) smoke dense enough to hinder road traffic is extremely rare.

The consequences for practice are very important. First, it does not make any sense at all to use coloured light for illumination in fog. Yellow fog lamps are nothing but rather inefficient as a part of the light is absorbed. These aspects have been discussed in detail by Schreuder (1975; 1976). The same holds for low-pressure sodium lights for street lighting. These lamps may have a number of advantages also in fog (as a result of their relative large dimensions), but not as a result of the colour of their light. Another consequence is that infra-red and millimetre radar may be very effective in penetrating fog, but not in penetrating rain. In fact, millimetre radar is used to detect rain showers and squalls.

Usually, fog consist almost exclusively of pure water - condensed water in fact. This implies that the absorption is negligible. This is, however, usually not the case in man-made fog and "smog". We have mentioned already the infamous London "pea soup". Although one must, from the point of view of the protection of the environment, strongly object that such aerosols are permitted to form, one should realize that they seldom hinder road traffic as a result of a reduction on visibility.

Fog does not scatter the light in all directions equally strong. The Mie-theory gives a mathematical treatment of the directional scatter; the scatter diagram shows a number of strong "peaks" and "valleys" in directions that can be assessed exactly. The directions of the peaks and valleys depend on the droplet size and the wavelength of the light (See Douglas & Booker, 1977, Middleton, 1952). When, however, the droplets are not of exactly the same size, or when the light is not exactly monochromatic, the scatter is much more diffuse (See Schreuder, 1964; Spencer, 1960). Still, also in real fog and using practical light sources, the scatter is far from uniform. The "forward" scatter (along the direction of the light) is by far the strongest; the backward scatter ("back scatter") is less strong, but still quite remarkable. And the scatter in crosswise directions ("side scatter") is by far the weakest. The scatter intensity in these different directions may vary over one or even two decades. In practice this means that the angle between observation and light incidence should be as close to 90 degrees as possible. This is the major advantage for catenary lighting; see paras. 5.5 and 5.6.

2.5. Fog formation

Fog is a very wide-spread meteorological phenomenon - albeit that the geographic distribution over the earth is very irregular.

Fog - and clouds for that matter - are formed when the temperature of water-carrying air is reduced. Here, one has to make a distinction between several different cases.

In the first case, the reduction in temperature is the result of a migration of the air. These result from changes in the atmospheric pressure and its local distribution. The most common type of fog of this sort is the advective fog. Moist air - usually coming from the sea, where the relative humidity did become very high - is moved by the general circulation towards a land area where the temperature may be lower. Heat exchange with the earth surface reduces the air temperature, causing condensation around the condensation nuclei. These nuclei are abundant, particularly when the air comes from the - salt - sea. As the land temperature must be lower than the water temperature for this type of fog to form, advection fog is more common in the winter than in the summer. A consequence is that the overall temperature is low, and thus the absolute humidity. So, advective fog usually is not very dense; however, it may be very extended. It is no exception if the larger part of Western Europe is covered by fog. And as long as the circulation continues, the fog will continue to form and to counteract any precipitation by clustering of fog droplets.

Another type of fog is the mountain fog. Mountain fog is similar to clouds, the difference being that clouds are in the sky and do not hinder road traffic, and mountain fog is on the earth surface and may hinder road traffic. In fact, the physical phenomena of the formation are the same. Again here, the droplets form as a result of a drop in air temperature. As the volumes one has to deal with in these meteorological phenomena are exceedingly large, it is enough to consider the changes of temperature as adiabatic. The driving force behind the fog or cloud formation is the ascent of the air. Air masses that are heated by the sun may ascent if they become lighter than the surrounding air; or they may ascent as they are forced up-hill by the prevailing wind. In both cases the atmospheric pressure is reduced. This means that - after the well known Boyle-law - the temperature will drop. This temperature drop is adiabatic, as has been explained before. When the temperature drops under the dew-point, condensation starts, and fog or cloud droplets will form. The fog may be very dense in cases where the temperature and the relative humidity - and thus the absolute humidity - of the air are high to begin with. For obvious reasons, mountain (or up-hill) fog is restricted to hilly or mountainous regions. It can form in any season; the location depends on the wind direction, and the fog usually is not very extensive, nor very patchy.

The third important fog type is the radiation fog. Radiation fog forms when in stationary - really stagnant - conditions the temperature drops. The main reason for the temperature to drop is the nocturnal radiation of the surface of the earth. This implies that radiation fog will from only at night, and particularly at the end of the night - near sunrise - when temperatures are lowest. Further, the sky must be clear for the radiation to reach a high level. And finally, the absolute humidity must be high enough for fog to form. This means that radiation fog is formed usually in the summer in open fields, particularly near water. As the radiation of the earth depends heavily on the vegetation, radiation fog can be extremely patchy. As the absolute humidity in summer can be quite high, the resulting fog can be extremely dense: a visibility under 10 m is not an exception. And finally, as air is a poor heat conductor, the layer where the radiation loss of the earth surface is felt can be very thin. Radiation fog often is under one meter thick, obscuring the legs of cattle while leaving the bodies perfectly visible. All these characteristics of radiation fog make it a very severe road accident hazard.

2.6. Fog abatement

The characteristics of the different types of fog and the physical aspects of fog formation that have been described in the foregoing sections show directly the ways to abate fog.

For fog formation the following factors are required:

- high absolute humidity
- high relative humidity
- sufficient condensation nuclei

If any of these three requirements is not fulfilled, or not fulfilled any longer, fog will not form, or existing fog will disappear. On this basis, a number of fog abating techniques can be indicated. We will discuss them in a brief outline, because not any of them has any practical significance.

2.6.1. Reducing the absolute humidity

When the water is removed from the air, fog cannot form. Two ways are possible: one can plant trees or construct sieves along the road, that "catch" the water droplets. This system can be useful for agriculture in some arid regions where the sparce rain may be supplemented by the precipitation of the fog; for road traffic its use is small as the majority of drops "slip through" and the fog is still there. Furthermore, it is expensive, and works only for advective fog coming from a distinct direction. The other way is to sprinkle additional (or more effective) condensation nuclei in the air. The most common is silver halide. This "seeding" is used with some sort of effect to interrupt the building-up of thunderstorms, and in some cases to remove fog from airstrips. For road traffic it is not feasible as roads are long and narrow, requiring a lot of expensive chemicals. Furthermore, these chemicals may pollute the environment, and may have negative side-effects, like causing the formation of clear ice).

2.6.2. Reducing the relative humidity

Reducing the relative humidity requires heating the air. During the Second World War this was done on some airfields by putting heaters (oil or gas burners) alongside the runway. Such systems cannot be applies in peace time on the road for reasons of costs, environmental pollution and safety.

2.6.3. Reducing the condensation nuclei

This is a good possibility for reducing fog or smog near industrial sites, waste burners etc. For normal natural fog it cannot be applied, as usually the nuclei are very much "overabundant". Taking away some if it, leaves enough for the fog to form. It should be stressed, however, that such types of air pollution should be avoided for other reasons!

2.6.4. Other methods

On a small scale, other measures can be used. One is by causing shock waves in the atmosphere (e.g. by firing guns or cannon). The shock waves cause a rapid coagulation of the droplets, and therefore a certain degree of precipitation.

Another method is to bleed cold air (e.g. fluid CO_2) into the atmosphere. The rapid cooling causes a local suprasaturation, leading to the formation of larger droplets, that precipitate more easily. Both methods are used only on a small scale and are not relevant for road traffic, as they are very local, and furthermore are effective only under very special fog conditions.

2.7. Conclusions

As a conclusion it can be stated that fog may be a considerable road accident hazard, and that it is not possible to abate the fog in a practical end economically feasible way. This implies that one must look for other ways to counteract the accident risk. Two ways are feasible: warning systems, and systems that improve visibility in fog. These ways will be discussed later in further chapters. An comprehensive overview of the different possibilities of fog abatement is given in Behrens & Kokoschka (1976).

3. FREQUENCY OF FOG

In most countries, fog is a rare phenomenon. We give some data for the Netherlands, more in particular for De Bilt where the national meteorological service is located. The data are derived from a non-published report of the Royal Meteorological Institute KNMI of the Netherlands. We give also data from the nearby Soesterberg airport. These data are derived from a non-published report of the Royal Netherlands Airforce. Both De Bilt and Soesterberg are close to the geographical centre of the country. Obviously, in other countries with different climate, geographical latitude or geomorphology the will be quite different.

First the De Bilt data. Figure 2 gives the frequency (number of hours) for the meteorological visibility to be less than the indicated value. The values are valid for the winter time (October to March inclusive); they are based on the observations of four years (1965 to 1969). The frequencies are given for five values of the height above the ground: 1 m, 2 m, 4 m, 6 m and 8 m. Several things are quite clear: firstly, dense fog is a rare phenomenon indeed, even in a country like the Netherlands that is "famous" for its fog. Furthermore, the frequency for very dense fogs decreases very steeply. For 1 m height (the most dangerous height for road traffic) v = 200 m occurs in winter only just over 2% of the time; 100 m (dense fog) in about 0.8%, and 50 m (very dense fog) only in 0.09% of the time. These percentages correspond to about 87 hours, 35 hours and about 4 hours! Incidently, according to the regulations, the use of fog rear lamps is permitted only for v = 50 m or less!

The Soesterberg data give a similar impression. The Figures 3, 4 and 5 give the frequency of the days per month where at specific hours the visibility was under 1000 m, 400 m and 200 m respectively. Sunrise and sunset are plotted as well (GMT). Again here, the trends are clear: the period around sunrise is the most fog-prone; fog occurs predominantly in the winter, and fog during the day is quite rare. And finally, there seems to be some indication that the early spring and the late fall are the most fog-prone periods.

4. TRAFFIC ASPECTS OF HIGHWAY FOG

4.1. Introduction

Fog is an aerosol consisting primarily of water droplets. As has been indicated in para. 2.3, the main effect on road traffic is the contrast reduction as a result of the scatter of the light in the aerosol; absorption plays only a small role. The scatter of the light leads to a "veil" that extends over the (major part of) the field of view. The visual effects of this veil can be expressed in terms of its luminance (aptly called the veiling luminance L_v). The luminance of all objects in the relevant part of the field of view is increased by the luminance of the veil, leading, as indicated in an earlier section, to a reduction of all visible contrasts. When the luminance of the object to be perceived is L_1 and the luminance of the background is L_0, the contrast without the veil (the intrinsic contrast C) is:

$$C = \frac{L_1 - L_0}{L_0}$$

When all luminances increase with L_v, the visual contrast C' becomes:

$$C' = \frac{(L_1 + L_v) - (L_0 + L_v)}{L_0 + L_v} = \frac{L_1 - L_0}{L_0 + L_v}$$

So, $C' < C$: all contrasts are reduced. Consequences of this calculations are given in Schreuder & Oud (1988). However, the "sharpness" of the visual images are not changed. The effect of the contrast reduction is that many objects in the field of view, that are very easily visible in a clear atmosphere, cannot be seen properly, and often not at all, during fog. When objects like other traffic participants (vehicles or pedestrians) are not visible at all, there is obviously a severe road safety hazard. However, also when those visually critical objects can be seen with some difficulty, but other objects disappear in the fog, the road safety may be seriously endangered. This aspects will be discussed in the following section.

4.2. The driving task

Taking part in traffic as a car driver, a bicycle rider or a pedestrian requires taking and implementing a series of decisions. We will focus, when clarifying these aspects, on the driving task of the driver of a (passenger) car, because here the accident risks usually are the largest. However, everything refers just as well to other modes of traffic participation.

The driving task consists of two main parts (subtasks):
- reaching the destination of the trip (the transportation aspect)
- reaching the destination safely (the road safety aspect).

The actual task can always be described in terms of a series (sequence) of manoeuvres that must be executed by the driver. Consequently, there are kinds of manoeuvres, viz.: normal manoeuvres that serve to reach the destination of the trip, and emergency manoeuvres that serve to avoid accidents (collisions). These manoeuvres can be arranged in an hierarchical sequence. Details are given in Padmos (1984) and Schreuder (1984, 1988).

Apart from the actual manoeuvres that are made while driving, also "higher" manoeuvres can be defined. These pertain to the selection of the destination, of the mode of transport, of the route etc. They are, however, the result of decisions made before the start of the trip, and consequently they are not influenced by the visibility conditions on the road.

By definition, all manoeuvres are the outcome of a decision-making process. Decisions follow after the acquisition of information. The speed and the efficiency of the acquisition and the processing of the information depends to a large extent on the degree in which the information is expected as regards type and time. Sudden, unexpected and unfamiliar instances require a much larger time for the processing of the information, and they may lead to a larger proportion of wrong decisions.

In road traffic, the information is mainly - almost exclusively - visual information. This information is derived in part from the surroundings, and in part from the store (memory). The visual information is the input of the decision making process; the manoeuvres (the behaviour) is its output. The decision concerns the selection of the most appropriate (the optimal) manoeuvre, given the conditions and the surroundings. In order to be able to make this most appropriate decision, the driver must be able to establish for himself a picture of the surroundings, and more in particular of the conditions as they may be in the near future.

As regards the road-traffic hazards resulting from fog, it seems that the sudden appearance of objects must be considered as the major cause for fog road accidents. The sudden appearance disrupts the "normal" flow of information, in so far as the traffic obstacles (trees, road side objects, or other traffic) are not seen well in advance. In other words, it is not possible to built a set of expectations as regards the traffic situation that is to be expected in the near future (the near future being in the order of magnitude of a minute or less). The disruption of the "normal" flow of expectations, and the means to restore this flow as fa as possible, are the major bases for all road-safety measures that are designed to counteract the road-safety hazards from fog. These aspects are not discussed any further in this note. This note concentrates on the role that street lighting can have in providing as much visibility as possible in during fog. The road-safety measures are discussed in detail in other publications. See e.g. Kocmond & Perchonok (1970); OECD (1971, 1976); Oppe (1988); Pfundt (1986).

4.3. The foresight

The picture from which the visual information is gathered, needs not be complete: it suffices to know the principal features of it. These principal features are called the "scene". In order to be able to look into the (immediate) future, it is necessary to be able to extrapolate from the (immediate) past over a period of about equal length. Together this is called a "sequence". The sequence incorporates the expectations of the driver about the near future.

It is possible only to arrive at sensible decisions regarding that particular stretch of the "near future" when the driver can be (almost) certain that there will be no sudden, unexpected and hazardous instances in that particular period of time. In other words, the driver must have a clear picture of what he or she may expect in that period.: he or she must be able to see ahead over that period. For this concept, the term "foresight" is coined (Schreuder, 1991a). This term is used to avoid confusion with the more common term "preview", as preview has a very special connotation in process engineering. The foresight can be expressed in time or distance, depending on the way the task is expressed in terms of time or distance. When the driving speed is known, the two are interchangeable.

The required foresight depends on the manoeuvre to be executed following the visual perception of the (visual) element. The smaller manoeuvres (elementary manoeuvres) such as making small corrections to the cross-wise position within the driving lane or to the driving speed are related to the actual handling of the vehicle. A foresight time of about 3 seconds seems to be sufficient in most cases. For "higher" manoeuvres like changing driving lanes the foresight time must be about 7 - 10 seconds. For still "higher" manoeuvres like coming to a stop, overtaking a preceding vehicle on a two-lane two-way road, or passing a priority intersection, a still larger foresight time is required. It is not possible to give generally applicable values, but 20 to 40 seconds may be regarded as values that are common in practice. For "strategic" manouevres like route selection on motorways, the forsight must still be larger. As a matter of fact, the required foresight distance often exceeds the optical range where any object may be seen. In such cases, pre-warnings are essential. As an example, pre-warning signs for motorway interchanges are often set up a distance of two to three kilometres. A survey is given in Schreuder (1991a).

For car driving, three elementary manoeuvres are particularly important: maintaining the lateral position on the road (in the traffic lane); maintaining the longitudinal position - usually the distance to the preceding vehicle, and the emergency manoeuvres that are required when traffic obstacles come up unexpectedly. The foresight values that are required (in seconds and metres, respectively) are given in Table 4.

In para. 2.1 we indicated that the meteorological visibility represents a border-line between objects being visible and non-visible, and that for practical applications a "practical visibility" could be introduced, measuring about three times the meteorological visibility. The values of the preview given in Table 4 are, obviously, expressed in the practical visibility. The corresponding values of the meteorological visibility are guiven (in rounded-off values) in Table 5.

4.4. Priorities for observation

The scenes need to be built up from a small number of individual elements in the field of view (the reconstruction of the scene). Not all individual elements are equally important: it is possible to establish an order of priorities in them. The highest priority is given to the visually critical elements: when these elements are not observed in time, it is not possible to built a correct scene, and accidents may happen. The manoeuvre that follows determines whether a particular element is visually critical.

One should make a distinction in different modes of visibility. Firstly, the "simple" observation or detection. This is related to the threshold measurements as are usually made in the laboratory. Secondly, the conspicuity. This means the possibility for observation, taking into account all disturbances that are found in the real world. And thirdly the recognition. This means the ability to classify the object under consideration in the right class to which it belongs. Obviously, one may recognize objects only if they are known in the first place: recognition presupposes earlier experiences. Adequate scene reconstruction requires not only visibility (detection) but conspicuity and recognition as well.

4.5. Visually critical elements

The next question is, what elements should be regarded as visually critical. As indicated earlier, this depends on the manoeuvre that is to be made. Presently it is not possible to indicate precisely what visual elements must be seen without doubt. Considerable research effort has been made in this respect; both the systematic observation of driving a car, and the analysis of accidents and "narrow escapes" were employed. (Padmos, 1984; Schreuder, 1984, 1985, 1988; Walraven, 1980). It became clear, however, that obstacles that form a hazard for traffic form only a small - be it important - fraction of the visually critical elements.

For the manoeuvres that have been indicated earlier, the following elements seem to be of special importance:
- for keeping the lateral position in the traffic lane: the lane markings and the (horizontal) general road markings, and the border of the pavement itself;
- for keeping the distance to the preceding traffic: obviously the preceding vehicle itself, and more in particular its markings (lamps and retroreflectors);
- for the emergency manoeuvres: a wide variety of objects, like signals (lights and other) on vehicles, pedestrians and cyclists on or near the road and obstacles like rocks and boxes.

One should take into account that these objects all need to be detected before they can be recognized as visually critical. Such objects are very common on the street, and they are therefore usually not critical at all. This underlines the need for an appropriate setting of the priorities for observation.

4.6. The visibility of visually critical elements

It is not enough that the visually critical elements are visible; it is necessary that there is a fair chance that they are effectively detected. The probability for an accident is not equal for each visually critical element: the consequences of missing a single road marking stripe are less severe than that of not detecting a pedestrian on the street. In this, the following questions come into consideration:
- Does the element itself present a hazard, or is it "only" a signal?
- Is the element standing on its own, or is it part of a series?
- What are the possibilities to avoid a collision once the element is missed?

In principle it should be possible to rank all visually critical elements in an order of priority as regards their need to be detected; at present, however, such ranking cannot be given.

In general terms, it is rather simple to guarantee the visibility of the visually critical elements that are placed expressly as such on or near the road. The visibility can be described in rather simple, well-established rules that concern in the first place the contrast between the object and its background, or the absolute light intensity (candle-power) when one deals with self-luminous objects like signalling lights. The conspicuity is primarily a matter of the supra-threshold contrast or the relation between the light intensity in relation to the adjoining disturbances. Again a number of well-known "rules-of-thumb" may be used. It is more difficult to guarantee the recognition: apart from the visibility and the conspicuity, the experience of the driver comes into play. Only objects that are well-known can be recognized. Training, education and information are essential.

It is more difficult to guarantee the visibility of objects that are not placed on purpose on the street. Most important are other traffic participants, and more in particular pedestrians and cyclists. Not only because they are the more "vulnerable" groups of road users, but also because their means to carry markings and signalling lights are very much restricted. Additionally, one has to deal with all sorts of objects like stones and boxes, and curbstones. During the day they are visible only if the contrast is large enough; at night a general lighting is indispensable.

4.7. Road accidents in fog

It is generally accepted that fog is a considerable road safety hazard. The accident frequency in fog is well documented. In Table 6, a number of data are quoted from OECD (1976) and from Oppe (1988). In most countries, the percentage of fog accidents is between 1 and 3 %, with peaks in both directions.

When comparing these frequencies with the figures quoted in Chapter 3 about the frequency of fog occurrence, it is clear that fog really does increase the accident risk. It is, however, very difficult to quantify this increase, as the accident data related to fog usually are not very precise, and furthermore it proves to be hardy possible at all to couple these data to the accurate fog data provided by the meteorological services. Further studies are required to assess the extra road-accident risks of fog more accurately.

5. THE ROLE OF ARTIFICIAL LIGHTING

5.1. The functions of traffic lighting

Generally, in clear air the visibility of the visually critical elements is adequate during the day. At night, artificial lighting is essential. As the artificial lighting is meant for the road traffic, the lighting may be called (road) traffic lighting. The function of road-traffic lighting is to permit the road traffic to proceed at a reasonable efficiency also during the time that (natural) daylight is absent. The efficiency is usually expressed in terms of speed, safety and comfort; the efficiency is higher when these goals are reached for a smaller amount of costs. The cost/benefit relation is essential in the judgement of the efficiency of road traffic lighting.

The efficiency will be expressed in the degree to which the functions for the road traffic lighting are fulfilled. These functions are:

- to permit the use of the open-air public-space also in darkness;
- to enhance the traffic safety (reduction of road accidents);
- to enhance the public safety (reduction of crime);
- to enhance the amenity (enhance feeling secure, particularly for the women, the elderly, the children and the bicycle riders);
- to enhance the aesthetics (promote the commercial aspects).

These five functions are not always equally important. More in particular, for motorways the emphasis on the first and the second function. This important to recall when we will discuss the colour of light for motorway lighting in fog (para. 5.6).

In order to reach an optimum, on has to design, to install and to maintain the lighting in such a way that these functions are met as good as possible for minimal costs. The costs are:

- monetary costs of installing and maintaining the installations
- monetary and non-monetary costs of pollution and the use of natural resources.

It must be kept in mind that the costs are carried in part by the authorities, and in part by the traffic participants. Although all costs are an equal burden for the community, in practice it turns out that most authorities are much more generous when it is the road user's costs that come into the picture!

The artificial road-traffic lighting comes in two types:

- lighting equipment installed on or near the road - the public (overhead) street lighting, usually called "road lighting";
- lighting equipment installed on the vehicles, usually called "vehicle lighting".

The first gives the better possibilities to guarantee the visibility of visually critical elements. At the other hand, this type of lighting is expensive; furthermore, the costs of installation and maintenance are the burden for the road authorities. Vehicle lighting can only be used by vehicles with a considerable energy source (engine); it can hardly be used by cyclists and not at all by pedestrians. Furthermore it is not possible to see the road over a considerable length ahead, particularly if one is blinded by the lights of opposing vehicles. However, the lighting is fairly cheap and the costs are for the road users, not for the road authorities.

On roads without (overhead) road lighting, one has to be content with the lighting that is carried along by the vehicles. The visibility of objects can be improved by using retroreflecting devices; these are devices that, by means of a special arrangement of optical elements, reflect back almost all light impinging on them into the defection where it came from. They are quite effective when lit by vehicle headlamps, that have sufficient intensity and that are located very close to the observer (the car driver). However, pedestrians carry no light, and usually no retroreflectors either. Cyclists may carry lights, but as the available energy is limited, the lights will be only weak. Bicycle headlamps are barely sufficient to light the path immediately ahead, although the modern halogen lamps perform considerably better than the traditional lamps. Cyclist, however, carry retroreflectors abundantly. At the other hand, cars, trucks, motor cycles and mopeds are hardly restricted as regards the amount of energy that is available for lighting. But also for them it is not possible to light the path ahead over more than just a few tens of meters. When the perspective foreshortening of the road scene is taken into account, it is obvious that the road cannot be illuminated at medium or large distances - distances that are directly relevant for fast driving vehicles; areas from which the drivers require visual information. The situation is deteriorated in real traffic even further by the glare from the lights of opposing vehicles. This glare can be avoided only in exceptional cases, e.g. on one-way streets.

When road lighting is absent, one therefore has to rely on self-luminous and retroreflecting objects. These objects have to comply with the packages of requirements that have been set up by the Commission Internationale de l'Eclairage CIE in collaboration with other international agencies like ECE, EEC and ISO (See e.g. CIE, 1987). These requirements include luminous intensities, coefficients of retroreflection, colours, dimensions, shapes and arrangements of light signals, traffic lights and markings for roads and vehicles.

Both theory and practice indicate clearly that vehicle lighting is not sufficient for the detection of all visually critical elements. As a result, the accident risk on "unlighted" streets usually is considerably higher than the risk on similar streets with public lighting. Throughout the years, a large amount of research has been devoted to this subject. The results are summarized in surveys like CIE (1960; 1991), Fisher (1977); OECD (1971) and Schreuder (1983; 1985a; 1988a). The overall conclusion is that when comparing "good" public lighting with very poor or absent lighting, one may expect a reduction of about 30 % in night-time injury accidents on urban thoroughfares and rural motorways.

This paper deals primarily with road lighting. The technical aspects of vehicle lighting in clear air as well as in fog conditions are an important subject as well, that deserves to be discussed separately. What we will discuss, however, is the conditions under which roads can be left unlit in clear air and in fog, focussing on some safety aspects of unlit roads in fog.

5.2. Road lighting in clear air

Road lighting represents only a relatively small post on the expenditure, both regarding costs and energy. Nevertheless, it involves considerable sums, and one should use the money and the energy for road lighting in the most sensible way, particularly in times where public expenditure is carefully considered, and where the interest in safeguarding the environment is rising. More energy used means more coal burned, and more CO_2 in the atmosphere.

Almost all road lighting is utilitarian. With the exception of some decorative lighting of major squares, and some amenity lighting in shopping malls, the lighting has a function - or rather a number of functions, as described in para. 5.1. The functions, and their relative importance may differ to some extent for different types of road. Optimising the road lighting means that the equipment is designed, installed and maintained in such a way that the ratio between costs and benefits is maximal; meaning that the benefits (according to the specific functions) is maximal whereas the costs (monetary and non-monetary alike) are minimal.

Road lighting is similar to daylight: the light comes from all sides, so that objects may be rendered visible by means of their contrast to the background. This contrast is determined primarily by the illuminance on the surfaces and by the (diffuse) reflection of these surfaces The luminance contrast suffices to describe the visibility as colours and colour differences play only a small role in road traffic. The visibility of the majority of visually critical elements is guaranteed if the light-technical requirements are fulfilled. For public lighting one may refer to the recommendations issued by the CIE and by many national standardizing bodies concerning the luminance and the luminance distribution of the road surface, the glare restriction and the optical guidance (CIE, 1977; NSVV, 1991).

One must keep in mind, however, that even under "ideal" conditions of lighting and visibility it is likely that many visually critical elements will be invisible - or at least remain unobserved. At present, one cannot be certain whether this is the result of the lack of visibility of the object or of inattention from the part of the observer. But it means that even under "ideal" conditions one has to reckon with road traffic accidents that result directly from defective visual input.

The way road lighting may fulfill the requirements according to the functions we mentioned earlier depends on the degree into which the visually critical elements are made visible. This may be expressed in photometric terms. So the quality of road lighting can be expressed in the degree into which the photometric requirements are met. The major photometric (and the related geometric) requirements are:

- the light level
- the non-uniformity
- the glare restriction
- the visual (or optical) guidance.

The level is expressed in the average road surface luminance for traffic routes, and in the average horizontal illumination (illuminance, Lux-value) for residential streets. The reason is that the road surface usually is the back-ground for most objects in the street. Recently, the semi-cylindrical illuminance is coming into use to describe the light level, particularly in pedestrian areas, because is a better measure for the recognition of human faces. The non-uniformity consequently is expressed in luminance terms or in illumination terms as well. The level and the uniformity describe the degree to which visually critical elements are visible. They are relevant for the performance of all manoeuvres as described in para. 4.2.

As a result of light scatter in the ocular media, glare can be described in terms of a veil over most of the field of view. The effect of the veil caused by glare is in a mathematical term similar to that caused by fog - both are caused in the last instance by scattered light - so that the formulae given in para. 2.4 may describe the glare. The final result is an increase in the threshold for the observation of small contrasts. This is termed the threshold increment. Glare therefore reduces the ability for precise detection. Consequently, it influences the visibility of visually critical elements, and must be incorporated with the level and the non-uniformity as requirements needed for all manoeuvres.

The effects of glare described here are of a physiological nature: the influence on the ability for perception. These glare aspects are called the physiological or the disability aspects of glare. Glare may have another effect on visual perception. This effect does not influence the ability for perception, but rather the ease of perception. It relates to the comfort of seeing, and includes psychological effects. In an era where money is scarce, and where utilitarian approaches are prevalent, the interest in discomfort glare has been reduced considerably. It is not included any longer as a criterion of quality in modern recommendations for road lighting (NSVV, 1991).

The fourth quality aspect of road lighting is the visual guidance. At present, there are no means available to quantify it, and consequently, modern codes refer only to this aspect in general, qualitative ways. The discussion in para. 2.4 suggests, however, that the visual guidance is extremely important for those manoeuvres that require a large preview. And it is precisely the visual guidance that suffers most in fog. As a matter of fact, it is the major requirement for road-lighting installations in fog to maintain as far as possible the visual guidance in spite of the fog!

5.3. Artificial light in fog

The function of artificial light in fog is essentially the same as the function for clear atmosphere. It is to make the visually critical elements (better) visible; and the objects classify as visually critical elements in view of the role they play in assuring adequate room for specific traffic manoeuvres.

In para. 5.2 we discussed in some detail then requirements of road lighting in clear air and dry conditions. However, when fog or rain is taken into account (and it should be kept in mind that during fog the road surface usually is wet or at least damp) the situation is much worse. Studies point out that the accident risk in the dark, in rain and in fog, when taken separately, is 50% to 100% higher that during clear, dry daytime. A combination of two of the three increases the accident risks considerably: during rain at night, the accident risk can increase to the ten-fold of the risk in dry daytime. Similar data are found for fog (OECD, 1971; 1976). The combination of these adverse effects seems to be more severe than just the sum of the adverse effects of the separate causes; they seem to reinforce each other.

The reason for this additional risk seems to be the fact that the adverse effects quoted above affect simultaneously the road safety in several ways. During rain, the long range visibility will be restricted somewhat - be it not dramatically - but the short-range visibility can be obstructed almost completely as a result of "splash-and-spray". Furthermore, the skidding resistance is decreased when the surface is wet, and often pools on the road resulting from rutting, may cause aquaplaning, reducing the skidding resistance to almost zero. Under conditions where a much longer preview is needed, the actual preview is restricted. This explains the beneficial effect of drainage asphalt, as both splash-and-spray and aquaplaning are reduced to almost zero. So, rain restricts the short-range visibility that is needed for manoeuvre parts, but not the long-range visibility that is needed for course holding. The effect of fog is quite different: usually the road is only damp, reducing the skidding resistance, but not dramatically like in aquaplaning. The short-range visibility may be restricted - depending on the density of the fog - but the long-range visibility is reduced to zero. It will be clear that rain and fog will influence road safety in quite different, but both in serious, ways; it will also be clear that the combined effect of rain or fog at the one hand and darkness at the other will cause additional road safety hazards!

In the following sections of this paper we will discuss in how far road lighting can help to reduce the (additional) accident risks that arise in fog on motorways. The first question regarding motorway lighting in fog is under what conditions, or alternatively, for which motorways, road lighting is required.

5.4. Road lighting versus vehicle lighting in fog

The lighting of motorways is a controversial question. In many countries, all, or a major part of the motorways have a continuous road lighting, whereas in other countries motorways are essentially unlit. Four different criteria are used:
- the function of motorways in the road network;
- the road dimensions (cross-wise profile);
- the accident rates;
- the traffic volume.

The first criterion is used in Belgium and in (Western) Germany, be it with opposite results. In both countries it is assumed that motorways are a category of their own, that should be treated uniformity. In Belgium it is realized that motorways, being high-speed roads, are inherently dangerous and require a road lighting, whereas in Germany it is realized that motorways are essentially a very safe type of road, and thus do not require road lighting. Both viewpoints, are, of course, correct: motorways have the largest number of accidents per unit of length of all road categories, but the lowest per unit of traffic (veh.km).

Most other countries follow the German policy, be it not completely consequent. Almost all motorways in countries like Spain, Italy, Sweden and Greece are unlit.

Some countries consider only the accidents. When the accident rate (expressed e.g. in vehicle kilometres) is over a certain limit, the motorway will be lit. This system is used in the UK and Denmark, and also in the US, be it that the criteria for lighting may differ from country to country or from state to state.

In the Netherlands, the main criterion is the cross-profile. Motorways with three or more lanes in each direction will be lit throughout. Additionally, the decision for lighting depends on the traffic volume per lane and on the frequency of additional traffic hazards (narrow roads, absence of a hard shoulder, urban spill light, etc.). Essentially, the Dutch criteria have been taken over in the present CIE-Recommendations (CIE, 1977).

Only the British and the Dutch systems refer to fog as a specific hazard that could influence the decision for road lighting. In the UK, fog accidents are considered as a special "subgroup" of accidents that influences the decision. So, several stretches of motorways in England are lighted throughout exclusively because they run in a fog-prone area. The Dutch system includes fog prone areas explicitly as an "additional traffic hazard". On these grounds, most of the major river crossings (bridges plus approach roads) are lighted. In these cases, the lighting is in operation at all times, also in clear weather. This of course has consequences for the lighting design: the lighting must be effective both in clear weather and in fog, contrary to the special fog lighting systems that are switched on only in fog, and which have to be designed specially for fog conditions.

Obviously, for countries that have not adopted the Belgium system of lighting all motorways, the Dutch system is to be preferred. It is well-known that fog is a severe road-safety hazard, and it is well-known as well that road lighting is an effective accident countermeasure, also in fog conditions. Leaving all motorways unlit may be acceptable in clear weather (even if there are severe doubts for this; see CIE, 1991); leaving them unlit in fog is often unacceptable. Presumably this is realized as well by German and Italian road authorities: in some fog-prone areas special lighting for fog conditions is installed. Looking only at accidents may seem to be a good course, but there are two draw-backs: first, the road must be in operation a considerable time before enough accidents have occurred (a form of vivisection that is frowned upon in many countries), and secondly it is not always possible to discern the fog accidents precisely enough from the non-fog accidents to come to a sound decision.

So it is recommended to install general purpose road lighting on motorways that run through noted fog-prone areas.

5.5. Requirements for motorway lighting in fog

The requirements for the lighting for motorways in fog are very similar to those for clear air, as it is the same kind of manoeuvres that must be performed, and therefore the same visually critical elements must be made visible. The relative importance of the different aspects of the lighting are, however, rather different as a result of the presence of the fog. In para. 4.3 we indicated the preview that is required for the different manoeuvres. The data are given in Tables 4 and 5. These data can be used in two ways: first, it is possible to find out what meteorological visibility is required in order that a specific manoeuvre can be performed at a specific speed. The second way is to select the speed (that should be the maximum driving speed under the prevailing conditions) for specific manoeuvres and a given meteorological visibility. As an example of the first: when lane changings at high speeds and/or overtaking manoeuvres at low speeds are deemed necessary, the visibility should be at least 700 m. As an example of the second way to use the data: when the visibility is

300 m, corrections to the lateral position within the driving lane are still possible at high speeds (120 km/h), and lane changings at low speeds (50 km/h) but overtaking is out of the question, even at 50 km/h.

This points to an aspect of road safety in fog that is often overlooked or not understood. Many people drive at high speeds in clear air - say 120 km/h. Under these conditions they can perform safely almost all relevant motorway manoeuvres. When fog begins, they reduce speed, and may consider themselves as real safe drivers: they slow down to - say - 90 km/h. What they do not realize is that for many manoeuvres, particularly involving other traffic participants, this speed is far too high for safe driving even under moderate fog. A speed of maybe 50 km/h would be called for.

As regards road lighting, the tables indicate that, in order to be able to perform the manoeuvre parts like corrections in speed or position, the road, the limits of the road, the road markings and any small object on the road must be visible up to 200 to 300 meters in order to permit safe, fast traffic. Normal general purpose road lighting of adequate standards will be able to provide the required information. More precise, the requirements as given in the CIE (and similar) recommendations suffice in almost all cases. These recommendations are for motorways: a luminance level L of 1 to 1.5 cd/m2, a uniformity U_0 better than 0.7 and regarding the glare restriction a TI of less than 15%. For moderate fog (v not less than some 300 m) the same requirements are valid. For more complicated manoeuvres, like lane changes, the preview requirements are much higher. Here, the visibility of the road itself is often not sufficient, due to the foreshortening of the road in the perspective view. For high speed traffic, additional information is needed. Usually, this information is provided by delineators. These delineators are equipped with retroreflectors, which are less effective in fog, as a result of the fact that the light has to traverse twice the fog layer between the delineator and the driver - once travelling from the lamp to the delineator, and once more on the way back. In fog, road lighting lanterns are indispensable. For still more complicated manoeuvres, the preview is still larger. The required information relates primarily to the run of the road. Here, the information requires both in clear air as in fog the presence of road lighting lanterns.

In this respect, three further remarks must be made. First, it should be noted - as has been indicated earlier - that the visual range from light sources is larger than the visibility as measured from the contrast threshold. The reason is that a dark object cannot have a contrast higher than 100%, whereas a light source can have a contrast that is much higher, being lighter than the back-ground (see Figure 1 and Table 1). A diffusely reflecting object cannot be seen as far as a light source. This means that for a medium- or long-range preview, light sources are much to be preferred, particularly in fog conditions.

The second remark has to do with the same facts. During the day, road-lighting lanterns are just (small) diffusely reflecting objects, but at night they emit light. This is the ground for the well-known phenomenon that the visual guidance at night can be much better than at day, provided the road carries a road-lighting installation. It will be clear from the foregoing that these factors are much heavier in fog conditions than in clear air.

The third remark is again related to the first and the second: in spite of the fact that disability glare is a negative factor in road lighting, that should be restricted as far as possible, the lanterns should be constructed in such a way that the light distributions are not completely of the "cut-off" type, particularly in fog conditions. Severe glare should be avoided, of course, but in this respect the TI value of 15% as quoted above form the CIE-Recommendations gives a good result in fog. The open cut-off lanterns that were popular on the continent of Europe several decades ago, showing a TI of 5% or even less, are to be avoided for fog conditions.

5.6. Installation characteristics for motorway lighting in fog

The following three types of lighting are relevant for motorways in fog:
- general purpose lighting
- special fog lighting
- support lighting

We have recommended already to install general purpose lighting in fog-prone areas; the system of considering "additional road-safety hazards" permits the selection of those types of general purpose lighting that are particularly suited for operation during fog. In countries where policy prohibits general motorway lighting, one has to get along with special fog lighting, which is only in operation during actual fog. In countries where only the general accident picture is used for deciding whether motorways are lit or not, fog-prone areas can benefit from (additional) support lighting.

5.6.1. General purpose lighting

If the lighting is supposed to be particularly effective in fog, it should be adapted in all cases to the specific characteristics of light scatter and light transmission in fog. First we will discuss the light scatter, that causes the most disturbances for the short-range visibility.

In para. 2.4 we have explained that the scatter is not equally strong in all directions: sideways scatter is lowest; back scatter is more pronounced, and forward scatter is strongest. And as the major disturbance of fog is caused by the veil that results from the scatter of light, it is clear that road lighting is most beneficial in fog when the light is emitted cross-wise in respect to the direction of view. This refers particcularly to those manoeuvres that require a short-range preview. The best results are found with lighting systems that emit the light perpendicular to the road axis, like e.g. catenary lighting. Cut-off lanterns, where in spite of the symmetric light distribution, the light emitted along the road axis in the same direction as the traffic is predominant, are less beneficial as the back scatter is more disturbing than the sideways scatter. And non-cut-off lanterns, where the light emitted along the road axis against the traffic dominates, are not suitable at all during fog.

Also in para. 2.4 it has been explained that the visual range of light sources usually is much higher than the visibility of diffuse reflecting objects. This characteristic of fog can be used to enhance the visual guidance, which, as was explained in para. 4.3, is particularly important for manoeuvres that require a medium-range or long-range preview. Here, a compromise must be found. Luminaires that emit much light against the traffic may have a large visual range, but they cause an intense light veil as the result of the forward scatter. Practice indicates that the normal catenary lighting lanterns give the best compromise: they remain visible in most fog situations; only in the densest of fogs they are clearly less visible than non-cut-off lanterns; however, under such conditions road traffic is hardy possible at all. Catenary lighting has another advantage: the rather short interdistance between the lanterns (usually between 15 and 30 m) support the view regarding the run of the road at intermediate distances. This is already a marked advantage in clear weather, but even more so in fog. Catenary lighting is therefore recommended for general purpose lighting in fog-prone areas.

We did not yet discuss the colour of the light. Contrary to what is often stated, natural (clean) fog scatters all visible light equally strong; there is no preference for any colour of the light (see para. 2.4). However, the scatter is influenced to a certain degree by the (intrinsic) luminance of the light sources. Therefore, large lamps show a certain advantage over concentrated sources. This favours low-pressure sodium lamps and fluorescent tubes over high-pressure sodium or mercury lamps. In view of the lumen output per unit, the low-pressure sodium lamps are to be preferred for motorway lighting, particularly because the monochromatic light is not a draw-back at all for lighting roads exclusively for motorized traffic - contrary to residential areas.

As the lighting is in operation under all conditions, the lighting should comply to the quality standards that are given for general motorway lighting (e.g those issued by CIE, 1977, or NSVV, 1991).

In conclusion, length-wise mounted catenary lighting systems equipped with low-pressure sodium lamps are recommended for general purpose lighting for motorways in fog-prone areas.

5.6.2. <u>Special fog lighting</u>

In some areas that are exceptionally fog-prone, some motorways are equipped with special fog road lighting systems. A well-known example is the system that was applied on the bridge over the Lippe river in West Germany, where, due to exhaust water of power stations, the temperature of the river water was much higher than normal. This resulted in frequent, and usually extremely dense, fog. The lighting system consisted of lanterns mounted on the median strip at about 1 meter (thus just under eye-height of car drivers), equipped with mercury lamps. The light was emitted almost horizontally in the direction of the traffic, so that especially the rear of preceding vehicles was lit up. The road surface luminance was very low, and the uniformity was very poor as well. As the lighting was switched on only in dense fog, this was not considered as a draw-back. The lighting was considered as successful, but when the environmental conditions were changed and fog frequencies dropped considerably, the lighting was removed. Similar systems were installed in other fog-prone locations in Germany, Britain, the US and Italy. There never was, however, any systematic evaluation of the systems.

5.6.3. Support lighting

In some cases, the general purpose lighting was not considered enough for dense fog situations. Several systems of (additional) support systems were designed and some of them were put in operation on an experimental basis. The best known may be the lighting system on several mountain passes in the Alleghanies in the East of the US, where small light units were mounted in the road-way itself. The idea came from airport runway lighting where such systems are standard practice. Due to cost factors, and to soiling by traffic and damage by snow-plows, the success was limited. The systems never came further than experiments. Details are given in Schreuder (1978; 1985b) where they are compared to regular raised pavement markers. The comparison showed that the system of additional support lighting is quite promising; further research is recommended. It might be added that such systems could be effective in road tunnels as well.

6. CONCLUSIONS AND RECOMMENDATIONS

- Fog is a considerable road safety hazard on all roads, and particularly on (high speed) motorways.
- The disturbance to motor traffic is a result of the scatter of the light. Absorption plays only a small role in natural (clean) fog.
- Sideway scatter is less than forward scatter and back scatter.
- The visual range of light sources is usually considerably larger than the visibility of diffuse objects.
- Road lighting is an effective road safety measure, also on motorways. The benefits are particularly clear in fog.
- It is recommended to install general purpose lighting systems on motorways, particularly in fog-prone regions.
- The general purpose lighting should follow the Recommendations regarding the quality aspects issued by the appropriate bodies (e.g. CIE or NSVV).
- More specific, it is recommended to apply length-wise mounted catenary lighting systems equipped with low-pressure sodium lamps for general purpose lighting for motorways in fog-prone areas.

REFERENCES

- Behrens, H. & Kokoschka, S. (1976). Beleuchtung der Kraftfahrzeuge bei Nebel. Lichtechnisches Institut, Universität Karlsruhe.
- Byers, H.R. (1959). General meteorology. 3rd ed. McGraw Hill.
- CIE (1960). Street lighting and accidents. Publication No. 8. CIE, Paris.
- CIE (1977). International recommendations for the lighting of roads for motorized trafic. Publication No. 12/2. CIE, Paris.
- CIE (1987). Properties and uses of retroreflectors at night. Publication No. 72. CIE, Vienna.
- CIE (1991). Road lighting as an accident countermeasure. Publication No. 8/2. (Draft). CIE.
- Douglas, C.A. & Booker, R.L. (1977). Visual range: Concepts, instrumental determination, and aviation applications. NBS Monograph 159. National Bureau of Standards, Washington, D.C.
- Fisher, A.J. (1977). Road lighting as an accident countermeasure. In: LITG, (1977).
- Hütte (1919). Des Ingenieures Taschenbuch. 23. Auflage. Ernst & Sohn, Berlin.
- Jiusto, J.E. (1964). Project fog drops, investigation of warm fog properties and fog modification concepts. NASA Contractor Rep. CR-72.
- Kocmond, W.C. & Perchonok, K. (1970). Highway fog. NCHRP Report 95. Highway Research Board, Washington, D.C.
- LITG (1977). Measures of road lighting effectivity. CIE-Symposium, Karlsruhe, July 5-7, 1977. Lichttechnisches Gesellschaft, Berlin.
- Middleton, W.E.K. (1952). Vision through the atmosophere. University of Toronto Press.
- NSVV (1991). Aanbevelingen voor openbare verlichting (Recommendations for public lighting). NSVV, Arnhem.
- OECD (1971). Road lighting and accidents. OECD, Paris.
- OECD (1976). Adverse weather, reduced visibility and road safety. OECD, Paris.
- Oppe, S. (1988). Verkeersonveiligheid bij mist (Road accidents in fog). R-88-49. SWOV, Leidschendam.
- Padmos, P. (1984). Visually critical elements in night driving, in relation to public lighting. In: TRB (1984).

- Pfundt, K. (1986). Verkehrssicherheit und Strassenbeleuchtung (Traffic safety and road lighting). Mitteilungen der Beratungsstelle für Schadenverhütung. No. 28, pp. 30-38. HUK-Verband, Köln.

- Schreuder, D.A. (1964). Lighting in adverse weather. Traffic Engng. Contr. 5 (1964): 720-723.

- Schreuder, D.A. (1975). Wit of geel licht voor autokoplantaarns (White or yellow light for car headlamps). Publicatie 1975-3N. SWOV, Voorburg.

- Schreuder, D.A. (1976). The scatter of light of different colour in the atmosphere. R-76-44. SWOV, Leidschendam.

- Schreuder, D.A. (1978). De zichtbaarheid van wegmarkeringen op natte wegen (Visibility of road markings on wet roads). SCW, Arnhem.

- Schreuder, D.A. (1983). De relatie tussen verkeersongevallen en openbare verlichting (The relation between traffic accidents and public lighting). R-83-12. SWOV, Leidschendam.

- Schreuder, D.A. (1984). Visibility aspects of road lighting. In: TRB, (1984).

- Schreuder, D.A. (1985). Fundamentele overwegingen omtrent visuele en verlichtingskundige aspecten van de verkeersveiligheid (Fundamental considerations about visual and lighttechnical aspects of traffic safety). R-85-61. SWOV, Leidschendam.

- Schreuder, D.A. (1985a). Het effect van vermindering van de openbare verlichting op de verkeersveiligheid (The effect of the reduction of public lighting on the road safety). R-85-58. SWOV, Leidschendam.

- Schreuder, D.A. (1985b). De zichtbaarheid van wegmarkeringen op natte wegen; Een aanvullende literatuurstudie (Visibility of road markings on wet roads; A supplementary literature survey). R-85-23. SWOV, Leidschendam.

- Schreuder, D.A. (1988). Visual aspects of the driving taks on lighted roads. CIE Journal 7 (1988): 15-20.

- Schreuder, D.A. (1988a). De relatie tussen het niveau van de openbare verlichting en de verkeersveiligheid; Een aanvullende literatuurstudie (The relation between the level of the road lighting and the road safety; A supplementary literature survey). R-88-10. SWOV, Leidschendam.

- Schreuder, D.A. (1991). Motorway lighting under fog conditions (In Japanese). Tokyo, 1991.

- Schreuder, D.A. (1991a). Visibility aspects of the driving task; Foresight in driving. R-91-71. SWOV, Leidschendam.

- Schreuder, D.A. & Oud, H.J.C. (1988). The predetermination of the luminance in tunnel entrances at day. R-88-13. SWOV, Leidschendam.
- Spencer, D.E. (1960). Scattering functions for fog. Journ. Opt. Soc. Amer. 50 (1960): 584-585.
- TRB (1984). Providing visibility and visual guidance to the road user. Symposium, July 30- August 1, 1984. Transportation Research Board, Washington, D.C.
- Van de Hulst, H.C. (1957). Light scattering by small particles. John Wiley and Sons, Inc., New York.
- Walraven, J. (1980). Visueel critische elementen bij nachtrijden; Een veldstudie (Visual critical elements by driving at night; A field study). IZF 1980-C22. IZF-TNO, Soesterberg.

FIGURES 1-5

Figure 1. The relationship between the visibility and the visual range for different values of the atmospheric transmission (Source: Douglas & Booker, 1977).

Figure 2. The relationship between frequency of fog (p) and meteorological visibility (m) only for winter half year; parameter h: height over ground.

Figure 3. Average of days per month with visibility < 1 km at the given time (Soesterberg 1946-1960).

Figure 4. Average of days per month with visibility < 0,4 km at the given time (Soesterberg 1946-1960).

Figure 5. Average of days per month with visibility < 0,2 km at the given time (Soesterberg 1946-1960).

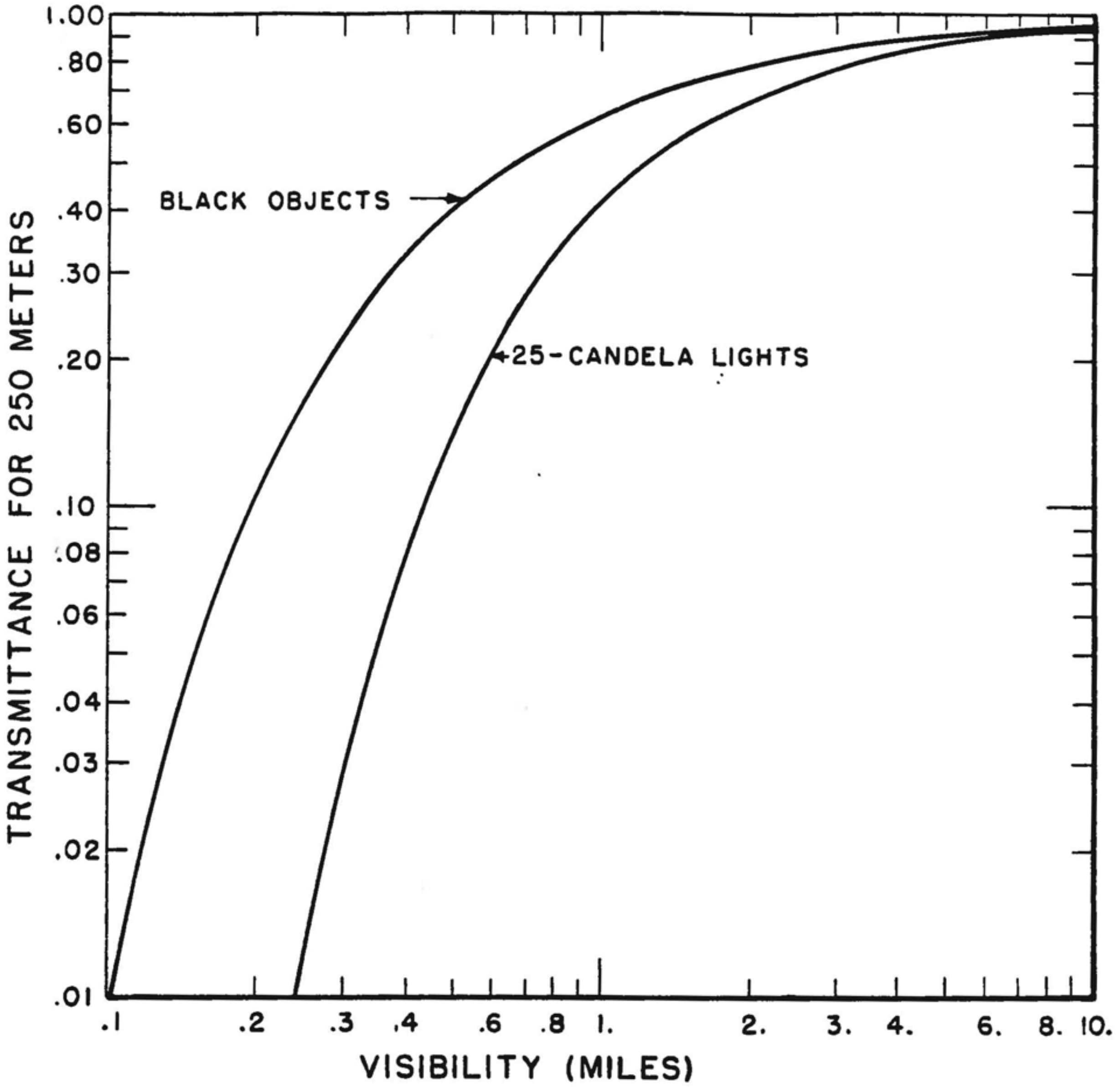

Figure 3.3 Transmissometer calibration curve developed at Nantucket. The visual range of objects is computed from contrast threshold of 0.055. The visual range of lights is computed from Allard's law assuming a light intensity of 25 candelas and an illuminance threshold of 0.084/V where V is the visibility in miles.

Figure 1. The relationship between the visibility and the visual range for different values of the atmospheric transmission (Source: Douglas & Booker, 1977).

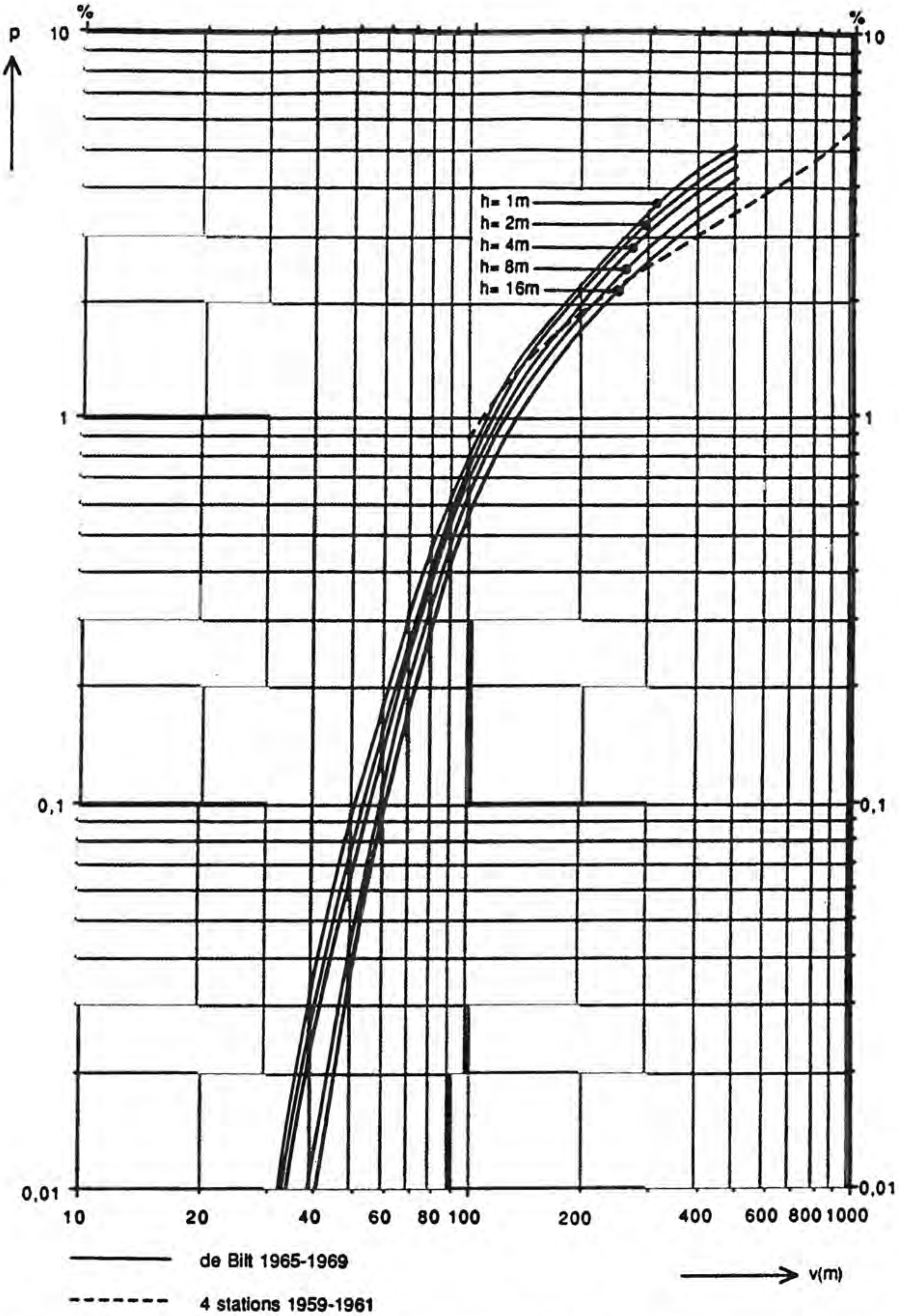

Figure 2. The relationship between frequency of fog (p) and meteorological visibility (m) only for winter half year; parameter h: height over ground.

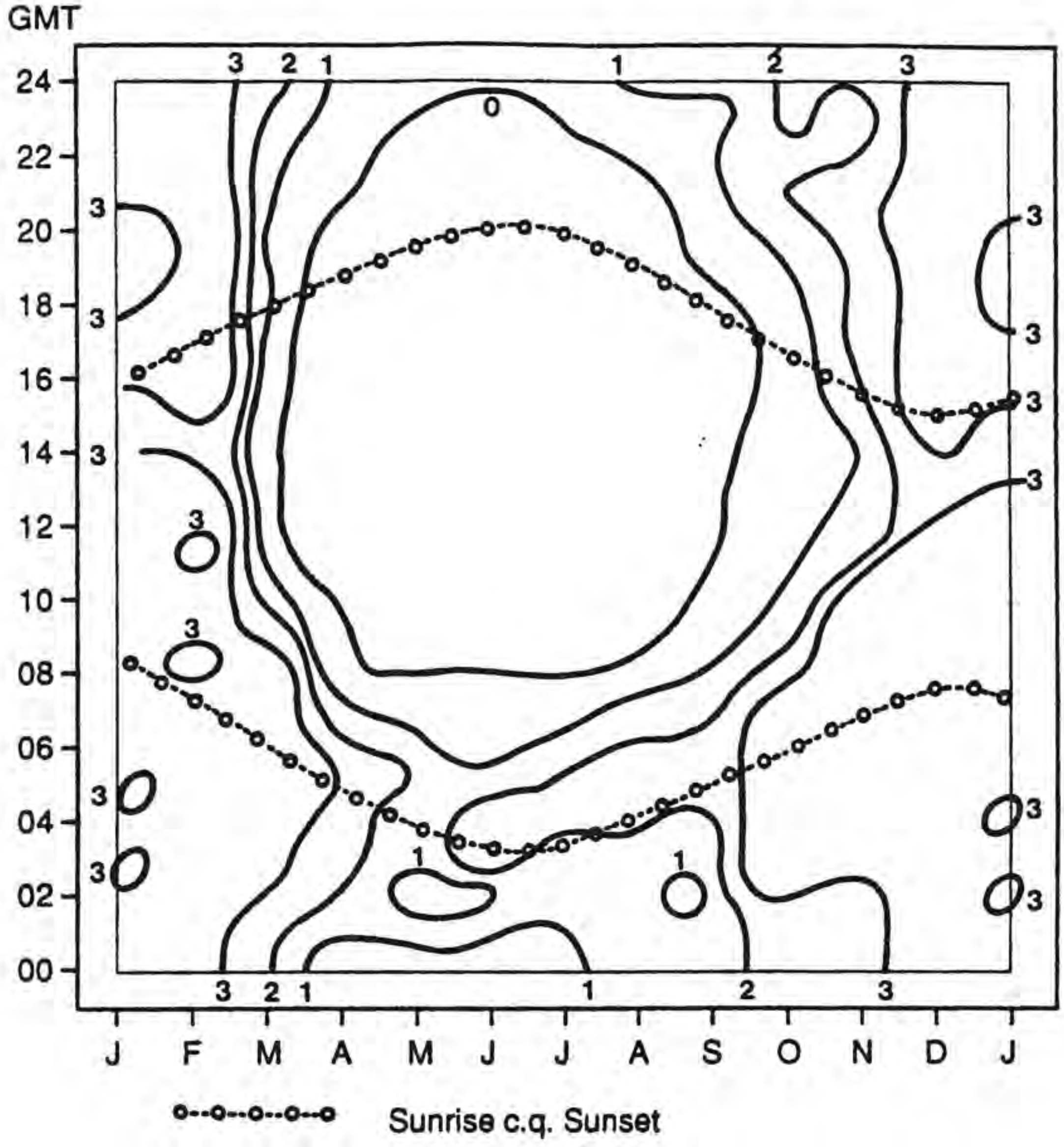

Figure 3. Average of days per month with visibility < 1 km at the given time (Soesterberg 1946-1960).

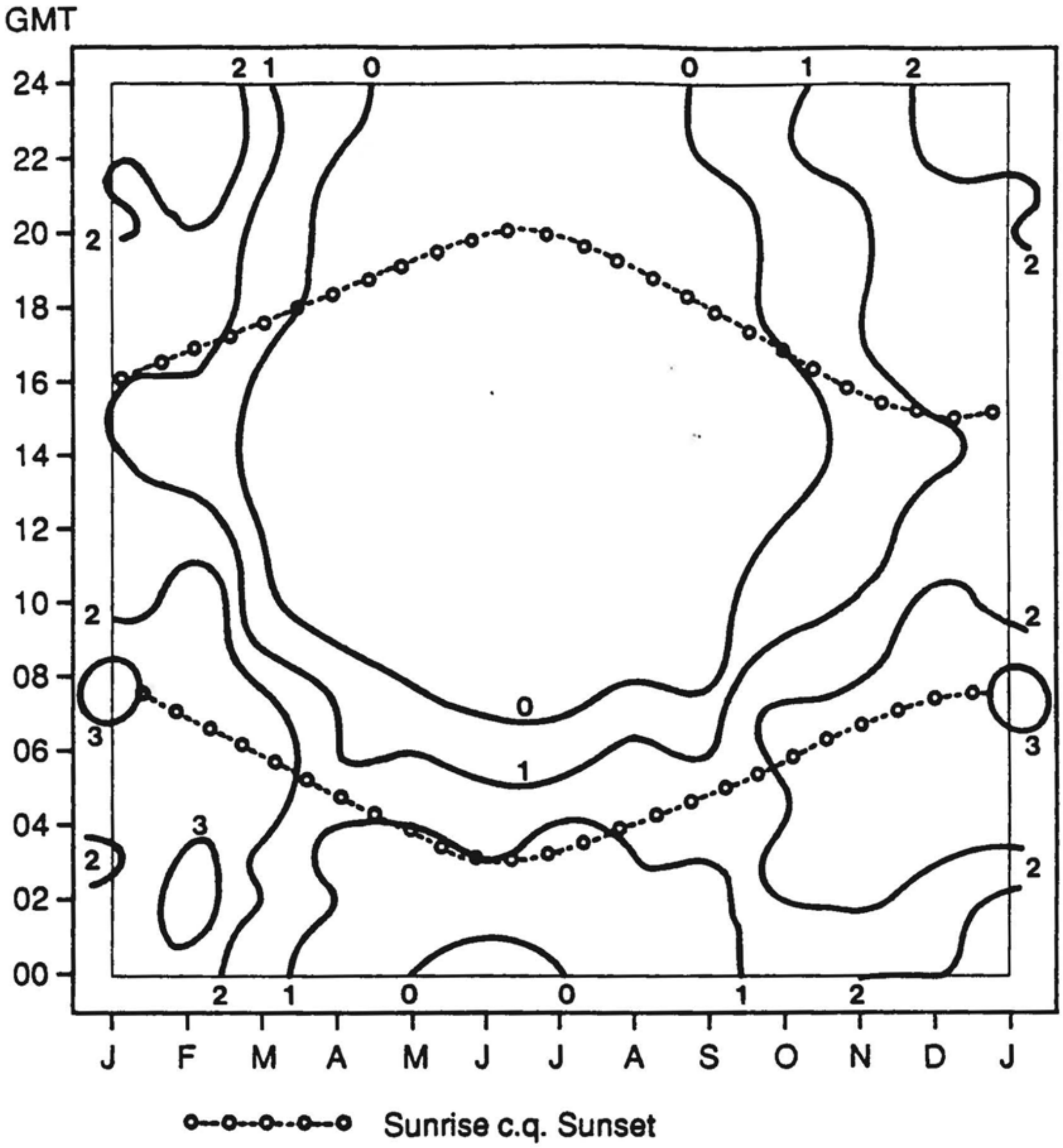

Figure 4. Average of days per month with visibility < 0,4 km at the given time (Soesterberg 1946-1960).

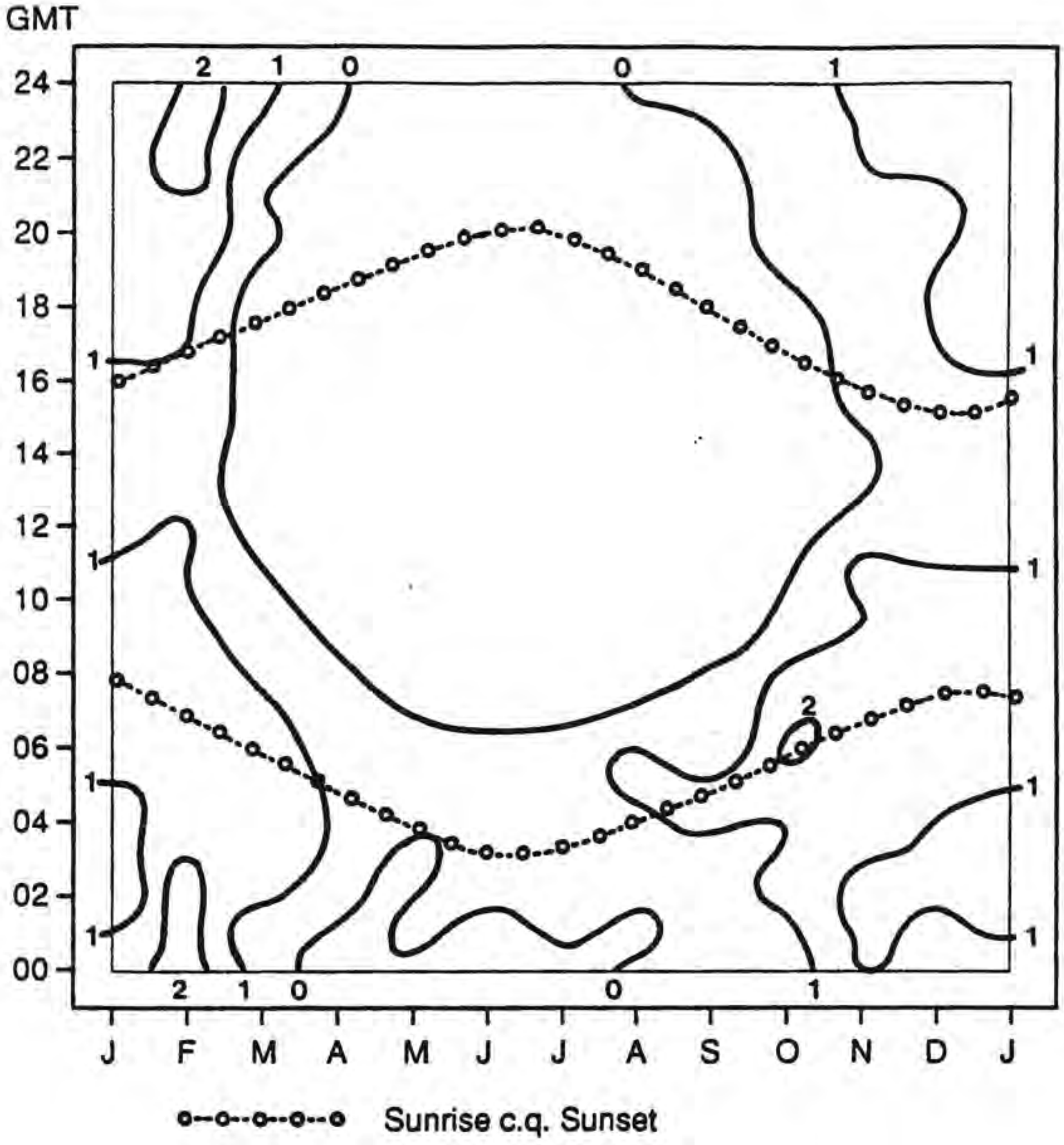

Figure 5. Average of days per month with visibility < 0,2 km at the given time (Soesterberg 1946-1960).

TABLES 1-6

Table 1. The relationship between the visibility and the visual range for different values of the atmospheric transmission (Based on data from Douglas & Booker, 1977).

Table 2. Fog density scale and visibility distances (all distances in m) (After: Behrens & Kokoschka, 1976, where the data regarding the situations are given in datail).

Table 3. The relationship between temperature (degrees Celsius) and the absolute humidity for relative humidity of 100% (d, in kg water per kg air) (Adapted from Hütte, 1919).

Table 4. Foresight values (time and distance) for different manoeuvres.

Table 5. Required meteorological visibility for adequate preview for different manoeuvres.

Table 6. Frequencies of fog accidents.

Transmittance at 250 m	Black object visibility (m)	25 cd white light visual range (m)
0.02	150	430
0.03	200	490
0.05	240	550
0.10	320	710
0.20	430	950
0.30	600	1300

Table 1. The relationship between the visibility and the visual range for different values of the atmospheric transmission (Based on data from Douglas & Booker, 1977)

Fog density scale	Standard visual range	Maximum visibility distance		
		vehicle outline		tail light
		day	night	night
thin fog	1000 - 500	200 - 140	170 - 120	400 - 300
moderate fog	500 - 200	140 - 65	120 - 70	300 - 200
thick fog	200 - 100	65 - 30	70 - 40	200 - 125
very thick fog	100 - 50	30 - 15	40 - 25	125 - 75
fog wall	<50	<15	<15	<75

Table 2. Fog density scale and visibility distances (all distances in m) (After: Behrens & Kokoschka, 1976, where the data regarding the situations are given in detail).

t	d
-20	0.001
-15	0.001
-10	0.001
-5	0.002
0	0.003
5	0.004
10	0.006
15	0.008
20	0.011
25	0.014
30	0.018

Table 3. The relation between temperature (degrees Celsius) and the absolute humidity for relative humidity of 100% (d, in kg water per kg air) (Adapted from Hütte, 1919).

Manoeuvre	Time (sec)	50 km/h	80 km/h	120 km/h
Corrections to the position or speed	3	42 m	67 m	100 m
Lane changing	7	98 m	155 m	233 m
	10	139 m	222 m	333 m
Stopping, overtaking etc.	20	278 m	444 m	666 m
	40	556 m	888 m	1332 m
Strategic manoeuvres		- - up to several km - - -		

Table 4. Foresight values (time and distance) for different manoeuvres

Manoeuvre	Time (sec)	50 km/h	80 km/h	120 km/h
Corrections to the position or speed	3	120 m	200 m	300 m
Lane changing	7	300 m	450 m	700 m
	10	420 m	670 m	1000 m
Stopping, overtaking etc.	20	750 m	1350 m	2000 m
	40	1700 m	2700 m	4000 m
Strategic manoeuvres		- - - up to several km - - -		

Table 5. Required meteorological visibility for adequate preview for different manoeuvres

Country	Province, State	Year	% fog accidents	Remarks	Source
Canada	Br.Columbia	1972	2	all accidents	OECD, 1976
	Ontario	1972	2	all accidents	OECD, 1976
	New Foundland	1972	5.5	all accidents	OECD, 1976
	Manitoba	1972	0.7	all accidents	OECD, 1976
USA		1972	2	total	OECD, 1976
		1972	3	damage only	OECD, 1976
Finland		1972	14.2	injury	OECD, 1976
		1972	13.7	damage only	OECD, 1976
Italy		1972	0.99	total	OECD, 1976
UK		1970	1.49	casualty	OECD, 1976
		1971	1.68	casualty	OECD, 1976
		1972	1.55	casualty	OECD, 1976
		1973	1.48	casualty	OECD, 1976
		1974	0.79	casualty	OECD, 1976
Spain		1972	0.78		OECD, 1976
Ireland		1973	1.1		OECD, 1976
Netherlands		1983	0.8	injury	Oppe, 1988
		1984	0.8	injury	Oppe, 1988
		1985	1.5	injury	Oppe, 1988

Table 6. Frequencies of fog accidents.