GLARE IN ROAD LIGHTING

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SUMMARY

Glare is an important criterion of quality in road lighting; however its importance in contributing to the overall quality is often over-emphasized. A re-evaluation is required as a result of important changes in road lighting practice. New lamp and lantern design results in more efficient installations where glare is more critical, particularly in combination with changes in vehicle windscreen design. A shift in interest from vehicular towards pedestrian traffic leads to lower light levels in main streets and to other requirements in residential areas. The paper suggests than in future road lighting recommendations glare requirements should be incorporated into general visibility requirements, to focus on disability aspects and to avoid very stringent glare restrictions.

1. INTRODUCTION

Glare has been always considered as an important criterion for the quality of road lighting installations. Together with the criteria for luminance level and uniformity, it has been part of the traditional design methods and appraisal systems of installations; these three follow directly from the principles of the luminance techniques prevailing in road lighting design. However, full agreement on the assessment of the glare has never been reached. Codes and standards in different countries are very different, and it is not clear at all in which way the future revisions of CIE documents should be directed. More particularly, recent changes in technology of lighting equipment and in socio-economic consideration of road lighting, query the relevancy of the present methods of assessment of glare. This report is drafted with the pertinent aim to stimulate the discussion on the different aspects of glare in road lighting, with the goal to find more secure bases for future CIE-Recommendations. The report follows form the working programme of the Subcommittee I (Performance) of CIE TC4.6 (Road Lighting). The opinions expressed here are, however, those of the author and not necessarily of CIE.

2. DISCOMFORT AND DISABILITY GLARE

The term glare usually is understood to mean the assembly of all disturbing aspects resulting from light entering the eye from directions other than the direction of observation. It is customary to make a distinction between disability glare and discomfort glare.

Disability glare can be thought of as the result of the fact that light reaching the eye from directions other than the direction of observation will be scattered within the ocular media. This scatter of light leads to the formation of a veil of straylight that covers the retina, and thus also that part of the retina (usually the fovea) that is involved in critical observation.

This luminouw veil leads to a reduction in the luminous contrasts on the retina, and therefore in a reduction in the possibility of observation. Hence the term disability glare. Disability glare is a result of a physiological phenomenon, and in severe cases it can be blinding. From this the term in French, German, Dutch etc.: physiological blinding.

However, it has been found that in certain conditions a noticeable disturbance can present itself even when one cannot find any reduction of vision. Clearly, it is a psychological phenomenon, and it causes discomfort, and furthermore it has a number of aspects in sommon with disability glare - hence the names of this phenomenon: discomfort glare, and psychological blinding respectively.

Contrary to disability glare, it is not possible to find a clear physiological cause for discomfort glare. Neither the pupillary reflex, nor the similarity to pain offers a due. Many researchers, particularly experimental psychologists, even consider discomfort glare just as an experimental artefact. A more modern approach leads to other suggestions; these are, however, not adapted yet to glare in road lighting (Schreuder, 1981).

For a number of reasons, the two kinds of glare have been applied separately to road lighting. The reasons are that in many cases the discomfort glare can be quite disturbing even if disability glare is absent; it must be pointed out here that the opposite may also be true. Furthermore, the two kinds of glare depend in different ways on the parameters of the lighting installation, the discomfort effects are dependent on the source size and finally - probably the most important factor in the past - the degree of discomfort glare seems to depend considerably on the colour of the light, whereas the disability glare is independent of the spectral composition of the light.

In the past, restriction of glare has been regarded as a very important factor in road lighting. However the importance of glare restriction relative to other criteria of quality (e.g. luminance and uniformity) has rarely been investigated and reported.

Cornwell, Schreuder and recently Fisher studied this question; of the three only Cornwell (1973) published, although Fisher informed CIE TC4.6 of his findings in 1981. However an important point emerges, the relative importance of glare is perhaps low. Cornwell found for appraisals made at 38 traffic route installations by the 36 British experts when the roads were wet and by the 18 British non-experts when the roads were dry, the following relationships were derived:

Dry road: $V = 0.55\ L + 0.14\ U + 0.04\ G + 0.45\ VG - 1.29$

Wet road: $V = 0.36\ L + 0.40\ U + 0.10\ G + 0.23\ VG - 0.59$

where

V is mean visibility appraisal

L is mean luminance level appraisal

U is mean luminance uniformity appraisal

G is mean glare limitation appraisal

VG is mean visual guidance appraisal

From the appraisals made by the 11 Continental experts at 38 traffic route installations when the roads were wet, the following relationship was obtained:

Wet road: $V = 0.49\ L + 0.34\ U + 0.04\ G + 0.25\ VG - 0.97$

The coefficients of determination (r^2) for the equations, were 0.97, 0.97 and 0.94 respectively.

Schreuder found that the general impression (GI) was:

$GI = 0.6\ L + 0.2\ U + 0.2\ G.$

Fisher reported that based on appraisals by 18 experts on 15 traffic route installations in the dry the overall installation performance (O) was given by:

$O = 0.4\ L + 0.5\ U + 0.2\ G - 0.5$.

The coefficent of determination (r^2) was 0.93 with $p > 0.001$.

The appraisals covered large ranges within the 9 point scales used for appraisal. These results suggest that glare is not so important as a criterion of quality as was first thought.

3. THE ASSESSMENT OF DISABILITY AND DISCOMFORT GLARE

The physiological aspects of glare can be described and assessed numerically as follows: the light coming from the surroundings - called the glare source - causes stray light in the eye. Now, one can imagine a veil outside the eye that reduces vision just as much; this veil is called the equivalent veil, and its luminance the equivalent veiling luminance L_{seq}. Incidentally, other veiling effects L_v like scatter in fog, or in dirty windscreens can be taken into account by a straightforeward addition of L_v and L_{seq} in spite of the fact that L_v is a physical and not an equivalent veiling luminance.
The value of L_{seq} follows from the so-called Stiles-Holladay relationship, which is based on a very large body of experimental work:

$$L_{seq} = k \frac{E}{\theta^n}$$

where: E is the illuminance (in lux) on a plane in the eye perpendicular to the line of sight, and θ (in degrees) is the azimuth-angle between glare source and the line of sight; k and n are factors that depend on the situation and on the characteristics of the observer. One has generally accepted $k = 10$ and $n = 2$. The relation is additive, as one should expect as it deals with veiling luminances. For small values of θ (under about 2 degrees) the relation must be amended. In particular the exponent n has a quite different value. Most details and some of the physiological background are give in Vos, (1963) and Schreuder, (1981), See also Vos et al (1976) Christie & Fisher (1966) Adrian (1963).

Very recently, Vos (1982, 1983) proposed a new glare formula, nearly as simple as the Stiles-Holladay relationship. This formula based on older and more recent research, is:

$$L_{seq} = 10\ E \left(\frac{1}{\theta^2} + \frac{1}{\theta^3} \right)$$

The negative consequences of glare result from the ensuing reduction of visual contrast. Consider an object with luminance L_o, seen against a background with luminance L_b. The contrast C is usually defined as:

$$C = \frac{L_o - L_b}{L_b}$$

In the case of glare, all luminances - at least in that particular direction - are increased by the veiling luminance. Thus L_o becomes $L_o + L_{seq}$ and L_b becomes $L_b + L_{seq}$. The 'new" contrast C^1 becomes:

$$C^1 = \frac{(L_o + L_{seq}) - (L_b + L_{seq})}{L_b + L_{seq}} = \frac{L_o - L_b}{L_b + L_{seq}}$$

And thus $C^1 < C$.

Now, a lower contrast usually means lower visibility; even if the rise in the adaptation level (viz. also $L_b + L_{seq}$!) is taken into account it is quite possible that C is above, and C^1 below the threshold of visibility (i.e. the minimum contrast that can be perceived at given L_b). It is customary to quantify the degree of disability glare by the increase in the threshold of visibility which is its result. This "Threshold Increment" (TI) is not a constant but depends upon the overall state of adaptation. Details are given by the CIE (1976, 1977). In the practice of road lighting, both TI and L_{seq} are used as quantifiers of glare.

The discomfort effects of glare are less tangible. Therefore, it is customary to assess the discomfort directly, by means of subjective appraisals. The basic idea is that observers give their opinion of the amount of discomfort they experience while observing a certain lighting installation, either full-scale or in a laboratory set-up. This approach has a number of advantages and disadvantages. The advantages are that one measures directly the quantity (or the quality?) one is interested in. The disadvantages are that experiences in principle are not quantifiable; they can be expressed only in nominal or ordinal scales. For numerical assessment, however, interval or metric scales are required, so that systematic inaccuracies are introduced. To this the experimental spread must be added, which usually is quite large in this kind of experiment. In point of fact, most of the objections to the application of discomfort glare restriction as a criterion of quality are based on these shortcomings, see e.g. Mainwaring & Stainsby (1968).

The methods for quantification of the discomfort aspects of glare are based on fundamental research of Hopkinson, De Boer, Schreuder and Adrian. A survey is given in De Boer (ed.) (1967). The result is the so-called G-system, adopted by the CIE and accepted by most of the member countries. G means the Glare Mark, a numeral between 1 and 9 which denotes the degree of the restriction of discomfort glare. In fact, the G-values are only jointed to certain steps in an ordinal scale. Thus, as an example, G = 3 corresponds with "disturbing glare"; G = 5 with "just acceptable glare" and G = 7 with "a satisfactory glare restriction". G can be calculated if the data of the lighting installation are known (such as luminance level, geometry, light distribution, colour of the light). The formula looks quite forbidding, but it can be calculated easily with a pocket calculator or assessed graphically.

The formula grew gradually. The different steps are described by De Boer & Schreuder (1966, 1967), Schreuder (1967, 1972) and Adrian & Schreuder (1970, 1971). The end result of all this is:

$$G = 13.84 - 3.31 \log I80 + 1.3 (\log I80/I88)^{\frac{1}{2}} - 0.08 \log (I80/I88)$$
$$+ 1{,}29 \log F + 0.97 \log L + 4.41 \log h' - 1.46 \log p + C$$

where

I80 and I88 the luminous intensity of the luminaires under angles of 80° and 88° respectively with the downward vertical (cd)

F is the flashed area of the luminaires (m^2)

L is het average road surface luminance (cd/m^2)

h' is het height difference between the eye and the luminaires (m)

p is the number of visible luminaires per km

C is a colour factor

It should be pointed out that the G-formula is essentially a construction based on laboratory experiments. A certain amount of full-scale validation in real traffic situations has been made, with results that are not quite conclusive. The overall trend presented by the G-formula is rediscovered in practice; however the formula is not very well suited for the assessment of the glare in individual lighting installations, because - as a result of the large spread - sometimes one may meet large discrepancies between the predicted and the actual values.

It is obvious that L_{seq} and G do not depend in the same way on the parameters of the lighting installation. This is the reason that both discomfort glare and disability glare are considered in most standards (e.g. CIE, 1977).

More particularly, the dependency upon the overall lighting level (comprising not only the road surface luminance and the level of adaptation but also the intensity of the luminaires) is not the same. This leads to the following fact - both peculiar and important: when the luminance level is low, the lighting installations suffer primarily from disability glare; when, however, the lighting level is high, it is mostly the discomfort glare that influences the quality. This fact caused some national codes to concentrate primarily and even fully on discomfort glare restriction (e.g. NSVV, 1974/1975) as at that time the interest was focussed particularly on high-quality road lighting installations; see also Van Bommel & De Boer, 1980).

4. A RE-EVALUATION OF GLARE

In recent years a number of important changes both in society in general and in lighting and transportation technology in particulare make a re-evaluation of glare necessary. The changes include a different outlook in using (or not using) natural resources and energy; a spectacular rise in costs of energy in combination with a lower economic standard; a trend to pay more attention in traffic to the more vulnerable, amongst them pedestrians, and changes in design and equipment of vehicles. This mus be viewed together with dramatic changes in lamp design, both as regards new types and improvements in existing types.

4.1. Lower lighting levels

The first reaction to the energy shocks was to reduce light levels in road lighting. Traditionally the recommended light levels (mostly luminance levels) were rather high, and based to a large extent on considerations of comfort. It is not really known in a general way what the actual lighting levels in operation were, as systematic design (either based on illuminance or luminance) was employed only for a relatively small number of important lighting installations. In less affluent times this vahue state-of-affairs cannot be toleratied any longer, so there is a strong pressure to develop simple, more accurate lighting design methods, and also to allott more precisely defined lighting levels to roads of different types. This work is under progress; the effect in combination with a more frugal outlook in general will be twofold:
- less emphasis on installations with high light levels
- less emphasis on considerations of comfort.

It is too early to give a quantitative evaluation of this in photometric terms, but it is quite clear that the main reasons - as quoted earlier - to distinguish between the disability and the discomfort aspects of glare will disappear.

4.2. More efficient installations

There are other ways to save money and energy, apart form being frugal:

the efficiency of the system may be improved. In this, the development of new, high-efficiency light sources is important. Incandescent lamps have - for traffic route lighting - been outdated already a long time; so are high-pressure sodium lamps with nearly double efficacy or with low-pressure sodium lamps with more than triple efficacy. The savings in energy are obvious, and in spite of higher lamp costs the total costs may be reduced as well. Longer lamp-life, and more realistic replacement schemes may reduce further the running costs.

Another way to improve the efficiency of the installation is to use larger lamps (larger units) on higher masts and with longer spacings. In many cases more realistic (lower) levels of the uniformity of the luminance pattern may be accepted as well. Furthermore, the dimensionally small high-pressure sodium lamps can be installed in smaller luminaires, optically better designed and thus more efficient. Also the optical efficiency of luminaires for the sometimes very large low-pressure sodium lamps may be improved. Finally, the installation efficiency may be raised considerably by applying well-designed road surfaces, e.g. open-textured surfaces with light (artificial) additives.

These newer development have considerable influence on the assessment of glare: particularly the small light sources, and to a certain extent the very large light sources, the high masts and the long spacings may fall easily outside the range of variability of the G-formula. Incidently, the use of mall sources did already require a correction term to be included in the present G-formula: $(\log I80/I88)^2$.

In view of the accuracy one may expect of the assessments of G one may wonder whether it is really justified to try and add further correction terms!

4.3. Other vehicle design

The design of motor vehicles is determined to a large extent by intangible factors like fashion and trends. The streamlined trend which suggests speed and is supposed to reduce the fuel consumption leads to lower seats (lower eye-height) and higher, more slanted windscreens. The windscreen upper cut-off angle becomes higher. Around 1960 the angle was some 8°

with the horizontal (Schreuder, 1964). More recent systematic measurements are not available but unpublished current estimations give up to 25°-30°. This has a profound influence on glare, glare experience and glare reduction. In the earlier work on glare, notably on discomfort glare, the run-back at the light distribution was considered only for values over 80° with the vertical. The first CIE recommendations quantified glare only in I80 and I90 (De Boer (ed.), 1967), the G-system applies I80 and I88 in stead. Only some German research recognized the need to consider lower angles but no quantitative system emerged (Range, 1980; Pfeffer, 1974). A windscreen cut-off angle of 30° makes, however, all "semi-cut-off" liminaires highly glaring, as the main beam usually is at some 20° with the horizontal and may enter directly into the driver's eye.

The new trend in vehicle design requires therefore a drastic change in the light distribution of luminaires. It should be added that modern road surfaces with open texture (favouring drainage and improving visibility in wet condition), are much less glossy than the traditional closed textured surfaces. Therefore, semi-cut-off light distributions are less efficient in yielding a high, uniform road surface luminance with modest luminumance output of the lamps.

Another aspect should be mentioned; when the windscreen cut-off angle is much higher, the glare experience is increasingly dominated by the flash-like effects when the luminaires are approached. This peripheral disturbance ("Schlag-effect") was included in the earlier research (De Boer & Schreuder, 1966) but it proved difficult to quantify this effect. At that time it did seem to be not important, but now it must be reconsidered.

All considerations of reduction of the glare by road lighting installations are rendered futile by the fact that nearly everywhere now, car drivers are obliged to use low-beam headlights. This follows from "easy" political decisions, in which the CIE point of view (CIE, 1974) and the results of research (Fisher, 1974; Schreuder, 1971, 1976) are completely and crudely disregarded. The situation, bad as it is in theory, is worsened considerably in practice by further aggravating factors. The first is the advance of halogen headlamps that multiply glare in important areas (particularly for pedestrians) in spite of the fact that the regulations cleverly give the impression to prevent this. To this the new developments of larger lights and plastic lenses may be added, that all increase glare even further. Secondly, the state of maintenance and aiming of vehicle headlighting is very poor, apart from the very large influence of loading of the vehicle. And thirdly the glare from vehicle headlights is most severe during rain when the road surface is wet and therefore more shiny and more slippery than when dry. It is well-known that particularly the combination of darkness and rain endangers road traffic (Schreuder, 1978). All this adds up to a very considerable amount of glare, from which all traffic participants suffer - pedestrians not in the least!

In conclusion one may say that changes in vehicle design and equipment lead to a situation where glare from road lighting is less critical and where the glare cannot be easily described in its discomfort effects.

4.4. More concern for pedestrians

In recent years, more attention is being paid to the weaker, the more vulnerable. This happy development, which is clear throughout the society, expresses itself in the traffic environment as putting emphasis on the well-being of dwellers of residential areas, and on the safety of the weaker traffic participants, such as pedestrians and cyclists, and more in particular of the elderly and the children. It may be noted, however, that the obligation to use low-beam headlights is not favourable for pedestrains at all! (Schreuder, 1976).

In street lighting, this leads to emphasis on the lighting of residential yards (Schreuder, 1979) and of the "woonerf" (Schreuder, 1979a). Here, discomfort glare is not a problem, on the contrary. Luminaires that are quite bright may be favoured to acquire a lively visual scene.

Disability glare, however, should not be excessive (Caminada & Van Bommel, 1980) as the visibility requirements in residential areas are considerable. These requirements follow primarily from public safety rather than from traffic safety.

5. CONCLUSIONS, SUGGESTIONS

Modern developments have resulted in a number of changes in the technology of lighting and of the appreciation of lighting in general. As regards to glare they lead to the following: firstly the emphasis on aspects of comfort is gradually decreasing in favour of "plain" visibility, and the applicability of the G-system to assess discomfort glare is being reduced. Secondly, it is found that the emphasis on disability glare relatively speaking is increasing, although the importance of glare and glare reduction seems to be much less than assumed in the past, and will be even less in the future.

Based on the foregoing, it is suggested to delete discomfort glare restriction as a separate quality criterion from CIE road lighting recommendation. National Committees can, quite naturally, keep it on if they prefer to do so.

Furthermore it is suggested to be less stringent than in the past when numerical values are selected for the recommendation on the restriction of (disability) glare.

And finally it is suggested that the values to be selected for these recommendations will be derived from research into the general aspects of visibility in road lighting, which has made progress in recent times (Fisher, 1968; Frederiksen & Rotne, 1978; CIE, 1981). In this way the glare restiction recommendation can be based primarily on requirements regarding visibility.

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