DESIGN of the MEETING BEAM of the AUTOMOBILE HEADLIGHT

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SYNOPSIS

The most-important factor in the design of the typical meeting beam, so far as the range of direct seeing is concerned, is the sharpness and form of the cutoff near the horizontal. But the effect which the cutoff will have on the likelihood of being dazzled (i.e., of being rendered incapable of seeing more than a short distance) when meeting other vehicles at night depends enormously on the accuracy with which meeting beams are aimed. The effect can be calculated when the standard of aiming is known; the basis of the calculation and some results are given in this paper. Curves are provided from which may be found the sharpness of cutoff required to give any desired level of freedom from dazzle, or glare. It is shown that if the standard of aiming is too low it will be impossible to design a beam to fulfill the required conditions. The necessary improvement in aiming can, however, be determined from the curves. The effect of deterioration in increasing the liability to dazzle is also considered. The pitching motion of the vehicle, and its effect on seeing distance and on intermittent glare, have had to be omitted from this analysis; the effect will be more important the sharper the cutoff employed.

HEADLIGHT beams must be judged by their performance in the conditions in which they have to operate: meeting beams, for instance, by how well the driver can see when meeting another vehicle. Tests of performance of this sort have frequently been carried out for meeting beams, but in almost all of them the lamps used have been new and have been correctly aimed. The conditions of the test have therefore been different from conditions on the road, and the tests may be misleading because they entirely omit the effects of misaim and deterioration, which in practice (in England at least) are of considerable importance. These effects would remain even if, as in the United States, all vehicles were fitted with lamps of essentially the same design. There would still be differences in the effective intensities of the beams on different vehicles, and in consequence, a driver meeting another vehicle would see well enough on some occasions and badly on others. He would also experience very different amounts of discomfort. The performance with which we are concerned is really the aggregate of the performances in the individual encounters, and in judging the suitability of a design all possible encounters should be borne in mind, particularly those in which seeing is poor. It is clear that performance, defined in this way, does not depend solely on the design of the beam itself; indeed, it is meaningless to speak of performance except in relation to a definite standard of aiming and level of deterioration. It follows, therefore, that the choice of beam must depend on the standard of aiming attainable and the degree of deterioration allowed. For example, a beam with a very sharp cutoff might be quite satisfactory if aiming was generally good but give a large proportion of short seeing distances and be intolerably dazzling if aiming was poor. Or again, a beam of low intensity might be satisfactory if a strict standard of maintenance was insisted upon but be unsatisfactory if severe deterioration was tolerated.

The paper shows how this overall performance of a beam may be calculated when the minimum seeing distance during an encounter is taken as a measure of the performance during that encounter. The relations between performance, sharpness of cutoff, and standard of aim are investigated; the effect of deterioration is also considered. Numerical results are obtained for a beam of simple design which approximates to typical modern designs in the region of the beam mainly responsible for glare and for distant seeing on the nearside of the road. These results go some of the way towards putting the design of meeting beams on a rational foundation. For example, if a certain level of performance is specified, then the necessary sharpness of cutoff and standard of aiming can be determined.

Factors which have had to be ignored in the present paper are the pitching motion of the vehicle, due mainly to the irregularity of the road surface, and the intermittent dazzle to which it can give rise. The effect of this will be more marked on beams having a sharp cutoff.

SEEING UNDER CONDITIONS OF GLARE

The glare of approaching headlights reduces a driver's ability to see. But, by revealing as dark silhouettes any pedestrians or vehicles which may be on the road between him and the approaching vehicle, these lights may, at times, actually assist him to see. A driver may see a pedestrian in silhouette long before he is able to see him directly. This silhouette seeing is sometimes of great assistance when direct seeing is poor. But it has been argued that less importance should be attached to it than to direct seeing, because it is not always effective and cannot, in any case, reveal a pedestrian who does not step on to the road until the approaching vehicle has passed him. In this paper the possibility of silhouette seeing is ignored, and discussion is confined to the performance of lamps in direct seeing.

The performance of a meeting beam in a single encounter is found by fitting two cars with identical beams and running them against one another on a straight track on which certain objects of a standard form have been placed. By means of distance-recording mechanisms in the vehicles, the drivers are able to record the distances at which they first see the object; after a number of runs with objects in different positions, a curve can be drawn which shows the seeing distance as a function of the separation between the vehicles, as in Figure 1, which is based on results given by Roper (1). The seeing distance diminishes as the vehicles approach each other, reaches a minimum before they meet, and then rises again more rapidly as the vehicles pass and the eyes recover from the effect of the glare. It is common to attach considerable importance to the minimum distance and to attempt to increase it by improvements in design so that it shall exceed the stopping distance by a comfortable margin. We shall therefore adopt it as a measure of the performance of the beam during the encounter and enquire how this minimum seeing distance is affected by lamp design and by misaim and deterioration.

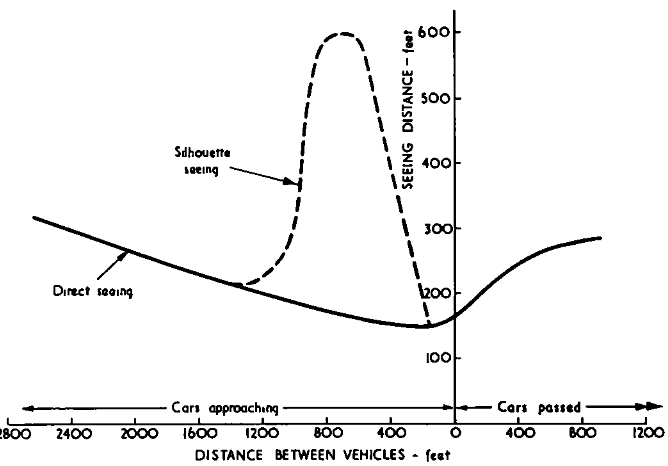

Figure 1. Seeing distance as function of distance between vehicles (after Roper).

BASIC DATA AND ASSUMPTIONS

The minimum seeing distance is obtained for an object which is almost level with the approaching vehicle at the moment of perception. Since, near a minimum, values do not change very rapidly, the seeing distance for an object just beyond the glare source is approximately equal to the minimum. Roper (2) has investigated seeing distance for this position. In his tests the glare vehicle was stationary, but such tests appear to give much the same result, as far as direct seeing is concerned, as those in which both vehicles are moving. Beams of uniform intensity were used so that the intensity directed at the object or at the driver's eyes did not change during the test run. This work has been extended at the Road Research Laboratory to those lower values of illumination and glare which are of particular importance in the design of meeting beams (3). The experimental results for a single observer have been plotted as smoothed curves in Figure 2. The question arises whether the same seeing distances would have been obtained with more-normal beams in which the intensities of illumination and glare were not uniform and would, therefore, have changed during the approach of the vehicles. This has been investigated by comparing, for a number of lamps, the seeing distances actually obtained in tests and those obtained by calculation from the beam distributions (4). It was found that the agreement was reasonably good, particularly as regards the relative performances of the different lamps. It will therefore be assumed that the results in Figure 2 apply to any distribution and that minimum seeing distances can be calculated from these curves and the beam distributions. It should be remembered, however, that these results are not completely general. They apply to conditions similar to those of the tests in which they were obtained. Briefly, the seeing distance is that for an object about 1.5 ft. high, with a reflection factor of 7 percent, seen on the nearside of a 20-ft. road. This standard object is a good deal lighter than the darkest clothing, which has a reflection factor of 2 percent or less, but is of smaller size than the average pedestrian. The broken curves in Figure 2 show that, provided the ratio of illumination intensity to glare intensity is kept fixed, an increase in absolute magnitude produces only a small change in seeing distance. In Figure 3 the same results have been plotted in a different way to show the ratio of illumination intensity to glare intensity required to achieve a minimum seeing distance of any desired value. These curves are more useful for our purpose than Figure 2.

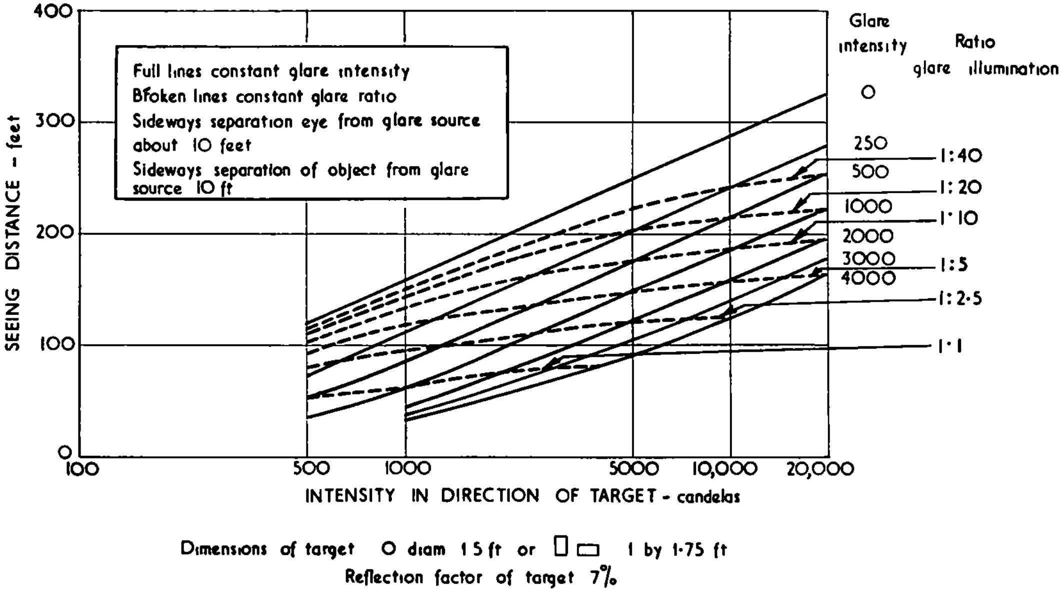

Figure 2. Seeing distance as function of glare and illumination intensities.

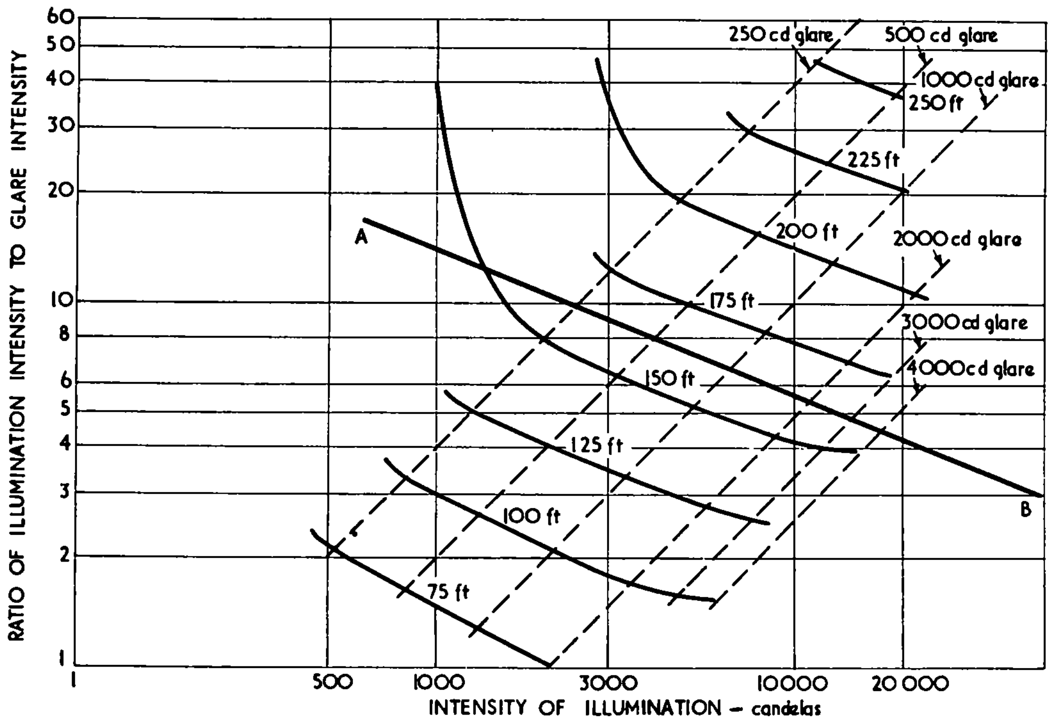

Figure 3. Seeing distance as function of illumination intensity and ratio of illumination to glare.

TYPICAL FEATURES OF BEAM DISTRIBUTION

Figures 4, 5, and 6 show the beam distributions from one lamp (5) of a British, an American, and a European meeting beam. Figure 4 also shows the

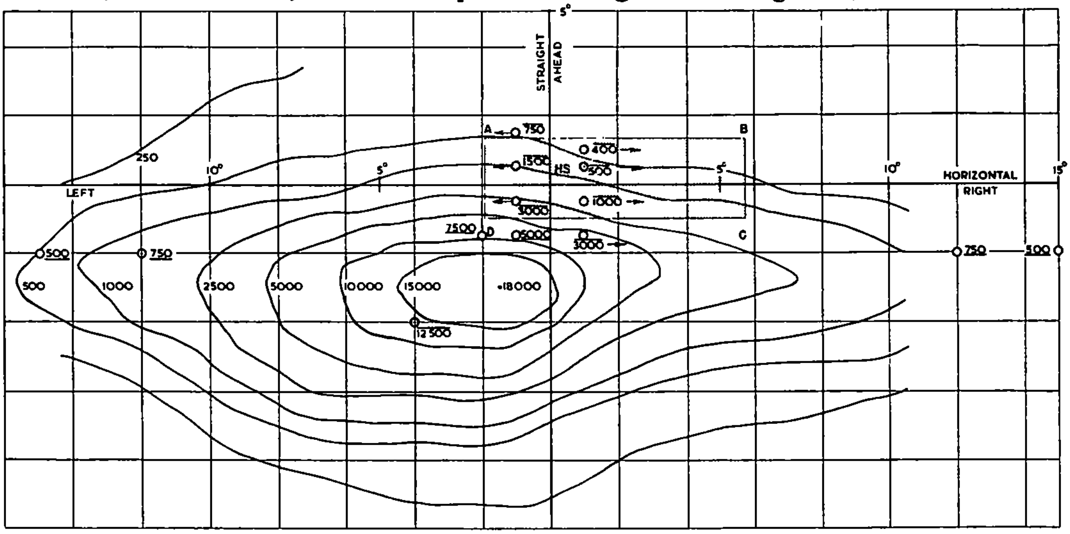

Figure 4. Beam distribution from one lamp of Lucas FF 700 system. Also SAE recommended practice for sealed-beam lamp. (Reversed from left to right to suit British rule of road.)

American intensity limits according to the specification of the Society of Automotive Engineers, reversed from left to right to fit the British rule of the road. The origin HS represents the horizontal direction straight ahead through the lamp; other directions are given in terms of their angular displacement to offside and nearside or up and down. Objects on a straight road 150 ft. or more ahead of the vehicle are illuminated by intensities which lie within the region ABCD marked on the diagram; the intensities causing dazzle are also found within this region. In this part

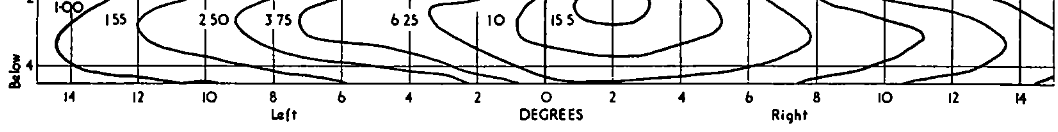

Figure 5. Beam distribution from one lamp of the General Electric Meeting system (see Reference 5).

of the beam the intensity increases in a downward direction. In the British or American lamp it increases towards the nearside also. In the

European lamp, which (unlike British or American lamps) dips vertically downwards without deflecting to the nearside, the beam has a much smaller sideways rate of change. The beam distribution in the region ABCD might be defined by stating the intensity I_o at HS and the rate at which the intensity increases downwards and to the nearside. Unfortunately the rate of change is not constant, so for most existing beams a description of this sort would be somewhat complicated. To simplify the calculations, which

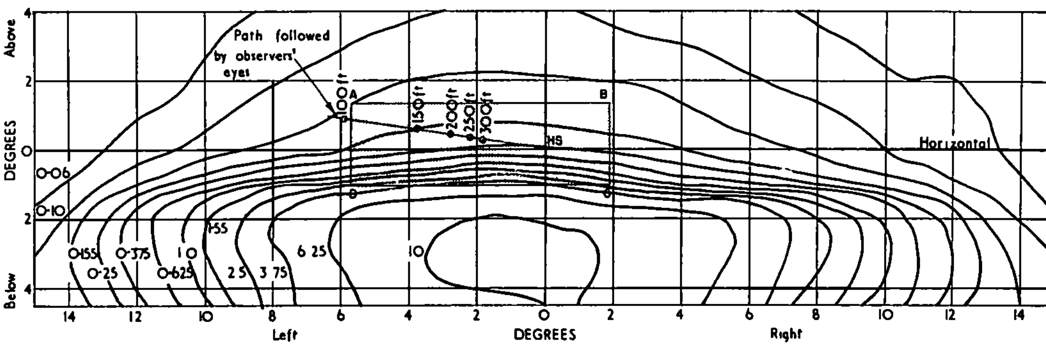

Figure 6. Beam distribution from one lamp of the Cibie meeting system (see Reference 5).

are described later, it will be assumed that the intensity is increased in a constant ratio for each degree downward or to the nearside. With this assumption the isocandela lines of the beam distribution become parallel, straight lines as in Figure 7. These can be fitted fairly closely to many existing patterns in the region which we are considering, although they diverge elsewhere. The factors by which the intensity is increased in a displacement of 1 deg. are denoted by n_1 for sideways and n_2 for downward displacements. The quantities n_1 and n_2 will be called the cutoff factors for side and top cutoff respectively.

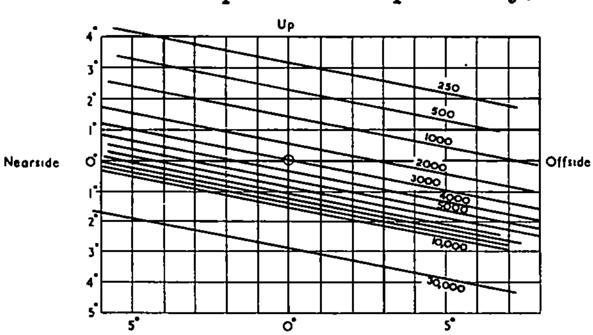

Figure 7. Idealized beam pattern used in calculations (actual example shown here has n_2 = 2.2 n_1 = 1.17 I_o = 3000cd).

Cutoff factors, as already mentioned, are not constant in the important region of typical British, European, or American meeting beams. Table 1 shows typical values of n_2, and it is evident that the European lamp has much higher values of n_2, i.e., much sharper top cutoff than the others. Even in the European lamp the highest values of n_2 are not at the horizontal but a degree or so below. European lamps also differ from the others in having a lower intensity at the horizontal.

TABLE 1

VALUES OF THE TOP CUTOFF FACTOR n_2 AVERAGED OVER RANGES OF 0.5 DEG. IN A VERTICAL PLANE STRAIGHT AHEAD OF THE LAMP

	Below Horizontal		Above Horizontal	
	1.0° to 0.5°	0.5° to 0°	0° to 0.5°	0.5° to 1.0°
British	2.5	2.4	2.2	2.7
American	3.1	4.1	2.3	1.6
European	11.9	6.1	2.2	1.5

AIM OF LAMPS

Errors may be present in both the horizontal and the vertical aim of the beam. It has been found in England that these errors follow fairly closely the normal law of errors and that their magnitude can therefore be defined by means of the standard deviation σ . The standard deviations for horizontal and vertical aim will be denoted by σ_1 and σ_2 respectively. A survey of several-hundred vehicles in Great Britain showed recently (6) that σ_1 and σ_2 were of the order of 2 deg. for the older types of lamp and about 1 deg. for newer vehicles with flush-fitting lamps. Therefore, even on the new vehicles some 25 percent of lamps are aimed more than o.7 deg. too high and another 25 percent 0.7 deg.too low; 5 percent are more than 1.6 deg. too high and another 5 percent 1.6 deg. too low. Vertical misaim is normally more important than horizontal misaim in its effect on driver vision, because top cutoff is sharper than side cutoff. A form of misaim which is distinct from that due to carelessness or neglect is the change of tilt produced by changes of load of the vehicle. This is particularly important for trucks, which may tilt upwards by as much as 3 deg. when being loaded.

BRIEF OUTLINE OF THE CALCULATIONS

Consider a pair of vehicles separated by a distance d on a road like that used in the tests from which Figure 2 and 3 were derived. If the lamps are aimed so that one driver has just reached the point where his seeing distance is a minimum, then the intensity of illumination of the object must be related to the glare intensity in the manner shown in Figure 3 for a seeing distance d. The probability that the intensities would have any of these suitable values can be calculated from the geometry of the layout, the beam pattern, and the probabilities of the necessary amounts of misaim. Thus it is possible to calculate for any beam pattern the probability that the minimum seeing distance for one of the drivers in a chance encounter should have the value d. But it would be a tedious calculation for the ordinary beam pattern, and it may be simplified by adopting the sort of pattern shown in Figure 7. When aiming is poor the intensities with which we are concerned may be derived from almost any part of the beam, but the better the aiming the more they will be restricted. Since the main purpose of the paper is to examine how far conditions may be improved by improvements in the standard of aim, we may, without serious error, assume that the whole of the beam pattern possesses the characteristics found in the restricted regions ABCD in Figures 4, 5 and 6, i.e., that it has the simplified character of Figure 7.

It would be possible, in the calculations, to allow for the fact that the beams encountered suffer from deterioration to varying degrees, but as this would complicate the working, the only cases which have been evaluated are: (1) deteriorated lamps meeting deteriorated lamps, all of which have deteriorated to the same degree, and (2) deteriorated lamps meeting lamps which have not deteriorated.

To carry out the calculations a given design of beam and a given standard of aiming are assumed, (i.e., values of I_0, n_1, n_2, σ_1, and σ_2) and the data in Figure 3. The fact that the curves of Figure 3 turn upwards rapidly at the low intensity end is ignored; the curves are assumed parallel to AB, and in consequence, low intensities of illumination are assumed to be more effective than they really are. It is then possible to calculate quite easily how often a minimum seeing distance falls short of any particular value d, or how often the glare intensity or the ratio of illumination to glare exceeds any chosen value.

In the calculations on which Figures 8 to 12 are based, it is assumed that, except for deteriorated lamps, the intensity straight ahead in the horizontal is 3,000 cd. This is a typical value for the beam from a new British double-dipper system and is higher than American and much higher than European practice. Where side cutoff is not zero, it is assumed that the isocandela lines are inclined at a slope of 1 in 5, as in the British lamp. It is assumed that the lamps are mounted at a height of 2.5 ft. and that at least 1 ft. of the target must be illuminated to the required level for it to become visible.

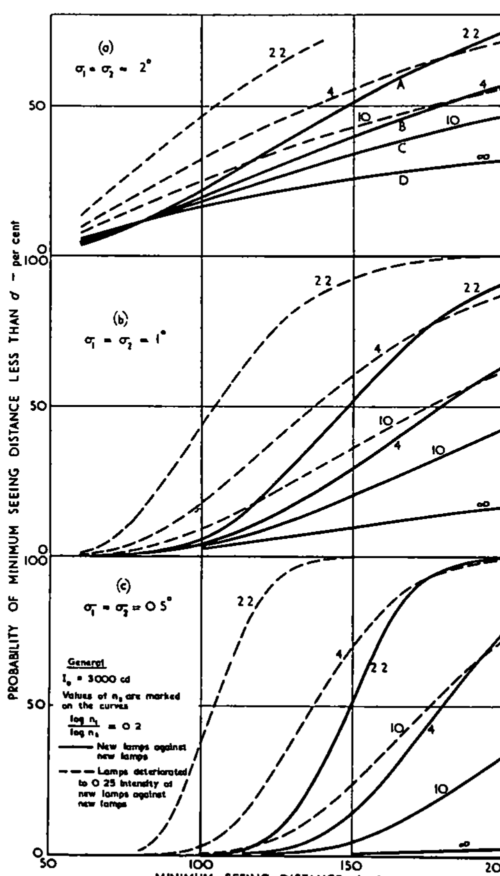

Figure 8. Probability of minimum seeing distance as affected by misaim and deterioration.

,RESULTS OF CALCULATIONS

The results of the calculations are shown in Figures 8 to 12. A word of warning should be given as to the exact meaning of the probabilities shown in these figures. In any encounter there are two drivers and, therefore, two minimum seeing distances, whose values are generally different. The probabilities for minimum seeing distances given in Figures 8, 9, and 10 are calculated on the basis of the number of seeing distances, not on the number of encounters. For example, curve A of Figure 8(a) shows that the probability of distances less than 100 ft. is 22 percent. In 100 encounters

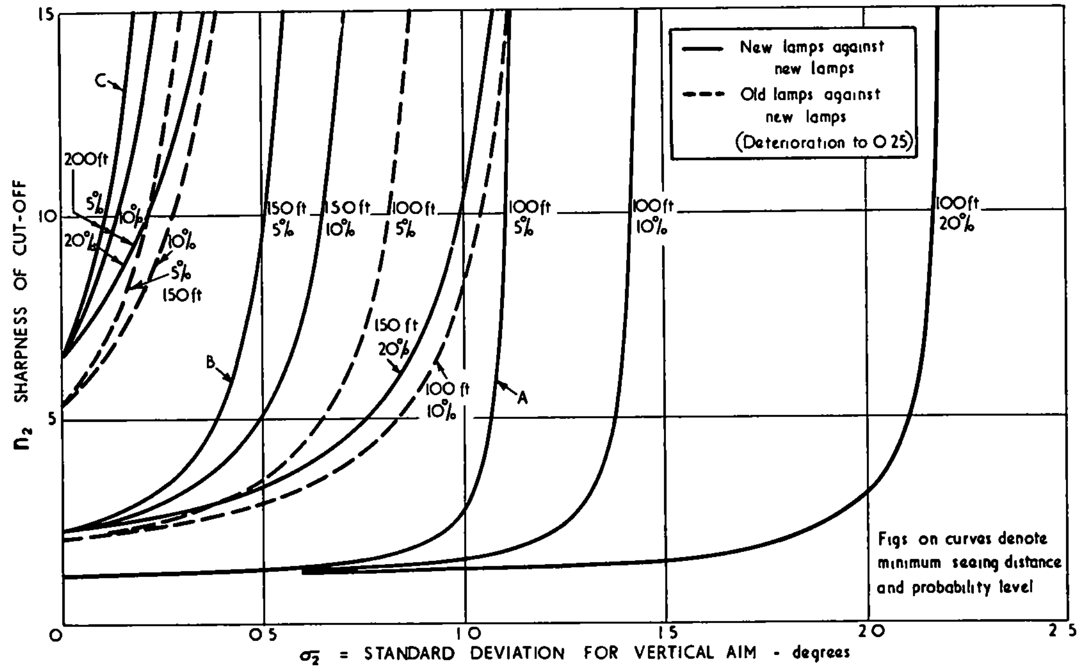

Figure 9. Relation between cutoff and misaim for given probability of given minimum seeing distance.

there are 200 seeing distances and therefore 44 of these may be expected to be less than 100 ft. A large seeing distance for one driver tends to be associated with a small one for his opponent, and these 44 short distances represent just under 44 different encounters; so at least one driver has a minimum seeing distance of less than 100 ft. in about 40 encounters out of 100. Thus, for encounters between similar vehicles, the probability based on the number of encounters is almost double the probability based on the number of seeing distances. When the encounters are between unlike vehicles, as in the broken curves in Figure 8 between vehicles with deteriorated lamps and vehicles with new lamps, the probabilities refer to the seeing distances for one type of vehicle, and the probability is the same whether based on the number of seeing distances or the number of encounters. Similar remarks apply to the probability for glare intensities in Figures 11 and 12.

The Effect of Misaim on Seeing Distance

The full lines in Figure 8 show the probabilities for different values of the cutoff factors and different standards of aiming. Each curve crosses the line denoting 50-percent probability at a distance which is the design distance for that lamp, i.e., if all lamps were of the same design and correctly aimed the minimum seeing distance would be the same for all and would have this value.

In Figure 8(a), Curve A gives results for a lamp approximating closely to the British lamp shown in Figure 4 and for the standard of aim which exists on older cars in Britain today ($\sigma_1 = \sigma_2$ = 2 deg.). Although the

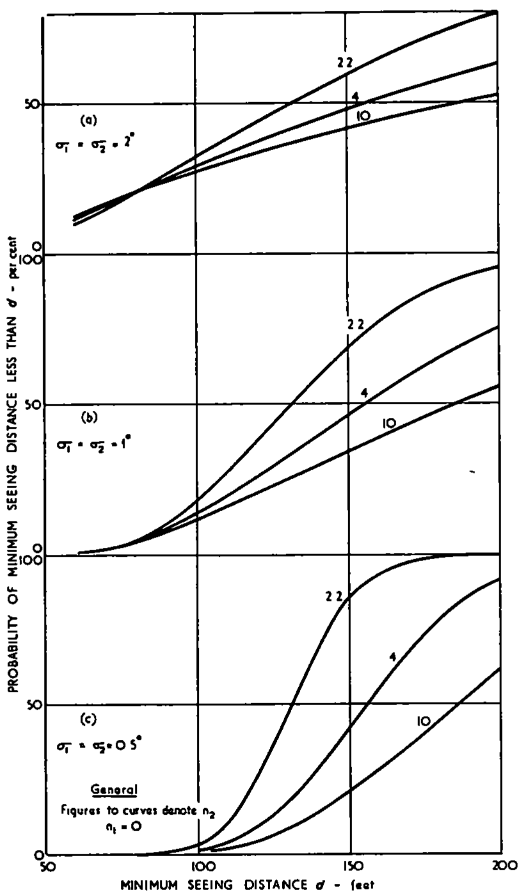

Figure 10. Probability of minimum seeing distance for lamps without side cutoff.

design distance works out at about 150 ft., 22 percent of distances (about 40 percent of encounters) are less than 100 ft.

Curves B, C, and D show the effect of sharpening the cutoff while retaining the same horizontal forward intensity. The design performance is improved, but the probability of getting seeing distances less than 100 ft. is only slightly affected, falling from 22 percent to 18 percent as n_2 is increased from 2.2 (British lamp) to 10 (maximum value for European lamps). The misaim is so large that it swamps the effect of the sharper cutoff at the low-performance end of the curves. At the high-performance end there are, however, far more cases in which the seeing distance is much greater, for example, than 150 or 200 ft.; so there is an improvement, though not where it is presumably most important.

Figures 8 (b) and 8(c) show the results obtained when the misaim is reduced to one half and then to one quarter of that assumed in Figure 8 (a). Design performance is not affected, i.e., the curves still cross the 50-percent probability line at the same values of d, but the probability of distances less than the design value is reduced, and in this example, for instance, the probability of distances less than 100 ft. is greatly reduced. If the standard deviation of aim could be reduced, as in Figure 8(c), to 0.5 deg., seeing distances less than 120 ft. would not occur in more than 5 percent of cases, i.e., in fewer than 10 percent of encounters with the present British lamp. A further improvement would be possible if there were some sharpening of the cutoff.

Another way of setting out the results, one which brings out more clearly the connection between design and standards of aiming, is shown in Figure 9. This shows what values of n_2 and σ_2 are required in order that the probability of distances of 100, 150, or 200 ft. should be kept at some low figure. For example, if seeing distances less than 100 ft. are to form 5 percent or less of the total, then n_2 and σ_2 must be given by points on or to the left of Curve A. If σ_2 is 2 deg., this is clearly impossible. If σ_2 just exceeds 1.1 deg. it becomes possible, but a sharp cutoff (n_2 greater than 8) is required. If σ_2 is less than 1 deg., it is possible to obtain the low probability with values of n_2 as low as that for the British lamp, or even lower.

Curve B for 150 ft. is similar but more demanding, both as regards aim and sharpness of cutoff. Curve C for 200 ft. calls for a still sharper cutoff and a standard of aiming so high that in order to attain it lamps on trucks would certainly have to be adjusted for changes of load, and it might even be necessary to readjust the aim on cars according to the number of passengers in the back seat. The addition of one passenger tilts the average British car about 0.2 deg.

Effect of Deterioration

It has been assumed in calculating the results given by the full lines in Figures 8 and 9 that the only differences between the beams on different vehicles were due to misaim. In practice there would be differences due to deterioration and to the effect of manufacturing tolerances which allow quite considerable variations between beam and beam. Drivers whose lamps have deteriorated will experience short seeing distances more frequently than the drivers we have just been considering, whose lights, though misaimed, are at least giving a normal output. Calculations have been made for lamps whose output in any direction is only one quarter of the normal. It is assumed that these lamps suffer from misaim as before. The probability of minimum seeing distances for drivers using these lamps but meeting new lamps is shown by broken lines in Figures 8 and 9. It is clear that for a seeing distance of 100 ft. the demands are fairly severe and for 150 ft. well-nigh impossible, somewhat similar, in fact, to the requirements for a seeing distance of 200 ft. with new lamps.

A more-elaborate study of the effect of mixing beams with various levels of deterioration is clearly required to give a true picture of the importance of deterioration. The results just quoted show, however, that a general deterioration to one quarter of the initial intensity will very seriously handicap the user when meeting beams from undeteriorated lamps. It is interesting in this connection that the recommended SAE standard is one half of the initial intensity.

Effect of Side Cutoff

Figure 10 gives the probabilities for beams which differ from those of Figure 8 (full lines) only in having no side cutoff. The curves show that the side cutoff adopted in the idealized beam (similar to that of the British lamp in Figure 4) increases the seeing distance by about 20 ft. For sharper side cutoff (isocandela lines sloping down more sharply) the increase would have been larger. The improvement thus produced in the visibility of objects on the nearside of the road may, however, be accompanied by a deterioration for objects more to the offside. If side cutoff is used it should not extend much below the horizontal or the visibility on the offside of the road will be seriously reduced.

Intensities of Glare

The discomfort caused by a headlight does not depend simply on the intensity of the beam, but intensity is probably the most-important factor. When the design of the meeting beam is governed by regulation, it is usual to have an upper limit to the intensity which can be directed into the eyes of approaching drivers. It is of interest, therefore, to find the effects of misaim and sharpness of cutoff on the intensities actually encountered.

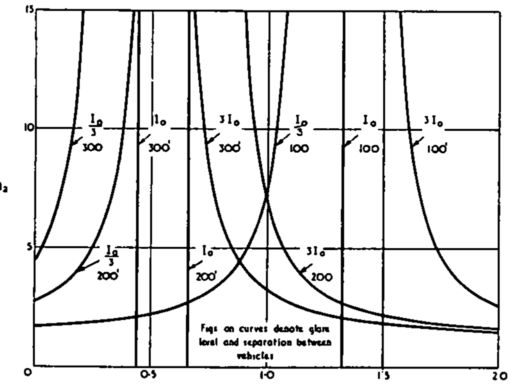

Figure 11. Relation between cutoff and misaim for 5-percent probability of glare exceeding $\frac{I_o}{3}$, I_o and $3\ I_o$.

Figures 11 and 12 give some results for the simplified beam of Figure 7. It is assumed, as before, that the horizontal intensity is maintained at the fixed value I_o, while the sharpness of the cutoff is varied. Figure 11 is similar to Figure 9 and shows the relationship between cutoff and aim required to keep the probabilities at the 5-percent level. Curves have to be drawn for each separation of the vehicles and each level of glare. The glare levels chosen for Figure 11 and 12 are horizontal intensity. I_o and one third and three times this intensity, i.e., 1,000, 3,000 and 9,000 cd. according to Figure 7. The glare intensity will not exceed the chosen value in more than 5 percent of cases, provided that the aim and cutoff are represented by a point on or to the left of the appropriate curve. As with the curves for seeing distance, the probabilities are calculated on the number of glare intensities, which is double the number of encounters, and the probability for encounters is not 5 percent but almost 10 percent.

In Figure 11, probabilities for glare intensities exceeding I_o are clearly independent of the cutoff, and for this special case the general relationship between probability and standard of aiming is given in Figure 12. The probability remains constant for this particular value of glare, because it is being assumed that I_o remains constant while the cutoff is changed. The misaim required to bring this intensity to the driver's eyes remains constant and so, therefore, does the probability. Other assumptions might clearly be made; in some countries, the United States for example, the intensities which are limited by legislation or agreement extend below the horizontal. Figures 11 and 12 may be used in investigating such conditions provided I_o is then regarded as dependent on the cutoff factor n_2.

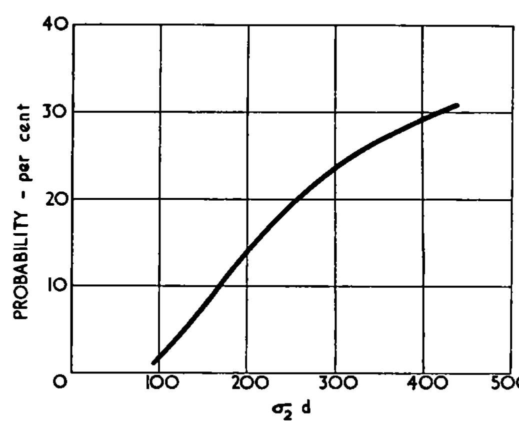

Figure 12. Probability of glare intensities exceeding the forward intensity in the horizontal I_o.

It is an important question whether changes in cutoff necessary to achieve large seeing distances can be made without running into serious trouble from high intensities of glare. An improvement in the standard of aiming makes it less likely that high glare intensities will be encountered; the effect of sharpening the cutoff is more complicated. If the cutoff is made sharper, high intensities become more probable and low intensities less probable; the intensity for which the probability remains unchanged is, as we have already shown, the intensity which remains fixed while the cutoff is varied, i.e., in our calculations the horizontal intensity I_o. A comparison of Figures 9 and 11 shows that to keep down intensities exceeding $I_o/3$ (1,000 cd.) to a probability of 5 percent at a distance of 200 ft. requires standards of aiming and sharpness of cutoff similar to those required to achieve seeing distances of the same order with the same probability level. There is, in fact, a correspondence between the two diagrams which may be expressed as follows: If the cutoff and standard of aiming give probability p for seeing distances less than d, then when the vehicles are separated by a distance d the probability for glare intensities exceeding kI_o is also less than p. The factor k is a function of the separation and is given in the following table. For distances greater than 150 ft. it is less than 0.3.

d ft.	100	150	200	300	400
k	0.7	0.3	0.125	0.02	0.004

It follows from this that if as a result of sharpening the cutoff and improving the aim the performance of beams is improved as to seeing distance it will also be improved as to glare intensities. This suggests that apart from intermittent glare due to the pitching motion of vehicles comfort will look after itself if visibility is dealt with. It is the intermittent glare, therefore, which probably sets an ultimate limit to the sharpness of cutoff that can be used.

CONCLUSIONS

The effectiveness of a meeting beam should be judged not by its performance when correctly aimed and in perfect condition but by the performances which will be given by such beams in actual use when subject to the inevitable effects of misaim and deterioration. A method of evaluating this overall performance is given, based on the minimum seeing distance and the glare intensity.

Judged in this way the performance of any given design depends on the standard of aiming and on the degree of deterioration which is to be tolerated. Curves are given from which the effects of the various factors and the connections between them may be seen.

An attempt to increase the minimum direct-seeing distance at most encounters to much over 150 ft. for the standard test layout makes demands as to accuracy of aiming and sharpness of cutoff which it will be difficult to meet, especially if deterioration to a small fraction of initial intensities is tolerated. The prospects of designing a beam which will effect any considerable improvement are therefore small.

The sharp cutoff, coupled with a high standard of aiming which is required if improved seeing distances are to be attained, is not likely to give rise to high intensities of glare, except for intermittent glare due to the pitching motion of the vehicle, or at places, such as hilltops, where the slope of the road is not constant. If it may be assumed that standards of aiming can be greatly improved, then it is the intermittent dazzle due to the pitching motion which probably sets a limit to the sharpness of cut-off which may be used.

ACKNOWLEDGEMENTS

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