Factors affecting seeing on the road at night

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FACTORS AFFECTING SEEING ON THE ROAD AT NIGHT

by

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DECLARATION

The candidate A. J. Fisher hereby declares that none of the work described in this thesis has been submitted for a higher degree to any other University or Institute.

A. J. FISHER

FACTORS AFFECTING SEEING ON

THE ROAD AT NIGHT

A TREATISE ON STREET AND

VEHICLE LIGHTING

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PREFACE

The factors affecting seeing on the road at night are of two types: those which are attributes of the human visual system and those which are associated with equipment providing the light which makes vision possible. The first have been discussed in the greater detail, leading to conclusions about the amount of light required. In only a few instances have detailed photometric requirements for equipment been investigated.

This is not to say that lighting practice has been ignored; specific problems have been analysed in terms of one or other of the established lighting modes. Hence the subtitle of a treatise on street and vehicle lighting.

Since the extension of community activity into the hours of darkness is a feature of modern society it is not surprising that there has been considerable effort put into developing lighting for road traffic. Lights were fitted to the earliest automobiles and these have never ceased to be upgraded, today involving the halogen source and, perhaps, tomorrow polarised light. The invention of the discharge lamp gave impetus to widespread installation of street lighting. Today computer techniques are being used in lighting design and tomorrow these could be incorporated into road design so that lighting is one of the basic parameters.

My association with lighting started at the then Road Research Laboratory, first with vehicle lighting as a member of the team led by Mr. V. J. Jehu. He established the mechanism of seeing by vehicle headlighting by drawing out the relationship between seeing distance, beam intensity and glare. This, to me, is the most comprehensive but most neglected work in the field. As shown later, its implications appear to be only now acknowledged. I became associated thereafter with Mr. A. W. Christie and street lighting. Here was a chance to research for the first time, virtually on my own; the resulting insights into disability glare

are mentioned in Chapter 2.

I was fortunate to be able to work with and learn from these two outstanding people in this field. A good grounding for my years at the Institute of Highway and Traffic Research and currently in the School of Transportation and Traffic, both at the University of New South Wales. Through the public lighting committee of the Standards Association of Australia my good fortune continued by my being brought into contact with the enthusiastic and extremely competent Australian street lighting engineering fraternity.

More recently, through the street lighting committee of the CIE, I have come into contact with the Continental European school of workers, pre-eminent in which is Prof. J. B. deBoer, chairman of the committee. Their development of appraisal techniques and application of road surface reflection characteristics to design have added to my own armoury.

This thesis gives an account of my work at the University of New South Wales in this field. The work is in the tradition of applied lighting research, it builds on and adds to the already considerable volume of knowledge. I have ranged over the whole field, however, in doing so I have been selective in that aspects explored in depth are those I feel have either been unsatisfactorily treated or neglected in the past. Hence, for example, the notions that the visual field includes the surrounds to, as well as, the carriageway and that special vehicle headlighting is necessary for use in street lighting.

As indicated in the text the results of studies on street lighting have been used in the recent revision of the Australian Public Lighting Code. It is gratifying and justifies my raison d' être as an applied research worker that this has happened, even if it means that this report is not as topical as it might be.

There is more reluctance to accept the results, or rather the implications of the headlighting investigations; perhaps this stems from them being somewhat unpalatable to some. As can be inferred by early remarks this is by no means a unique experience but it means Australia still has no national headlighting standard.

In writing this thesis, I have adhered largely to the SI system of units. However, some of this work was completed before Australia changed to the SI system and has particular relevance to standards written in imperial units. Therefore, these units have been retained in several chapters. The conversion factors are trivial so as not to prevent readers visualising quantities in either system and the units of course do not influence conclusions. I have noted that SI units and CIE definitions are not always the most convenient. For example it is often more convenient to use the apostilb than the cd/m^2 or replace luminance factor by luminance coefficient.

Although chapters vary considerably in length, each is self contained in that each encompasses one review or investigation. The references, figures and tables relevant to each have been collected at the end of the chapter, even if this has lead to some duplications.

Much of the work was undertaken in projects sponsored by the Australian Road Research Board. I acknowledge gratefully their long term interest and the considerable financial support entailed. The work on the town headlight beam was undertaken during study leave at the University of Birmingham, England. I gratefully acknowledge the help of Prof. J. Kolbuszewski of the Department of Transportation and Environmental Planning to make this possible.

Many of the investigations were carried out single handed but others involving the field investigations described in Chapters 4, 9, 12 and 13 involved teams of people by necessity. Whilst in each I was the innovator

and leader many others helped in data acquisition, some gave valuable suggestions as to methodology and data analysis. I thank my colleagues at the University and elsewhere for their assistance, often under uncomfortable and tedious conditions. In particular, I acknowledge Mr. R. R. Hall as a loyal lieutenant and for devising and running the computer programme for the evaluation of the disability glare equation developed in Chapter 5.

My final thanks go to the two people who influenced me to start and insisted I finish this thesis; to Mr. H. J. Turner, my colleague and friend, for his encouragement and for commenting on the draft manuscript and to my wife, Anne, for her encouragement and support.

A. Fisher,
West Pymble, N.S.W.
January, 1975.

ABSTRACT

The factors affecting seeing on the road at night are of two types: those which are attributes of the human visual system and those associated with equipment providing the light which makes vision at night possible. The first have been discussed at the greater length leading to conclusions about the amount of light required for visual tasks. However, the analyses have been made in the context of the two established lighting modes, street lighting and vehicle headlighting.

This lighting practice has influenced the presentation, which is in four parts. Part 1 deals with the problem generally; Part 2, with street lighting; Part 3, with vehicle headlighting and Part 4, with the interface of these two modes. The format of the last three parts is the same: each starts with a review of research work and practice. Areas are identified where, in the opinion of the author, data is sparse. These areas are explored either by on-paper analysis or by field measurements and experiments.

PART 1: ELEMENTS OF THE PROBLEM.

The hypothesis is made that the low light level at night leads to poor visual performance by individuals which in turn leads to poor driving performance. Poor individual performance is reflected in lower traffic system efficiency at night, which is improved if the light level is raised. It is shown that indeed the accident rate is higher by night and this can be ameliorated by the provision of good street lighting. However, it is suggested that detailed lighting requirements can only come from analysis of individual visual and task performance.

Two aspects of vision, contrast sensitivity and disability glare, are explored in detail and methods for their use in analysing the specific problem areas are developed.

PART 2: STREET LIGHTING.

Research and developmental work on street lighting are discussed,together with the quality criteria and their numerical values. The conclusion is reached that a modest level of road luminance (about 1cd/m^2) leads to satisfactory visual conditions provided luminance uniformity and glare restriction are good. A survey of installations designed to the then Australian Code of Practice is reported. A general conclusion is that the design objectives were being realised, however, guidance is given on aspects that could be improved. It is indicated where these recommendations have been incorporated in the subsequent revised code, AS 1158, Part 1.

Two areas were identified for further analysis; it was found that the surrounds to the road against which objects can be viewed are often dark and that high values of disability glare occured in some installations. The relationship between visibility, background luminance and glare is analysed and suggestions made as to precautions that should be taken in installations on intrinsically dark roads. These include the use of lanterns emitting a large component of light onto the surrounds and with good glare restriction.

A relationship between disability glare and parameters of the lantern light distribution is developed and values of these are suggested for degrees of glare control.

PART 3: VEHICLE LIGHTING.

Vehicle headlighting practice is reviewed and the conclusion is reached that conventional lighting has been exploited to its limits, whilst the visibility afforded still remains poor. Indeed it is suggested that further technical innovations could exacerbate the situation because of in-service degrading factors. Radical improvements on otherwise unlit non-urban roads can only come from polarised lighting.

One possible innovation is an increase in the intensity of upper beams.

The hypothesis is made that any increase will make this beam virtually unuseable in traffic, because of the discomfort to oncoming drivers. Field trials gave the relationship between comfort rating of a vehicle meeting, the upper beam intensity and the intercar distance on dipping of lights: the data supports the hypothesis.

In addition it is shown that seeing distance (d) is approximately related to beam intensity (I) by $I = kd^4$. Thus practical increases in beam intensity will give little increase in seeing distance to off-set a large increase in discomfort. There is an upper limit to visibility distance with headlights and the safe speed of driving needs to be tailored to this fact.

PART 4: STREET AND VEHICLE LIGHTING INTERFACE.

The review suggests that the use of vehicle headlights on urban roads with good street lighting is an inefficient way of providing marker lights on moving vehicles. These lights produce discomfort, and probably impair visibility and safety.

An analysis is made of the visibility of objects viewed against the road surrounds, often intrinsically dark. It is shown that the glare from vehicle headlights affects visibility generally and that the additional illumination improves visibility marginally and only when the vehicle is close to the object.

Two field trials were conducted to evaluate a town beam: a light of intensity intermediate between the present marker light and dipped headlights, which would provide a conspicuous but glare free marker. Observers had a significant preference for a town beam after seeing it and the normal lower beam in use in a simulated traffic stream. Further appraisals of a range of lighting parameters showed that a light could have an intensity as high as 1000cd and elicit 50% observations that it was not too bright and as low as 10cd with 50% observations that it was conspicuous. For

95% observations that it was satisfactory the light had to be about 100cd to be both conspicuous and comfortable. However, area of the source has an effect: with equal illuminance at the eye a small bright source is judged more discomforting and less conspicuous than a larger dimmer one. The optimum town beam is a light the size of the present headlight with a straight ahead intensity of 80cd.

The ideal lighting appears to be good street lighting in urban areas with vehicles using town beams, and polarised headlights for rural roads.

PART ONE

SEEING ON THE ROAD AT NIGHT

CHAPTER 1: The Elements of the Problem

CHAPTER 2: Contrast Sensitivity, Glare and Visual Performance

Boswell: Then, Sir, what is poetry?

Johnson: Why, Sir, it is much easier to say what it is not. We all <u>know</u> what light is; but it is not easy to <u>tell</u> what it is.

BOSWELL'S LIFE OF JOHNSON.

"Having noticed that the effect of a dazzle-source in the field of view of an observer seemed to be very similar to that of a veiling brightness, it was determined to study the phenomena in a comparative manner."

L. L. HOLLADAY, The Fundamentals of Glare and Visibility, 1926.

CHAPTER 1

THE ELEMENTS OF THE PROBLEM

INTRODUCTION

The traffic technologist seeks, through appropriate combination of its constituents - the users, the vehicles and the roads - to operate the road transport system at optimum efficiency, in terms of traffic flow, speed and safety. Driving can be thought of as a complex psycho-physical motor task consisting of detection of information, mainly of a visual nature, its processing and the implementation of decisions arising from this processing (1.1). Inefficiency in the system, e.g. the occurrence of accidents, may arise from the malfunctioning of this process in the individual.

Man is not naturally a nocturnal animal. At night the provision of artificial light in the road environment can be intuitively considered necessary in order to maintain the flow of visual information and by so doing maintain the system efficiency at the day level. By day accidents may be caused by the discarding of readily detectable relevant information through overloading of the neural processing system (1.2). By night inefficiency may be compounded because some information is just not readily detectable on account of darkness.

There is rarely complete darkness on the road at night. In urban areas street lighting is provided extensively as part of the road system, and motor vehicles carry headlights as part of the traffic system. The former is akin to daylight in that the road environment and potential sources of information are generally illuminated but luminance levels are much lower. The latter provides a more restricted coverage of the way ahead. Nonetheless there is a great disparity between light levels by day and night.

From the discussion above a simple relationship can be postulated governing the efficiency of the road transport system at night, as shown in Fig. 1.1. Low light levels induce poor visual performance in individuals; this leads to a lack of information input on which individuals depend in order to do well their task of driving. Poor individual performances react within the system to produce inefficiency. However, if sufficient light is provided, improvement is made at the individual level and so system efficiency is improved.

In this chapter it will be shown that in general the system is more inefficient at night; there are relatively more accidents and they are more severe in their consequences. It will be demonstrated that the provision of light, by street lighting, reduces the accident rate. It is suggested, however, that only by examining the visual performance of individuals will the fundamentals of lighting systems be understood. From this understanding flows the relationships between factors which influence the quality of lighting and working specifications giving design criteria and their values.

There are fundamental difficulties in defining the visual task and visual performance which are discussed. Investigations by the author, detailed in later chapters, are here placed in the context of the discussion.

SYSTEM EFFICIENCY: NIGHT ACCIDENT RATE.

Looking at the system as a whole, it can be shown that system efficiency is in fact poorer at night than by day. The writer has reviewed data from around the world to show unequivocally that accidents are relatively more numerous and more severe at night than by day, over the whole hierarchy of roads (1.3). Typically, an Australian study showed that 42% of all casualty accidents and 60% of all fatal accidents occurred at night, in spite of the fact that only 20 - 25% of all vehicle kilometres were travelled at night. Persons involved in multiple vehicle accidents at night were about twice as likely to be killed than if involved by day; the corresponding figure for pedestrians is four times (1.4).

The writer has pointed out that even without darkness, one should expect the accident rate and severity of accidents to be somewhat higher by night than by day (1.3). Firstly, the traffic volumes at night are much less than by day. Several investigators have found that the accident rate at low volumes increases sharply over the fairly constant value associated with the range of higher flows. Secondly, as the volume decreases, single vehicle accidents are generally more severe in their consequences than multiple vehicle accidents. In addition, at night, multiple vehicle accidents tend to be less of the intersection/angle collision type and more of the severer midblock/ head-on type. Thirdly, man being a diurnal animal is disadvantaged at night simply because of natural fatigue. Also the night hours are those of pleasure and relaxation, with the attendant ills, traffic-wise, of alcohol and drugs.

THE EFFECT OF LIGHT ON ACCIDENTS.

It has been elegantly demonstrated that the disparity between light levels by night and day is the major cause of the decrease in system efficiency at night. Tanner and Harris (1.5) were able to exclude many of the extraneous factors referred to above by examining accident data accruing in periods immediately before and after changing both to and from daylight saving. Most "clock" hours of the day were always light or dark but a few changed from light to dark, or vice versa, on the clock change. By taking ratios of accidents in the periods immediately before and after the change in daylight saving it was found that, whereas the ratio was approximately unity for the unaffected hours, the ratio rose above unity for the affected hours. It appears that darkness increases the ratio to about 1.5 for all casualty accidents, both in urban and rural areas, and to about 2.5 and 4.5 for pedestrian accidents in the two areas respectively.

A corollary of this finding is that a reduction of the disparity between light levels by night and day will improve the accident situation. By night there is almost always some artificial light present which is variable in both level and coverage of the visual field. Vehicles will show headlights and on urban traffic routes there will be street lighting.

Many studies have shown that the initial provision of traffic route lighting, or its upgrading, has reduced the incidence and severity of night accidents substantially (1.3). The classical study in this field is due to Tanner (1.6). It is on the basis of his data that the CIE (1.7) concluded that street lighting reduced both the incidence and severity of night accidents: the general conclusion was that casualty accidents were reduced overall by 30% with pedestrian and serious accidents being alleviated the most.

There have been many substantiations of these conclusions, the latest being based on data accruing from a government subsidised lighting programme in New South Wales, Australia (1.8). Turner showed lighting improvements significantly reduced all accidents by 27%. The data was collected over two year "before and after" periods for 105 km of road.

Thus it can be concluded that the hours of darkness lower the efficiency of the transport system generally, and this can be offset by the provision of street lighting. (Efficiency may not be returned to the day level because of factors other than darkness associated with the night hours.) The lower efficiency and the subsequent improvement with the provision of light applies even to those roads, such as freeways and motorways, where the environmental design is such as to reduce the opportunities for accidents, in comparison with the ordinary roads.

Such data validates the intuitive supposition that light is necessary and, indeed, has been extensively provided in the past. However, public lighting is generally erected according to the limited requirements of the current specification in use. The accident data can be used to justify its use and show it is an economic proposition in terms of costs and benefits to the community (1.3). The range of light level and quality in application is not great enough to draw all embracing conclusions about the relationship between system efficiency and lighting parameters. The indications are that as the light level is increased from a very low level accidents are reduced sharply at first but thereafter there is a decreasing benefit with increasing light level: See Fig. 1.2.

It can be stated with confidence that only a modest amount of artificial light in the form of street lighting needs to be provided in order to improve system efficiency at night. The minimum light level requirement implicit in the Australian Public Lighting Code is along the flattening portion of the curve. The requirements are such as to produce a maintained average road surface luminance of $0.7 cd/m^2$.

In order to obtain a basic understanding of the reasons why this level and form of lighting is necessary resort must be made to the visual performance attributes of the individual. To deduce the relative importance of various lighting parameters, such as road luminance, luminance uniformity and glare limitation, the influence of these on the performance of the visual tasks by individuals must be investigated. Understanding of the system comes from a study of the individual.

VISUAL PERFORMANCE OF INDIVIDUALS.

Basic psycho-physical investigations have shown that as the light level falls human visual performance deteriorates. Contrast sensitivity, acuity, distance judgement, speed of seeing, colour discrimination and tolerance to glare are all impaired. From a cursory examination of the <u>night</u> road environment it can be deduced that contrast sensitivity and glare sensitivity play an important role in determining the overall visual and hence task performance of individuals.

Contrast Sensitivity.

The deterioration of contrast sensitivity at night is demonstrated by the work of Blackwell (1.9). Fig. 1.3 shows the relationship between the just detectable fractional luminance difference and the light level. It can be seen that this necessary fraction increases sharply with decreasing light level, especially for objects of small angular size.

For an object to be visible at night at the same distance (same angular size), with say the light level applicable to headlights, the threshold contrast needs to be about 10 times that by day. Obviously, if the intrinsic contrast of object and background remains constant (as it will for non self luminous objects) the distance at which the object will be detected will be less at night, since its angular size would need to be increased to compensate for the reduced light level. Provided the angular size of object required to be seen is large, i.e. the information source has intrinsically large dimensions and it does not have to be seen at a long distance, the light level needs to be raised only modestly to obtain similar visual performance as by day. It has already been noted that street lighting reduces the involvement of pedestrians in urban road accidents. A pedestrian subtends about 1^{o} at 100m. However, if the object has to be seen at a greater distance or in greater detail the light level would probably need to be raised, because of the smaller angular dimensions involved.

Disability Glare.

Glare becomes more pronounced at night. The disability effect of glare is well documented and quantitatively described by the classical Holladay-Stiles formula (1.10, 1.11). That the general visual field is dark and the sources of artificial light are relatively close to the line of sight gives rise to adverse visual conditions. The effect may be likened to that of superimposing an external luminous "veil" on the field of view. Such a luminous veil would raise the effective luminance of both object and its background but leave the difference between them the same. Since the necessary luminance difference increases with increasing background luminance, an object previously seen in the absence of glare can become invisible in the presence of glare. This rise in threshold due to glare may be calculated, using Holladay-Stiles glare formula and the curves of Blackwell.

THE LIMITATIONS OF BASIC DATA IN APPLICATION.

The basic psycho-physical data give insights into the mechanisms of vision and the importance of parameters; they cannot however be used to predict visual performance in the real driving task with any quantitative certainty. This is because the data were obtained under laboratory conditions using simple uniform visual field configurations, using threshold or 50% probability of detection techniques.

The curves of Blackwell would indicate that even on an unlit road at night the difference between the luminance of the object to be detected and its background needs to be only 10% or so. However, it has been shown that when the object position in time and space and its type are unknown, as on the road, and when certainty of detection is required, the fractional difference is of the order of 10 times that indicated in Fig. 1.3 (1.12). In addition the visual field in the real road environment is not uniform and is dynamic in character. Efforts to predict visual performance in it, from basic data, have been unsuccessful (1.13). In short, the basic data needs to be modified by field factors.

VISUAL TASK IN DRIVING.

In order to be certain of the relative importance of lighting parameters and to establish their necessary values, investigations involving simulations of the real environment need to be made. By their nature simulations fall short of actuality but attention to basic knowledge (and the real environment) should ensure their relevance.

Stress has been laid previously on the availability of readily detectable visual information as the prerequisite of successfully accomplishing the driving task at night. Fundamental difficulties arise as to what information is necessary in the first place and how visual performance should be measured.

Types of Information: Formal and Informal.

It will be useful to introduce here the notions of formal and informal information, which can be both relevant and irrelevant. Formal information is that which has been deliberately introduced into the environment in a more or less systematic manner. This can be part of the road in the form of lane markings, traffic signals and signs, or part of the vehicle in the form of signal lights. Informal information is in the make-up of the total environment; the carriageway and its surrounds and the users, pedestrian and vehicular.

Any of this information which is necessary for successful maintenance of the task is relevant. Relevancy operates at two levels. The first is at the pre-processing stage; for instance a "no right turn" sign is irrelevant to the driver proceeding straight ahead. This type of irrelevant information would ideally be kept out of the psycho-physical processes, since a surfeit could overload the neural system.

The second type of irrelevant information arises only after processing of potentially relevant information. Thus the appraisal of a pedestrian at the side of the road may lead to the conclusion that the pedestrian will stay in his own space (irrelevant) or, that he will cross the road and intrude into the observer's space (relevant).

Several workers, particularly, Schreuder (1.14), have made a theoretic analysis of the information requirements of drivers in different road environments, leading to the justification of different lighting modes for them. The information required by drivers in urban, non-freeway environments, is thought to be mainly informal, using the classification proposed above. This is because the road environment is not systematic in its layout and is occupied by a variety of users. Street lighting is seen as the necessary lighting mode, since it gives general illumination to the whole road environment.

However, Schreuder considers that in freeway and rural environments, having only one class of user and a more systematic layout, information could be entirely formal; lane markings to guide the driver and vehicle signals to inform of the potential trajectories of other users. Vehicle headlighting is seen as the necessary lighting mode. This lighting, confined to a limited angular coverage, is sufficient to illuminate retro reflective guide markings.

To the writer, this analysis is not satisfactory. It is evident that most formal road information is designed for macro traffic control; it channels and supervises the movement of the traffic stream, albeit through information to individuals. Vehicle based formal information, such as marker and signal lights, provides some information on the micro movements within the general stream. However, the plethora of subtle information used in the successful accomplishment of micro movements on which the final efficiency of the system depends are informal in nature.

The Importance of Informal Information.

A view of the carriageway as a whole and of its surrounds are necessary to provide a reference frame for the judgement of position and speed and for maintenance of position within the driver's space. The outlines and details of other vehicles and users adjacent to the driver's space provide necessary information on their trajectories and possible incursions into his space. Details of the vehicles and road ahead give a dynamic picture of the future road to be traversed.

It is suggested that at night it is informal information which is likely to be lost and the provision of formal information is unlikely to be a reliable substitute. There is much current research into improving vehicle signalling systems and road markings. However, the basic data suggest that to improve visual efficiency the <u>general</u> light level needs to be raised and glare restricted. This is certainly necessary for the detection of informal information at night.

This expression of the need for informal information is as much a hypothesis as that for formal information. Several examples of findings of investigations into performance on the road support the hypothesis and suggest limitations to formal information as a means of ensuring visual efficiency. It is known that drivers can successfully negotiate a circuit with far vision attenuated whereas they are less successful when near vision is attenuated (1.15). Complex brake light displays reduce reaction time to a lead vehicle when mild braking occurs but not when braking is severe (1.16). Lack of detail, on featureless roads, leads drivers to lose their sense of speed resulting in multiple crashes (1.17). The display of discrete lights (e.g. rear lights) on the rear of a vehicle by itself will give a clear indication of its position. The perspective view of the lights of several vehicles can lead to incorrect assessments of the true situation of the road ahead of the driver (1.18).

Compounding the uncertainty of what information is necessary is the question of how observers sample and assimilate information. Studies on the scanning of the road environment and the assimilation of formal information to which the driver has been alerted, are scanty. Only the case of the approach to a tunnel entrance has been studied systematically, using an eye movements camera in real environments (1.19).

MEASUREMENT OF VISUAL PERFORMANCE.

Whilst the simulations used for investigations may be realistic of the real environment, the visual task itself is less likely to be so realistic. Certainly, when investigations are made into formal information the visual task is defined once the information source is formalised. However, in quantifying general visual performance within, and the necessary attributes of a lighting mode, investigators have tended to identify the visual task (mostly without rationalisation) with the acquisition of informal information.

Visual performance is related then to lighting parameters through the detection of a standardised object styled on a common object deemed necessary to be detected on the road, such as a pedestrian (1.20) or indicative of the size of detail deemed important, e.g. a vertical square 200 mm x 200 mm (1.21, 1.22). Some investigators have dispensed with an objective visual task in assessing what they call ease of perception, rather than reliability of perception. Observers are asked to make appraisals of situations and to rate their subjective impressions (1.22). These types of investigation lead to relationships between a rather generalised visual performance and lighting parameters.

All simulations based on the assimilation of informal information appear to have been specifically concerned with the two conventional modes of providing light i.e. street or public lighting and vehicle headlighting. The simple visual field of the basic experiments has been turned into reality. Whilst this anticipates the solution of how to raise the adaptation level it is not unreasonable since we have already noted that for conclusions from investigations to be valid in practice the simulation must approach practice as closely as possible. The two modes lead to different visual environments. In street lighting there is a large angular field with a significant level of luminance and this level does not drop off sharply as the distance from the observer increases; the reverse is true with vehicle lighting. Only in certain circumstances do the two modes impinge to the extent that they need to be considered together and this is in the determination of the effects of glare from <u>all</u> sources in the field of view. It is reasonable to conduct investigations centred on the two possible modes of lighting, fixed, as part of the road and moving as part of the observer (vehicle).

A great many investigations using both indoor scaled-down and outdoor full-scale simulations, both static and dynamic have been carried out over the years. These have yielded complex relationships between visual performance within the driving task and lighting parameters. From these, lighting specifications have been drawn up and methods for producing the necessary lighting environment have developed and been refined such that street and vehicle lighting are well established practices. These investigations will be dealt with in more detail in the introductions to Parts 2, 3 and 4.

THE WRITER'S INVESTIGATIONS.

The investigations carried out by the writer, and to be described below, are concerned more with individual performance and individual task performance than with system efficiency. The implicit basis of most is the importance of informal information. The writer draws on his rational discussed above and the data from basic experiments in visual performance to justify this approach rather than on experimental work, which would form an ambitious study as an end in itself.

The investigations have sought to extend our understanding and provide practical solutions to problems of artificial lighting by concentrating on areas where past effort has been lacking; for instance, by considering the surrounds to the carriageway to be equally important with the carriageway in providing a satisfactory visual environment. They have sought also to point up limitations to the exploitation of lighting, e.g. that human visual performance will place a practical limit on how far ahead it is possible to see with vehicle lighting.

Some additions to basic knowledge of the disability glare aspects on individual visual performance are described using detection techniques. This basic knowledge is used to make on paper predictions of the limits of visual performance at night. Photometric measurements in practical environments plus basic data plus data from simulations of others are used to analyse deficiencies in the present night road environment. Field simulations of street and vehicle lighting situations are used to gauge observer reaction to changes in present practice, using objective appraisal techniques.

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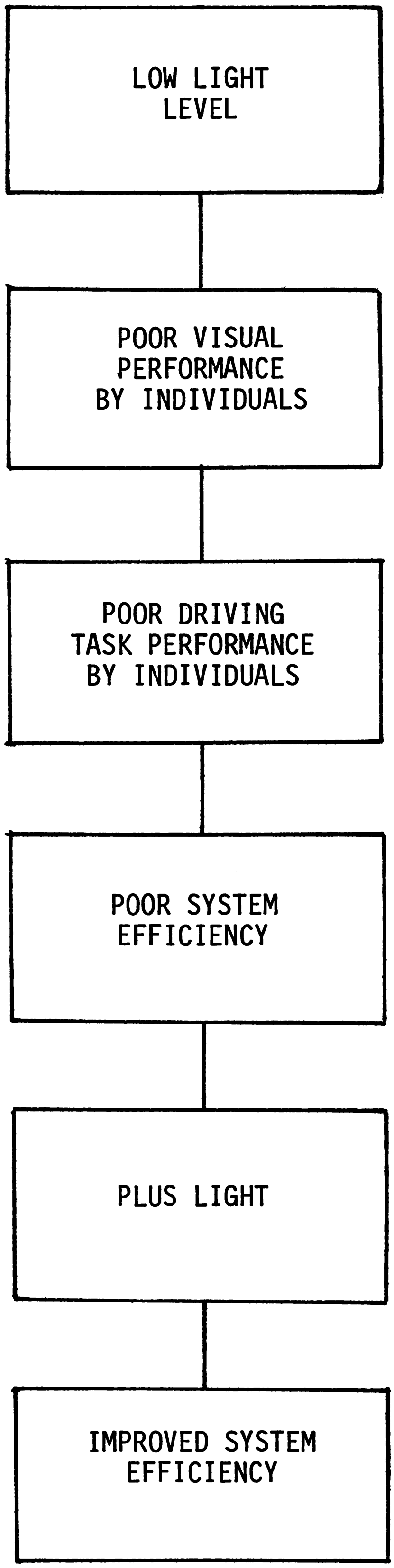

Fig. 1.1. The chain of elements determining the efficiency of the night road environment.

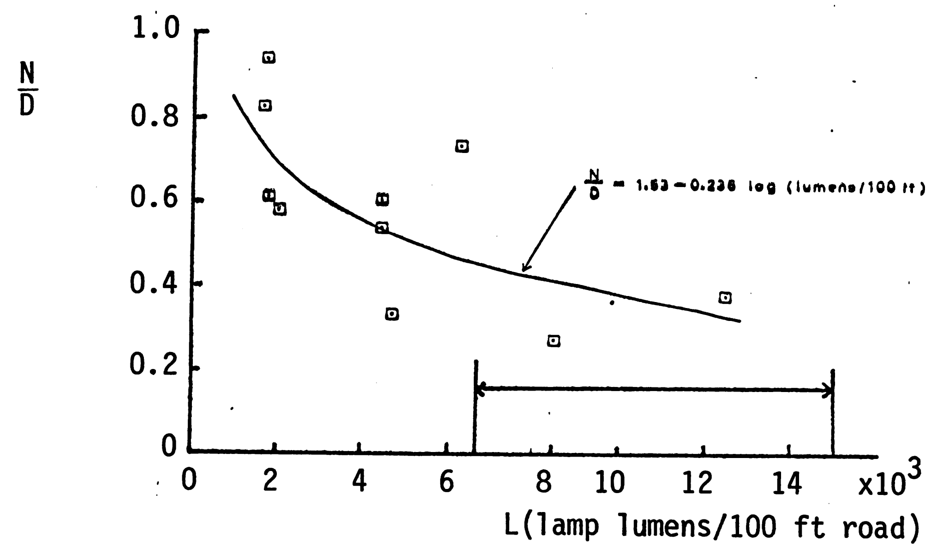

Fig. 1.2. The effect of the level of street lighting (L) on the ratio of night to day accidents ($\frac{N}{D}$).
(Installations to the Australian Code lie within the range shown.)
(After Turner)

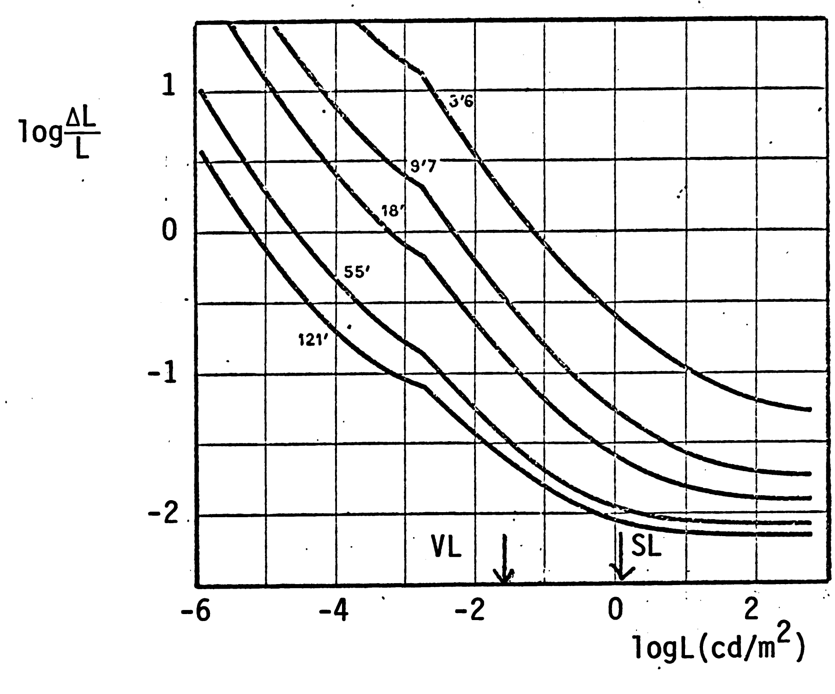

Fig. 1.3. Data relating the necessary fractional luminance difference ($\frac{\Delta L}{L}$) to detect objects of a given angular size against a background, luminance (L). (Arrows mark the approx. L for street and vehicle lighting.)
(After Blackwell)

CHAPTER 2

CONTRAST SENSITIVITY, GLARE AND VISUAL PERFORMANCE

INTRODUCTION.

In the previous chapter it was suggested that contrast sensitivity and inhibition through glare play an important role in determining the overall visual and, hence, task performance of individuals on the road at night. The concepts involved in these two aspects of vision are expanded in this chapter, since they will be used later in chapters 5, 6, 8 and 11, in detailed analysis of visual performance on the road at night.

CONTRAST SENSITIVITY.

It was noted in chapter 1 that data, shown in Fig. 1.3, relating the necessary fractional luminance difference ($\Delta L/L$) between an object and its background for it to be detected, the angular size of the object and the luminance of the background (L) could not be applied to the road situation directly. These data were obtained under laboratory conditions using a threshold of detection criterion. A factor (contrast multiplier) needs to be applied so the data take into account the need for a 100 per cent probability of detection with a low reaction time, that the object position may be unknown in space and time, that the observer may be unalerted and that the driving task is a dynamic one.

Hills (2.1) has analysed various studies of object detection and has shown that contrast multipliers of 4 and 8.5 need to be applied to laboratory data to raise the visibility of an object to "just visible" and "just obvious" on the road at night. This is for expected objects, observed at low speed; he suggests that the contrast multiplier needs to be raised over 20 if the observer is unalerted, does not know where the object will be and is travelling at speed.

Street Lighting.

In Chapter 1, it was stated that investigators of street lighting have tended to relate the visual task with the detection of standardised objects and the range of object size has been limited. The necessary contrasts for standardised objects have been investigated a number of times under road conditions, therefore there is no need in this case to use laboratory data modified by a somewhat uncertain contrast multiplier.

Probably the earliest but still the most realistic investigation was by Dunbar (2.2). He had observers drive at 48 km/h along a lighted road on which there were placed objects 0.45m in diameter. The observer was asked to state whether the object contrast, at a distance of 33m or more, was just sufficient for safe driving at that speed. A range of road luminances and object contrasts was used. The visibility criterion used will yield contrasts such that an object will have a 100 per cent probability of detection. His results are shown in Fig. 2.1. The results of other like investigations are shown in Fig. 2.2, the agreement between them is good.

Vehicle Headlighting.

The use of a standardised object is justified in street lighting research because the pedestrian is assumed to be the most important object and it needs to be seen at a moderate distance ahead commensurate with the needs of the speed of the city driving. In addition, the background luminance along the lighted carriageway is reasonably constant.

In situations, such as the rural roads, where vehicle head lighting is the primary lighting mode, speeds can be higher and hence, the necessary visibility distances longer. Smaller objects such as animals, fallen trees and branches may be important. The background luminance will not be uniform; falling off with increasing distance ahead from the vehicle. In this case it is necessary to resort to the laboratory data shown in Fig. 1.3 in which these parameters are linked.

For the analysis in Chapter 8, these data have been used with a contrast multiplier of 10, as shown in Fig. 2.3. It will be shown that seeing distances with upper headlight beams derived on this basis agree closely with those measured in field trials carried out by Jehu to be described in Chapter 7.

Disability Glare

Glare from unshielded light sources will inhibit seeing. It is usual to divide the adverse effects into disability and discomfort glare. The former affects visibility but may pass unnoticed except in extreme conditions, whilst the latter, which affects visual comfort, may be more apparent being manifest by mild annoyance at one extreme, to pain at the other. The disability glare affect may be likened to that of superimposing an external luminous veil (G) over the field of view. Such a veil would raise the effective luminance of both object and its background but leave the difference between them (ΔL) the same. Since ΔL increases with increasing background luminance an object previously seen in the absence of glare might become invisible in the presence of glare. Disability glare (G) may be measured directly in street lighting installations or calculated using a formula of the type:

$$G = \sum_{i=1}^{n} \frac{f\ (E_i)}{f\ (\theta_i)} \qquad (2.1)$$

where E_i is the illuminance at the eye from source i and θ_i is the angle between the line of sight and the direction of glare source i (2.3, 2.4).

There have been many investigations into disability glare since those of Holladay and Stiles, who derived the first mathematical description of the phenomenon. Others have shown f (E_i) to depend on individual variations, particularly age, the size of the adapting field

(2.5), θ (2.6) but not colour of the glare source (2.7, 2.8) and f (θ) to depend on θ (2.6) and the size of the glare source (2.8). A number of these investigations have been critically reviewed by the writer, as to their applicability to road lighting situations (2.9).

It appears that the conventional form of eqn (2.1) gives a reasonable description of the effect, by far the major influence on the numerical value of glare being the choice of line of sight of the observer, which determines θ_i. Then (2.1) becomes

$$G = \sum_{i=1}^{n} \frac{kE_i^m}{\theta_i^n} \qquad (2.2)$$

With k = 10, m = 1 and n = 2 when E is in lux, θ in degrees and G in cd/m^2.

The writer, associated with Christie, has shown G to depend on the age A of the observer (factor cA) and the distribution of luminance in the visual field (factor C) such that:

$$K = (cA + C)$$

In one experiment, they examined in great detail the responses of 16 subjects, aged 17 to 65 years, for a range of glare conditions (2.5,2.9 2.10).

It can be seen in Fig. 2.4 that the examples of data show a 60 year old subject to be more susceptible to glare than a 20 year old subject. The values of n and k for equation 2.2 derived for each subject are shown in Fig. 2.5. It can be seen that whereas n is invariant with age, k is strongly influenced by age (significant at the 0.1 per cent level) and

$$k = (0.20A + 0.4).$$

In a second experiment, over a hundred people were examined but each gave only one response to a glare situation. The data for this experiment confirmed the effect of age and

$$K = (0.19A + 5.8)$$

Thus the factor cA was but little different in the two experiments but there was a large discrepancy in the factor C.

A difference between the conditions of the two experiments was that in the first the test object was viewed against a small uniform background (1^o dia.) whereas in the second it was viewed against a simulated road scene of extended size. A third experiment was carried out in which seven subjects made detailed observations using the two background configurations but without any other experimental differences. The data obtained confirmed that the difference in C was due to the background configuration.

The explanation for this effect appears to be that in the absence of glare the different background configurations resulted in different contrast sensitivities, the fractional luminance difference for the restricted background being higher than that for the roadway scene for equal luminances of each. In the presence of the rather severe glare used, the fractional luminance difference was almost the same for each background, i.e. the glare and not the background most influenced contrast sensitivity in this case.

The conventional glare equation used in situations with extensive lighted backgrounds, such as occur in street lighting, gives values of veiling luminance which apply for younger observers. In situations with restricted lighted backgrounds, such as occur in vehicle lighting, the values apply to older observers.

VISUAL PERFORMANCE.

The data described above allow for the assessment of visual performance in lighting situations. Visual performance may be described in general terms: for a given roadway luminance L the value of $\Delta L/L$ may be determined and expressed as contrast sensitivity $L/\Delta L$. This value can, in turn, be expressed as a fraction of the best possible contrast sensitivity, i.e. referred to some reference background luminance at which contrast sensitivity is a maximum. Similarly, the effect of glare can be expressed as a fractional increase of $\Delta L/L$ or conversely a fractional decrease in contrast sensitivity. A corollary to this approach is that a lighting situation could be deemed satisfactory if specified values of contrast sensitivity are obtained.

However, a knowledge of general visual performance does not necessarily lead to a determination of how well the visual task, specific to a road situation can be carried out. For example, a specific level of contrast sensitivity might allow the ready assimilation of visual information of large angular size but not that of small size. Similarly, glare will have differing effects on different tasks. Thus for any meaningful assessment there must be a description of the visual task.

In the following sections, street and vehicle lighting are treated separately. In street lighting the visual task is taken to be the detection of pedestrians, a single angular size of object implying the necessary visibility distance for safe driving. As street lighting is continuous seeing conditions are relatively insensitive to distance ahead. On the other hand in vehicle headlighting the illuminance ahead falls off sharply as the inverse of the square of the distance. Thus distance is a necessary parameter, especially as headlighting will be used in situations where low urban speed limits do not apply. Since distance becomes an important factor so too does the dependent angular size of objects.

Street Lighting.

Let L be the luminance of the background (cd/m^2)

ΔL be the luminance difference between object and background required to see an object

l be the luminance of the object for it to be seen,

β be its luminance factor, and

E be the illuminance falling on the object

then $$1 = L \pm \Delta L$$

The subtraction covers objects seen by silhouette (S), and the addition covers those in reverse silhouette (RS). It can be assumed that ΔL is the same for both (2.1), and since

$$1 = \beta \, {}^{E}/\pi$$

$$\beta_S \leq \frac{\pi (L - \Delta L)}{E} \qquad (2.3)$$

$$\beta_{RS} \geq \frac{\pi (L + \Delta L)}{E} \qquad (2.4)$$

Allowing for disability glare (G), by use of eqn (2.2), eqns (2.3) and (2.4) become

$$\beta_{S(G)} \leq \frac{L - \Delta G}{E} \qquad (2.5)$$

$$\beta_{RS(G)} \geq \frac{L + \Delta G}{E} \qquad (2.6)$$

where ΔG is now the luminance difference for background of luminance $L + G$ and

$$\Delta G > \Delta L$$

$$\beta_{S(G)} < \beta_S$$

$$\beta_{RS(G)} > \beta S$$

i.e. in the presence of glare, objects must be darker or lighter to be seen without glare. It has been assumed that the visibility of pedestrians is of primary importance on urban traffic routes. This is not unreasonable since it has already been shown that pedestrians are particularly vulnerable to accidents. The visibility of pedestrians can be thought of as involving detection of an element of area of the pedestrian, e.g. the upper torso, covered by a garment of some luminance factor. The data of Dunbar, based on the detection of a simulated element, gives the values of ΔL for various values of L pertaining to street lighting, for use in eqn (2.5) and (2.6).

The general relationship between the parameters is shown in Fig. 2.6. For any combination of L, G and E there will be a range of values of β for which the object cannot be seen with certainty. (This does not mean that within this range objects cannot be seen at all; but the further into this range the luminance factor of an object lies, the greater will be the uncertainty). As G increases and/or L decreases, the level of uncertainty increases. For high values of L and/or low values of E objects will be seen predominately as silhouettes whereas for low values of L and/or high values of E reverse silhouettes will predominate.

This analysis can be extended from the probability of one specific object being seen to the probability of any object being seen with a knowledge of the distribution of luminance factors for the objects likely to be encountered. Continuing with the notion that pedestrians are of primary importance, Smith (2.11) measured the luminance factors of men's and women's clothing, both in the summer and winter, in the United Kingdom in the later 1930's. His data, weighted for night usage, is shown in Fig. 2.7 togetherwith other cited by Hentschel (2.12). The trend is for a large probability that clothing will be dark. Fashions change to alter this distribution, although gross changes in it are unlikely. A luminance factor of 0.3 is for very light clothing indeed and most men's clothes, except white shirts, will have luminance factors of 0.1 or less.

Waldram (2.13) combined the data of Dunbar and Smith, calling this concept of visual task performance "revealing power". Related to a given background, revealing power is defined as the percentage of elemental objects having the same distribution of luminance factors as pedestrian clothing which will be adequately visible when viewed against the background.

For example, from Fig. 2.6, if L = 0.17 cd/m^2, E = 5 lux and

G = 0, objects must have values of β less than 0.054 to be seen in silhouette and greater than 0.14 to be seen in reverse silhouette. From Fig. 2.7, the percentage of objects having these values are 61 per cent and 19 per cent respectively, hence the revealing power of the background is 80 percent. This method is used in analysis of street lighting situations in Chapters 6 and 11.

Of course, this concept can be further developed but at the cost of unmanageable complexity:

(i) Instead of a specific elemental object being assigned either a unity probability of being adequately visible or effectively a zero probability if it has a luminance factor lying in the uncertainty range, it can be assigned a true probability value on a continuous range. However, it can be argued that unless a complex model is developed, along the lines of (ii) following, any probability less than unity is of no interest in the road situation.

(ii) An object, such as a pedestrian, can be split up into a number of elements each with a probability of detection and hence a revealing power associated with it. The revealing powers of the elements can be combined, using probability theory, so that the revealing power associated with the object will be enhanced over that associated with a single element (2.14). Problems arise from modifying revealing power to take into account non-unity values of probability of seeing, dividing objects arbitrarily into elements and determining the number of elements to take into account in the probability functions (in reality the detection of complex objects probably does not occur on this basis) and the possible non-independence of the distribution of luminance factors for each element (e.g. dark jacket with dark trousers).

(iii) The revealing power refers to a background; in the street situation, there will be a number of backgrounds such as carriageway, footpath and houses along the alignment and of various luminances.

A single value of revealing power of the street could be deduced from a knowledge of the backgrounds weighted by the importance of each (2.15). A pedestrian seen against the carriageway may be crossing the road to the safety of the footpath, whereas a pedestrian on the footpath may be stepping onto the carriageway into a collision course with a vehicle.

Hentschel produced a single value of revealing power for a number of motorway/freeway lighting designs. Besides, of course, using an entirely inappropriate visual task, he did not pay sufficient attention to the points made above. In the writer's view, the relatively simple concept of revealing power remains a very useful tool with which to analyse street lighting situations.

Vehicle Lighting.

Chapter 8 is concerned with how far ahead objects can be detected using high beams on the open road, i.e. with no glare from oncoming traffic. Using the same notation as above,

$$\frac{\Delta L}{L} = \left|\frac{L - 1}{L}\right|$$

$$= \left|\frac{\beta_B - \beta_O}{\beta_B}\right| \quad \text{— (2.7)}$$

since $\beta_B = \pi L/E$ and $\beta_O = \pi l/E$, where the suffixes B and O denote background and object respectively and E is measured on plane perpendicular to the incident light.

Substitution of a range of combinations of values for β_B and β_O lead to the necessary values of $\Delta L/L$ for detection of all objects for each combination. Fig. 2.3 gives the background luminances, for each such value of $\Delta L/L$, required to detect objects of given angular sizes. Each object angular size is converted to an equivalent object distance (d) by assigning the object a linear size. The headlight beam intensity I(cd) required to detect any object is that necessary to produce the background luminance adjacent to the object at the calculated distance away i.e.

$$I = \frac{\pi}{\beta_B} Ld^2 \qquad \text{— (2.8)}$$

For example, let the luminance factor of the background and object be 3 percent and 7 percent respectively. Then $\Delta L/L = 1.33$ and from Fig. 2.3 $L = 0.1$ cd/m^2 for an object of size 10 min of arc (approximately) with this contrast. If the linear size of the object is 0.45m diameter, the object will be 154 m distant. In order to produce a luminance of the background of 0.1 cd/m^2 at the object position, the necessary beam intensity will be 2.5 x 10^5 cd approximately.

The method could be elaborated:

(i) The background luminance is taken to be that adjacent to the base of the object. Viewed against the carriageway the object will have a length of surface as a background both in front and behind. The luminance along this length will vary because the illuminance produced will vary according to the inverse square law. Thus, the true value of L is probably an average value of the weighted distribution (which in itself is a complex experimental problem).

It is considered, however, that the field factor applied to the laboratory data will include the effect of non-uniform background.

(ii) The objects considered are circular cross-section; thus the derived beam intensity values do not necessarily apply to objects of different shape. For example a log or person lying across the road would be about 0.45 m in height but considerably greater in extent across the road. Thus different families of curves, like those in Fig. 2.3 must be generated (or further field factors applied) if different objects are considered (2.1). However, the approach outlined is consistent with the standard object concept discussed above and yields meaningful relationships between the relevant parameters.

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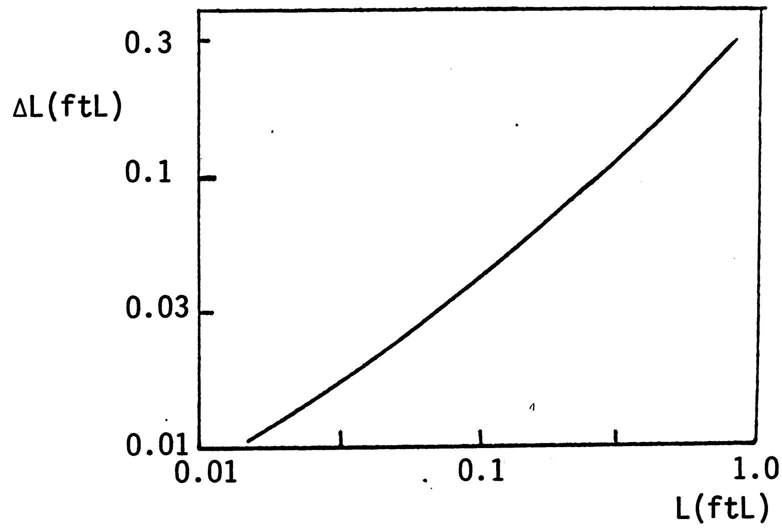

Fig. 2.1. The luminance difference (ΔL) required for an object to be seen adequately in street lighting against a background luminance (L).

(After Dunbar)

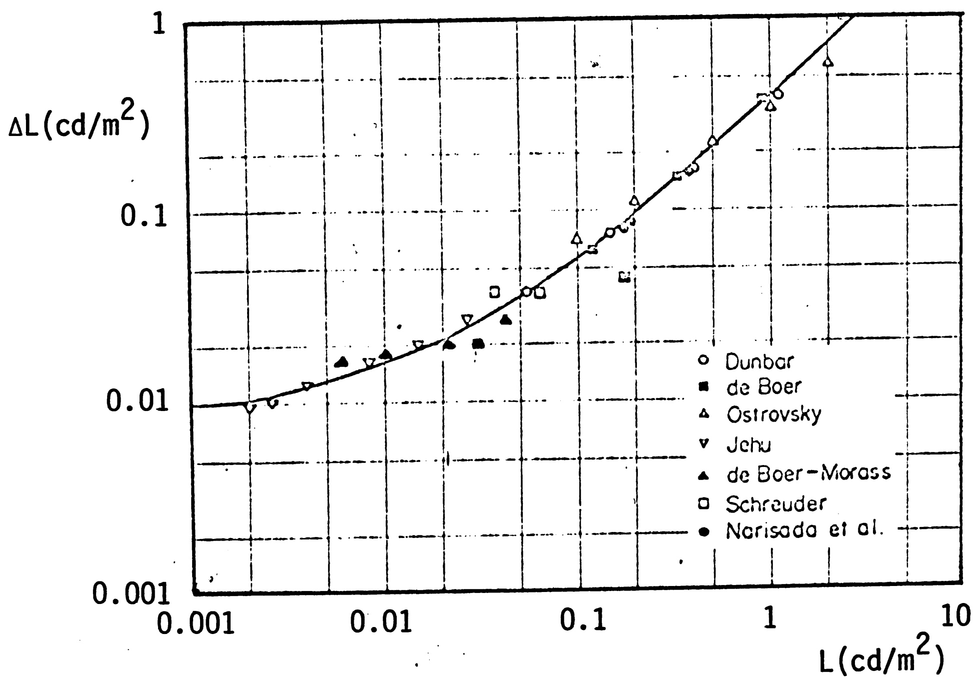

Fig. 2.2. Comparison of the data of Dunbar with that of others.

(After Narisada)

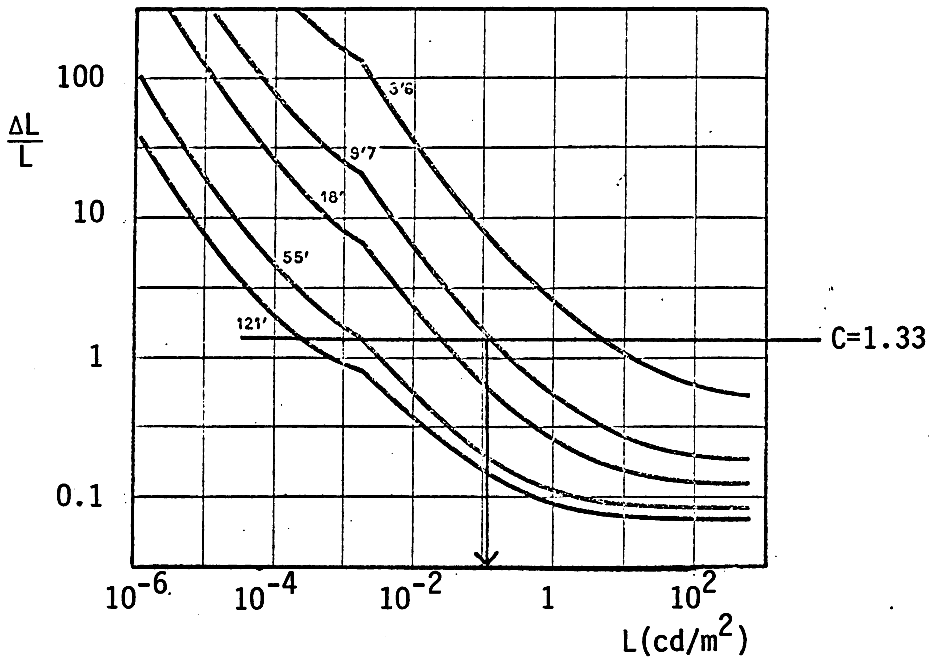

Fig. 2.3. Contrasts required to detect objects in vehicle lighting: those shown in Fig. 1.3 have been increased x10. The contrast used in the text is shown.

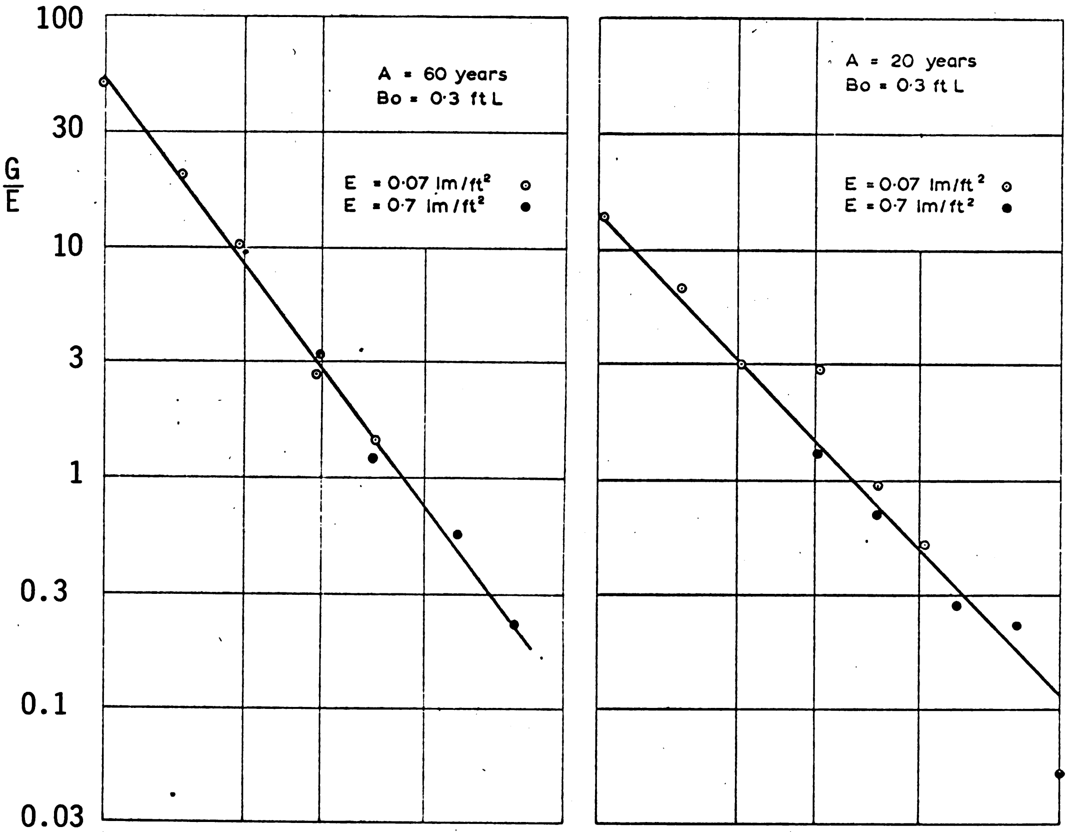

Fig. 2.4. The veiling luminance G for given conditions showing the greater susceptibility of the older to glare.

(After Christie & Fisher)

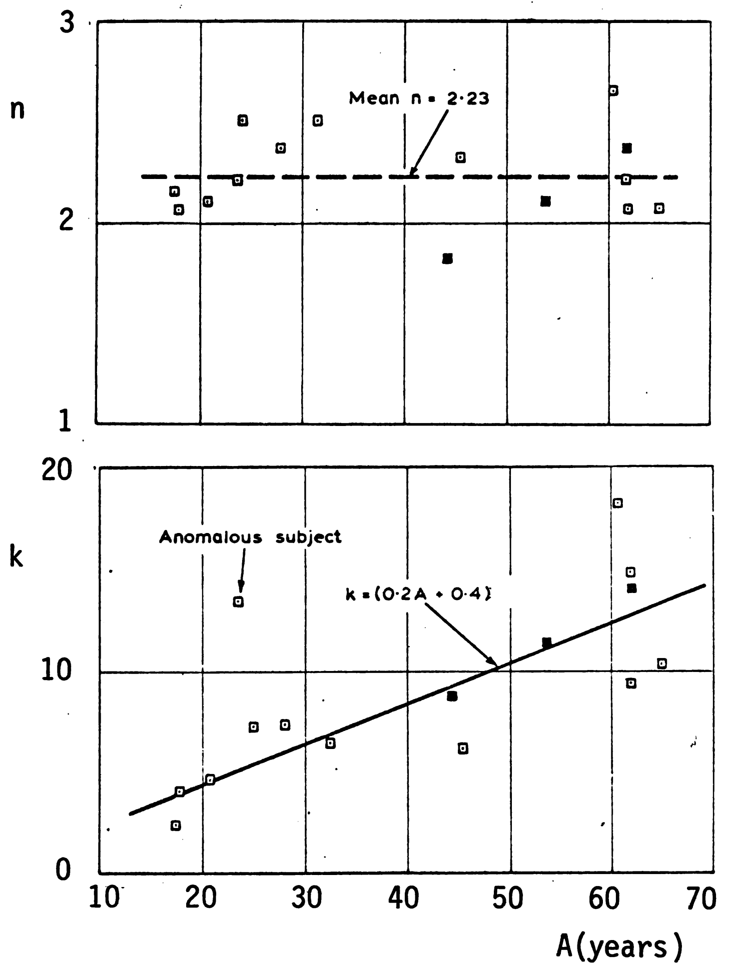

Fig. 2.5. The effect of age (A) on the constants n & k in the conventional glare formula.

(After Fisher & Christie)

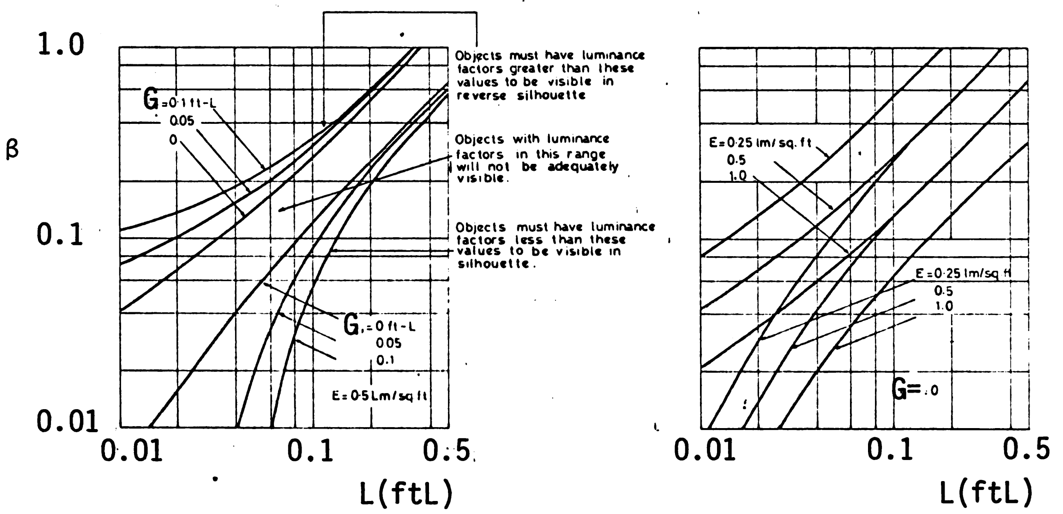

Fig. 2.6. The effect of background luminance (L), illuminance (E) and glare (G) on the necessary luminance factor (β) of an object for it to be adequately seen.

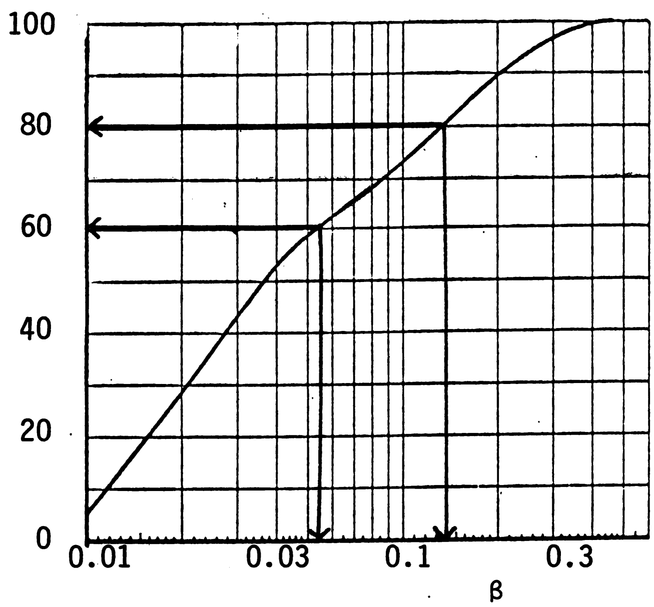

Fig. 2.7a. Percentage of objects (P) having luminance factor (β) which does not exceed a given value. (The values used in text are shown.)

(After Smith)

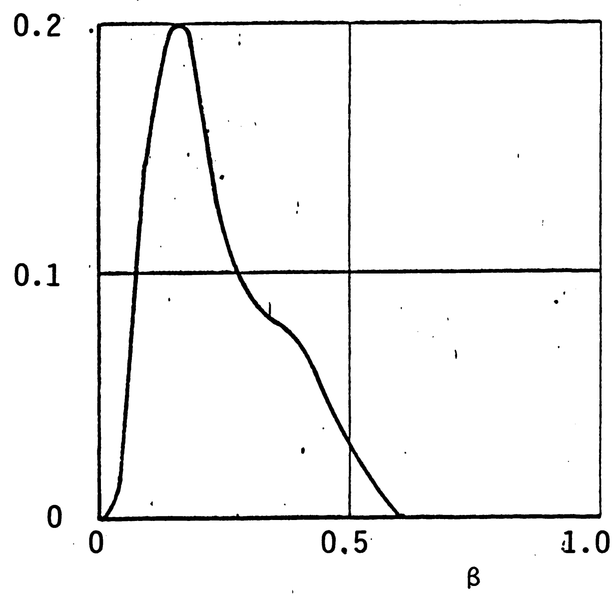

Fig. 2.7b. Probability distribution (p) of the luminance factor (β) of pedestrian clothing.

(After Hentschel)

PART TWO

STREET LIGHTING

I saw myself the lambent easy light
Gild the brown horror, and dispel the night.

DRYDEN, HIND AND PANTHER.

"A general conclusion is that ....
.......dark regions of the road are the sensitive regions, where objects may disappear, where disability glare can have an effect, and where reverse silhouette can occur. Any factor which acts adversely upon revealing of objects generally has most effects on regions of low brightness, and these regions are for several reasons the weak spots in the installation."

J. M. WALDRAM, The revealing power of street lighting installations, 1938.

CHAPTER 3

A REVIEW

INTRODUCTION.

It was shown in Part One that the road transport system runs less efficiently in the hours of darkness. This results from the gross disparity between light levels by night and day and man's poor visual performance under the conditions of lower light level. It was noted that two forms of artifical lighting have developed as a night aid, street lighting and vehicle lighting. The former, akin to daylight, increases markedly safety at night on urban traffic routes.

THE GROWTH OF STREET LIGHTING.

The administrations of towns, where community activity will be carried on into the hours of darkness, have from early times recognised the need for public lighting. In the 1400s the Aldermen of the City of London were issuing regulations controlling the positioning and make up of candle lanterns. By the early 1800s the same city was extensively lit using gas. The early 1900s saw the introduction of the tungsten filament electric lamp. But it was not until the 1930s, with the introduction of the relatively efficient low pressure sodium and high pressure mercury discharge lamps, that electric street lighting displaced gas lighting. This form of lighting is now an accepted part of urban traffic routes all over the world (3.1).

No doubt early lighting was provided for road user safety at night, but to discourage crime, rather than as an accident counter-measure. As vehicular traffic became greater and more complex, street lighting was recognised and used to promote safety by reducing accidents. It is only recently that street lighting is seen again as a deterrent to crime and vandalism on all urban roads. However, this survey and investigations to be described deals only with lighting of urban traffic routes. The concern is to provide those visual conditions which will lead to good visual performance in individuals and, therefore, good system efficiency.

THE GROWTH OF SPECIFICATIONS AND RESEARCH.

As the advent of the discharge lamp and its subsequent improvement gave impetus to traffic route lighting through the readily availability of relatively high light levels, so there was increased activity in scientific investigation and specification of lighting. Street lighting specifications now exist in most urbanised countries (3.2) and the CIE have issued international recommendations (3.3).

Before the second world war, British lighting engineers, notably Waldram, established principles of the general reflection characteristics of road surfaces and of the measurement of visibility, which is discussed in Chapter 2 (3.4). Hopkinson showed the relationship between lighting parameters and discomfort glare (3.5). After the war the British Road Research Laboratory (now Transport and Road Research Laboratory) continued this work, notably establishing a relationship between lighting and accident reduction, as discussed in Chapter 1 (3.6).

After the second world war and to the present, Continental European investigators have been very active. De Boer and his associates have described in detail the reflecting properties of road surfaces and how they may be used in computer based calculations to design lighting systems. They have used subjective methods to determine which parameters influence quality of installation and their values (3.7). Others in Russia, U.S.A. and Australia have also contributed.

This review will describe these investigations into the mechanisms of street lighting including the importance of the road surface, the distribution of light from the lanterns, investigations into visibility and the importance of the distribution of luminance in the field of view, the control of glare and finally the specification of street lighting.

THE MECHANISMS OF STREET LIGHTING.

It has been suggested earlier that street lighting acts like daylight. Light is distributed over the whole visual field to show up informal information, the carriageway and surrounds to the road and objects such as pedestrians. Nonetheless the carriageway, being the area of greatest activity and of possible interaction between the road users, has always been given primary consideration. The necessity to control disability & discomfort glare has more recently assumed importance. These considerations have led to emphasis on directing the light from lanterns mainly on to the carriageway surface whilst restricting the release of light in directions towards the motorist's eyes.

CARRIAGEWAY LUMINANCE: THE SILHOUETTE PRINCIPLE.

Under daylight conditions, objects are seen against their backgrounds by contrasts in luminance and colour, by form, texture and highlights. Under light levels pertaining to streetlighting many of these cues are diminished and that of luminance contrast dominates.

Luminance contrasts may be enhanced by exploiting the reflecting characteristics of backgrounds and objects and the directional characteristics of the lighting systems. If light is released in the direction of travel the horizontal road surface will tend to be dark and the vertical objects light, if light is released against the direction of travel the reverse situation generally arises.

That it is better to make the background bright, i.e. to silhouette the objects, can be deduced from five facts:

(i) Contrast sensitivity improves as the background light level is raised;

(ii) The effect of glare becomes less as the background light level is raised;

(iii) Visual comfort is greater if there is background lighting;

(iv) The luminance factors of pedestrian clothing are mostly low, whereas those for the road surface can be very high;

(v) The carriageway surface is in itself an important source of information, in its surface condition and its direction.

Of course, objects are not always seen in total against a background that can be made bright. Higher levels of lighting of the present day allow other cues to be present. But the silhouette principle of lighting is of paramount importance and making the road surface bright and even is a main aim in installation design.

CARRIAGEWAY LUMINANCE: THE ROAD SURFACE.

The light from a lantern reflected from the road surface forms a characteristic T shaped patch: Fig. 3.1. The head, close to a point below the lantern extends across the road and the tail extends along the road towards the observer. The relative magnitudes of the two components of the T depend on the reflection characteristics of the surface. If the surface is uniformly diffusing, the tail will be non-existent. However, if the surface acts as a mirror, say, e.g. when the road is flooded, the tail is extensive and the head absent.

The reflecting properties of road surfaces are complex and vary from surface to surface. The success of lighting depends on using lanterns with suitable beam distributions and locating them in relation to each other so that the light patches are overlaid, and the resulting carriageway luminance is substantially uniform.

The complexity of surface reflecting properties and the mechanism of patch formation was recognised by Waldram (3.4). Measurements of these properties for various surface types was carried out by the TRRL and the properties related to both texture and surface wear in a qualitative manner (3.6, 3.8). Sabey (3.8) has shown that the reflecting properties vary throughout the year, probably cyclically depending on temperature variations.

An extensive bank of reflection data has grown up through the measurements of continental investigators, including data for wet surfaces. The greatest variations in properties occur through rain, the extreme case being when the surface is flooded and becomes a mirror (3.7, 3.8, 3.9, 3.10).

Standard procedures for measurement and presentation of properties have been proposed (3.11).

It is normal practice to express the reflecting property as the luminance coefficent q, where

$$q_{\alpha,\delta,\gamma} = L/E$$

and where L is the luminance of the surface (cd/m^2)

E is the illuminance at the surface ($\ell m/m^2$)

q is a function of the viewing angle α, the angle of incidence of the illumination γ and δ the angle between the planes containing α and γ (The relationship between α, δ, γ are shown in fig. 3.2.)

It is usual to neglect the effect of α and express q in terms of δ and γ with $\alpha = 1^o$. This value is chosen because α varies little as the observer shifts his gaze along the road. For an eye height of 1.2 m, $\alpha = 0.5^o$ at 35 m and 1.5^o at 100 m approximately.

Dependence of q on δ and γ.

The variation in q with δ and γ for one surface is shown in Fig. 3.3, from measurements by Jackett and the writer (3.12). It can be seen that for the range of δ and γ investigated, q varies over three orders of magnitude. For small values of γ where the light is incident on the surface close to the lantern, q is small but as γ increases q grows and its highest values are for light incident at grazing incidence. As δ increases, i.e., the point of interest moves laterally across the road surface away from the line joining the observer to the lantern, q decreases.

The luminance at any point is given by L where

$$L = \frac{I}{H^2} \cdot q \cos^3\gamma$$

$$= \frac{I}{H^2} \cdot r \qquad (3.1)$$

writing $r = q \cos^3 \gamma$ (the reduced luminance coefficient)

and where I is the directional intensity of light from the lantern towards the point

H is the height of the lantern.

Thus the effectiveness (r) of the surface in producing luminance at any point is proportional to $q \cos^3 \gamma$. Although q is great for large values of γ, $\cos^3 \gamma$ is small and so overall the efficiency declines markedly as γ increases as shown in Fig. 3.4. This fact limits the practical length of the light patch since large values of I would be required to extend the patch in these directions which also would give rise to glare. For example, the useful length of the light patch given by a semi-cut-off lantern on an asphaltic concrete surface is taken as 5H, i.e. $\gamma = 78.5^{\circ}$, in the Australian Specification AS 1158, 1973.

CLASSIFICATION OF SURFACES.

The intrinsic lightness of the surface will influence q for small values of γ. But at large values of γ the surface texture will have the dominant influence. Surface texture can be thought of as having two attributes: (i) macrotexture; and (ii) microtexture.

Macrotexture is determined by the size of the aggregate making up the surface and the surface can be coarse or fine according to whether the aggregate is large or small. Microtexture is determined by the surface profile of the individual pieces of aggregate and can be of a harsh or smooth nature depending on the degree of irregularities in the profile.

Macrotexture has little effect on the reflecting properties of dry surfaces. In the wet, coarse surfaces are more likely to retain their dry properties because the aggregate protrudes above the moisture layer and the surfaces drain better. Surfaces with different microtextures will have different reflecting properties: smooth surfaces will give high values of q and rough ones low values. This leads to long tails in the light patches on smooth textured roads and short ones on rough textured surfaces.

In order to quantify this descriptive classification various parameters have been suggested. De Boer and Westermann (3.13) devised the q_o, K system, which has been widely used, in which,

q_o is the average q and gives a measure of the surface lightness and

$K = \log_{10} (q_o/q_{\gamma = 0})$ and gives a measure of the shininess or specularity of the surface.

It has been pointed out that the reflection properties may be classified with greater precision if more parameters are used to describe the distribution of q (3.14).

The two parameter system above has been developed into a three parameter one: k being replaced by two parameters S_1 and S_2 to describe the distribution of q, where:

$$q_o = \text{average } q$$

$$S_1 = \frac{r(\delta = 0,\ \gamma = \tan^{-1} 2)}{r(\delta = 0,\ \gamma = 0)}$$

$$S_2 = \frac{q_o}{r(\delta = 0, \gamma = 0)}$$

i.e. $S_2 = 10^K$

The characteristics of real road surfaces can be divided into a number of classes. In each class the characteristics of these surfaces can be typified by a single surface. In the two systems above five such classes have been used. Complete r tables (see eqn. 3.1) have been drawn up for each representative surface for use in computer calculations of installation design. It is claimed that if a representative surface is used instead of the actual surface a high degree of accuracy in luminance calculations is maintained (3.11, 3.14).

average luminance	± 6% standard deviation
carriageway uniformity	± 8%
lane uniformity	±10%

The use of representative surfaces is more convenient than actual surfaces, since no removal of surfaces for complete measurement is necessary, although there appears to be no very precise practical way of making an on-the-spot classification of surfaces.

In spite of the vast amount of measurement and classification, there is little work on the theoretical basis of the reflection mechanisms (3.15) and little success in fitting generalised equations to the data (3.16).

LIMITATION OF GLARE.

It was shown in Part One that at the modest levels associated with artificial lighting on roads, vision could be easily impaired by glare. Both disability and discomfort glare is proportional to the light intensity directed towards the observer's eyes and inversely proportional to a function of the angle between the direction of this light and the line of sight along the road.

The roof of the driving cab of a vehicle cuts off a considerable portion of the light from lanterns: See Fig. 3.5. The cut-off will be of light in directions of $\gamma < 70^{o}$—78^{o} (3.6, 3.7, 3.17). Therefore, glare can only arise from light emitted in directions $\gamma = 70^{o} \rightarrow 90^{o}$. It has been shown above that light at large angles of γ is not useful in producing road luminance. So in general there is little point in allowing light to be emitted at angles close to 90^{o}. It is, therefore, around the angle of cut-off of the vehicle roof, that it is necessary to compromise between projecting light for the production of road luminance and restricting it in order to limit glare. This angular range will be referred to as the run-back of the light distribution.

THE LIGHT OUTPUT DISTRIBUTION FROM LANTERNS.

The quality of a street lighting installation for any road surface depends critically on the distribution of light from the lanterns and their placement. The light must be directed from the lantern so that the light intensities directed along the road are higher than those directed immediately adjacent to the lantern. On the other hand, the intensity must be reduced radically in those directions which give rise to glare.

Those lanterns with a sharp run back, and severe limitation of glare, are known as "cut-off lanterns", those with a less sharp run back are known as "semi cut-off lanterns" - see Fig. 3.6.

It can be surmised that whilst the use of cut-off lanterns will give light quality in glare limitation, generally the number of lanterns needed to adequately illuminate the carriageway surface will be greater than if semi cut-off lanterns are used. Thus the cost is related to the quality of installation. It is only by investigation into individual visual performance and system efficiency that the necessary degree of quality can be established. Data from such investigations can be used to set the necessary level of luminance and its uniformity and glare control. Through the knowledge of the mechanisms of street lighting outlined above, the type of beam distribution and placement of lanterns, for a given carriageway, can be deduced, in order that the required quality may be achieved.

VISUAL PERFORMANCE IN STREET LIGHTING.

Many detailed investigations using simulations of street lighting have been made to establish precisely the relationship between visual performance and lighting parameters. The methodology of these investigations has been discussed fully in Part One. It was concluded that most experimenters using objective measures concerned themselves with some general measure of visual performance which emphasised the importance of informal information. However, many investigations, particularly into quality, rather than utility, make use of subjective appraisals. Investigations into road luminance requirements and glare limitation using objective and subjective criteria will be discussed, referring wherever possible to field checks of laboratory findings.

AVERAGE ROAD LUMINANCE

Objective Measures.

It has been shown in Chapter 1 that visual performance, as measured by Blackwell in terms of contrast sensitivity, is approaching maximum for a background luminance (L) of about 1 cd/m^2 for objects of pedestrian size: Fig. 3.7. It was shown in Chapter 2 that if contrast sensitivity (ability to see) pertaining to the street lighting environment is combined with the distribution of luminance factors for pedestrian clothing (objects to be seen) then revealing power (objects adequately seen) is 100% at a background luminance of about 1 cd/m^2: See Fig. 3.8. At this luminance disability glare from installations has little effect on visual performance.

It has been shown earlier in Chapter 1 that street lighting installations, giving this average level of carriageway luminance ($\bar{L}$), substantially reduce night accident occurrence and severity.

These objective investigations have been carried out by British investigators (with the exception of the basic visual performance data of Blackwell) (3.18, 3.19, 3.20, 3.21, 3.22). There appears to be a paucity of objective experiments elsewhere. De Boer (3.23, 3.24) reports the results of two investigations, one static the other dynamic, on the visibility of square standard objects in street lighting installations. He concludes that a road luminance of 2 cd/m^2 is necessary to perform a standard test of detecting a 200mm x 200mm flat object of contrast 1.5 from 100m.

The requirements of the then Australian Street Lighting Code CA19:1964 were based on extensive visibility observations on standard objects in an experimental street lighting installation (3.25). The recommended minimum value of average road luminance was 0.2ft L (0.7 cd/m^2).

A novel approach to this question has been made by de Boer (3.7). As dusk falls he observed the numbers of motorists switching on marker lights and lower beams as a function of light level. By 5 cd/m^2 80% had switched on marker lights and by 1 cd/m^2 20% had switched on lower beams. He concluded that a level of 2 cd/m^2 would give satisfactory visual conditions to motorists and they would not switch their headlights on, so causing glare.

Subjective Appraisals

A number of subjective appraisals have been made of lighted streets in which the observers were asked to rate the lighting level on a semantic scale with classification ranging from bad to excellent. The average ratings were compared with the average road luminance.

De Boer (3.24) reports that appraisals by 16 qualified persons of 70 streets led to the conclusion that lighting is judged "good" if the level is 1.5 cd/m^2 (between 1.3 and 1.8 at the 95% confidence level).

Fig. 3.9 shows some of the results of more recent appraisals in the Netherlands (3.26). It can be seen that the mean appraisal score rises to "fair" quickly as the average luminance level increases but then the rate of increase in score decreases and a state of diminishing return sets in. Values of required road luminance were:

		Fair	Good
Series (1)	All roads	0.4 cd/m^2	1.3 cd/m^2
Series (2)	Secondary roads	0.6 cd/m^2	1.2 cd/m^2
	Main roads	(0.6 cd/m^2	1.6 cd/m^2
		(1.3 cd/m^2	2.8 cd/m^2

(The two values for main roads arise from observations in two cities.)

In a British appraisal, in which the observers had to rate installations in terms of a number of qualities, it was found that the variation between scores of individual observers and between the mean score for apparently similar installations is large. Confidence limits were wide and coefficients of determination poor. It was found that average road illuminance was a better predictor of luminance level appraisal than was road luminance (3.27).

NECESSARY REQUIREMENTS FOR AVERAGE LUMINANCE.

It can be concluded that for mixed road user, low speed urban traffic routes an average road luminance of about 1 cd/m^2 will result in good visual performance. At such a level the subjective appraisal will be "fair" to "good". A level of about 2 cd/m^2 should ensure a rating of "good", although the rating will tend to be influenced by road importance.

APPLICATION TO FREEWAY LIGHTING.

Whilst the appraisal results could well be applied to motorway and freeway lighting, the objective data needs treating with caution. Speeds are normally higher on motorways and hence it is necessary to be able to see further ahead with reliability. As this necessary distance increases, so the angular size of objects decreases. The data of Blackwell (Fig. 3.7) suggests that in order to maintain the level of contrast sensitivity the light level will need to be increased in these situations. To what level depends on what is deemed to be the visual task in motorway driving. The writer has dispensed with observations of standard objects. He considers a primary task in freeway driving to be that of station-keeping within the traffic stream. He is currently investigating the influence of light level on detection of relative longitudinal motion i.e. change of headway of a leading vehicle through its acceleration or deceleration.

The writer has measured, in a laboratory simulation, the effect of light level on reaction time to the detection of change in visual angle for objects with different initial sizes (simulating different headways), different rates of change of size (simulating different accelerations and decelerations)(3.28). A sample of the data is shown in Fig. 3.10; as the light level increases reaction time decreases, quickly at first then more slowly, until a point is reached when further increases in light level produce little further reduction in reaction time. This effect is the same regardless of the initial value of simulated headway & deceleration, although as the difficulty of the visual task increases (long headways, small decelerations) the reaction time increases. The writer has devised a mathematical model linking reaction time and the parameters investigated: this is shown in a numogram in Fig. 3.10. It is concluded that for traffic operations found on freeways a light level recommended by the CIE (2 cd/m^2) is a better basis on which to design lighting installations than that of the Australian standard for urban traffic routes (0.7 cd/m^2).

UNIFORMITY OF ROAD LUMINANCE.

Objective Measures.

Both visual performance and subjective rating increase as the average road luminance increases, but with diminishing return. However, the road carriageway cannot be absolutely uniform in luminance and an object will therefore be seen against luminance gradients. It is intuitively obvious that if the object to be detected is large the non uniformity along the road, in the form of light and dark bars as may be experienced with installations employing cut off lanterns, will hardly effect its visibility. This is because the road behind the object is foreshortened and the object will be seen against several light bars. Streaks along the road, as occur when the road is flooded, are more serious since an object could be viewed within a longitudinal dark streak. In addition it is known from basic psycho-physical experiments (3.29) that luminous gradients effect contrast sensitivity: it declines in the regions of light/dark boundaries.

Early work of de Boer (3.7) suggests that ratios of maximum to minimum luminance of 10 to 1 along the road and 3 to 1 across the road are permissible, for $\bar{L}$ = 2 cd/m^2, without significantly effecting the visibility of the 200mm x 200mm standard object.

Narisada(3.30) simulated, in the laboratory, a cut-off lighting installation. He determined the probability of detection (p) for 200mm x 200mm objects of 25% contrast for various light levels ($\bar{L}$) and non uniformities (u). He found:

$$\bar{L}\,u^2 = \text{constant}$$

for p = 75% and u = Lmin/$\overline{L}$.

Thus as the average road luminance increases uniformity may be relaxed: for $\overline{L}$ = 1 cd/m^2, u = 0.43 approximately and for L = 2 cd/m^2, u = 0.28 approximately. These results show that the minimum luminance should not be less than about 0.5 cd/m^2 in any installation. It should be noted that these conclusions apply only to objects at 100m or less from the observer, uniformity had no demonstrable effect on the visibility of more distant objects.

Schreuder (3.31) in an investigation into the "black hole effect" at tunnel entrances showed that at an adaptation luminance of 2 cd/m^2, the entrance must have a luminance of 0.8 cd/m^2 i.e. Lmin/$\overline{L}$ = 0.4, for a 75% probability of detection of an object of 7 min. of arc diameter (200mm at 100m) and contrast 20%. Whilst this result is similar to that of Narisada the experimental set up was different in that the "black hole" was only shown intermittently with the test object and did not contribute to the overall state of adaptation.

Others in Britain (3.32) and Australia (3.25) have reported observations in experimental installations, the former in a scale model and the latter in full scale field trial. Their results are given in terms of installation layouts giving satisfactory results. Photometric measurements in Australian installations designed on the basis of these observations to be described fully in the next chapter, show $\overline{L}$/Lmin and Lmax/Lmin to be better than 3.5 and 8 respectively, the majority better than 3 and 6 respectively.

Subjective Appraisals.

De Boer and his associates have used appraisal methods to determine the permitted degree of non-uniformity. Twenty five observers appraised an experimental installation in an outdoor laboratory in which a range of light levels and uniformities were presented (3.7). He found that as the average luminance increased poorer uniformity would be accepted. However, uniformity had to be better than was necessary for good visibility in order to ensure "good" ratings. For example, at a level of 1 cd/m^2 the ratio of maximum to minimum luminance could not exceed three to obtain a rating of "fair" or two to obtain a rating of "good".

Extensive appraisals were made on a scale model installation over a large range of light levels and light patterns, the light patterns appearing to move as in the normal course of driving (3.33). The results showed that the quantity Lmax/Lmin is not as important as the luminance gradient in determining ratings. Luminance gradient (Smax) is defined as the maximum luminance variation found over any 1m transverse or 3m longitudinal distance in the light pattern.

The rating Q on a numerical scale could be represented by

$$Q = 6.8 + 4 \log \bar{L} - 2 \log S_{max}.$$

A subjective rating of "good" (Q = 7) can be obtained with the following combinations:

$\bar{L}$	Smax
5.0	20%
3.0	7
1.5	2

It can be seen again that the subjective rating of uniformity is a function of light level.

Appraisals have been carried out in lighted streets (3.26, 3.27, 3.34, 3.35). In the Dutch ones referred to above, no correlation was found between rating and the quantity Lmin/$\bar{L}$. However, when appraisals were examined on the basis of installation layout, it was found that reasonable correlations were obtained between mean appraisals score and the parameter Lmin/Lmax: See Fig. 3.11. It was found that for opposite and staggered arrangements a value of Lmin/Lmax = 0.6 gave an appraisal of "good" and a value of 0.4 gave a "fair" response. For single sided arrangements Lmin/Lmax had little effect on subjective response.

Thus the degree of luminance gradient appears to effect appraisal response. It is known that sharp step like gradients, especially of high spatial frequency and amplitude induce a greater sensation of brightness difference than would be indicated photometrically. Thus it is to be expected that ladder-like patterns likely to occur in installations of cut-off lanterns will be visually unpalatable.

It is interesting to note that in wet weather, when the luminance gradients might be expected to increase sharply the subjective appraisal scores were only slightly less than in the dry. This seems to be another example of subjects modifying their appraisals to their expectations.

In the British appraisals, referred to above, no good correlations were found between scores and any photometric parameters. However, it was found that uniformity appraisal significiantly contributed towards the overall visibility appraisal of subjects.

NECESSARY REQUIREMENTS FOR LUMINANCE UNIFORMITY.

It would seem that to ensure good visual performance a limit to non uniformity should be set, as well as an average luminance. Objective measurements suggest that the minimum luminance should not fall below about 0.5 cd/m^2 regardless of the average value $\bar{L}$. It would seem better to quote one absolute minimum rather than a limiting value of Lmin/$\bar{L}$, which should strictly vary with $\bar{L}$: See Narisada

It will be shown in the next chapter that the distribution of luminance varies with lantern arrangement. It is difficult to get rid of small areas of low luminance, particularly in staggered arrangements: See Fig. 3.12. Rather than base the conformity with the minimum value requirement on a single spot measurement, it would be better to say that this minimum value should not occur over an area of roadway of more than a given size.

In order to ensure a reasonable subjective rating, some restriction in luminance gradient over a span of lighting is necessary. The results of appraisals suggest that the ratio of Lmax to Lmin should be two or less for a "fair" to "good" rating. This seems an onerous restriction applied to the whole carriageway. If for good visibility minimum values of $\bar{L}$ = 1.0 cd/m^2 and Lmin = 0.5 cd/m^2 are specified then the value of Lmax/Lmin must be expected to be greater than two in practical installations. It has already been noted that step-gradients are probably the most unpalatable and these are likely to occur in cut-off installations. Thus it would be better to restrict the Lmax/Lmin $\leq$ 2 requirement to each traffic lane separately. However, this does not overcome the difficulty that in staggered installations severe gradients can arise in the areas adjacent to near lanterns on the opposite side of the road. This pattern will be in the motorist's field of view as he scans the scene, especially on relatively narrow roads. The specification of Lmax/Lmin $\leq$ 2 along a lane does not overcome this problem. It seems that some relaxation is necessary for this practical situation.

GLARE LIMITATION

Objective Measures.

It has been shown in Part One that disability glare in terms of a veiling luminance (G) can be readily calculated and its effect on general visual performance in terms of rise in threshold deduced. Both Hentschel in Germany (3.36) and Ovtrovsky and his colleagues in the U.S.S.R. (3.37) have suggested that a rise in threshold of 18% can be tolerated before the visibility of objects against the carriageway is adversely affected. Then,

$$L_o = a\bar{L}^b \qquad \text{— no glare condition}$$

$$L_o' = a(\bar{L} + G)^b \qquad \text{— glare condition}$$

$$L_o' - L_o = 0.18$$

Where L_o is the luminance of an object necessary for it to be seen under threshold conditions against a background of luminance $\bar{L}$ and a and b are constants. Values of a = 0.4 and b = 0.6 to 0.9 are given in (3.36, 3.37).

hence, $G/\bar{L} = 0.2$ to 0.3.

Thus it appears that disability glare in terms of veiling luminance has to be a considerable fraction of the roadway luminance before it is a problem. However, Christie and the writer (3.38) have pointed out that the surrounds to the road are often dark and the low values of revealing power associated with them can be further reduced by glare: See Fig. 3.8.

Christie and Fisher elicited the appraisals from 121 drivers using two experimental installations. One had non cut-off lanterns with $\bar{L} = 1.2$ cd/m^2, G/L = 0.6, the other cut-off lantern with $\bar{L} = 0.6$ cd/m^2, $G/\bar{L} = 0.2$. The calculated values of revealing power (RV) through each installation, both uncorrected and corrected for glare, were about the same except those for the dark backgrounds. There RV was 42% for the cut-off installation and only 6% for the non cut-off installation; without correction for glare they were 75% and 79% respectively. There was a marked difference between the mean scores for the rating of freedom from glare which may indicate different degrees of discomfort. Visibility of objects was rated appreciably higher in the cut-off installation, which is in agreement with revealing power corrected for disability glare and not with incorrected values.

There was also little difference in ratings for the level of brightness, though the luminance was twice as high in the non cut-off installation as in the cut-off one. This suggests that disability glare lowers the subjective brightness of the carriageway (3.39).

Subjective Appraisals.

Before the second world war Hopkinson (3.5), using a static laboratory simulation of a street scene, related the degree of discomfort to classical lighting parameters. (Source luminance and their size and number and position in the field of view). He claimed reasonable correlation between field observations and predictions based on his laboratory data.

De Boer (3.24) essentially repeated the investigation of Hopkinson, obtaining the relationship between the illuminance at the eye (E), the source size (W), its position (θ) and the carriageway luminance (L), over the range of these parameters met with in lighting, for criterion of "satisfactory" discomfort glare control. He took considerable pains in the experimental method to remove sources of bias that may have influenced the observer's judgement.

He expressed his data in the form

$$E = 7.5\,\bar{L}^{2/3}\,\theta^{4/3}\,W^{2/5}$$

where E is in lux, $\bar{L}$ in cd/m^2, θ in degrees and W in steradians. Like Hopkinson he found the effect of several sources to be additive. The exponents in the formulae given by the two workers are different.

Hopkinson's observers appear less prone to glare than those of de Boer although large variations in response between observers are to be expected in this type of investigation. In addition there appears to be differences in the semantic descriptions of glare, leading to large differences in tolerable intensities emitted by lanterns, for the same degree of stated glare.

The chief drawback to these observations is that they were static: in real installations the illumination at the eye varies cyclically and its magnitude depends on the lantern light distribution. De Boer and Schreuder (3.40) constructed an impressive scale model road in which the surface and lanterns moved to simulate movement of the observer. Observations on luminance uniformity using it have already been discussed above.

They asked observers to rate on a multiple scale the glare experienced in a "standard" installation which had the following apparent dimensions:

road width:	10 m
mounting height of lantern:	9 m
length of road:	300 m
number of lanterns:	11 m
flashed area of lanterns:	0.07 m^2
cut-off of car roof:	12^o
speed of travel:	50 km/h

The light distribution was characterised by the ratio I_{80}/I_{88} = 1.75 where I_{80} and I_{88} are two intensities on the run back of the distribution at angles of 80^o and 88^o to the downwards vertical: this simulates a semi cut-off distribution. A large number of situations were employed with different values of I_{80}, $\bar{L}$ and S max i.e. the glare, road luminance and uniformity were all varied. In order to avoid concentrating the subjects' attention on the glare aspect, appraisals were made of all three attributes of the installation.

The subjects were asked to rate glare on the scale:

Unnoticeable	9
Satisfactory	7

Just admissable	5
Disturbing	3
Unbearable	1

The semantic descriptions are allocated numerical values as shown in order that the data may be manipulated using normal mathematical methods.

The glare data can be expressed in the form

$$G = 14.56 - 3.31 \log I_{80} + 0.97 \log \bar{L}$$

i.e. the degree of glare in the standard situation is dependent on the intensity within the run back and the carriageway luminance but not its uniformity.

De Boer and Schreuder investigated the effect of other practical parameters and used the results together with those from the static investigation in order to make their formula general:

$$G = 13.82 - 3.31 \log I_{80} + 0.97 \log \bar{L} + 4.41 \log h'$$
$$+ 0.65 \log (I_{80}/I_{88} - 0.9) + \log F - 1.46 \log n + \Delta C$$

where h' is the height of the lanterns above the observer's eyes.

I_{80}/I_{88} is a measure of the severity of run back or cut-off.

F is the flashed area of the lanterns.

n is the number of lanterns per km.

ΔC is a correction for colour.

A graphical representation of these results is shown in Fig. 3.13.

These quantities are the practical parameters of street lighting and replace the classical parameters of the early workers and the need to sum the effects of several light sources. The writer has detected an apparent change in assignment of the numerical scale to semantic descriptions of glare with time and there is a somewhat poor correlation between results from the static and dynamic investigations which casts some doubt on the validity of combining the results from two experiments

However, it would be churlish to emphasise these since a very useful and unified relationship between discomfort glare experienced and lighting parameters has emerged. De Boer and Schreuder (3.40) claim good agreement between observations in lighted streets and predicted values from the formula. Others also have obtained good agreement (3.26, 3.35), see Fig. 3.14. Adrian and his associates (3.41, 3.42, 3.43) have confirmed the laboratory data of de Boer with a long series of observations using a static road simulation.

Only the British appraisals referred to above gave a grossly differing result: Cornwell (3.27) found a better correlation between the subjective assessment of glare and a simplified formula containing only terms in I_{80}/I_{88} and F. It is surprising indeed that his observers found the absolute intensity emitted by the lantern to have no effect. He found also that the assessment of glare played little part on his observers' overall assessment of visibility.

The de Boer and Schreuder formula contains a correction for the colour of light. The original experiment used white light; subsequently it was found:

$\Delta C = 0$ for incandescent and fluorescent lamps

$= +0.4$ for low pressure sodium lamps

$= -0.1$ for high pressure mercury lamps

$= +0.1$ for high pressure sodium lamps (3.44)

The writer, after analysing the then available data on visual performance on the road, concluded that the colour of light has little influence on performance, <u>except</u> that discomfort is less from low pressure sodium lamps than from other sources (3.45).

The value used above for the cut-off angle from the car roof appears to be excessive, the writer would have preferred a value of 20°

to have been used rather than 12^{o} (3.17). The degree of cut-off will influence the length of time lanterns are in view, the amount of the lantern distribution run back and the highest intensity experienced by the observers and the subjective impression of build-up and fall-off glare as each lantern is successively approached and then cut off.

De Boer and Schreuder used their dynamic road model to investigate the effect of the last two parameters (3.46). They found that in order to keep the state of build up of illuminance (dE/dt) at the driver's eye within a tolerable rating (5 - fair), the value of lux/sec should not exceed 85. As an example, they suggest for both discomfort glare and illumination build up not to fall below a subjective rating of 5 the absolute intensity in the lantern beam should not exceed 20 kcd and this peak should not be higher than 70^{o} to the downward vertical.

The one remaining deficiency yet to rectify is that the general formula contains no allowance for the effect of the luminance of the surrounds. The investigators seem to assume that the bright carriageway alone determines the general adaptation luminance. The writer would expect bright facades of buildings to also mitigate discomfort glare. The simulation appeared to have dark backgrounds to the carriageway.

NECESSARY REQUIREMENTS FOR GLARE LIMITATION.

As discussed earlier there must be a compromise between requirements of road illumination and glare restriction in that part of the beam distribution termed the run-back. If attention is only paid to visibility of objects against the carriageway, disability glare is not a problem and needs no formal consideration. However, the surrounds to the carriageway are considered an essential part of the visual field and disability glare becomes appreciable when the surrounds are intrinsically dark. Some restriction in terms of veiling luminance or rise in threshold should be devised.

It is discomfort glare, the brightness of the lanterns, that is most obvious to road users and since there is now a full description of the effect it is a simple matter to set a tolerable level of glare. Having done so the requirements of the run back of the light output distribution of the lantern can be calculated and, if required, formalised. For general application a rating of 5 (just admissable glare) is probably sufficient: this allows the use of semi cut-off lanterns. However, where higher quality is required or the general environment is dark a rating of 7 (satisfactory) or above is warranted: this rating takes the lantern performance into the cut-off classification.

THE SPECIFICATION OF STREET LIGHTING.

The criteria of quality for street lighting have been assessed as level of road luminance and its uniformity and limitation of glare. It has been shown how the light output distribution from lanterns, their arrangement and the reflection characteristics of the road surface influence the performance of an installation in terms of these criteria. Further there is an impressive amount of data on visual performance and system efficiency upon which to base numerical values of the criteria.

Discussed next is the way in which this knowledge can be formalised into specifications for lighting design and the equipment. Whether the specified lighting is used or not in any particular situation will not be discussed here in detail. Obviously, specified lighting has to be an economic proposition. Urban traffic route lighting can be justified because the cost of it can be more than set against accident savings. The form of the lighting cost benefit equation and the various costs and benefits that need to be taken into account have been discussed fully by the writer (3.47). These discussions lead to traffic warrants for the implementation of lighting.

LIGHTING LEVELS.

What emerges from this review is a set of minimum values for the lighting criteria for mixed road user, low speed, urban traffic routes. For example:

Average luminance $\geq$ 1 cd/m^2

Minimum luminance $\geq$ 0.5 cd/m^2

Glare restriction $\geq$ 5 (on the de Boer/Schreuder scale)

These values, which can be expressed in different ways are those below which the lighting engineer should not go. If a higher quality is required the various relationships discussed above show in what way and by how much parameters should be adjusted. For example average luminance needs to be raised to 2 cd/m^2 and glare restriction increased to 7 before the next subjective rating is reached.

The minimum requirements may be upgraded for other road situations. In many specifications the level of lighting depends on the road importance, i.e. the level of activity (3.2). In the writer's view, this is not justified per se. There is no evidence in the street lighting literature that visibility of objects, level of lighting and complexity of situation interact. In the writer's view, if the lighting is sufficient for objects to be visible in isolation added complexity of the situation will not make them less visible. As discussed in Chapter One, complexity can lead to relevant information being ignored; this is a traffic management not a lighting problem.

However, in difficult situations, the general engineering principle of having margin for safety is sensible; the experimental data does have limits of resolution and confidence. On high volume routes, where accidents have a greater probability of happening and when they happen, have a greater potential repercussion, say in terms of delay to traffic, a higher level is warranted. Economically, a higher level can be justified because the potential savings in accident costs are higher, the higher the traffic volume.

Generally, higher values of lighting criteria are also specified for motorways. Higher volumes justify higher levels as before simply because it is better to err on the side of safety. However, it has also been pointed out that the visual task is probably more difficult in motorway driving justifying higher light levels.

Thus the minimum standard can be readily justified together with increases on it for various situations, the increases being at least one step in the rating scales. The question arises whether a specification should be written just in terms of the criteria and their values or whether a specification needs to be amplified into a specification for installation and equipment design.

NATIONAL LIGHTING CODES.

Some national lighting codes of practice state the design criteria and their values explicitly, describe necessary lantern attributes and give methods of design procedure, e.g. U.S.A. (3.48). Others, whilst stating the design criteria, jump over the necessary values and basic design procedure and end up as working documents of installation layouts. These cover all likely road configurations and employ lanterns of specified attributes, e.g. United Kingdom (3.49).

The present CIE International recommendations (3.3) state design criteria and values, some in a rudimentary manner. They indicate the minimum amount of illumination, maximum lantern spacing to height ratios and lantern attributes necessary in order to fulfil the criteria. Only the CIE document gives quantitative data on the effect of the road surface on installation design and requirements.

BASIC FORMAT OF CODES

The upsurge of experimental data on the requirements for good visual performance and appraisal rating, on the reflection characteristics of surfaces and easy access to computers for data manipulation have led to a reappraisal of lighting specifications. In particular the CIE recommendation, which may be expected to influence national codes of practice, is being revised. Committee papers suggest that the criteria of road luminance, luminance uniformity and glare restriction will be precisely specified. Emphasis will be laid on the influence of the road surface in determining installation performance. Much less emphasis will be given to specification of practical installations and lanterns. However, standard methods of measurement and presentation of surface and lantern data will be specified, togetherwith computer methods using this data to predict installation performance.

Protagonists of this approach seem to be saying that each lighting installation must be an individual design based on precise knowledge of the road surface. Further, they would say that each criterion is not independent, they interact in a complex manner which does not lead to simple tabulations of installations. Thirdly, they would affirm that rigid specification of light distribution impedes development of efficiency. Others have questioned the implied complexity of lighting insisting that only a limited number of solutions for day to day applications are feasible. They suggest that current data should be used in the development stage but not in the application stage (3.50, 3.51).

It is certainly true that current methods yield many insights in street lighting mechanisms. The data on reflection characteristics and glare limitation show how the run back section of the beam distribution should be designed. Computer techniques allow the expected performance of installations designed to specifications to be checked and analysed

(3.12,3.51). Outstanding problems can be investigated; Frederikson (3.10) has shown how the wetness of surfaces and lantern beam distribution influence the appearance of installations in wet weather. It appears to the writer, however, that computer design of installations is an iterative process, criteria values are arrived at by trial and error by feeding in designs until the required results are achieved.

The writer has pointed out that the form of the specification must reflect to what use it will be put and how street lighting is administered (3.52). In Australia, for instance, there are many relatively small authorities responsible for installing lighting, they buy equipment and government pays a subsidy on installations reaching a given standard. This requires a document which not only clearly states the criteria and their values but which also gives working tables of installation design and details of lanterns. This enables installations to be easily designed, equipment to be easily specified and, finally, proposals to be easily checked and passed, in the design stage. Checking after implementation is laborious and difficult, as will be seen in the next chapter.

AUSTRALIAN CODE OF PRACTICE:

The first revision of the Australian Traffic Route Lighting Code after the war, ASCA19:1964, was based on field observations referred to above. It was found that satisfactory road luminance, uniformity and glare restriction was achieved in a standard installation (3.25):

Arrangment of Lanterns:		Staggered
Road width	:	(13.7m) 42ft
Lantern spacing	:	(36.6m) 120ft
Lantern mounting height	:	(7.6m) 25ft
Lantern type	:	semi-cut-off

Lantern lower hemisphere flux	:	5000 lumens
Road surface	:	asphaltic concrete.

This standard installation embodies the quantitive design criteria

(a) Level of luminance - 0.2 ft L (0.7 cd/m^2)

(b) Uniformity - No dark area

should cover a longitudinal distance greater than 80 ft(24.4m). When seen from the position of a driver, eye height 4 ft(1.2m) at a distance of 250 ft(75m). The ratio of average to minimum luminance should not exceed 5:1 across and 10:1 along the road.

A single minimum standard of lighting was specified by tabulations of installation geometries and lantern requirements, the requirements being extrapolated from the standard installation, using stated procedures and boundary conditions (3.53, 3.54).

This code of practice has been recently revised and reissued as AS1158, 1973. The revision was based substantially on the old requirements with upgrading which took into account:

(a) Proven success of installations in accident reduction (3.55);

(b) Practical experience of implementation of over 1000 km of installations in one state alone under the government subsidy scheme (3.54, 3.56);

(c) Measurements in in-service installations of photometric parameters, to be described in the next chapter (3.57);

(d) Results of experimental work into the requirements for good visual performance, including those embodied in the CIE recommendations and proposals before its street lighting committee.

Upgrading included raising the luminance level to at least 1 cd/m^2 for new installations, not falling to below 0.7 cd/m^2 in service; improved uniformity by raising the minimum mounting height to 8.5 m (27.6 ft), preferred 9.0m (29.6 ft) and by reducing the lantern spacing to height ratios; simplifying glare restriction by not permitting non cut-off lanterns and reducing the semi-cut-off class to one instead of two.

The stated design criteria are now:

(a) Level of luminance. The luminance of surfaces against which objects on the road and its verges are to be seen in silhouette must be sufficiently high to provide the contrast necessary for visibility. The recommendations relating to the installation geometry and lantern flux to be provided will ensure that an average road surface luminance of at least 1.0 cd/m^2 is attained initially. Provided that maintenance is carried out in accordance with the recommendations, the average road surface luminance will not fall below 0.7 cd/m^2 throughout the life of any installation.

(b) Uniformity of luminance. The luminance of the roadway should be sufficiently uniform to prevent the occurrence of dark areas of such size as to conceal an object of significant dimensions (0.3 m square). On a straight road at uniform grade, the top of an object 0.3 m high and 75 m away is seen against the road surface 100m away, from a driver's eye-height of 1.2m. The recommendations have therefore been framed to ensure that no dark area will extend a longitudinal distance of more than 24 m when seen from 75 m away so that any concealment from an approaching driver at that distance would be momentary only.

The uniformity of luminance should also be such that the appearance of the road is comfortable to the driver for long periods. Considerable non-uniformity will cause both discomfort and fatigue. Installations will provide ratios of minimum-to-average luminance of greater than 0.33, taken over the whole carriageway. Ratios of minimum-to-maximum luminance of greater than 0.25 along the centre-line of each traffic lane will also be provided.

(c) Direct illumination. Objects on the carriageway are seen partly against the carriageway but also against the road verges as a background. Thus lighting of the verges is as important as that of the carriageway.

The general concept of traffic route lighting is the seeing of objects in silhouette. This may be achieved when the material surfaces comprising the verges are sufficiently light in tone. But frequently the nature of these surfaces makes silhouetting impossible. It is therefore necessary to consider the direct illumination of the road verges and of objects on them, especially pedestrians.

Direct illumination is also important in revealing roadway features such as the islands of channelizations, and other vehicles on the road particularly in dense traffic conditions.

(d) Control of glare. At the illumination levels economically practicable in street lighting, glare from lanterns is accentuated by the low level of average brightness and may cause both visual discomfort and disability.

To minimize glare, requirements for the distribution characteristics of lanterns are included which provide for a choice between cut-off and semi-cut-off distributions.

It should be noted that glare limitation is given only in terms of necessary lantern characteristics. However, it has been shown that semi-cut-off lanterns give rise to a discomfort glare limitation rating, according to the de Boer method, of about 5 (just admissable). Qualitative reference is also made to the importance of the surrounds.

The tables of installation layouts refer to an asphaltic concrete surface, that of the original test site, assumed to be typical of those in Australia. Jackett and the writer (3.12) have shown, by means of computer analysis using road surface reflection data, that over a wide range of installation geometries, average road luminance and uniformity vary little on this surface, using a specified semi-cut-off lantern; see Table 3.1. They point out that some other surfaces measured had different reflection characteristics. Installations on them could be of high luminance but less uniform or lower in luminance and more uniform, depending on the characteristics.

In the writer's view the Australian code of practice has evolved logically, paying regard to and keeping pace with necessity, experience and knowledge. In due course more attention will be paid to the road surface aspect, if it is shown to be a problem, as sufficient knowledge is accumulated and as it becomes amenable to action. It is relatively easy to measure reflection characteristics in the laboratory. It is relatively easy to draw up a classification so that once a surface is classified, standard reflection data for that classification can be used to determine the photometric performance of an installation to a few percent accuracy.

What is not easy or indeed possible to do at present, is to measure a surface insitu for classification or predict the classification of a surface to be laid. Present experimental equipment for on site measurement is hardly practicable (3.7) and none is available commercially. Currently a lighting organisation in the U.K. holds a government contract to develop viable equipment for this purpose. Until this comes along, it is not feasible to include detailed requirements based on surface characteristics in working specifications.

In the writer's view it would be a simple modification to the present Australian code,when the time is ripe, to give tabulations of installation geometries for several classes of surfaces in common occurrence. However, one could hopefully look to the day when the wearing, skid resistant, lighting, noise producing and riding properties of surfaces are optimised so one surface type is always used.

DISCUSSION:

It has been shown that quality criteria for street lighting are well established. There is an impressive amount of knowledge on those factors which influence lighted appearance and an equally impressive amount of knowledge on what appearance is necessary for good visual performance. How those data can be used to draw up a code of practice has been indicated, with particular reference to the Australian Standard.

Whilst it is easy to check by computor methods that a design will give a particular performance on paper, it is less evident what actually happens in practice. Chapter 4 describes an extensive check of the photometric characteristics of installations designed to the then current Australian Standard.

Earlier it was pointed out that the whole of the visual field is important. Current specifications develop detailed requirements for the carriageway and the lanterns. A similar treatment for the surrounds to the carriageway is not evident, because it is very difficult to give them the same degree of formalisation as the carriageway. It will be shown in the next chapter that the surrounds can be dark and disability glare can be appreciable in real installations. Chapter 5 shows what parameters of the run back of the light distribution from lanterns are important in the control of disability glare. Chapter 6 investigates the visibility of objects viewed against the surrounds and the influence of disability glare. It will be suggested that surround luminance and restriction of disability glare should be included in the criteria of quality.

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MOUNTING HEIGHT	INPUT DATA			RESULTS	
	Spacing	Road Width	L.H.Flux	Average Luminance	Luminance Uniformity
h(m)	S(m)	W(m)	$F \times 10^4$ (lumens)	$\bar{L}$ cd/m^2	$\frac{L_{min}}{\bar{L}}$
9	38.1	13.2	0.85	0.69	0.31
10	42.3	14.5	1.05	0.68	0.31
11	46.6	15.8	1.27	0.67	0.32
12	50.8	17.1	1.51	0.66	0.32
13	55.0	18.4	1.78	0.66	0.32
14	59.2	19.7	2.06	0.65	0.32

Table 3.1. Calculated values of average luminance and uniformity for staggered installations of semi-cut-off lanterns on an asphaltic concrete surface, using the installation layout relationships of AS 1158, 1972.

(After Jackett & Fisher)

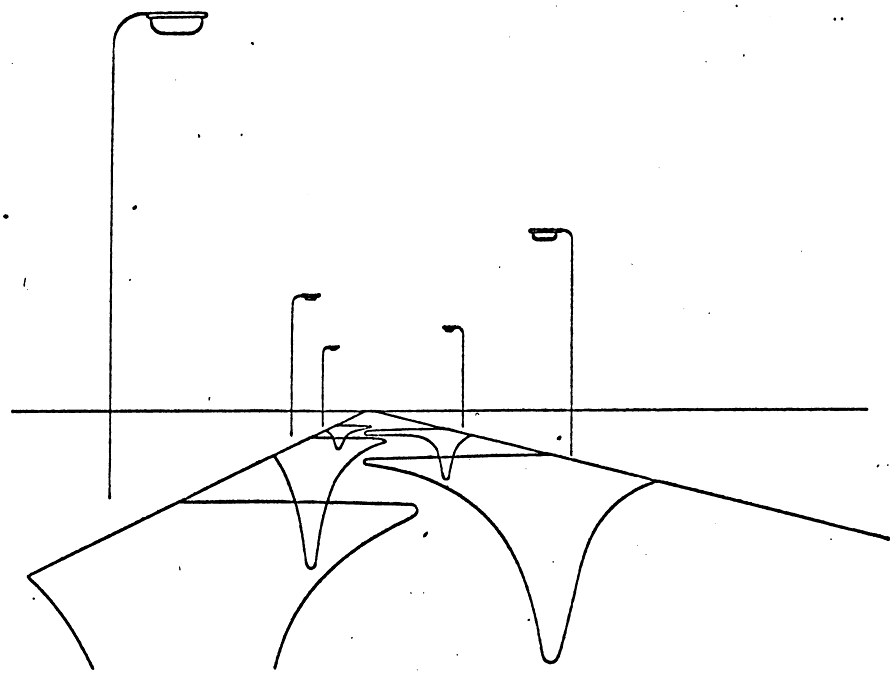


Fig. 3.1. Perspective view of carriageway showing light patches produced by the lanterns.

(After HMSO)

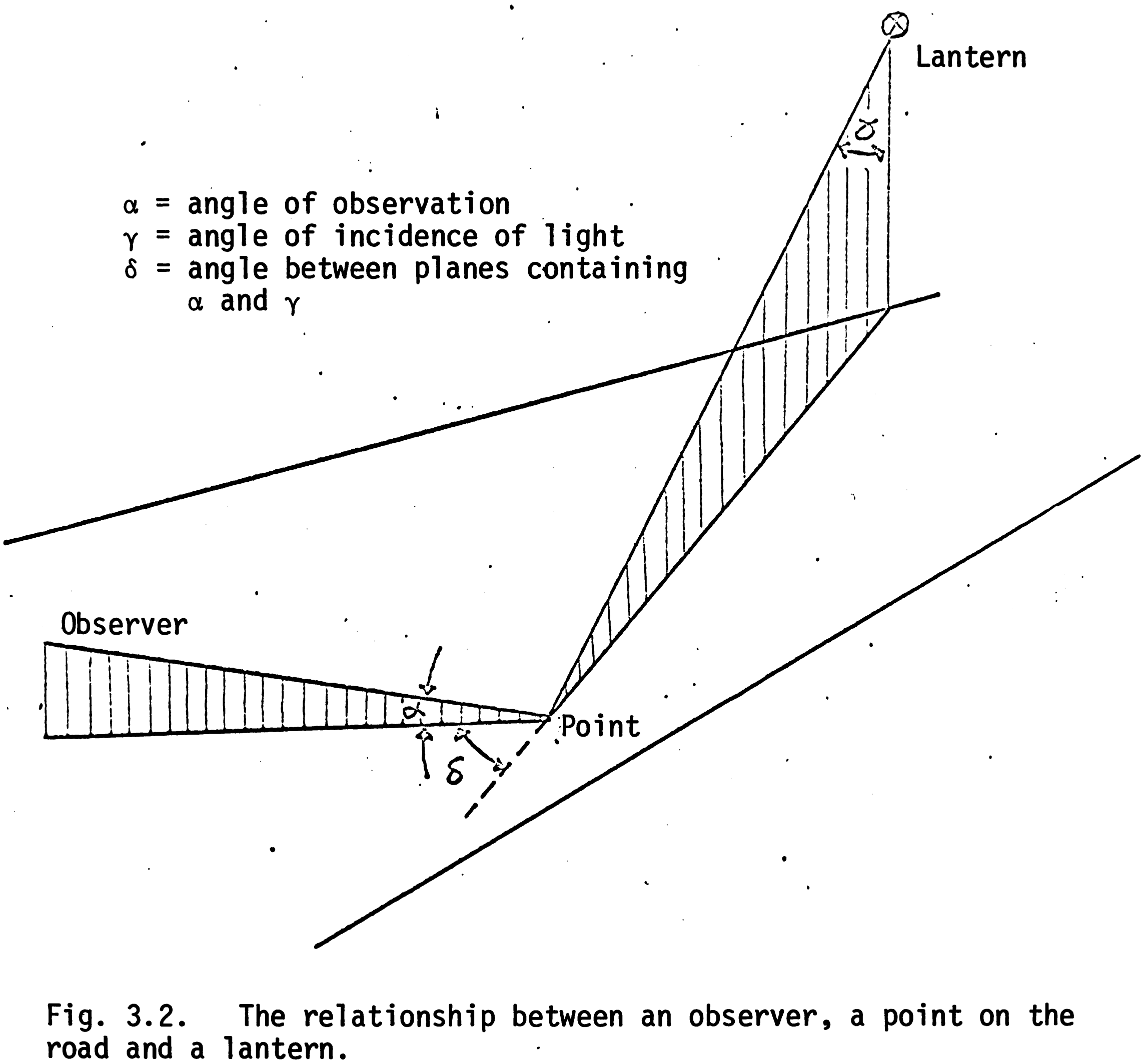


Fig. 3.2. The relationship between an observer, a point on the road and a lantern.

(After de Boer)

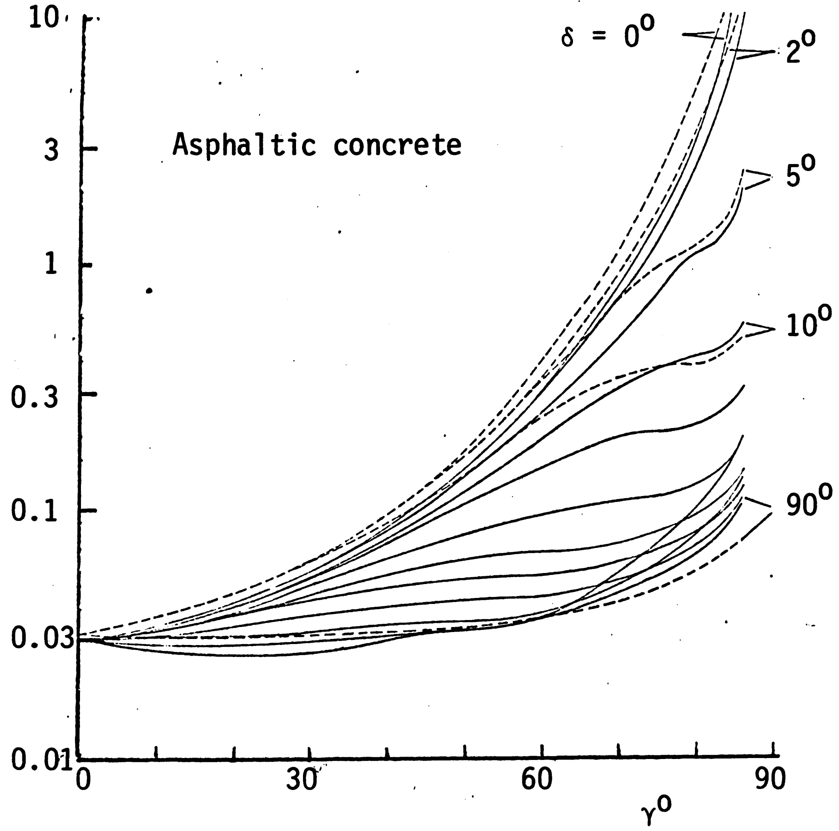


Fig. 3.3. The variation of the luminance coefficient q with γ and δ for a surface. The dashed lines refer to a second sample from the same site.

(After Jackett & Fisher)

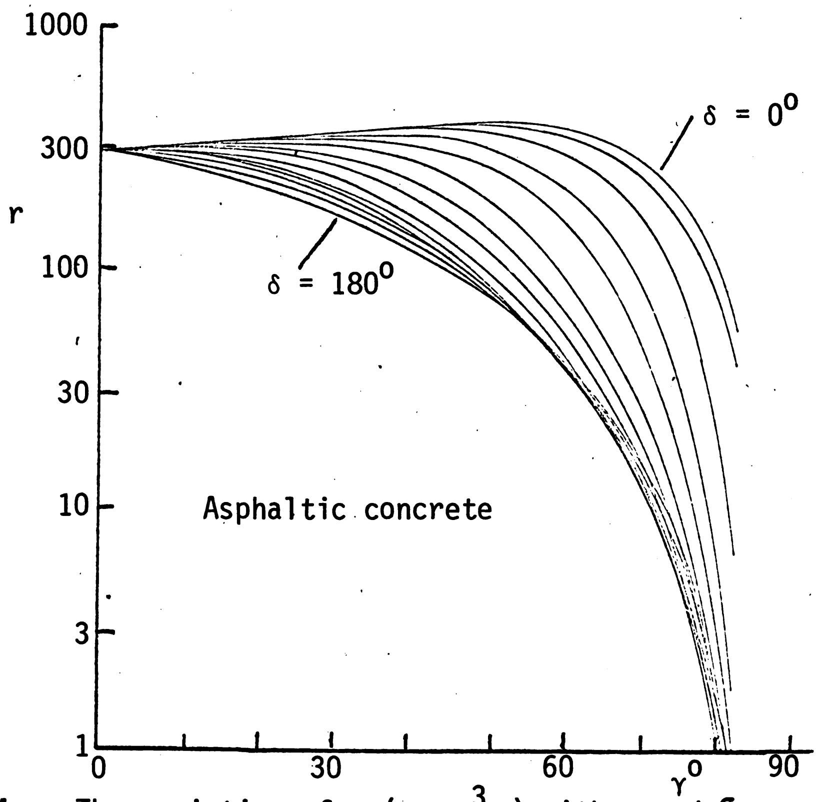


Fig. 3.4. The variation of r ($q \cos^3 \gamma$) with γ and δ.
(After Jackett & Fisher)

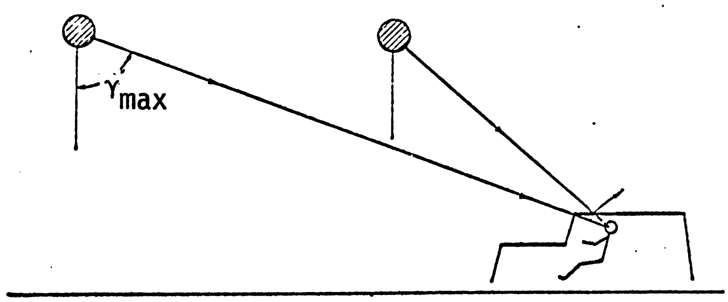


Fig. 3.5. Drivers eyes are shielded by the roof of the car from light emitted at an angle less than γ_{max}. (Values of γ_{max} of 70^{o} to 78^{o} are quoted in the literature.)

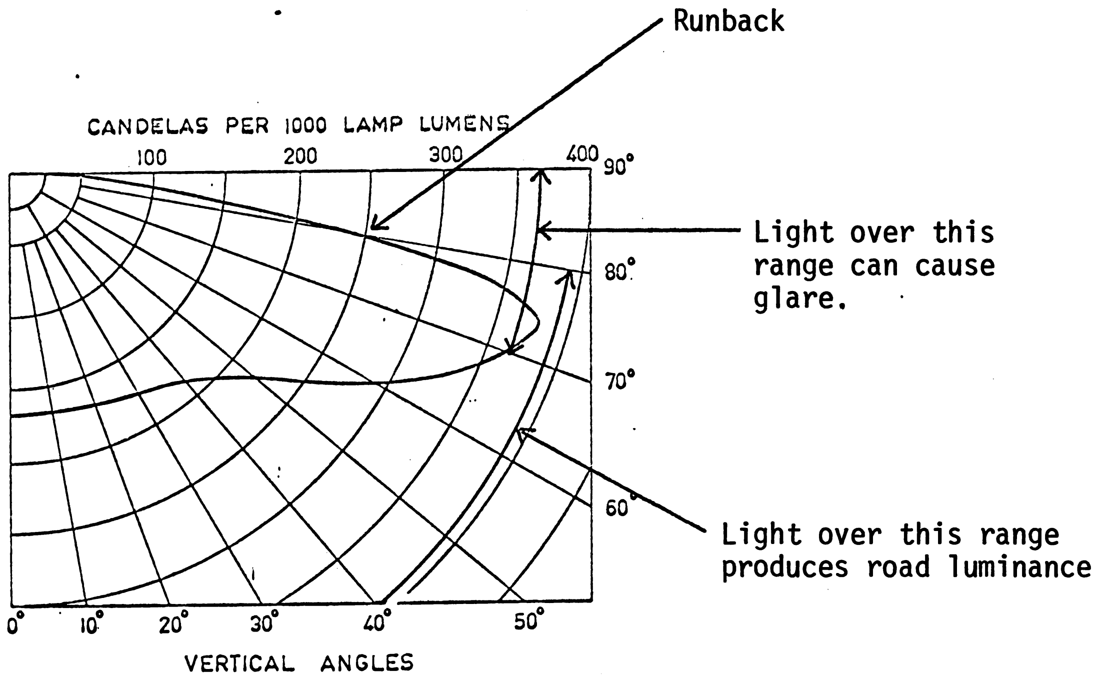


Fig. 3.6. The intensity distribution in a vertical plane parallel to the road edge for a semi-cut-off lantern, showing importance of the runback.

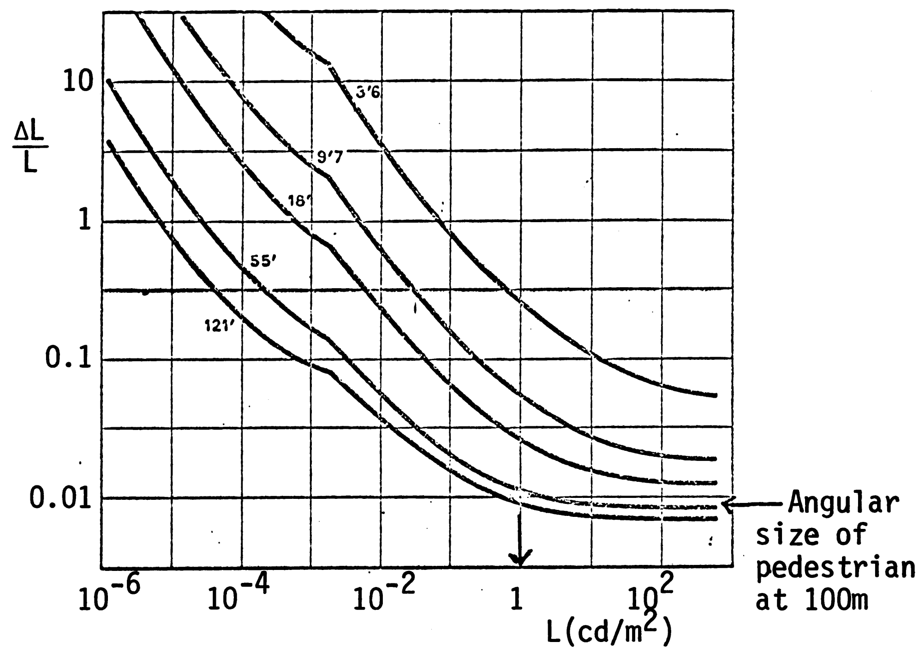


Fig. 3.7. Blackwell's data showing contrast detection ($\frac{\Delta L}{L}$) is close to maximum at light level (L) of 1cd/m^2 for pedestrian sized objects.

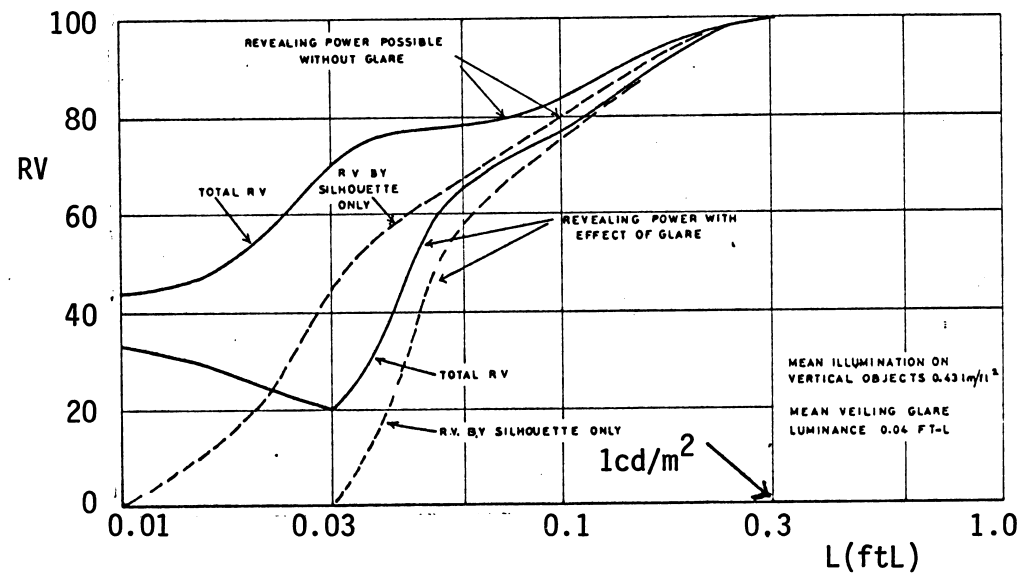


Fig. 3.8. Variation of revealing power (RV) with background luminance (L) in a lighted street. (RV approaches 100% at about 1cd/m^2: disability glare effects RV at L values less than this.)

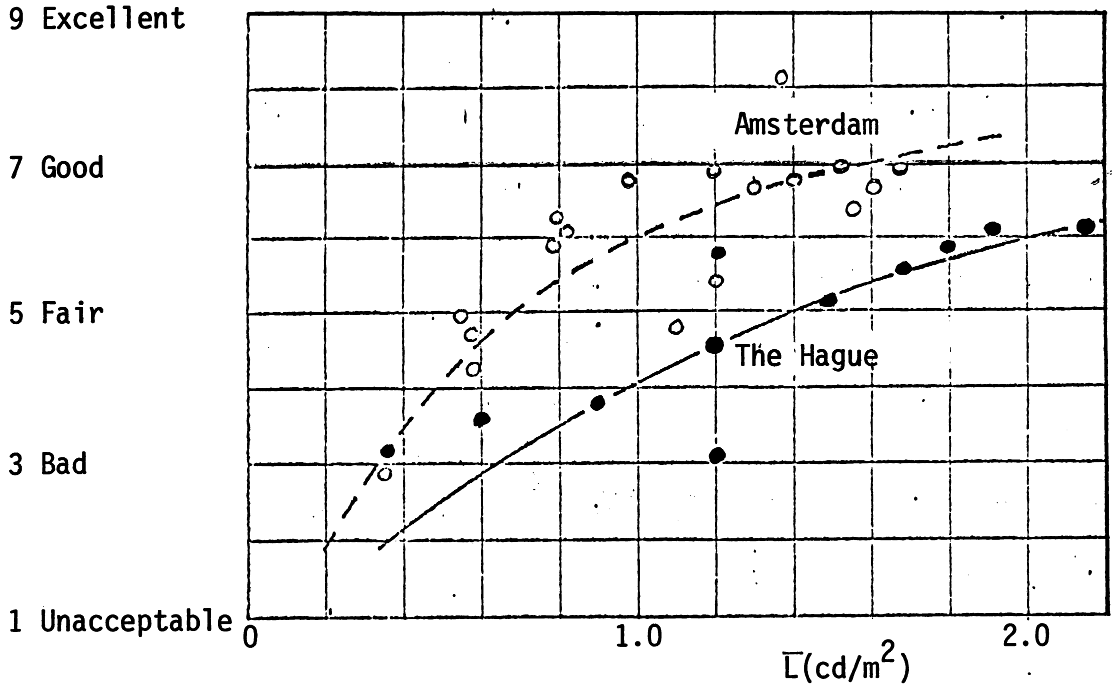


Fig. 3.9. Subjective assessment of level of luminance $\overline{L}$ in installations on main and through roads in two cities.
(After de Grijs)

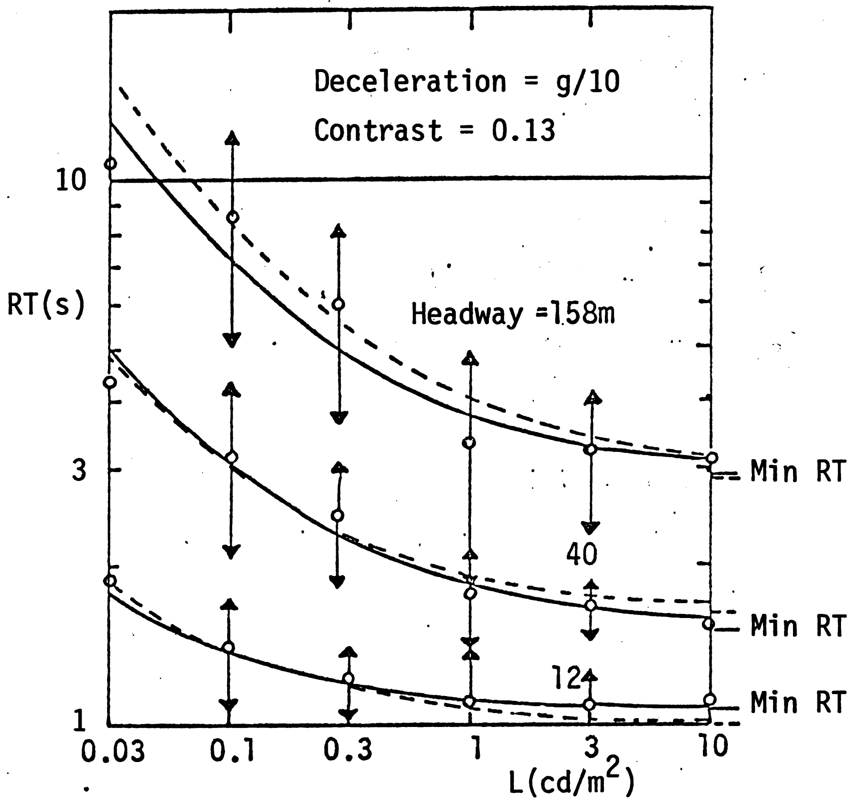


Fig. 3.10a. Variation of mean reaction time (RT) with light level (L) to object of changing size. The full lines are calculated for each data set, the dashed from a general model. The bars indicate RT ± 1σ.

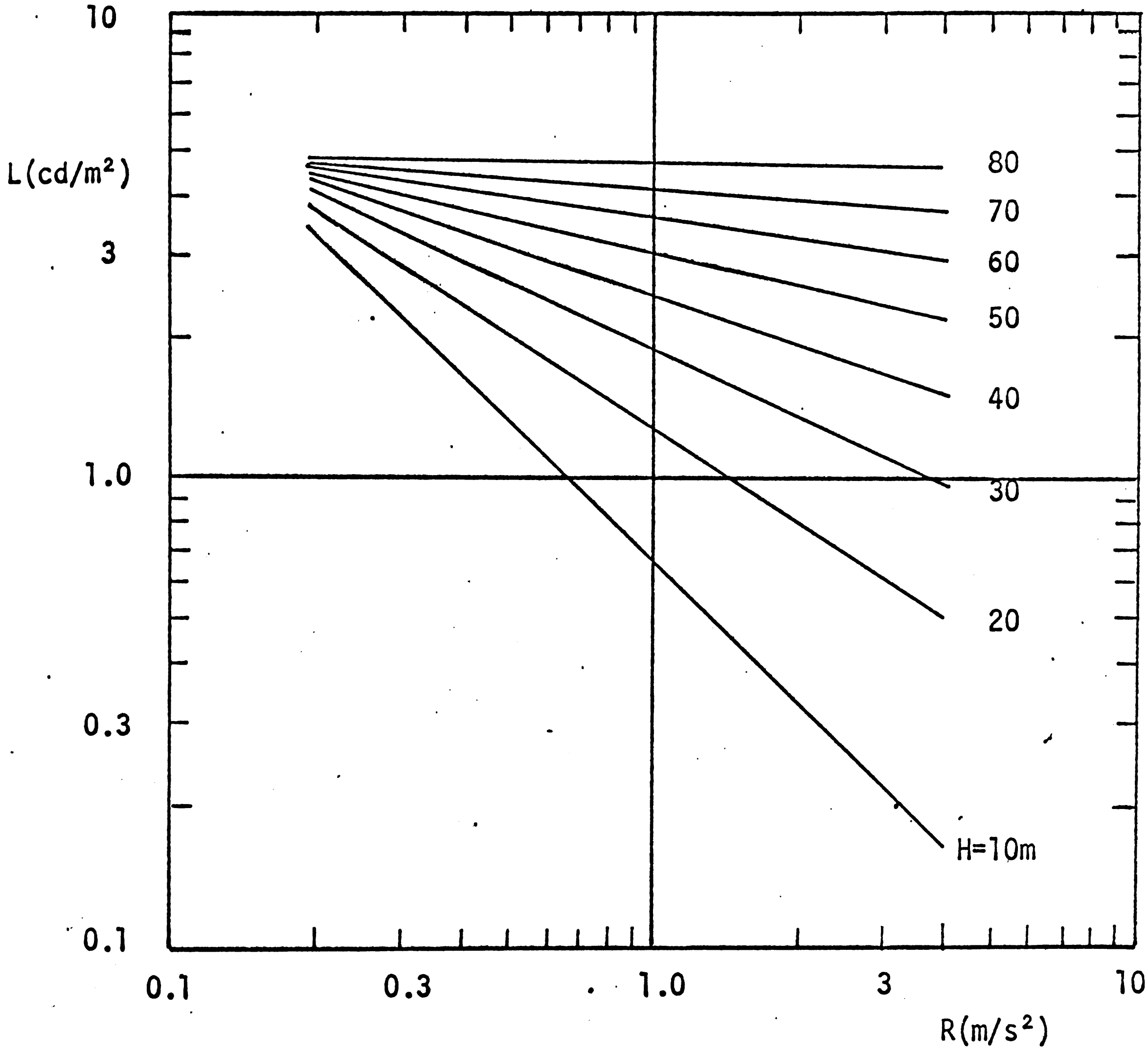


Fig. 3.10b. Nomogram relating light level (L) required to detect apparent change in vehicle headway, for initial headway (H) and acceleration/deceleration (R), with a minimum reaction time plus 10 per cent.

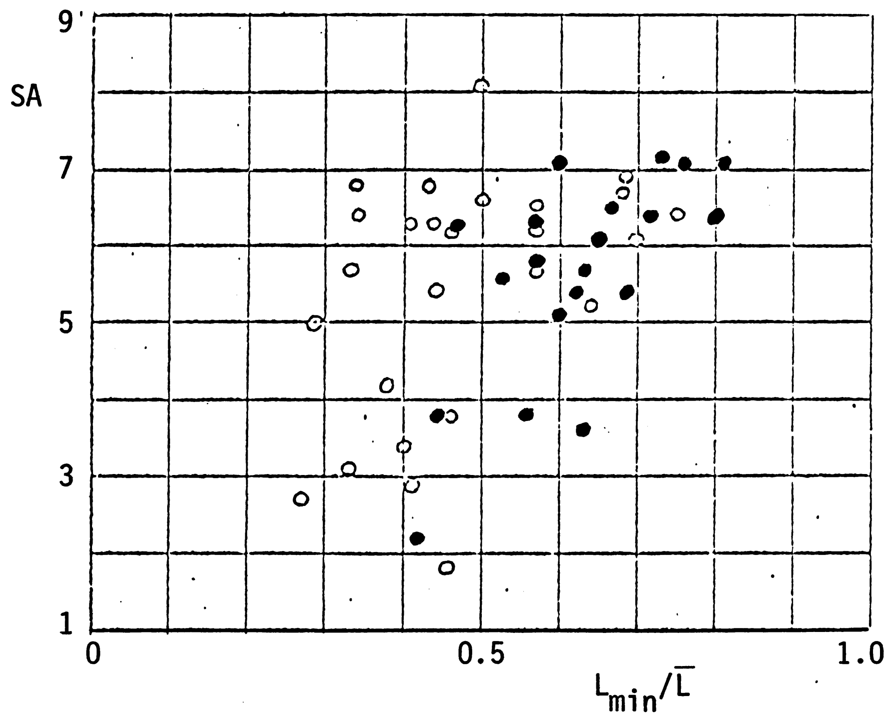


Fig. 3.11a. The subjective assessment (SA) of uniformity of luminance ($L_{min}/\overline{L}$) in lighted streets of two cities.

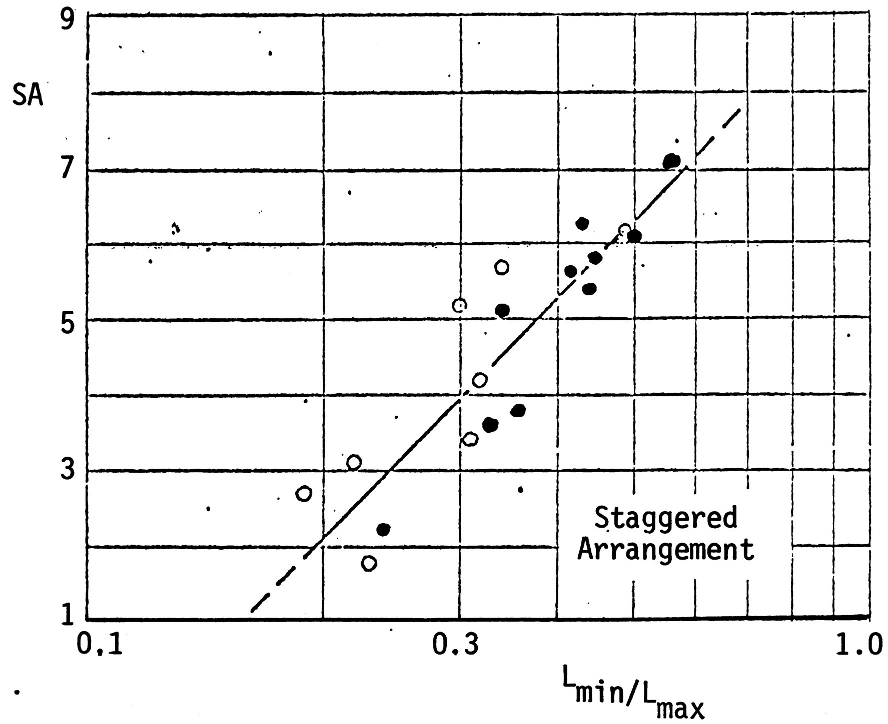


Fig. 3.11b. The subjective assessment (SA) of luminance uniformity (L_{min}/L_{max}) in the streets of two cities. The numbers have same meaning as in Fig. 3.9.

(After de Grijs)

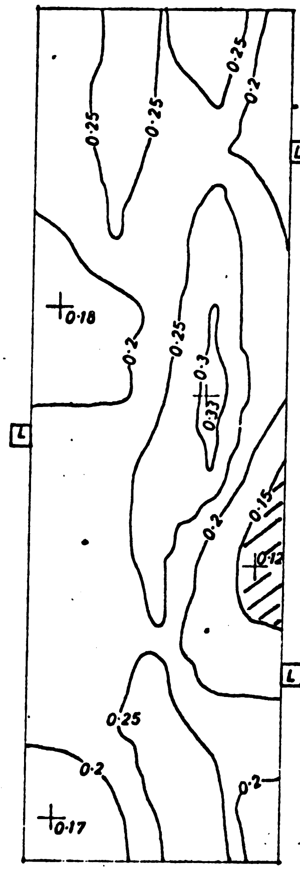


Fig. 3.12. Contours of luminance (ftL) in a staggered installation with semi-cut-off lanterns on an asphaltic concrete surface. (Typical area of low luminance across road from observer is shaded.)

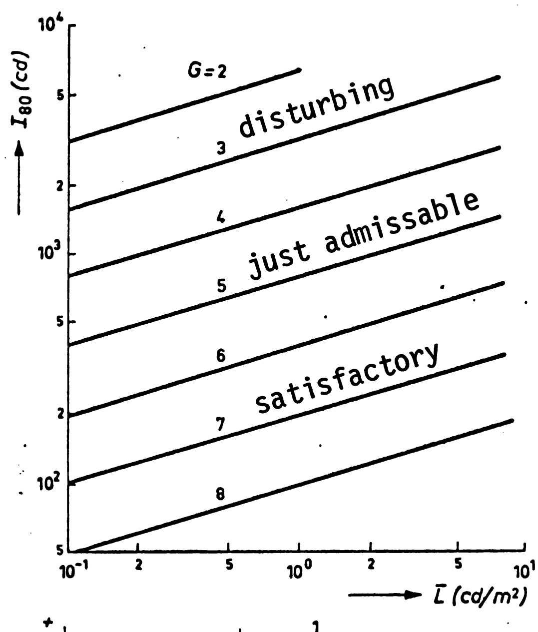
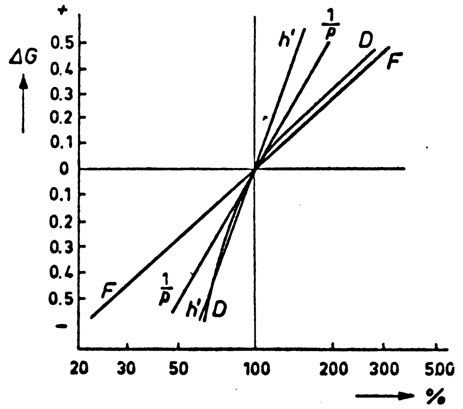


Fig. 3.13. Graph of results of de Boer and Schreuder on appraisal of discomfort glare.

The relation between the maximum luminous intensity of the lanterns at an angle of 80° to the downward vertical (I_{80}) and the average road-surface luminance ($\bar{L}$) for different values of the glare mark (G). These curves refer to the "standard installation".



The relation between the correction (ΔG) to the glare mark G and the relative mounting height (h' = difference between height of lantern and height of observer's eye), spacing ($1/p$, where p = number of lanterns per km of road), light distribution ($D = I_{80}/I_{88}$) and size of the fittings (F). This figure thus indicates how the glare mark G
must be changed if the installation concerned differs in some way from the standard installation

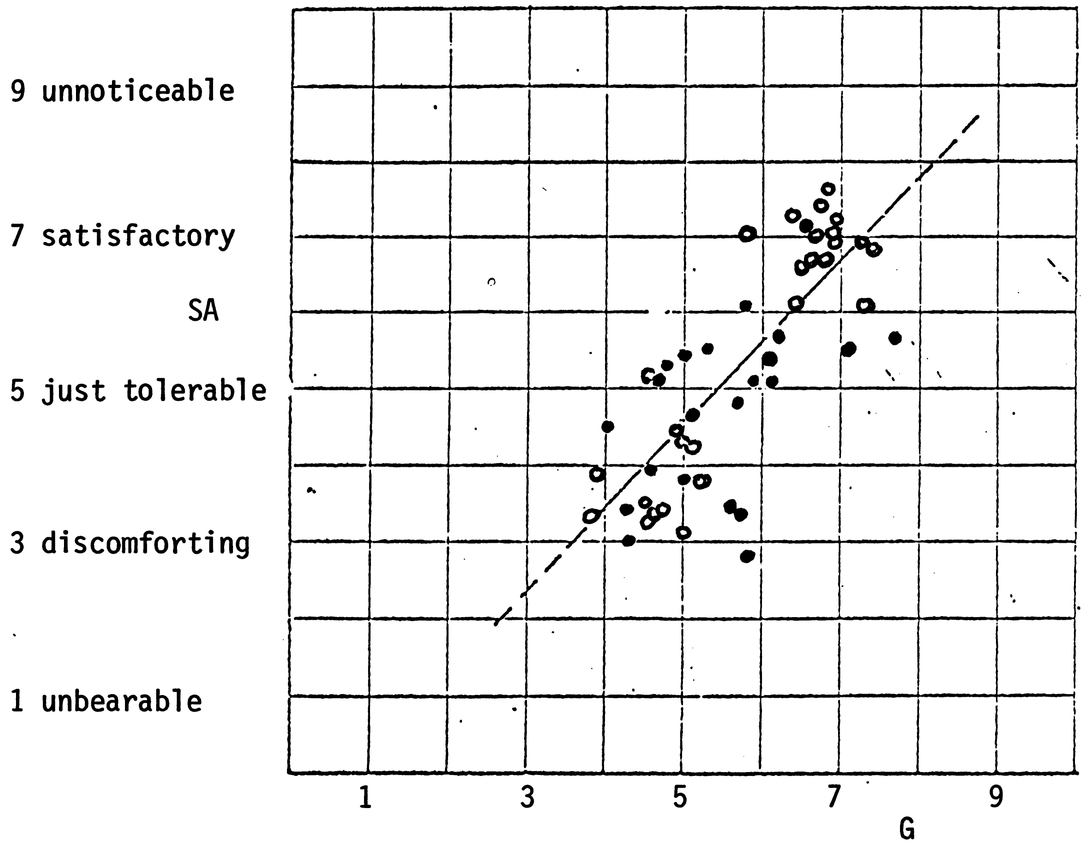


Fig. 3.14. Subjective assessment of glare (SA) made in lighted streets of two cities and calculated glare mark (G).
(After de Grijs)

CHAPTER 4

PHOTOMETRIC MEASUREMENTS IN IN-SERVICE STREET LIGHTING INSTALLATIONS DESIGNED TO AS CA19 PART 1 (1964)

INTRODUCTION.

In the last chapter, the bases of street lighting practice were examined, pointing out the common design criteria and their suggested values, and how these are translated into working specifications and hardware for practical implementation. This chapter describes photometric measurements carried out on in-service installations to the then current Australian standard to see how successfully the design criteria can be implemented. The measurements provide data from real environments on which to base a re-assessment of the fundamentals of the lighting specification and practice.

Since these measurements were taken, and before the publication of this thesis, the Australian Standard AS CA19 was revised and re-issued as AS 1158 Part 1 1973. These measurements were available to the revision committee (SAALG/2) and were made use of by the committee (4.1, 4.2).

METHOD.

Two sets of measurements were carried out:

(i) at 14 sites, on road luminance, its uniformity, disability glare, illumination and luminance of the surrounds. Each installation was at least to the minimum requirements of Australian Standard CA19 Part 1 (1964). The sites were chosen to cover as wide a range of parameters, i.e. installation geometry, lantern type and pavement surface, as was possible at the time of the investigation. In fact, the majority were staggered installations using mercury lamped semi-cut-off reflector lanterns. Site details are given in Table 4.1.

(ii) at six further sites, into disability glare. Site details are given in Table 4.2.

The procedures adopted for the measurement of the various parameters were:

Pavement Luminance.

A Pritchard Spectra Photometer was mounted 5ft(1.5m) out from the kerb at an eye height of 4ft(1.2m) and 300ft(92m) from a lantern on the same side of the road. The luminances at 40 or 50 test spots (depending on carriageway width) were taken at the intersections of imaginary grid lines of which there were 10 across the road and four or five along the road, within a length of road bounded by distances 150ft(46m) either side of the lantern.

The instrument was aimed at the cross piece of an inverted T, which had torch bulbs at the extremities, held at the various test points in turn. The circular field aperture of the instrument was replaced by a specially made rectangular one; the size of the rectangles was varied in three steps so that the area of pavement sampled was always about 15ft (4.5m) long and 5ft(1.5m) wide. The instrument was calibrated at frequent intervals and found to be stable. Inter-range agreement was within ±5 per cent and calibration of one range varied over ±4 per cent. No significant colour correction (<5 per cent) was necessary for mercury fluorescent lamps.

Surround Luminance.

The photometer was placed 10ft(3m) out from the kerb at a suitable position within the installation and aimed at various components which made up the roadway background. Circular field apertures were used commensurate with the size of detail to be measured.

Disability Glare.

Glare was measured using the disability glare integrator fitted to the photometer. The glare was measured at 11 intervals through two spans of each installation. The instrument was mounted 5ft(1.5m) from the kerb at a height of 4ft(1.2m) and aimed at a spot 300ft(92m) ahead, ie. approximately 0.75° down. The instrument was shielded to simulate the cut-off of a car roof.

In the second series of measurements, only a single glare measurement was taken, with the photometer looking horizontally along the road and positioned in the installation at such a distance from a lantern that the angle to the downward vertical to that lantern was 84°. The first method is extremely tedious and somewhat dangerous when the instrumentation has to be moved manually along the road.

Illuminance.

The illuminance which would fall on a vertical object facing the traffic was measured with a Weston Illumination Meter Model 756 placed 3ft (0.9m) above the surface at various points through two spans. For increased sensitivity the photocells were neither colour nor cosine corrected. Calibration showed no significant correction was necessary for mercury fluorescent lamps. Departures from true cosine response are not significant for angles of incidence less than 60°, i.e. for distances from the bases of lamp columns greater than 0.58H.

General.

Sites were chosen on straight level sections of road where possible; in a few sites the pavement was on a uniform grade. The work was undertaken in the autumn and early spring on clear nights. A complete set of measurements for one site, including marking out of the pavement, involved a team of four people working from about 9.30 p.m. to 1.30 a.m.

Two people operated the photometer and two people the marker (one to look out for vehicles and so protect the exposed marker man). The photometer team was protected by a parked van showing two intense rear lights and by reflectorized warning triangles. Sufficient protection was provided without drawing undue attention to the team and so disrupting the flow of traffic. Because vehicle lights interfered with measurements these had to be taken during gaps in the traffic flow.

RESULTS.

Average Pavement Luminance.

The average pavement luminance $\overline{L}$ (arithmetic mean of all the grid point readings) together with variations in pavement luminance are given in Table 4.3. A cursory examination of the table shows that 11 out of 14 sites yielded values of $\overline{L}$ greater or equal to the minimum average road luminance criteria of 0.2ftL (0.7 cd/m^2).

The minimum $\overline{L}$ requirement is based on the use of lanterns directing a minimum amount of light flux - lower hemisphere flux (F) - downwards onto the carriageway and its surrounds. In Chapter 3 it was shown that installations of minimum quality are designed on the basis of the nominal lower hemisphere flux per unit area of carriageway being 1 lumen per square foot or $^F/SW$ = 1lm/ft^2 (11 lm/m^2) where S is the lantern spacing and W is the carriageway width.

In Fig. 4.1 $\overline{L}$ is plotted against $^F/SW$ for each installation. They all have values of $^F/SW$ equal or greater than 1 lm/ft^2. In fact, all installations except 1 and 12 have values of $^F/SW$ of 1.5 or over; the values for installations 8 and 9 are between 2 and 3 and for 13, a prestige installation, it is over 4. The actual in-service values of $^F/SW$ are compared to the minimum requirements for each installation in Table 4.4 taken from AS CA19. It would appear that in practice installations are rarely at minimum level. This is due probably to the tailoring of the installation to fit in with existing electricity reticulation poles and commercially available lamps which come in a range of discrete lumen outputs and to making sure the installation is to the minimum standard so as to attract a government lighting subsidy.

Even so installations 1, 2 and 14 have values of $\bar{L}$ below the minimum value — installations 8 and 9 have values of $\bar{L}$, which though up to the minimum, are low in relation to their values of $^{F}/SW$. The eight other installations, 3, 4, 5, 6, 7, 10, 11 and 12, with values of $^{F}/SW$ between 1 and 2 have values of $\bar{L}$ between 0.2ftL (0.7 cd/m^2) and 0.35ftL (1.2 cd/m^2). In general the value of $\bar{L}$ increases as $^{F}/SW$ increases although installations 10 and 12 appear to give relatively low values of $\bar{L}$ for their corresponding values of $^{F}/SW$.

If both the actual $\bar{L}$ and $^{F}/SW$ values relative to the minimum requirements in Table 4.4, are plotted as shown in Fig. 4.2, it can be seen that if $^{F}/SW$ is increased over the minimum requirement for any installation, the average road luminance can be expected to increase proportionately in that installation, within a reasonable tolerance for experimental errors. Clearly installations 1, 2, 8, 9 and 14 are anomalous; the reasons will be discussed fully below. It will be deduced that installations 1, 2, 8 and 9 have suffered deterioration through an industrial environment and that installation 14 performed adversely due to the road surface with poor reflecting properties.

Road Luminance Uniformity.

An examination of Table 4.3 shows that the uniformity of pavement luminance at all sites satisfies the requirement that the average to minimum luminance should not exceed 5:1 across and 10:1 along the road. Only site 14 reaches a values of 5 for the ratio average to minimum luminance.

It can be hypothesised that diversity of road luminance (D), given by a ratio such as $\bar{L}/L_{min}$ or L_{max}/L_{min} will be related to another dimensionless quantity SW/H^2, where H is the lantern mounting height since:

(i) D is assumed proportional to the area of road (width(W) x length (l)) to be covered by the light patches from a number (n) of lanterns at spacing S and height H, i.e.

$$D \propto WL$$
$$\propto WnS$$

(ii) D is assumed inversely proportional to the size of patch, i.e. $D \propto 1/H^2$

(iii) D is assumed inversely proportional to the number of light patches available to cover the area, i.e.

$$D \propto 1/n$$

Figures 4.3 and 4.4 show plots of SW/H^2 against D expressed as ratios of both average to minimum luminance and maximum to minimum luminance. In both cases as SW/H^2 increases D increases, i.e. as the spacing increases, as road width increases and as mounting height decreases so the diversity of luminance increases.

There is a better correlation between SW/H^2 and the ratio of average to minimum luminance than there is between it and the ratio maximum to minimum luminance. The former appears to be relatively insensitive to factors such as lantern arrangement and type of road surface whereas the latter is probably not. In addition it should be remembered that each measure of diversity relies markedly on the accuracy of spot measurements, the former on one, the minimum and the latter on two, the maximum and minimum.

Fig. 4.5 shows, through luminance contours in three different installations drawn by computer from the grid measurements, the effect of the installation parameters on luminance uniformity. The first installationhas the lowest permitted mounting height 25ft (7.6m) and the greatest spacing 120ft(37m) for the road width, using a staggered arrangement. It can be seen that the luminance distribution is patchy. The brightest patch, within the observational area, extends from the furthest lantern on the opposite side of the road towards the observer. Adjacent to this bright patch, on the same side of the road, nearer to the observer is the darkest patch in the area. The lantern on the observers side of the road gives a patch of lower brightness. In reality the area will be viewed in perspective so the bright patch will be angularly smaller and therefore subjectively brighter than the luminance measurements suggest. The bright patch on the observer's side will appear angularly larger and more diffuse. The value of SW/H^2 is 8.0 giving rise to D values of $D(\bar{L}/L_{min}) = 3.5$ and $D(L_{max}/L_{min}) = 7.9$.

In the second installation the spacing has been reduced and the mounting height is greater for essentially the same width of road. The spacing is 2/3 the minimum requirement for the given mounting height and road width, reducing the value of SW/H^2 to 3.7. It can be seen that the distribution of luminance is similar to that in the first installation but that both the maximum intensity and area of minimum intensity have been reduced substantially. The values of D have been reduced to 1.8 and 2.8 respectively.

The third installation is an opposite arrangement again of minimum installation design but with a higher (30ft) than absolute minimum mounting height (25ft). It can be seen that the contours run almost parallel along the road. The value of $SW/H^2 = 5.2$ gives rise to values of D of 2.7 and 5.3 respectively. In this type of installation the greatest diversity is across the carriageway rather than along it.

Surround Luminance.

The range of values of luminances of the various components of the surrounds taken at 12 sites in five installations covering the range of parameters given in Table 4.1 have been shown on a composite street scene in Fig. 4.6. Although this scene does not give the frequency of occurrence of the components it can be seen that the luminance of components is often very much lower than the minimum pavement luminance and that uniformity of luminance could be much poorer than is encountered on the pavement. The standard is correct in its contention that white painted backgrounds will be sufficiently illuminated to provide good backgrounds up to a distance of 1.5 H from the lanterns.

Disability Glare.

The average values of disability glare G (mean of the 11 readings through two spans of lighting) for the installations are shown in Table 4.5. The variation of G, while moving through an installation, is shown in Fig. 4.7. The peak value is reached as a lantern on the same side of the road is apprached. This variation is repeated cyclically going through an installation. If the installation has a single side or opposite arrangement of lanterns only the first half of the cycle is repeated. It can be seen that amplitude of the variation of G is about 2:1. The amplitude of variation was found to diminish as lantern spacing (S) decreased. A simulated car roof alters the variation markedly for lanterns on the same side. The value of G with a roof is, on average, about 0.8 that without the roof in all installations.

In Fig. 4.8 installations are compared by plotting the mounting height H against a quantity, specific veiling luminance (SVL), where

$$\mathrm{SVL} = \frac{S}{F} \cdot G$$

i.e. the values of G are normalised to the flux ratings of the lanterns and the number of lanterns per unit length of road. It should be noted that values for sites 1, 2 and 8 would be expected to be low because of deterioration.

There is little correlation between SVL and H, with this data. Although one might expect glare to be reduced at higher mounting heights since the lanterns are further away from the line of sight, however, the flux ratings of the lanterns are normally increased in proportion in order to maintain average road luminance and hence the direction intensities giving rise to glare are also increased.

Over a wide range of installation geometry parameters, but with lanterns restricted to the semi-cut-off mercury lamped reflector type, the values of SVL lie within a range of 2 to 1.

In AS CA19, the semi-cut-off lantern classification is subdivided into two classes: low semi-cut-off (LSCO) and high semi-cut-off (HSCO). The run back of the light distribution for HSCO lanterns is not as severe as that for LSCO lanterns. In addition lanterns lamped with sodium discharge lamps have less restrictive run back requirements than for those lanterns using other sources. In Fig. 4.8 the values of SVL for LSCO lanterns appear to be no lower than those for HSCO lanterns. The installation employing non-cut-off lanterns has a SVL value about three times the average for semi-cut-off installations.

Table 4.2 shows the values of spot measurements of glare taken in six different installations, three years after the first series of comprehensive measurements. The values for refractor type lanterns are two to seven times those for reflector type ones. The refractor type lanterns employed sodium sources whereas the reflector type employed mercury sources. Thus, the increased values of G with the former could be partially due to the relaxation of glare requirements for sodium lamped lanterns mentioned above. The possibility remains that the refractor types employed as SCO lanterns are inherently more glaring than the reflector types.

There is also considerable discrepancy between the measured and calculated values for reflector lanterns, the measured values being only

1/3 to 1/2 the expected ones. The measured values for refractor lanterns are equal to or higher than calculated.

Anomalies.

It has been shown that differences exist between some measured values of average road luminance and glare and the expected values. These anomalies are discussed next.

Referring to Fig. 4.2 it can be seen that installations 1, 2, 8 and 9 appear to be only about one half as efficient as the others in producing average road luminance for a given value of $^F/SW$ (neglecting installation 14 for the moment). Yet in Figs. 4.3 and 4.4 these installations appear to be normal in respect of uniformity of luminance. Thus it can be reasonably surmised that the relative distribution of light within these installations is normal but its magnitude is severely diminished.

A comparison of the mean values of $\overline{L}$ / (F/SW) of two similar groups of sites, 1, 2, 8, 9 and 3, 6, 11 and 12, using Student's t-test showed these groups to be statistically different at the 0.01 level. Since there are no major differences between the anomalous sites and the other sites, e.g., in pavement surface and since the uniformity of luminance is as expected it would appear that the anomaly may be put down to there being less light flux provided in the installations.

As a check on the previous measurements the spot luminances and some illuminations were remeasured in site 8 after an interval of five months. The value of $\overline{L}$ was 5 per cent lower and the illuminations were 10 per cent lower - a satisfactory check result. A check on the electricity supply showed that the voltage was normal at site.

An analysis of some illuminance measurements taken at comparable sites is shown in Fig. 4.9. All the installations had HSCO lanterns of the same manufacturer. Illuminations (corrected for differences in lantern mounting height and flux)are plotted against distance from lantern pole(corrected for mounting height). It will be seen that the illuminations for the anomalous group of sites are generally below those for the comparison group. This confirms the supposition made of less light flux in the anomalous sites. It was then surmised that some deterioration had taken place. However, these installations (sites 1, 8 and 9) were about nine months old whereas the oldest (site 6) was 18 months and showed no anomaly. The common factor between the anomalous installations is that they are all situated in an industrial area.

Further work was concentrated on site 8. The four lanterns which contributed to the pavement luminance of the test site were cleaned by the County Council responsible and one adjacent lantern was removed for examination, being replaced by a new lantern. Cleaning made improvements to the illumination values on site ranging from 6 per cent to 40 per cent. Even after cleaning the illuminations were in general lower than two comparison lanterns, the new replacement lantern together with a lantern at site 6.

The removed lantern was cleaned (i.e. inside and outside of the bowl, reflector and lamp). Luminous intensities of light emitted from it and a new lantern fitted with the same lamp were measured in the laboratory at various directions to the downward vertical to the lantern. There was an average increase of illumination of 25 per cent (range 20 - 30 per cent) after cleaning. However, values for the new lantern were on average 38 per cent (range 20 - 59 per cent) higher than for the uncleaned lantern, confirming that cleaning does not return the lantern to its new state. Thus deterioration appears to be responsible in a large part for the anomaly of installations 1, 2, 8 and 9.

Examination of an in-service lantern from site 8 showed an accumulation of dirt in the bottom of the bowl and a general covering of dirt on the bowl. The bowl was stained with moisture run marks and there were stains and tide marks in the bottom of the bowl. The reflector appeared to be little effected though general chemical action may have impaired its reflecting properties. The run marks emanated from the join of the bowl and reflector (itself an upturned bowl in shape). The reflector had a downturned lip into which the bowl lip fitted. A layer of plasticized rubber sealing compound was deposited between the two lips which were finally clamped together with a clip running the full length of the lips and whose ends were pulled together with a nut and screw. From dirt marks on the sealing compounds it was evident that it did not adhere to the lips along their complete length. The sealing is made difficult by the length of the lip and the inexactness in their matching. There is no sign of moisture entrance at a small opening sealed by a felt washer in the top of the reflector to facilitate lamp changing.

Since general deterioration has been demonstrated, it could also be responsible, in particular, for the low measured glare values associated with reflector type lanterns. However, these low values are associated with both normal and deteriorated installations. Further measurements were taken during the second series of disability glare measurements to clarify this point.

In each installation the instrument was position and aimed directly at a lantern such that it sampled light from the lantern at directions 80^{o}, 84^{o} and 86^{o} to the downward vertical, in turn. The instrument was so arranged that the single lantern only was viewed and all the light from it in the particular direction chosen reached its photoelectric cell. The measured values of intensity, based on at least two lanterns of each type, together with the expected values derived from photometric test data are given in Table 4.6. It can be seen that the measured values of intensity for the reflector type of lanterns are about 1/3 to 1/2 the expected values. Thus the low measured values of glare

are explained by low light output. On the other hand the measured values for refractor lanterns are similar to the expected values, and this fact is reflected in the measured and calculated glare values.

On the face of it, it might be supposed that the refractor/ sodium lanterns maintain their performance in-service better than reflector/mercury lanterns (assuming equal life of the installation). However, this is not the whole story, for it can be seen in Table 4.6 that the new production refractor/sodium lantern appeared to give higher initial measured intensity values than would be predicted from the photometric data. The reverse is true to a lesser extent for the new reflector/mercury lantern. Therefore, maintenance of runback in production contributes to the problem. If the values in the last column of Table 4.6 are normalized to the test lantern data, new values of 54 and 75 per cent are obtained for lanterns types 3 and 5 instead of 50 and 94 per cent respectively.

This lessens the apparent difference in maintenance of performance of the two basic types of lanterns. However, the problem of poor maintenance of performance of the reflector lantern remains, together with the high glare values given by new lanterns, particularly of the refractor type.

Turning to installation 14 it can be seen that as well as the value of $\overline{L}$ being lower than expected, the values of D are higher than expected. The one parameter which can effect both level and uniformity is the road surface.

The majority of sites had an asphaltic concrete pavement; however, one site (5) had concrete over the full width of the pavement and another (9) had concrete over the centre pavement area with asphalt kerb strips. Two other sites (11 and 13) had kerb strips of concrete. The data in Table 4.3 and Figs. 4.2, 4.3 and 4.4 suggests that values of $\overline{L}$

and D will be very similar for concrete and asphaltic concrete surface in similar installations. The data for site 14 which yielded a low value of L and a high value of D suggests that a patched flush seal surface is inferior to the other two surfaces considered above, from a road lighting point of view.

DISCUSSION.

The overall picture that emerges from the analysis of measurements taken on in-service installations is that the design objectives of AS CA19 Part 1 were being achieved in practice. Average carriageway luminance in installations not subject to gross deterioration, is equal to or greater than the minimum of 0.2ftL (0.7 cd/m^2) and the uniformity of luminance is equal to or better than the maximum of 5 to 1 in the ratio of average to minimum. Thus the basis of design of installations of maintaining the lantern lower hemisphere flux per unit area of carriageway constant appears sound, within the range of lantern distributions and road surfaces considered. However, the analysis points to areas where relatively minor amendments to the standard will improve the installations and ease of specification.

The discussion refers to AS CA19 (1964) but before the publication of this thesis this standard was revised and reissued as AS 1158 (1973). As noted above these measurements were available to the revisers. Many of the recommendations made below have been incorporated in the revision in part or in whole (4.1 and 4.2) and where this has been done will be indicated at the end of each section of the discussion. Thus the discussion will indicate how a standard has been upgraded and evolved. The revision is not radically different from the original and aspects which presented difficulties before are those which still need attention to make sure they have been corrected. The standard is a minimum one and the discussion points to the best ways of further upgrading if required.

Finally, many of the points discussed, such as lighting the surrounds, restriction of glare, have universal relevance to street lighting practice and are used as bases for further chapters.

Average Road Luminance.

The internationally (CIE, 4.4) recommended value of maintained average road luminance ($\bar{L}$), for principal local traffic routes is 1 cd/m^2 (0.29ftL). It can be seen from Fig. 4.2 that to attain this value of $\bar{L}$, the present values of $^F/SW$ for installations need to be increased by 50%, i.e. the flux used in any installation needs to be increased by 50% if the present spacings are maintained for particular road widths. It can be seen in practice that the majority of installations contributing to the regression line in Fig. 4.2 already have values of $^F/SW$ which give rise to values of $\bar{L}$ of about 1 cd/m^2. It could be said that a recommendation to increase the value of F by 50% is merely formalising practice.

It has been shown that lighting to the AS CA19 is responsible for a large decrease in the night accident rate. It has been suggested that the level of lighting provided is such that any increase in it is unlikely to give rise to a further drastic decrease. However, increasing the value of $\bar{L}$ to 1 cd/m^2 would be advisable on several scores. The minimum standard installation has, by Fig. 4.4, a ratio of average to minimum luminance of about 3, i.e. L_{min} = 0.07ftL (0.24 cd/m^2). It was recommended in the previous chapter that L_{min} should not fall below 0.5 cd/m^2. If $\bar{L}$ is raised from 0.2ftL(0.7cd/m^2) to 0.29ftL (1 cd/m^2), L_{min} will be raised from 0.07ftL to 0.10ftL (0.34 cd/m^2). Whilst there will be little increase in visibility of objects, in terms of revealing power, by an increase in $\bar{L}$ there will be a substantial rise in visibility by increasing L_{min}, even though this increased value is still short of the recommendation: See Fig.3.8.

An increase in $\bar{L}$, which will also increase F, will mitigate three other adverse aspects which are discussed fully below:

(i) high values of disability glare possible in installations;

(ii) surrounds to the carriageway often dark;

(iii) deterioration in some installations;

In AS 1158 the expected initial average road luminance has been increased to 1 cd/m^2 (0.29ftL) and should not fall to below 0.7 cd/m^2 (0.2ftL) through life. This has been achieved by increasing the required flux and decreasing lantern spacing.

Uniformity of Luminance.

To ensure that areas of low luminance do not affect visibility along the carriageway, the CIE recommends that the ratio of average to minimum luminance should not be greater than 2.5. The values for the practical installations are close to this. According to the regression line in Fig. 4.4, the quantity SW/H^2 has to be decreased radically to obtain a substantial decrease in the value of $\bar{L}/L_{min}$. If SW is kept constant, i.e. the present spacings are maintained for a given road width, the lantern mounting height (H) needs to be increased:

SW/H^2	$\bar{L}/L_{min}$	H(ft)
8	3	25
6	2.7	28.8
5	2.5	31.6

It would be good practice to raise the minimum permitted mounting height from 25 ft(7.6m) to 30 ft(9.1m) to obtain better uniformity, although the gain in terms of reduction in $\bar{L}/L_{min}$ would be small. Again this recommendation would formalise what is becoming practice. It has been shown over the last few years that for the majority of installations the mounting height has increased from the minimum 25 ft to 30 ft (4.3).

Together with the suggested increase in $\bar{L}$, the implementation of this recommendation should raise L_{min} to 0.12ftL (0.41 cd/m^2). The increase in light flux required to achieve this new luminance level would be X $({}^{H30}/H_{25})^2$ i.e. x 1.44. This coupled with the recommendation above to increase $\bar{L}$ would lead to a total flux increase of 1.44 x 1.50 i.e. x 2.2. Improvements in visibility then need apparently large increases in power with probably slight if any increase in system efficiency.

The cost of an installation would not increase by this factor. Perusal of the charges of a local County Council (the authority responsible for installing street lighting) shows that approximately doubling the flux in an installation by increasing the wattage of the lamps results in a cost increase of about x 1.25.

The value of ${}^{SW}/H^2$ has a greater influence on the ratio ${}^{L_{max}}/L_{min}$. The CIE will probably recommend that this ratio, along the centreline of the observer's lane, should not be greater than 2. The purpose of this recommendation is to ensure a comfortable visual field by avoiding installations that are patchy in brightness distribution. In staggered installations, on relatively narrow roads with little other traffic, it is obvious on inspection that it is the brightness distribution over the whole carriageway that determines the sensation of brightness diversity.

Reference to Fig. 4.3 shows that it is a practical impossibility to ensure that ${}^{L_{max}}/L_{min}$ over the whole carriageway is less than 2. However, the increase in mounting height proposed above will decrease ratio for the whole road substantially:

SW/H^2	L_{max}/L_{min}	H(ft)
8	6.8	25
6	5.6	28.8
3	5.0	31.6

In practice reducing the value of SW/H^2 to 5 - 6 instead of 8 should ensure that the CIE recommendation based on the lane centreline is met. From Fig. 4.5 of the luminance contours in three installations the following figures have been derived:

Site	SW/H^2	L_{max}/L_{min} Lane 1	Lane 2	Lane 3
3	8.0	3.3	2.0	---
10	3.7	1.3	1.25	---
12	5.2	1.3	1.7	1.5

In AS 1158 the preferred minimum mounting height has been raised to 9m with an absolute minimum of 8.5m. Spacings have been reduced. The expected maximum diversity of luminance $\bar{L}/L_{min}$ is 3 and L_{max}/L_{min} is 4.

Glare.

There are no quantitative requirements as such for the restriction of glare in AS CA19. It is assumed that if the lantern distribution is complied with then the restriction of disability and discomfort glare will be satisfactory. However, the present measurements can be used to analyse the relative merits of the various requirements for the beam distribution which are thought of as affecting glare.

A big reduction in disability glare is gained in going from non cut-off lanterns (NCO) to semi cut-off lanterns (SCO). However, there appears little difference between the two classes of SCO lanterns, high and low cut-off: Fig. 4.8. The use of NCO lanterns, with the attendant release of light closer to the horizontal which might be thought to extend the lantern patch length on the road, does not appear to lead to a substantially higher average road luminance: see site 7 on Fig. 4.2. The use of LSCO lanterns leads to a value of $\bar{L}$ slightly on the inefficient side of the regression line: site 10 in Fig. 4.2.

Since the beam distribution has little effect on $\bar{L}$, recommendations for modifications can be made on the basis of the glare results. They suggest that the use of NCO lanterns be abandoned and that a single class of SCO lantern distribution be adopted, possibly encompassing either the present HSCO or both the present HSCO and LSCO classification.

Whilst in-service mercury lamped reflector lanterns give modest amounts of glare, the calculated permitted values and the measured in-service values for sodium lamped refractor lanterns are so high as to give cause for concern. It is, therefore, suggested that the dispensation for sodium lamped (refractor) lanterns, whereby given intensities are allowed higher up the run back of the beam distribution than for mercury lamped (reflector) lanterns, is withdrawn.

The effect of high values of glare on visibility, especially of objects viewed against the surrounds will be examined in Chapter 6. The influence of the shape of the beam distribution on disability glare will be examined in Chapter 5 in order to expand the background knowledge at present lacking, on which future lighting specifications can be based.

In AS 1158 the use of non cut-off lanterns for traffic route lighting is not permitted. The two semi cut-off classifications have been amalgamated intoone which embraces the old tolerances except that the less restrictive requirements for sodium lamped lanterns are withdrawn. The glare restriction remains based on requirements for the run back of the light distribution.

Road Surfaces.

It has been shown in the previous chapter that variations in light distribution from the lantern and road surface reflection characteristics, in a given installation, can influence both $\bar{L}$ and D. It has been shown that using a given SCO lantern specification and asphaltic concrete pavement, that the tabulations in the Australian standard give constant values of $\bar{L}$ and D over a wide range of installation geometries. However, it was pointed out that the small range of actual surfaces examined could give rise to departures from the expected values of $\bar{L}$ and D.

The measurements reported here show reasonable confidence limits about the regression lines for $\bar{L}$ and D, taking into account all possible sources of variation, of which the road surface is but one. It can be assumed, within the natural variability of street lighting, that the tables of installation geometry cater satisfactorily for most surfaces.

The outstanding exception was site 14 which had a patched flush seal surface. With further work it would be possible to give a clear indication in a specification of the effect of a road surface on the appearance of an installation. A simple classification of road surfaces and a method of recognising them could be the basis for modifications to the general practice. This may be indicated as necessary to correct for gross degradations arising if general practice were adhered to without regard to the road surface.

No indication of the effect of road surface on performance is given in AS 1158. The values of quality criteria are stated as being those expected with an asphaltic concrete surface, of composition to the relevant Australian standard.

Surround Luminance.

The luminances of the road surrounds show a greater range in values than those encountered on the pavement; the lowest luminances are much lower and it is probable also that average luminance is much lower and the rate of change of luminance much greater. Although higher mounting heights are inefficient in terms of the utilization of light flux in producing pavement luminance, this is because light falls on the surrounds and this may be beneficial. In general, because of the results obtained, it may be supposed the more light that falls on the surrounds the better. However, the light reflecting properties of the surrounds are different from those of the pavement surface for which the lantern is designed. Thus the light falling on the surrounds is probably not utilized in the most efficient manner. In surrounds with very poor light reflecting properties, i.e. of brick and shrubbery, it might be more advantageous to try to light objects, i.e. pedestrians in order that they be seen as reverse silhouettes, light against dark.

Whilst the values of disability glare might have little effect on visibility of objects on the carriageway it is likely they effect visibility along the road edges. Since this area has received little attention in the past, it will be examined in detail in Chapter 6.

In AS 1158 the importance of lighting the verges to the carriageways is stressed. Glare will be reduced by the withdrawal of the dispensation for some lanterns.

Deterioration.

It has been seen that gross deterioration takes place in industrial environments. AS CA19 virtually makes no allowance for deterioration, the minimum requirement assumes clean installations. The standard suggests that servicing should be carried out in order to maintain the light output of lanterns above 70 per cent of initial values.

Deterioration can be tackled in three ways:

(a) by providing more light initially;

(b) by servicing lanterns; and

(c) by designing lanterns to reduce deterioration to a minimum.

The CIE recommends that installations should be designed so as to give an increase of 1/3 in $\bar{L}$ initially, to combat deterioration. It has been suggested above that the value of $\bar{L}$ implicit in the Australian standard should be raised to 1 cd/m^2, i.e. from 0.2ftL to 0.29ftL. It is further suggested that this be the initial value and the maintenance procedures should be such that $\bar{L}$ does not fall below 0.2ftL (0.7 cd/m^2), the figure at present implicit in the specification.

The first alternative (a) means a more costly installation which may be economically justified when weighed against the cost of more frequent servicing which may be required in areas where lamps are subjected to deterioration. AS CA19 suggests that the interval between servicings, i.e. cleaning alone, should depend on atmospheric conditions. It suggests also that lamps should be replaced in bulk, therefore it would be advantageous to service only at times of bulk replacement of lamps. Such a replacement should take place after say two years, and this interval between servicing is reasonable for installations in environments such as site 6. However, it would seem that intervals in industrial areas should be six months. The economics of alternatives (a) and (b) should be the subject of study by the local authority from data gathered in its locality.

It would appear that some attention should be paid both by manufacturers and local authorities to lantern construction. Acceptance tests on lanterns should include not only photometric tests but also tests aimed at gauging resistance to deterioration.

In AS 1158 attention is paid to the maintenance aspect. Likely rates of deterioration of lamps and lanterns are given with recommendations of preventative procedures so that the average road luminance does not fall below 0.7 cd/m^2. A further programme of measurement on in-service installations has been initiated by the relevant authorities.

REFERENCES.

4.1 Kenway, B. D., Revised SAA Public Lighting Code: Part 1, Lighting of Urban Traffic Routes AS 1158, 1973, IES Lighting Review, Vol. 35, No. 5, 1973.

4.2 Fisher, A. J., Revising the SAA Street Lighting Code, Part 1, Traffic Routes, Public Lighting Vol. 35, No. 149, 1970.

4.3 Whittemore, J., Street Lighting, progress and problems, IES Lighting Review,Vol. 33 No. 1, 1971.

4.4 CIE, International recommendations for the lighting of public thoroughfares, Pub. No. 12, Commission International de l'Eclairage, Paris 1965.

Site	Installation Geometry				Lantern	Road Surface
	Arrangement	W	S	H		
1. Abercrombie St	Staggered One Carriageway	42	116	26	HSCO Type 1 Merc. Fluor. 250W lamp	Asphaltic Concrete
2. Australia St	Single Side One Carriageway	30	139	27.5	HSCO Type 1 Merc. Fluor. 250W lamp	Asphaltic Concrete (Fine texture)
3. Beecroft Rd	Staggered One Carriageway	42	120	25	HSCO Type 1 Merc. Fluor. 250W lamp	Asphaltic Concrete
4. Beecroft Rd	Staggered One Carriageway	42	120	25	HSCO Type 2 Merc. Fluor. 250W lamp	Asphaltic Concrete
5. Canterbury Rd	Staggered One Carriageway	42	108	27.5	HSCO Type 1 Merc. Fluor. 250W lamp	Concrete
6. King Georges Rd	Staggered One Carriageway	42	87	30	HSCO Type 1 Merc. Fluor. 250W lamp	Asphaltic Concrete
7. King Georges Rd	Staggered One Carriageway	42	119	23	NCO Tub. Fluor. 4 x 40W lamps	Asphaltic Concrete
8. O'Riorden St	Staggered One Carriageway	42	122	30	HSCO Type 1 Merc. Fluor. 400W lamp	Asphaltic Concrete
9. O'Riorden St	Staggered One Carriageway	42	103	30	HSCO Type 1 Merc. Fluor. 400W lamp	Concrete with A.C. strips along kerb
10. Rocky Point Rd	Staggered One Carriageway	45	93	35	LSCO Type 1 Merc. Fluor. 250W lamp	Asphaltic Concrete
11. Rocky Point Rd	Staggered Divided Carriageway Narrow Median	75	96	40	HSCO Type 1 Merc. Fluor. 400W lamp	Concrete with A.C. strip along median
12. Taren Point Rd	Opposite Divided Carriageway Narrow Median	75	142	30	HSCO Type 1 Merc. Fluor. 250W lamp	Asphaltic Concrete
13. Taren Point Rd	Single Side Divided Carriageway	33	148	40	LSCO Type 1 Merc. Fluor. 700W lamp	Asph. Concrete with concrete kerb strip
14. Telegraph Rd	Staggered One Carriageway	40	121	27.5	HSCO Type 1 Merc. Fluor. 250W lamp	Flush Seal — very patched

NOTES: W = carriage width from kerb to kerb
S = lighting span (average of 2 spans in test section)
H = mounting height
HSCO = High semi-cut-off light distribution
LSCO = Low semi-cut-off light distribution
NCO = Non-cut-off light distribution

Installations 3 & 4 were of 6 lanterns each at the experimental site referred to in chapter 3.

Table 4.1. Details of sites in first series of comprehensive measurements. (Distances in feet.)

Site details (ft)				Lantern type	Measured glare (ft. L)	Calculated glare (ft. L)
(a)	H = 29	S = 120	W = 42	(1) Reflector 250W MBF/U	0.051	0.146
(b)	H = 30	S = 130	W = 42	(1) Reflector 250W MBF/U	0.061	0.134
(c)	H = 31	S = 83	W = 42	(3) Reflector 400W MBF/U	0.072	0.165
(d)	H = 33	S = 144	W = 75	(3) Reflector 400W MBF/U	0.069	0.110
(e)	H = 30	S = 108	W = 42	(4) Refractor 100W SOX	0.152	0.182
(f)	H = 30	S = 128	W = 60	(5) Refractor 150W SOX	0.354	0.245

NOTE: The calculated values are based on 11 lanterns in the field of view. Some of the discrepancies could be due to varying numbers of lanterns and atmospheric attenuation of the light, as well as in-service conditions.

Table 4.2. Details of sites in second series of measurements into disability glare only, together with measured and calculated values, on the same basis as the measuring procedure.

Site	Average* Luminance ft — L	Maximum Luminance ft — L	Minimum Luminance ft — L	Average / Minimum	Maximum / Minimum	Variation of † Luminance Across	Variation of † Luminance Along
1. Abercrombie St	0.16	0.31	0.06	2.7	5.1	4.2	4.0
2. Australia St	0.14	0.23	0.06	2.3	3.9	3.1	2.4
3. Beecroft Rd	0.28	0.80	0.10	2.8	7.9	4.8	7.5
4. Beecroft Rd	0.28	0.80	0.08	3.5	9.6	6.4	8.0
5. Canterbury Rd	0.28	0.49	0.10	2.8	4.9	4.8	3.6
6. King Georges Rd	0.33	0.79	0.12	2.8	6.6	6.6	3.0
7. King Georges Rd	0.20	0.37	0.06	3.3	6.1	5.1	6.1
8. O'Riorden St §	0.22 (0.22)	0.44 (0.36)	0.09 (0.10)	2.4 (2.2)	5.2 (3.6)	3.2 (2.1)	2.6 (2.6)
9. O'Riorden St ‡	0.20 (0.24)	0.45 (0.45)	0.07 (0.09)	2.9 (2.7)	6.3 (5.3)	3.9 (3.3)	3.4 (3.4)
10. Rocky Point Rd ‖	0.22 (0.22)	0.33 (0.36)	0.12 (0.12)	1.8 (1.8)	2.8 (2.9)	2.2 (1.9)	2.1 (2.3)
11. Rocky Point Rd	0.27	0.49	0.19	1.4	2.6	2.5	1.6
12. Taren Point Rd	0.22	0.41	0.08	2.8	5.3	4.4	2.2
13. Taren Point Rd	0.43	0.66	0.16	2.7	4.1	3.6	2.0
14. Telegraph Rd	0.10	0.24	0.02	5.0	11.8	9.3	11.8

NOTES: * Average for all test points
† Across and along grid lines with greatest variation
‡ Figures in brackets refer to concrete section of carriageway
§ Figures in brackets refer to asphalt section similar to concrete section at site 9
‖ Figures in brackets refer to measurements using 8 ft viewing height

Table 4.3. Measured pavement luminances.

Site	Minimum recommended $\frac{F}{SW}$	In-service value of $\frac{F}{SW}$
1	1.02	1.51
2	1.28	1.76
3	1.02	1.46
4	1.02	1.46
5	1.05	1.62
6	1.15	2.01
7	1.14	1.02
8	1.15	2.56
9	1.15	3.03
10	1.35	1.76
11	1.17	1.82
12	1.34	1.38
13	—	4.38
14	1.11	1.52

Notes. (i) The minimum values of $\frac{F}{SW}$ were calculated from AS CA19, using the values of W and H for each site, given in Table 4.1.

(ii) The in-service values of $\frac{F}{SW}$ were calculated from values of W H and S given in Table 4.1. The lantern lower hemisphere flux values were the 85% initial values of the lamps, from published data and independent photometric tests. Sites 1,2,3,4,5,6,10,12,14 - 7,350 lm, site 7 - 5,100 lm, sites 8,9,11 - 13,100 lm, site 13 - 21,400 lm.

Table 4.4. In-service values of $\frac{F}{SW}$ for the installations compared with the minima allowed by AS CA19.

Site	1	2	3	4	5	6	7
$\bar{G}$	0.027	0.029	0.031	0.030	0.038	0.025	0.071
Site	8	10	11	12	13	14	15
$\bar{G}$	0.043	0.045	0.042	0.043	0.065	0.031	0.033

NOTE: Site 15 (Sandringham Rd) is included here as an additional example of the glare in a LSCO installation — staggered arrangement of 250W Type 1 lanterns. W = 42 H = 35 S = 109

Table 4.5. Average veiling luminances ($\bar{G}$ ftL) at test sites, measured using Pritchard Spectra glare integrator.

Lantern type	Measured values (1)			Photometric data (2)			(1 ÷ 2) %		
	80	84	86	80	84	86	80	84	86
1	1172	377	232	3300	1075	900	36	35	26
3	1631	757	457	4550	1500	800	36	50	57
4	2100	1980	1733	2600	1950	1575	81	102	110
5	2632	2507	2025	3950	2675	2125	67	94	95
—(a)		1625			1750			93	
5(b)		3345			2675			125	

Note: The photometric data are based on clean lanterns with new lamps. Values a and b were measured, lantern a was of a type similar to 3.

Table 4.6. Intensities at three points on the runback of different lantern types, taken from photometric data and laboratory measurements.

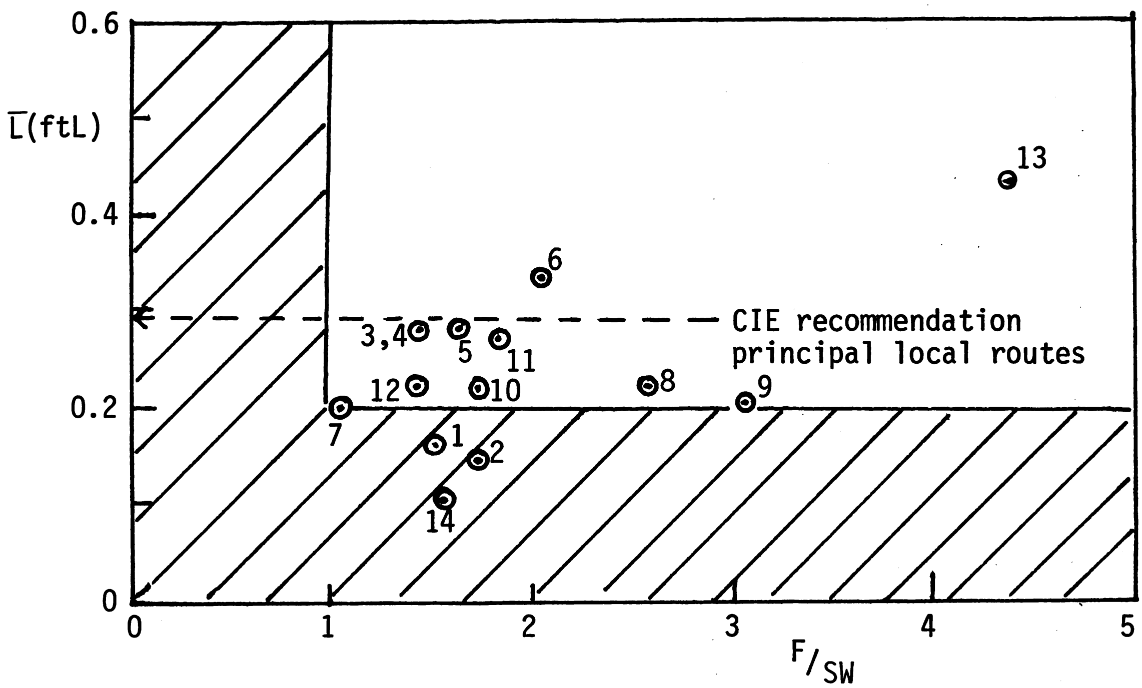


Fig. 4.1. Measured values of average luminance ($\bar{L}$) and lantern lower hemisphere flux per unit area of carriageway ($^F/_{SW}$) for each installation. The values should lie outside the shaded area if installations are to min. requirements of AS CA 19.

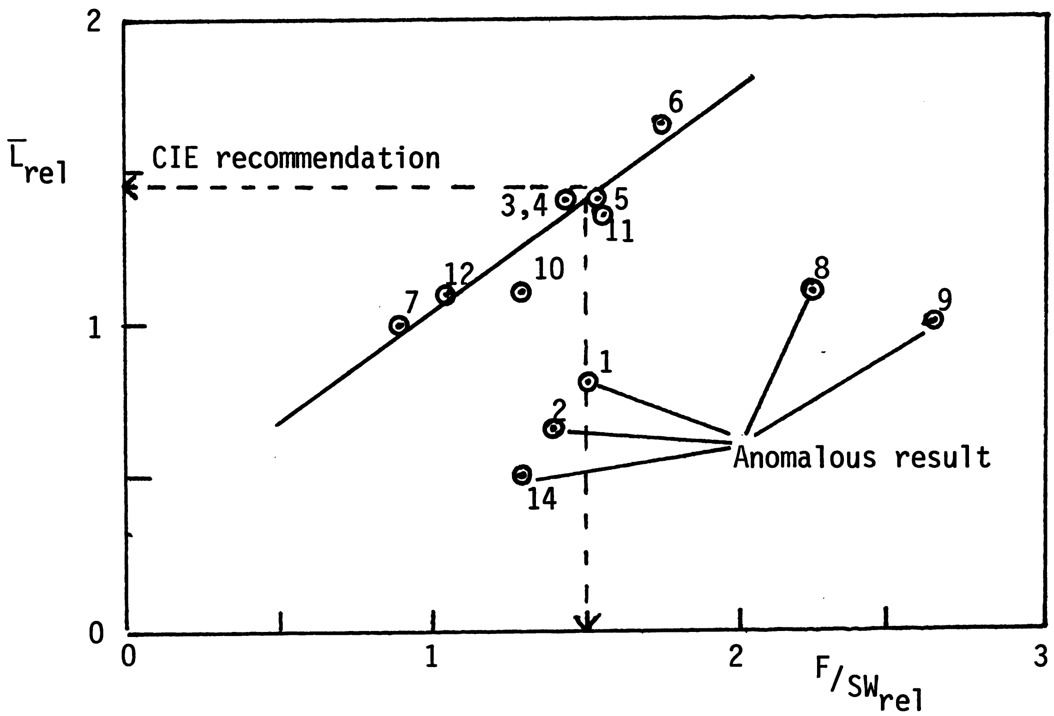


Fig. 4.2. Variation of the measured luminances, as a ratio of the minimum allowable ($\bar{L}_{rel}$), with in-service values of $^F/_{SW}$, as a ratio of the minimum allowable ($^F/_{SW_{rel}}$). A regression analysis gave $\bar{L}_{rel} = 0.71\ ^F/_{SW_{rel}} + 0.31$, significance level 0.001.

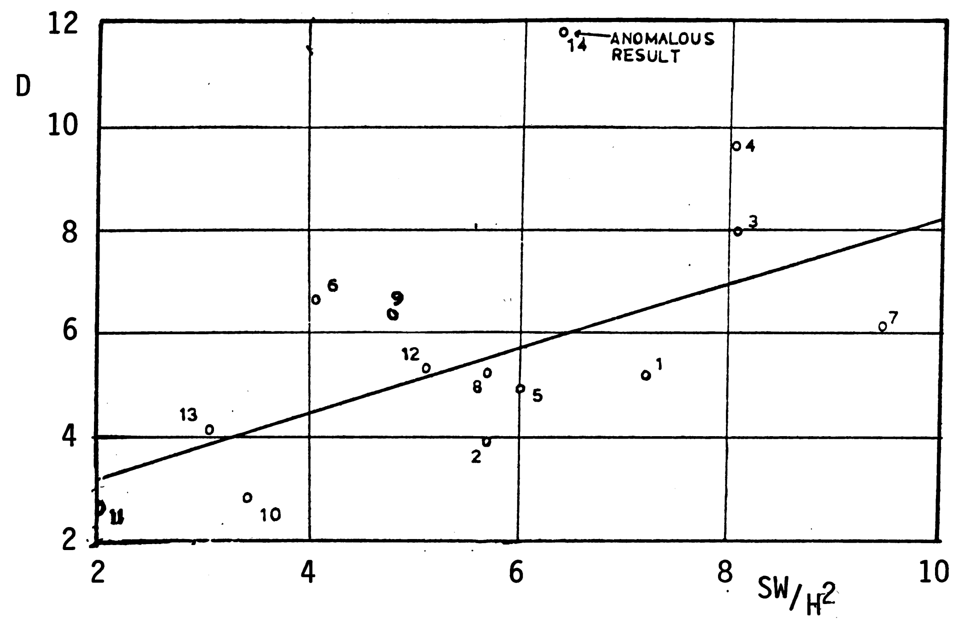


Fig. 4.3. Variation of diversity of pavement luminance $D(L_{max}/L_{min})$ with the quantity $SW/_{H}2$. A regression analysis gave $D = 0.63\ SW/_{H}2 + 1.8$, significance level 0.02.

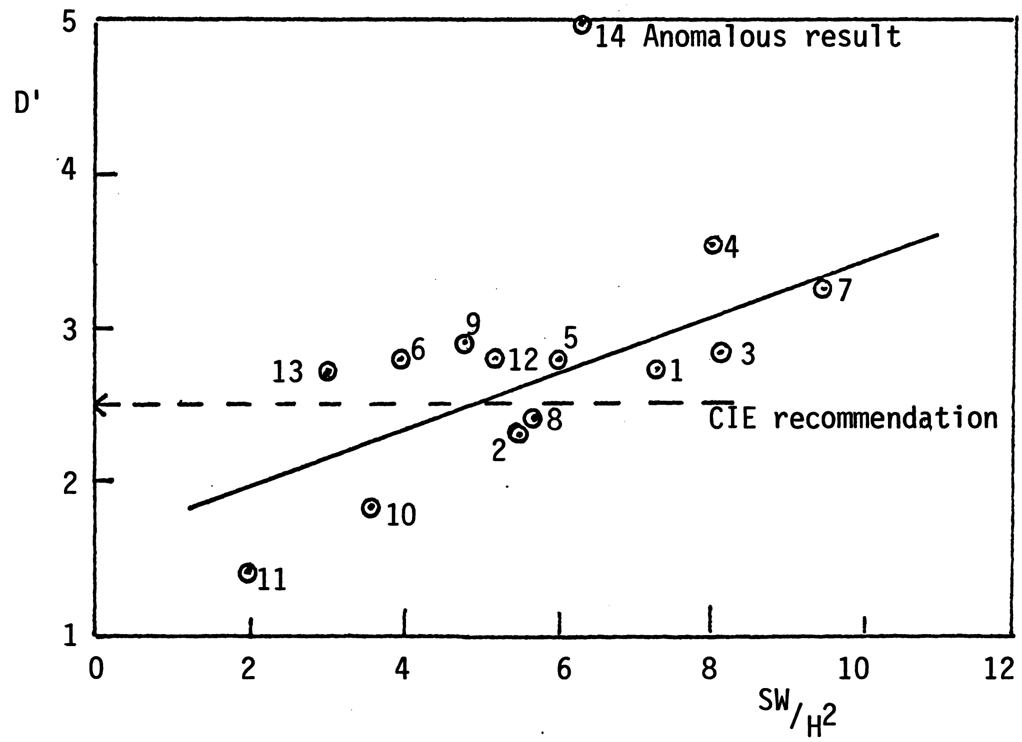


Fig. 4.4. Variation of diversity of pavement luminance D' $(\bar{L}/L_{min})$ with the quantity $SW/_{H}2$. A regression analysis gave $D' = 0.18\ SW/_{H}2 + 1.6$, significance level 0.02.

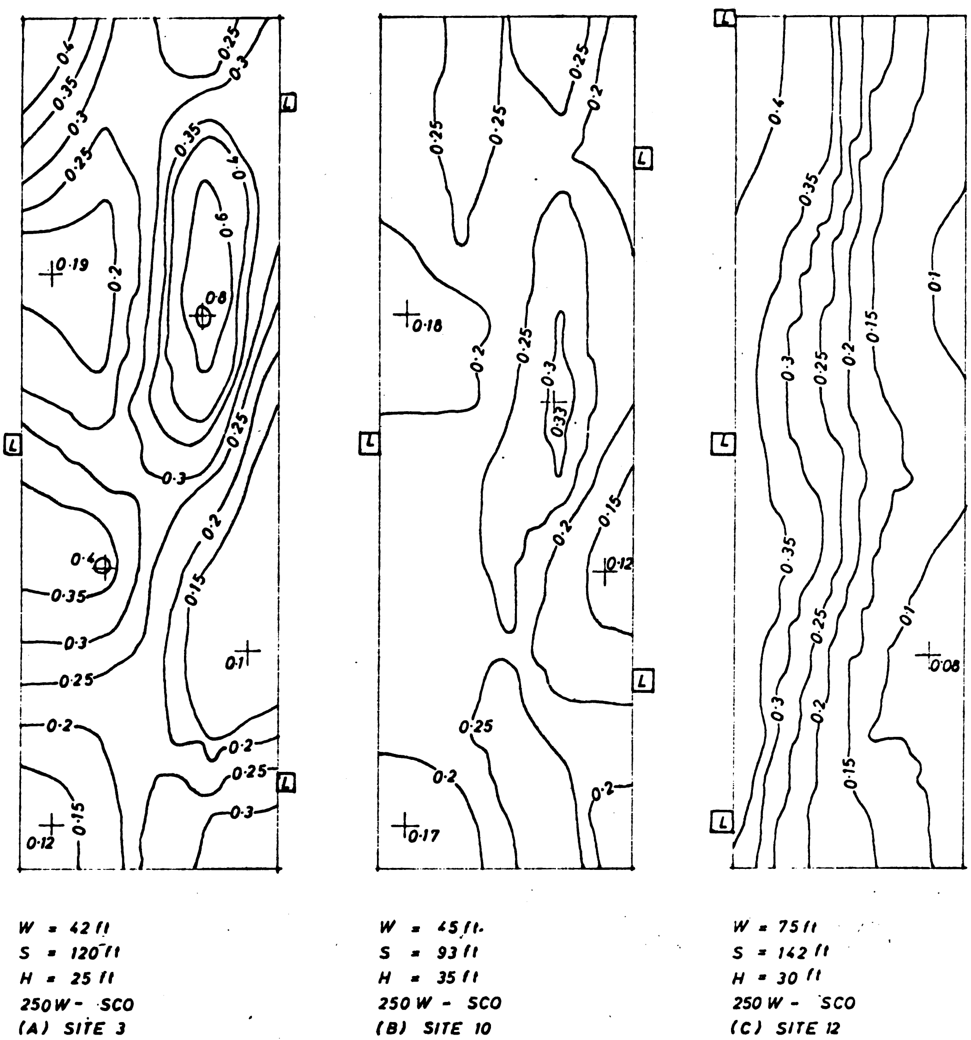


Fig. 4.5. Contours of road luminance, in ftL, for three installations with different parameters all on asphaltic concrete pavements. The first two are for the single carriageways of non divided highways, the third is for one carriageway of a divided highway.

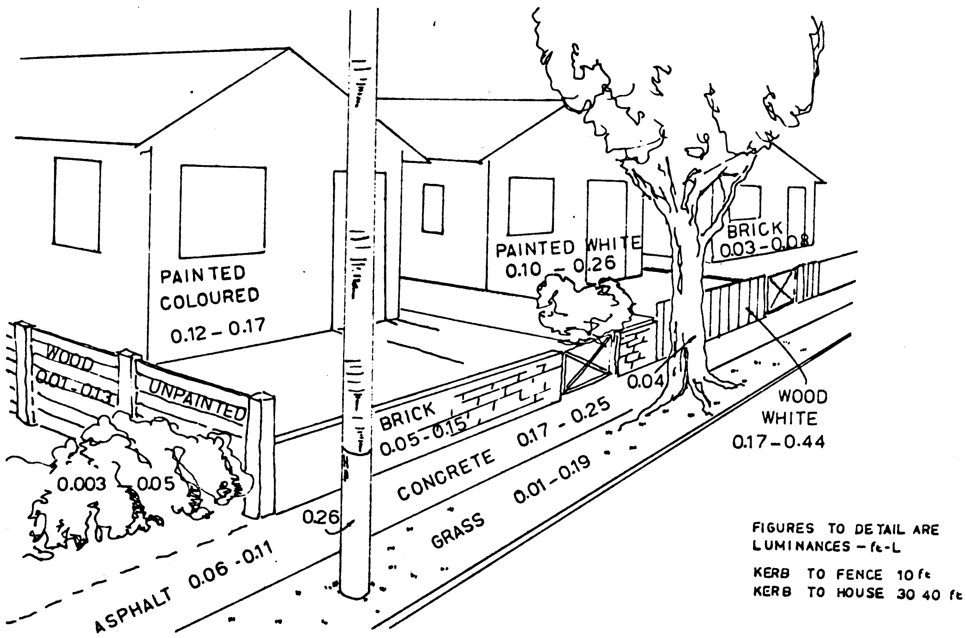


Fig. 4.6. The luminance of the surrounds to the carriageway in ftL. The scene is a composite one made up from measurements at several sites.

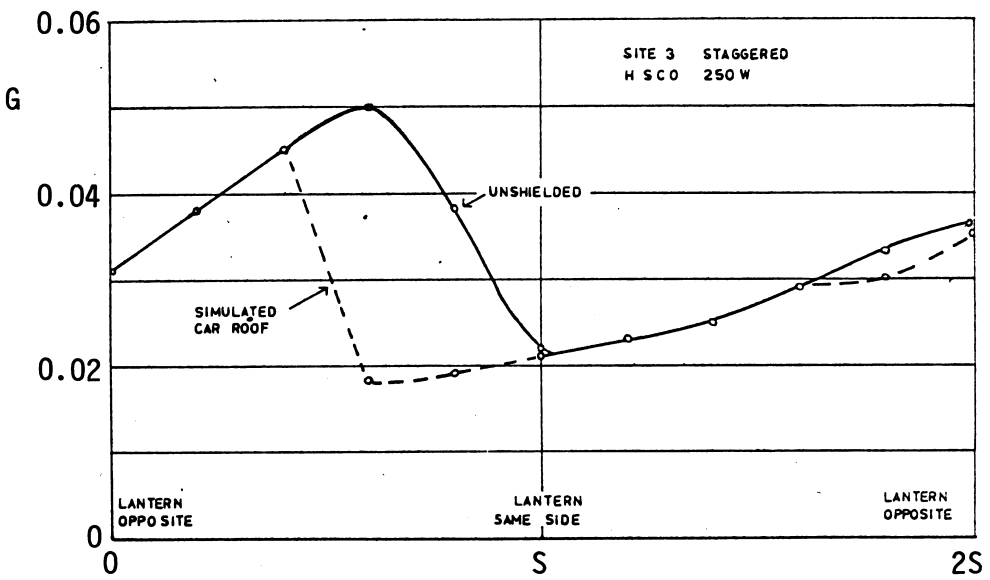


Fig. 4.7. Variation of disability glare G (ftL) with observer position in an installation as measured with a Pritchard Spectra photometer, with and without the cut off of a car roof.

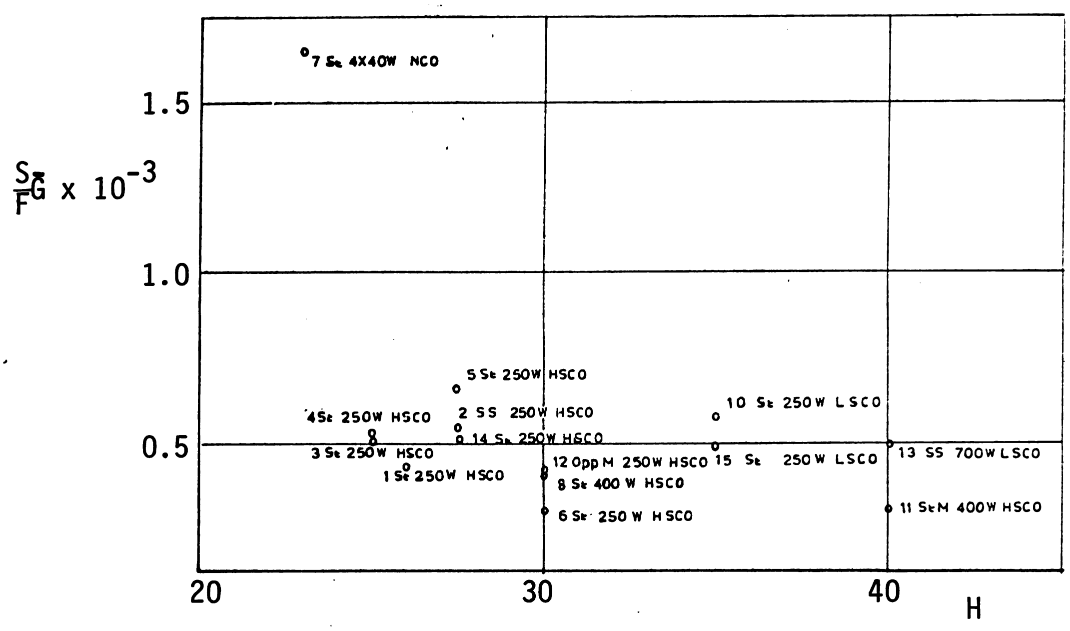


Fig. 4.8. Variation of specific veiling luminance $\frac{S}{F}\bar{G}$ with lantern mounting height H(ft) for the installations.

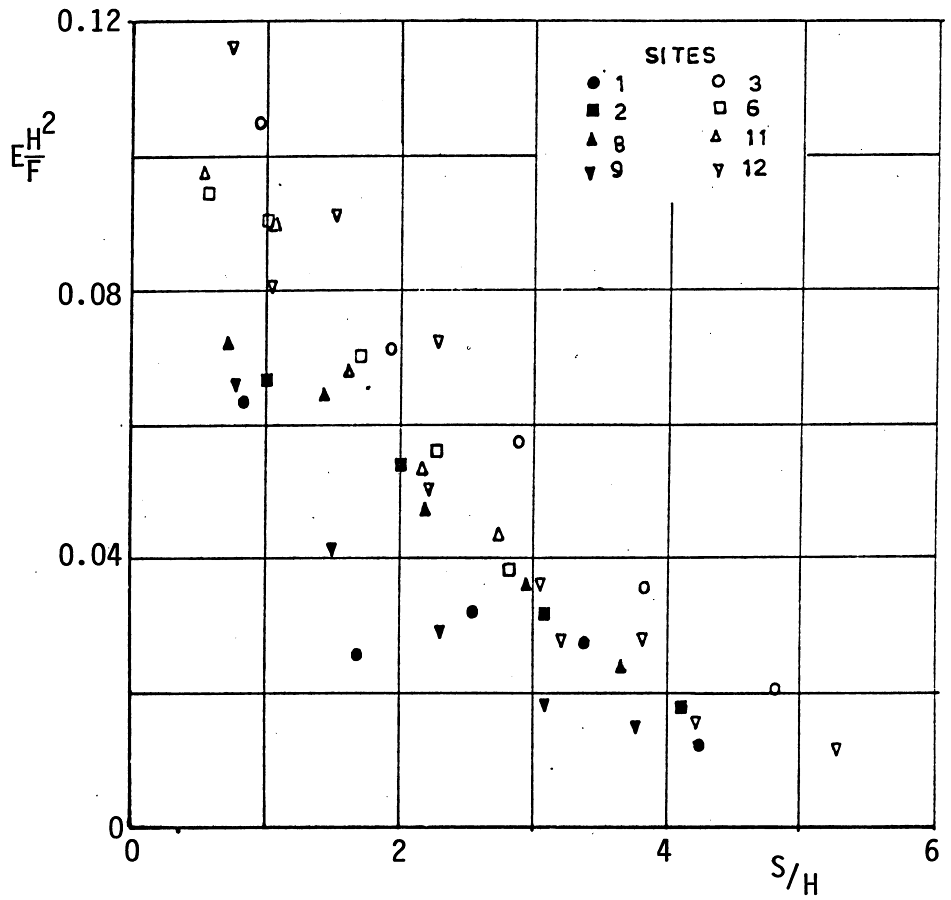


Fig. 4.9. Variation of specific illuminance $E\frac{H^2}{F}$ at a distance $^S/_H$ from lantern at various sites, on vertical surface 3ft above and 5ft out from kerb (solid points refer to anomalous sites and open ones to normal sites).

CHAPTER 5

DISABILITY GLARE AND LANTERN DESIGN

INTRODUCTION.

It has been suggested in Chapters 1 and 2 that disability glare is an important quantity in determining visual performance on the road at night. Lighting engineers have paid great attention to the restriction of light from equipment in those directions which give rise to glare. However, it will be seen in Chapter 7 that disability glare is still the major inhibitor of seeing by vehicle headlights. In street lighting, disability glare has, in general, been successfully restricted in that it does not interfere with the visibility of objects viewed against the bright carriageway. However, measurements on in-service installations cited in the previous chapter suggested that this might not be the case for low pressure sodium lamped refractor type semi cut-off lanterns. Further it has been advocated that attention should be paid to the whole of the visual field; in particular, the immediate surrounds to the road can be dark and glare plays an important role in determining visibility of objects viewed against them. This aspect is discussed in detail in the next chapter.

From Chapter 2 it has been shown that the conventional veiling luminance formula is a good description of the effect; viz,

$$G = \sum_{i=1}^{n} \frac{10E_i}{\theta_i^2} \quad cd/m^2 \text{----------} \quad (5.1)$$

where E is the illuminance, in lux, in the plane of the eye from the glare source i;

θ_i is the angle, in degrees, between the line of sight and the direction of the glare source i.

The questions arise:

(i) how can equation 5.1 be readily evaluated for the purpose of exploring visual performance by means of the revealing power concept, discussed in Chapter 2;

(ii) what is the relationship between veiling luminance and the installation and lighting parameters?

METHODS OF EVALUATING GLARE.

The measurement of veiling luminance on in-service installations has been described in Chapter 4. However, the basis of design of the instrument is that the term θ^2 in equation 5.1 has been replaced by $\theta(\theta + 1.5)$. Thus, the measured G will be different from the computed G. Although such measurements are tedious they can serve as a practical check and if sufficient measurements are taken broad implications for installation design can be drawn, as in Chapter 4.

The glare through an installation varies cyclically as shown in Fig. 5.1. The glare rises as a lantern is approached and then falls as the vehicle roof cuts off the direct light. The variation from maximum to minimum is about 2 to 1, for the SCO lanterns used in Australian streets. The rate of variation is greatest in the short duration truncated spike on approach to a lantern. From these measurements a mean or maximum value can be derived for further use.

G can be calculated from the installation geometry and the isocandela diagram of the lantern light output. Adrian (5.1) has simplified this tedious process somewhat by devising a graphical method. The principal polar curve is plotted on a special grid, which makes allowance for angles and distances implicit in equation 5.1. The contributions of individual lanterns can be read off and the total glare is the sum of these values. An example of the calculation is shown in Fig. 5.2. The assumptions are that one polar curve describes the beam, that the observer is static and immediately under a lantern, i.e. S from the first lantern, and is looking along the road and 1° downwards.

The method is still tedious and does not give directly any insights into the connections between glare and installation and lantern parameters. It is claimed that the method yields the maximum glare value in the installation.

In computing the effects of disability glare by means of revealing power various investigators have used mean values (5.2, 5.3). The use of mean values of parameters does not introduce any significant error (5.4) and leads to manageable analyses. Others have maintained that in setting limits to glare, the maximum value should be used (5.1) However, as seen above, the computation of a maximum value is made on the basis of simplifying assumptions.

For the analysis of revealing power undertaken in Chapters 6 and 11 an average value will be used for the following reasons.

(i) what is required is a manageable method of analysis yielding the broad effect of glare;

(ii) the conventional glare formula is a reasonable description of the effect and should be used within that understanding. It can be refined by including more complex terms discussed in Chapter 2. Even the sensitivity of conventional formula is dependent on the assumptions made about the road situation, particularly as to the line of sight of the observer;

(iii) it has been shown that the variation of glare in a street lighting installation is small: in a later chapter it will be seen by comparison that the glare from vehicle headlights varies over a range of 100:1, in which case the use of individual glare values is justified;

(v) the maximum value of glare is a transient spike and it can be reasonably argued that the restriction of glare should not be based on this aspect, but on some suitably weighted average;

(v) whilst the response of the eye to changes in glare level will be fast since it will not involve long term chemical adaptation but short term pupil and neural adaptation, there will be inertia in the visual system and the peaks and troughs of changes will tend to be blunted;

The method by which equation 5.1 may best be related to practical installationsand lanterns can be determined by reference to work on the discomfort glare aspect of street lighting. In Chapter 3, the work of Continental European investigators was discussed. They derived single discomfort glare ratings of installations using a dynamic simulation. The glare rating is related to installation parameters, e.g. mounting height and spacing, and lantern parameters, e.g. intensities in directions giving rise to glare and the severity of the run back. Since this system of rating discomfort glare is finding increasing use in installation and lantern evaluation it seems reasonable to try to express disability glare in similar terms. In addition current lantern light distributions are in terms of restricted intensities at certain angles or angular ranges.

CALCULATION OF DISABILITY GLARE.

A method will be developed by which the time-averaged veiling luminance experienced in running through an installation is related to the installation and lantern parameters and based on the conventional glare formula given in equation 5.1.

Consider the variation of the glare G_i from a single lantern at a variable distance d from an observer as shown in Fig. 5.3. At any time t the total glare G experienced from the lanterns in an installation is, by equation 5.1, the sum of the individual values of G_i. On Fig. 5.3 these will be G_1, G_2, G_3, etc., from lanterns each a distance S apart. On moving a distance S, in time T, G_3 increases to G_2, G_2 increases to G_1. G_1 increases not to G_0 but rather to $G_{0'}$, the value of which is determined by the cut-off of the vehicle roof. Thus the average glare experienced is a function of the area under the curve given in Fig. 5.3.

The average total glare $(\overline{G})$ is:

$$\overline{G} = \sum_{i=1}^{n} \frac{\int_{G(i)}^{G(i-1)} G_i\,(t)\,dt}{\int_0^T dt}$$

but t = vd where 1/v is speed of travel and when t = T, d = S, then

$$\overline{G} = \frac{1}{S} \sum_{i=1}^{n} \int_{G(i)}^{G(i-1)} G_i\,(d)\,dd$$

$$= \frac{1}{S} \int_{d_o'}^{d_n} G_i\,(d)\,dd \qquad \text{-----------(5.2)}$$

where d_n is the length of the installation observed and d_o' is the value of d at which the first lantern is cut-off by the vehicle roof.

By equation 5.1 and Fig. 5.4

$$G_i = \frac{10\ I_i}{d_i^{\,2}\ (\emptyset'_i + a)^2} \quad *$$

where I_i is the intensity in the direction of the observer from lantern i and $d_i = \dfrac{180}{\pi}\ \dfrac{h'}{\emptyset'_i}$, $\emptyset'$ in degrees.

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* More rigorously, $G_i = \dfrac{10\ \ I\cos\theta}{d^2\ (\emptyset' + a)^2}$

However, for the values of θ used, the deviation of cos θ from unity is insignificant.

then equation 5.2 becomes,

$$\overline{G} = \frac{1}{S}\,\frac{1}{h'}\,10\,\frac{\pi}{180} \int_{\emptyset'_n}^{\emptyset'_o} \frac{I\,(\emptyset')}{(\emptyset' + a)^2}\,d\emptyset' \quad \text{-----}(5.3)$$

where $\emptyset'_o$ and $\emptyset'_n$ correspond to d_o' and d_n respectively.

Let the run back of the light distribution be linear and the intensity at $\emptyset'_A$ be I_A and at $\emptyset'_B$ be I_B, then:

$$\begin{aligned} I\,(\emptyset') &= I_A - (\emptyset'_A - \emptyset')\left[\frac{I_A - I_B}{\emptyset'_A - \emptyset'_B}\right] \\ &= K\emptyset' + K' \end{aligned}$$

where K and K' are two characteristics of the runback which controls glare. K is the rate of change of intensity with angle and K'is the intensity where $\emptyset' = 0$.

Substituting for $I(\emptyset')$ in equation 5.3 and integrating,

$$\overline{G} = C\left[K \log_e (\emptyset' + a) + \frac{(aK - K')}{(\emptyset' + a)}\right]_{\emptyset'_n}^{\emptyset'_o} \quad \text{---------}(5.4)$$

where $$C = 10\,\frac{\pi}{180}\,\frac{1}{S}\,\frac{1}{h'}$$

EVALUATION OF $\overline{G}$.

Equation 5.4 can be readily evaluated for any values of the variables. However, it is reasonable to replace h', a, $\emptyset'_o$ and $\emptyset'_n$ with fixed values so that equation 5.4 contains only variables associated with the installation and the lanterns, i.e. S and H, K and K'. Then $\overline{G}$ will be evaluated for standard observational conditions. These will be taken as: cut-off angle of the vehicle roof 20^o,

driver's line of sight along road and 1^o down,

driver eye height 1.2m(4ft),

length of installation 450m (1500ft),

thus,

$$\phi'_o = 20^o$$

$$\phi'_n = \tan^{-1} ({}^{h'}/450)$$

$$a = 1^o$$

$$h' = H - 1.2$$

In the Australian street lighting code of practice, AS CA19, 1964 (and its revision AS 1158, 1973) restrictions on the light distribution run-back are given in the following form. The intensity at $\phi = 90^o$ ($\phi' = 0^o$) is specified together with an angular range in which a second intensity may lie. Since this work was done in order to assist the committee revising AS CA19, this method of specification is used in evaluating $\overline{G}$ in imperial units.

$\overline{G}$ has been computed from Equation 5.4 using the observational conditions set out above, the parameter values of what is referred to as a standard installation of S = 120ft (37m) and H = 30ft (9m) and the lantern characteristics:

$$I_A = 1200\text{cd}, \quad 70^o \leq \phi_A \leq 88^o$$

$$100\text{cd} \leq I_B \leq 700\text{cd}, \quad \phi_B = 90^o$$

The results are shown in Fig. 5.5.

It will be seen that:

(a) as ϕ_A increases the corresponding increases in glare become progressively larger, and

(b) for the lower values of ϕ_A glare increases with increasing I_B but as ϕ_A increases the glare value becomes less and less dependent on I_B. Finally, for values of $\phi > 86^o$, glare decreases with increasing I_B (the reason for this is shown in Fig. 5.6).

Extension to other Parameter Values.

(a) Values of $\overline{G}$ for values of I_A, other than 1200 cd, may be simply found by reading off the glare value for I_A = 1200cd in Fig. 5.5 for the appropriate value of I_A/I_{90} and multiplying it by $I_A/1200$. These correction factors are shown in Fig. 5.7.

(b) For glare values in installations where S is other than 120ft multiply the values from Fig. 5.5 by 120/S. These correction factors are shown in Fig. 5.7.

(c) For glare values in installations where H is other than 30ft multiply readings by the correction factors shown in Fig. 5.7.

The lantern mounting height correction factor is not simply proportional to $1/h'$ or $(1/h')^2$ as may be expected from the glare equations. The limits of integration are a function of h' and hence the correction factor varies with h' and the characteristics defining lantern glare. The relationship between $\overline{G}$ and h' for a range of parameters is shown in Fig. 5.8. From these data it can be seen that a working relationship of $\overline{G} \propto (1/h')^{1.34}$ may be used, as was done to derive the height correction factor in Fig. 5.7.

Thus, with one graph and a set of simple correction factors, $\overline{G}$ can be evaluated without the recourse to lantern data other than the intensities at two angles on the run back. This method provides the answer to the two questions posed in the introduction to this chapter. If the limiting value of installation glare is set desirable lantern characteristics can easily be deduced from Fig. 5.5. Conversely, if the characteristics of practical lanterns are known the glare to be expected in an installation can be deduced. The method will be used to analyse the relationship between glare and lantern run-back parameters. Before this is done the effect of assuming the set observational conditions and of a linear run-back will be examined.

However, before proceeding it is pointed out that equation 5.4

can also be evaluated using the same parameters that are used in the discomfort glare determination discussed in Chapter 3. There the lantern run-back characteristics are designated by the intensities at two angles, i.e. I_{80} and I_{88}, then:

$$K = \frac{I_{80} - I_{88}}{8}$$

$$K' = \frac{5\, I_{88} - I_{80}}{4}$$

Thus, $\bar{G}$ can be expressed in a similar form to the glare mark equation:

$$\bar{G}' = \log \left(0.122 + 0.114 \frac{I_{88}}{I_{80}} \right) + \log I_{80} + \log n$$

$$- 1.34 \log h' - 3.152$$

where $\bar{G}' = \log \bar{G}$ in cd/m^2

The first term gives the value of $\bar{G}$ for the conditions H = 10m, S = 40m, I_{80} = 100cd, driver eye height 1.5m, length of installation 500m, cut-off of car roof 20^{o}, line of sight 1^{o} down. The other terms embody correction factors similar to those discussed above, to extend the determination to anyother value of H, S and I_{80}.

OTHER FACTORS AFFECTING DISABILITY GLARE.

Four other factors have been mentioned which will affect the magnitude of disability glare and which now will be examined further. They are, cut-off by the vehicle roof, length of installation, line of sight and the specific relationship between glare and θ. The first three have been given fixed values in equation 5.4 for the purpose of computing glare in installations.

Cut-off of the Vehicle Roof.

It can be seen from Fig. 5.3 that the angle at which the vehicle roof shields the driver's eyes from light rays, from a lantern, will influence the amount of glare from the first lantern and hence the average glare, running through the installation. It has been assumed above that any rays less than 70^{o} to the downward vertical will be cut off and will not cause glare. This angle has been found to be representative of the modern vehicle-driver combination (see also 5.5), however, others have used larger values, e.g. 77.5^{o} (5.6). The following figures, which were obtained by evaluating equation 5.4 using the appropriate values for the limit ϕ'_o, show how the vehicle-roof cut off affects $\overline{G}$ in an installation for which H = 30ft(9m) and S = 120ft(37m).

Angle ϕ'_o	20	17.5	15	12.5	10
$\overline{G}$	1.00	0.96	0.91	0.86	0.78

Each result, relative to that at $\phi'_o = 20^{o}$, is the mean of the values computed for 5 sets of lantern characteristics met with in practice. The largest deviation of any value from the mean is 4 per cent.

Length of Installation.

$\overline{G}$ has been evaluated for an installation length of 1500ft(450m) which is equivalent to 12 spans, when S = 120ft. Other investigations have used about this number of lanterns in the field of view (5.6). Disability glare for any other span length, using the correction factor in Fig. 5.7 always refers to the constant installation length. However, glare for any other length of installation (d) may be found by evaluating expression 5.4 using the appropriate limit of ϕ'_n, where $\phi'_n = \tan^{-1}(h'/d)$.

In practical installations the first three lanterns contribute 1/2 to 3/4 of the value of $\overline{G}$ and the twelfth lantern only contributes 1 to 3 per cent of the total. Thus consideration of an installation length of 1500ft appears appropriate. This is illustrated by the following table:

Lantern	1	2	3	4	5	6	7	8	9	10	11	12
% of $\overline{G}$	17	26	10	8	7	6	5	5	4	4	4	3

The example given is for a Type 1 lantern, (see Table 5.1), H = 30ft, S = 120ft.

Line of Sight.

Although the driver's eyes are in constant movement, some general line of sight is usually taken to which data may be referred. So far, the driver has been assumed to be looking straight along the road and 1^o down from the horizontal (5.7, 5.8). However, others have assumed a horizontal line of sight (5.6). Values of $\overline{G}$ for any inclination of the line of sight to the horizontal may be computed using equation 5.4 and the appropriate value of a. Values of $\overline{G}$ for an inclination of 1^o (a = 1) have been compared to those for a horizontal line of sight (a = 0), for a range of lantern characteristics met with in practice and with S = 120ftand H = 30ft. It was found that:

$$\frac{\overline{G}\ \text{(Horizontal)}}{\overline{G}\ (1^o\ \text{down})} = 1.82 \pm 0.1$$

Relationship Between Glare and θ

Equation 5.4 was derived on the basis:

$$G_i \propto \frac{1}{\theta_i^2} \qquad (x)$$

A glare meter has been designed on the basis:

$$G_i \propto \frac{1}{\theta_i(\theta_i + 1.5)} \qquad (y)$$

The equation for $\overline{G}$ using this relationship can be derived in a similar way to that used to derive equation 5.4. Thus average values of glare derived using the meter in measurements discussed elsewhere may be corrected to the more usual basis by using the following factors, based, as above, on a range of practical installations:

(a) Line of sight 1^{o} down $\dfrac{\overline{G}\ (x)}{\overline{G}\ (y)} = 1.45$

Range (1.54 - 1.26)

(b) Line of sight horizontal $\dfrac{\overline{G}\ (x)}{\overline{G}\ (y)} = 1.84$

Range (1.96 - 1.61)

RESULTS USING PRACTICAL LANTERNS

The principles involved in the calculation of glare were derived on the basis of linear runback. The writer and his associates (5.9) have compared results derived from a linear runback with those from actual runbacks. It can be seen, from Fig. 5.9, that the runbacks of practical lanterns can diverge from linearity. From the data of Fig. 5.9 values of $\overline{G}$ have been derived for actual runbacks, using a summation process based on equation 5.3. Further values of G have been derived using the process described in the previous section by using only the lantern characteristics given in Table 5.1, that is assuming a linear runback.

The two sets of values are shown in Table 5.2. For six of the seven installations considered, which include five lantern types in two arrangements, the difference between the values of $\overline{G}$ is 10 per cent or less. For the remaining installation the difference is less than 20 per cent. This shows that for most practical lanterns a knowledge of the exact form of the runback is unnecessary to compute disability glare: two characteristics defining the runback only are necessary.

Values of disability glare calculated using Adrian's method, outlined in Fig. 5.2 are also given in Table 5.2 for comparison. It can be seen that there is good correlation between the two methods. The method described in this paper however is considerably simpler than Adrian's method, there being no need to use any special grid on the polar curve, which has to be altered for each lantern arrangement, and virtually no computation. This agreement is rather surprising since Adrian's method is supposed to yield a maximum rather than an average value.

The assumption by Adrian that the observer standing one span from a lantern produces conditions for maximum glare may be unwarranted. Reference to Fig. 5.3 suggests that instantaneous values of glare are very sensitive to observer position. Approaching the first lantern increases the glare from it and the second lantern until the peak from the first lantern is passed. By positioning the observer optimally an increase of about 40% can be made in the glare over that obtained by positioning the observer one span from the first lantern. This effect adds a further point in favour of the averaging method described here since no optimisation procedure is necessary as would seem appropriate for the maximum method.

ANALYSIS OF LANTERN CHARACTERISTICS.

It has been shown that disability glare can be evaluated with good accuracy by assuming lanterns to have a linear runback which is characterised by two parameters. The two characteristics used are the intensity at 90° and the angle at which a given intensity occurs. This characterisation has been used because of its relevance to Australian practice.

Other characterisation can be readily used, in Great Britain the same system is used, the CIE currently use the intensities at 90° and 80° although it is likely that in a revision of the international recommendations intensities at 88° and 80° will be used.

In this section the relationship between glare and the runback characteristics used in Australian practice will be explored first then this will be compared to CIE recommendations. The discussion refers to AS CA19 but as in the previous chapter it will be indicated how this analysis ties in with the revision, AS 1158.

Australian Practice.

The requirements for the lantern runback given in AS CA19 are shown in Table 5.3. The intensities are given in terms of MHI (mean hemispherical intensity); MHI takes into account light losses in the lantern and is equated to the lamp output:

$$MHI = \frac{1000B}{2\pi} \text{ cd per 1000 lamp lumens} \quad \text{--- (5.5)}$$

where B is the fraction of the lamp flux emitted by the lantern in the lower hemisphere (c varies between 0.6 and 0.7 for different types of lantern).

Data from Fig. 5.5 relevant to the lantern requirements have been redrawn in Fig. 5.10. The glare values produced by S C O lanterns in which the 1.2MHI value is allowed to range between $\emptyset = 78^o$ and 84^o (L S C O 78^o - 81^o H S C O 81^0 - 84^o) vary by about 25 per cent. However a dispensation was allowed for sodium lamped lanterns in which the 1.2MHI value may occur up to $\emptyset = 86^o$. It will be seen that the glare is increasing sharply at this point and can rise by a further 30 per cent. If the 1.2 MHI value occurs up at the extreme end of angle tolerance, the intensity value at $\emptyset = 90^o$ makes little difference to the glare value. In Fig. 5.10 the curves for $I_{90} = 0.6$ MHI and $I_{90} = 0.15$ MHI are close together. However if the 1.2 MHI intensity occurs at smaller values of $\emptyset$ then the value of I_{90} affects the glare value. It can be seen from Table 5.4 that mercury lamped reflector lanterns are more likely to be on the lower curve and the sodium lamped refractor lanterns on the higher one. These values, derived from photometric data, are supported by in-service measurements, described in Chapter 4.

It has been suggested that for glare to be adequately restricted to facilitate visibility of objects viewed against the bright carriageway $\bar{G}$ should be not more than 0.2 - 0.3 of the carriageway luminance. Glare on this basis in a practical installation, derived by Fig. 5.10 and 5.7, will be about 0.34 for lanterns working at $\emptyset = 84^o$ and 0.4 for lanterns working at $\emptyset = 86^o$. Thus for lanterns to be satisfactory on this basis they should be working at $\emptyset < 84^o$. In the next chapter it will be shown that glare should be further restricted where the surrounds to the road are dark. In order to achieve this it will be suggested that SCO lanterns need the intensity at 90^o to be reduced from 0.6 MHI to 0.15 MHI; quite a reasonable proposition by the data in Table 5.4.

For lanterns having a nominal cut-off distribution, the glare value will increase by 50 per cent over the tolerance range of $\emptyset_{1.2MHI}$. The glare from C O lanterns will be about half that of S C O lanterns according to the two curves shown in Fig. 5.10. However, it has already been noted that values for S C O reflector lanterns are more likely to be close to the lower curve than the higher one. Then the difference between the two classes becomes less marked on the basis of equal MHI values.

The Australian method of allowing an angular tolerance on the 1.2 MHI intensity value (or any type of intensity value) appears justified. The glare, especially from S C O lanterns, is not critically dependent on the value of $\emptyset_{1.2MHI}$. If manufacturers prefer this method of specification and it allows for easier quality control, then there is no reason why it should be abandoned in favour of a maximum intensity at a specific angle.

CIE Glare Requirements.

The present CIE restrictions for the light distribution runback are shown in Table 5.3. The CIE requirements have been compared to the Australian requirements in Fig. 5.10 by assuming a value of B = 0.63 in equation 5.5 by which the MHI in cd/1000 lamp lumens is 100.

The maximum CIE glare value for S C O lanterns coincides with values obtained from the lanterns at the lower end of the Australian tolerance range for $\phi_{1.2MHI}$ but with I_{90} = 0.6 MHI. Actual reflector S C O type lanterns would be likely to fall within the CIE tolerance because of their relatively low values of $\phi_{1.2MHI}$ and I_{90} as discussed above.

The maximum CIE glare value for C O lanterns is half that of lanterns at the low end of the Australian tolerance. The maximum CO glare value is ¼ that of the maximum S C O glare value. The Australian figure is ½ and in practice is likely to be less. On this basis a case can be made for tightening the Australian tolerances. Halving the present values, i.e. 0.6 MHI between $\phi = 72^{o}$ and $\phi = 78^{o}$ and I_{90} = 0.075 MHI would bring the Australian C.O. glare control more in line with that of the CIE and give a more marked difference between S C O and C O lanterns, than is evident at present.

Revision of AS CA19.

In the revision, in AS 1158 1973, the less restrictive angular tolerance for the 1.2 MHI intensity for sodium lamped lanterns (up to 86^{o}) was withdrawn. One class of semi-cut-off lanterns replaced the two classes of high and low. The angular tolerance of the 1.2MHI intensity for the new class is 78^{o} - 84^{o}. The method of specifying intensity is now in terms of cd per 1000 lamp lumens. The new values are virtually unchanged being the direct equivalent of those in terms of MHI, obtained by using a B value for lanterns representative of those in use in Australia (5.10).

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5.10 Kenway, B. D., Revised SAA Public Lighting Code: Part 1, Lighting of urban traffic routes, AS 1158, 1973, IES Lighting Review,Vol. 35, No. 5, 1973.

Lantern type	Lamp	Lamp lumens	1.2 MHI (cd)	$\phi°$ 1.2 MHI	I_{90} (cd)
All h.s.c.o.					
1. Reflector	250W MBF/U	12,000	1670	82	840
2. Reflector	250W MBF/U	12,000	1590	82.5	160
3. Reflector	400W MBF/U	21,000	2880	81	310
4. Refractor	100W SOX	14,850	1710	84.5	810
5. Refractor	150W SOX	24,500	2940	83	1210

Table 5.1. Photometric characteristics of some semi-cut-off lanterns, the polar diagrams of which are given in Fig. 5.9.

Lantern type	Installation geometry	Linear runback	Exact runback	Adrian's method
1		0.101	0.099	0.105
2	H = 30 ft	0.076	0.080	0.086
3	S = 120 ft	0.120	0.102	0.110
4		0.121	0.124	0.127
5		0.186	0.177	0.187
3	H = 40 ft	0.062	0.056	0.074
5	S = 150 ft	0.097	0.090	0.096

Table 5.2. Values of $\overline{G}$(ftL) for practical installations using the approximate and exact runback of lanterns whose polar diagrams are given in Fig. 5.9. Values derived by Adrian's method have been normalised to k = 10.

AUSTRALIA

Lantern type	Intensity at horizontal (max.)	Intensity 1.2 MHI to be between angles to downward vertical (min.)	(max.)	Max. intensity angle to downward vertical (min.)
Cut off	0.15 MHI	72°	78°	62°
Low semi cut off	0.6 MHI	78°	81°	68°
High semi cut off	0.6 MHI	81°	84°	70°
High semi cut off (sodium only)	0.7 MHI	81°	86°	70°

C.I.E.

Lantern type	Maximum intensity at angle to downward vertical		Direction of maximum intensity
	90°	80°	
Cut off	10 cd/1000 lm*	30 cd/1000 lm	0 - 65°
Semi cut off	50 cd/1000 lm*	100 cd/1000 lm	0-75°

*Up to maximum of 1000 cd.

Table 5.3. Glare control through lantern specification. The recent revision of the Australian standard gives lantern characteristics in cd per 1000 lamp lumens. The numerical equivalents are a direct conversion from this table.

Lantern	Lamp	$\phi_{1.2\ MHI}$	I_{00} (MHI)
l.s.c.o. reflector	250W - 400W MBF/U	Mean of 9 - 80.3° Range 78° - 81°	Mean 0.16 Range 0.09 - 0.34
h.s.c.o. reflector	250W - 400W MBF/U	Mean of 6 - 82.2° Range 81° - 83.5°	Mean 0.25 Range 0.12 - 0.6
h.s.c.o. refractor	100W - 200W SOI or SOX	Mean of 9 - 83.6° Range 81° - 86°	Mean 0.49 Range 0.35 - 0.63
c.o.	250W - 400W MBF/U	Mean of 4 - 76.1° Range 74° - 77.5°	
c.o.	100W - 200W SO/L or SOX	Mean of 5 - 74.5° Range 72° - 76°	

Table 5.4. Values of the characteristics defining glare control for types of lanterns in-service in New South Wales.

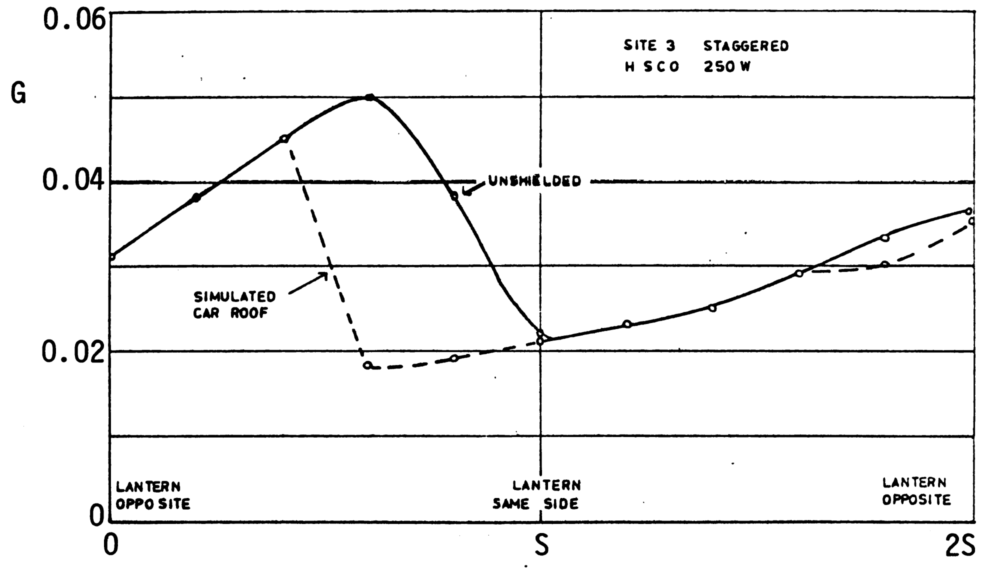

Fig. 5.1. Variation of disability glare G(ftL) through an installation, showing the effect of the cut off of a car roof. The diagram is based on measurements described in chapter 4.

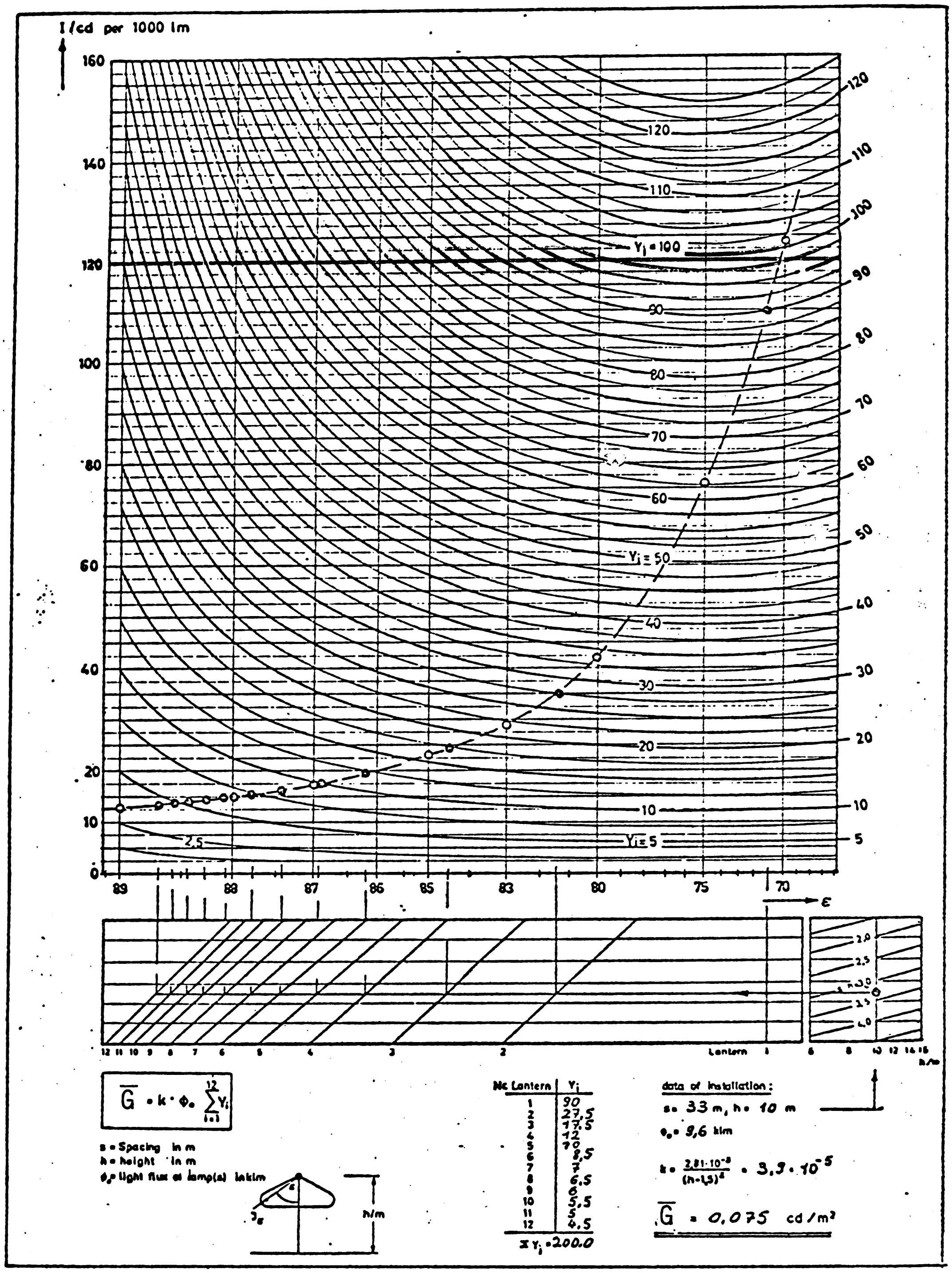

Fig. 5.2. Example of Adrian's method. The runback of the polar curve is plotted on the special grid. Values of Y_i are read off for each lantern. The angular positions of the lanterns are determined by the use of the series of scales for various values of S and H. The method is based on eqn. 5.1 but using 9.2 instead of 10. (Adrian now places his observer at the angle of the car roof cut-off rather than beneath a lantern, this new configuration will give values of $\overline{G}$ closer to max but not necessarily the max; see Fig. 5.3.)

(After Adrian)

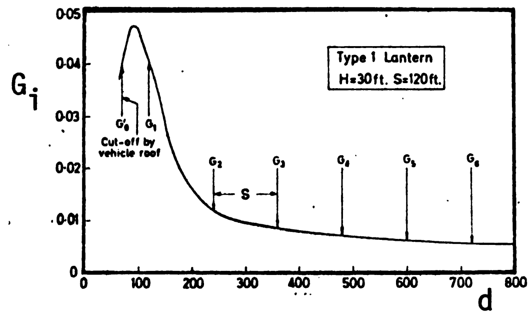

Fig. 5.3. Variation of disability glare G_i(ftL) from a single lantern with its distance d(ft) away. The values marked G_1, G_2, G_3 etc. on the curve represent the glare from individual lanterns in an installation at one instant in going through the installation.

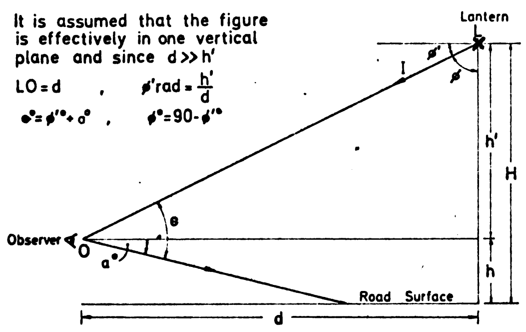

Fig. 5.4. Schematic diagram of the relationship between observer and lantern, involving the symbols used in the text.

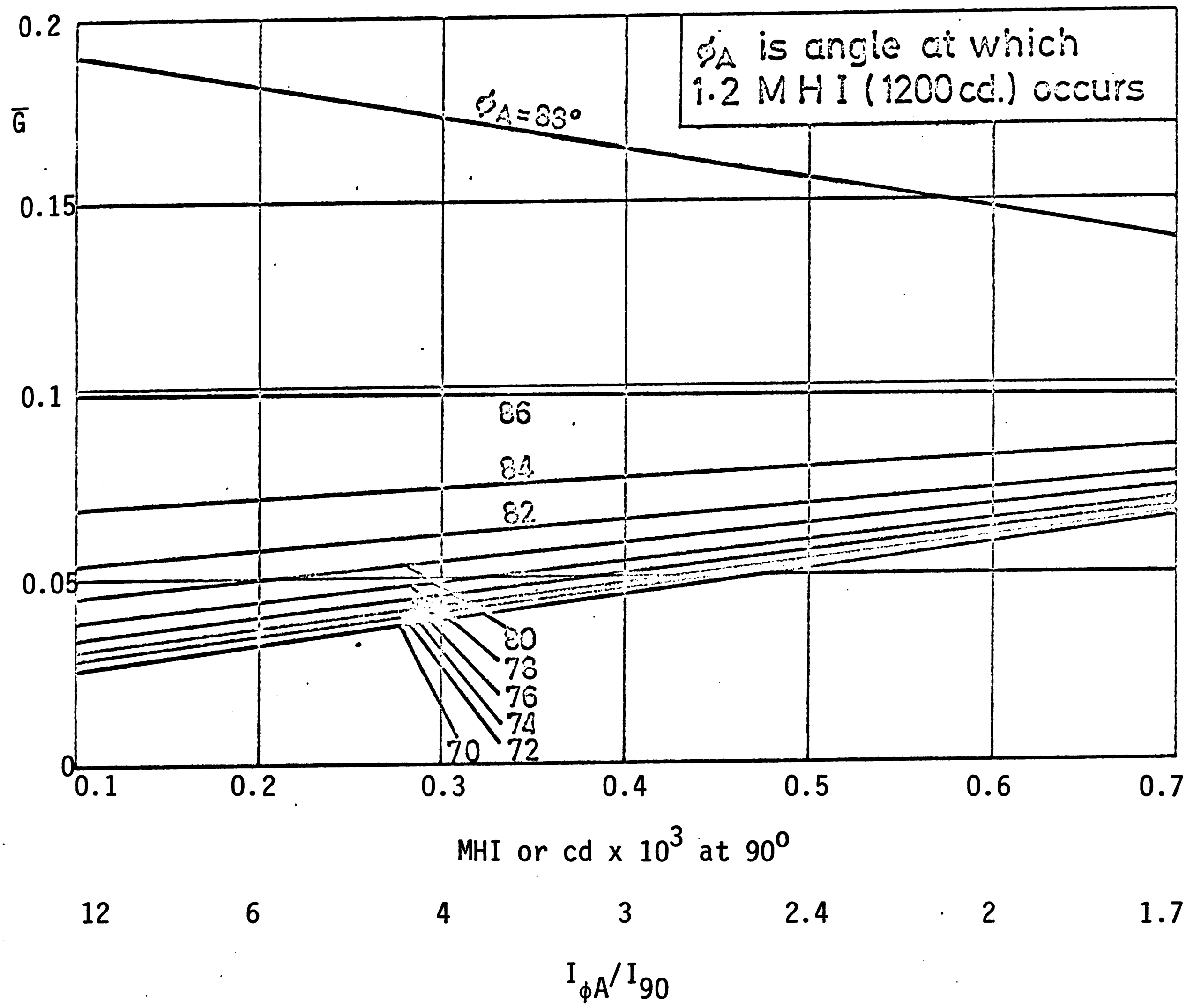

Fig. 5.5. Nomogram relating the average glare $\overline{G}$(ftL) in an installation to the two runback characteristics of the polar curve (i) ϕ_A the angle at which the intensity 1.2 MHI occurs, and (ii) the MHI value of $\phi = 90^o$. The nomogram is based on the following values: MHI = 1000 cd, H = 30 ft, S = 120 ft; for other parameter values use the correction factors in Fig. 5.7.

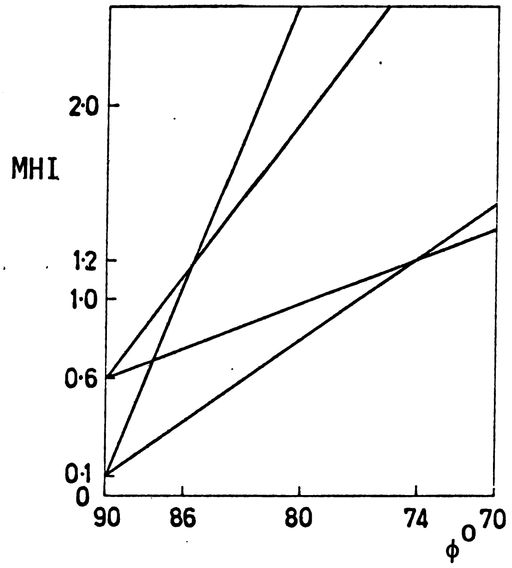

Fig. 5.6. Examples of linear runbacks, showing how small values of MHI at $\phi = 90^0$ coupled with large values of ϕ for the 1.2 MHI intensity can give rise to large intensities at smaller values of ϕ.

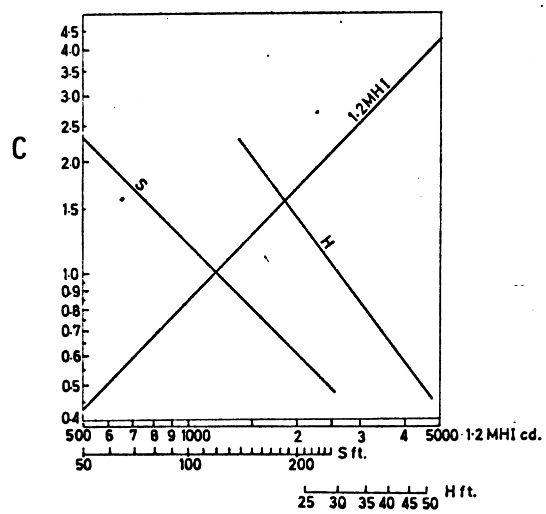

Fig. 5.7. Correction factors C for variation in lantern intensity (1.2 MHI), lantern spacing (S) and lantern mounting height (H) from the standard conditions of the nomogram of Fig. 5.5.

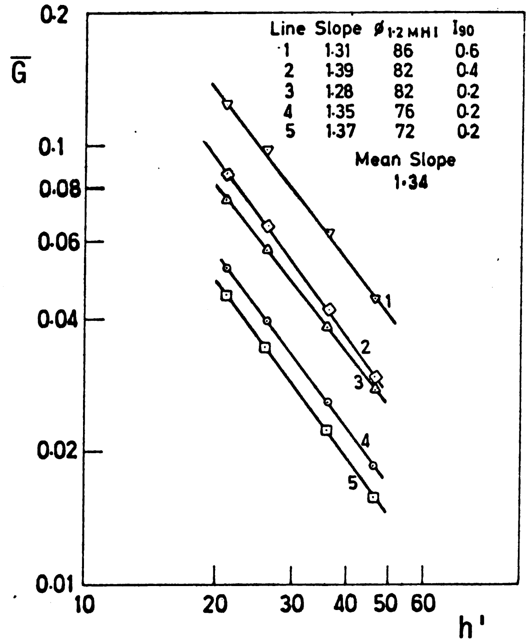

Fig. 5.8. Variation of glare, $\bar{G}$(ftL), with the height of the lanterns above the drivers eyes, h'(ft), for different values of lantern characteristics, using the standard conditions MHI = 1000 cd and S = 120 ft.

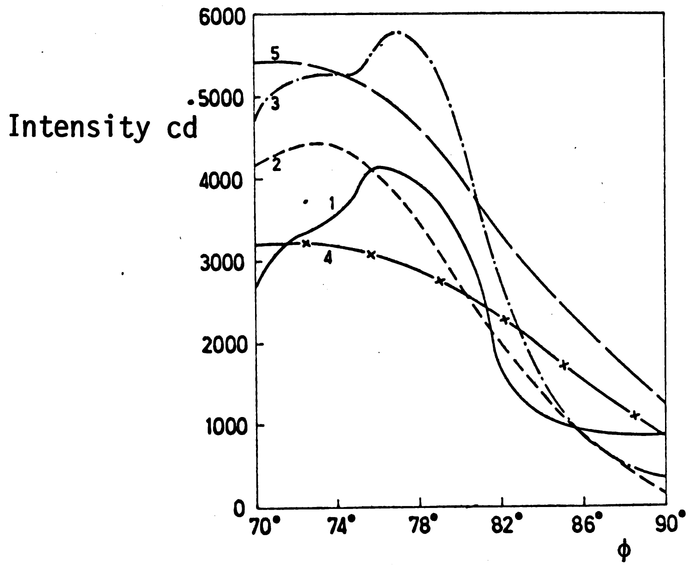

Fig. 5.9. The runback portions of the polar curves of some lanterns in common use in New South Wales. Details of the lantern types are given in Table 5.1.

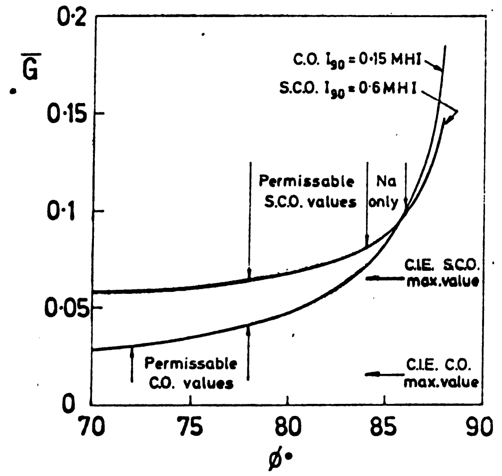

Fig. 5.10. Variation of glare, $\bar{G}$(ftL), with position of ϕ for the intensity 1.2 MHI on the lantern runback and the intensity at ϕ_{90^o}. The curves are for the standard conditions MHI = 1000 cd, H = 30 ft and S = 120 ft. The range of values inherent in the Australian and CIE glare control requirements are indicated.

CHAPTER 6

VISUAL PERFORMANCE IN STREET LIGHTING: THE INFLUENCE OF THE SURROUNDS AND GLARE

INTRODUCTION.

In Chapter 4 it was shown, from measurements on in-service installations, that in general the carriageway luminance reached values recommended in the current Australian Street Lighting Code. However, it was pointed out (Fig. 6.1) that the surrounds to the carriageway are often dark. It is inferred that where visibility of objects viewed against the carriageway may be satisfactory, the visibility of those viewed against the surrounds may not be so satisfactory. It has been suggested that the immediate backgrounds to the road are important as a source of informal information, in particular for the visibility of pedestrians and their movements.

The measurements showed that the values of disability glare from installations employing reflector lanterns were low being in the range 0.036 to 0.072ftL (0.12 to 0.24 cd/m^2) whereas those from refractor lanterns were high being in the range of 0.15 to 0.35ftL(0.5 to 1.2 cd/m^2). The influence of the parameters of the lantern light output distribution has been discussed in the previous chapter and it has been shown that with tighter requirements for this type of lantern it can be assumed that such high values of glare will no longer occur. Therefore, further discussion will be limited to the lower range of glare veiling luminance values.

In Chapter 3 it was deduced that disability glare is sufficiently controlled if the ratio of the veiling luminance ($\bar{G}$) to the average carriageway luminance ($\bar{L}$) is less than about 0.2 to 0.3. The measurements gave values of $\bar{L}$ in the range 0.2 to 0.3ftL (0.7 to 1.0 cd/m^2) excluding these installations showing deterioration. Thus the best and worse values of $\overline{G}/\overline{L}$ in the installations are 0.12 and 0.36 respectively, with the majority having values of about 0.2. It can be said on this basis that restriction of glare to facilitate visibility along the carriageway is adequate. However, because of the possibility of low surround luminance it cannot be assumed that this glare restriction is sufficient also for other parts of the visual field.

This chapter will be devoted to the analysis of visual performance, using the method of revealing power discussed in Chapter 2, associated with the immediate surrounds to the road. Only light from street lighting lanterns is taken into account. The effect of vehicle head lighting is considered in Chapter 11.

GENERAL SITUATION.

Method.

In order to calculate revealing power of a background, it is necessary to have values of the veiling luminance and object illuminance; see equations 2.5 and 2.6. Both quantities will vary cyclically through an installation, as illustrated in Fig. 6.2. The variation of object illuminance is large, over 7 to 1. However, much of this variation is due to a spike caused by the sharp rise and fall in illuminance as the object approaches up to and moves in front of a lantern on the same side of the road. For 75 per cent of the cycle the variation does not exceed 3 to 1. The maximum variation of veiling luminance is much less, about 3 to 1. The potential spike in approach to the lantern on the same side is cut off by the vehicle roof. For nearly 90 per cent of the cycle the variation is reduced to 2 to 1.

It is convenient to use average values of illuminance and veiling glare to make the analysis manageable since it would be very difficult mathematically to predict the exact distribution of instances of linked values of veiling luminance, illuminance and background luminance with the observer's line of sight. For instance a pedestrian behind a lantern will have high illuminance whereas if he stepped a short distance in front the illuminance drops sharply. In each case the illuminance and hence the luminance of the background will remain much the same. Harris and Christie (6.1) have shown that no serious errors are introduced into the analysis by using mean illuminance where the variations are as small as those indicated above.

In addition there is the problem of where exactly the driver looks. For the measurements and computations of glare, the line of sight is assumed to be along the road axis and directed down one degree. However, objects are distributed across the carriageway and the observer's eyes are in constant movement. This has implications to both the value of veiling luminance and the necessary contrast required for an object to be seen. Objects need to be seen about 300ft(90m) ahead and if the driver is 10 ft(3m) in from the road edge, a kerbside pedestrian at this distance will be displaced horizontally about 2^{o} from the direction of travel of the vehicle.

For the purposes here the effect of this displacement can be regarded as small:

(i) if the driver is looking at the object the measured veiling glare will be reduced by the effect of a horizontal component in the angle term of the glare formula. This component is small since it is by Chapter 5, the closer lanterns that contribute mainly to the veiling luminance and they are considerably displaced vertically. For example the third lantern at its furthest distance away during an approach will be about 5^{o} vertically off the line of sight, the angle increasing thereafter for it and the other closer lanterns. The error, in neglecting the horizontal component will be an overestimation by

15 per cent of the glare value from this one lantern at this point. However, this lantern contributes only 10 per cent to the total glare and therefore the total installation error of overestimation will be much less than 15 per cent.

(ii) If the observer is looking along the carriageway axis the object will be slightly outside the cone of central vision. The threshold values of necessary contrast for detection will rise. However, it has been pointed out that the data used applies to certainty of detection where the exact location in space and time is uncertain.

Results.

Fig. 6.3 gives the values of revealing power for backgrounds encountered in a hypothetical street lit with semi-cut-off lanterns according to Australian Street Lighting Code. The mean illuminance on vertical surfaces along the road edge facing the traffic and the mean veiling luminance were derived from the measurements in a number of streets, as described in Chapter 4.

The revealing powers of backgrounds encountered in different areas of the visual field on measured roads are given in Table 6.1. It can be seen that the carriageway pavement is associated with high values of revealing power. Often these are close to 100 per cent; only in some areas of minimum luminance are more than 20 per cent of elemental objects likely to be less than adequately visible. Where the surrounds to the road are made up of painted house fronts and fences or of light coloured brick, the revealing power will be similarly high. Where house fronts and fences are generally of brick and where there are bushes flanking the footpath, values will be low, around 50 per cent but as low as 20 per cent i.e. 80 per cent of elemental objects will be less than adequately revealed.

Splitting revealing power into components of silhouette and reverse silhouette shows that as the luminance of the background decreases the reverse silhouette component increases. For the value of glare used, vision is entirely by reverse silhouette below background luminances of 0.03ftL (0.1 cd/m^2).

Further analysis in Fig. 6.3 shows that the glare has an increasingly marked effect on revealing power as the background luminance decreases, especially if it is below about 0.05ftL (0.17cd/m^2). Fig. 6.4 shows how revealing power is affected by increasing glare. At high background luminances of say 0.3ftL (1 cd/m^2) glare up to even 0.1ftL (0.33cd/m^2) i.e. $\overline{G}/\overline{L}$ = 0.33, has virtually no effect on revealing power. As noted above at lower background luminance there can be a dramatic effect: as glare increases there is an increasing loss of revealing power over an increasing range of background luminances. Only at the lowest background luminance levels does increasing glare have a small effect on vision; but in this case revealing power is already low.

The reason why glare has such a general drastic effect is because it reduces both the silhouette and reverse silhouette components of revealing power. At the background luminances where the silhouette component is declining, i.e. by Fig. 6.3 at about 0.03 - 0.06ftL, the decline is sharpened by glare. In addition, the potential increasing component of reverse silhouette which could compensate for the declining silhouette component is also depressed by glare.

Thus three remedial measures emerge that could be exploited to increase the visibility of objects viewed against the dark surrounds to the carriageway:

(i) raise the luminance of the backgrounds;

(ii) increase the illuminance of objects to enhance reverse silhouette;

(iii) reduce disability glare;

These possibilities are examined in the next section within the context of providing practical guidance.

APPLICATION TO PRACTICE.

Glare Restriction.

The method for computing average glare from a street lighting installation is given in Chapter 5. In particular Fig. 5.10 gives the veiling luminances from lanterns with runback characteristics in the light distribution required in the Australian Code of Practice. The data in the figures applies to a standard installation: H = 30ft; S = 120ft; and MHI = 1000cd. In order to relate these to an example of a practical installation H = 30ft, W = 40ft; $^{S}/H$ = 5 (semi-cut-off) or $^{S}/H$ = 3 (cut-off) a factor needs to be computed for the change in S and in MHI. In the semi-cut-off installation the increased spacing will give rise to less glare and in the cut-off installation the decreased spacing will give rise to increased glare. Off setting this the lantern flux and hence the MHI value will rise in the SCO installation and fall in the CO one. The design factor works out to X0.8; in practice this factor could be higher. This arises because the MHI value might be greater than the design figure since the nearest appropriate lamp wattage will be used. In the example it could be a 250W MBF lamp, in which case the factor rises to 1.1, since the lamp gives nearly 40 per cent more flux than the design requirements.

Then the expected glare values, in ft - L are:

Lantern Class	Intensity at 90°	Pos^{n} of 1.2 MHI		CIE (max. value)
		78°	84°	
SCO	0.6 MHI	0.052	0.068	0.052
		(0.071)	(0.093)	(0.071)
	0.15MHI	0.032	0.052	
		(0.044)	(0.071)	
		72°	78°	
CO	0.15MHI	0.024	0.032	0.012
		(0.033)	(0.044)	(0.016)

NOTE: The values in parenthesis refer to the over-designed installation.

Semi-cut-off lanterns in which the full upper angular tolerance for the 1.2 MHI intensity is taken advantage of give excessive glare when used on roads with dark surrounds. However, it has been shown in the previous chapter that reflector lanterns using mercury discharge lamps tend to be working at the lower end of the tolerance: in fact the intensity at 90° is closer to the cut-off requirement of 0.15 MHI than the semi-cut-off requirement of 0.6 MHI. This has been shown by reference to photometric data and by in-service measurements of glare.

There is a big reduction in the glare effect in going from the use of SCO lanterns at one end of the range ($\bar{G}$ = 0.07-0.09ftL) to those at the other end ($\bar{G}$ = 0.03-0.04ftL). There appears to be little point in going further and using CO lanterns since there will be little further reduction in glare, unless a more severe cut-off, of the type advocated by the CIE, is used. However, economic considerations need to be taken into account at this stage because the spacing of lanterns must then be reduced from $S/H = 5$ to $S/H = 3$.

It is apparent that lighting engineers should use only those SCO lanterns with good glare restriction in situations where the surrounds are dark. It is probably not appreciated by them that a wide range of glare effects can arise from lanterns all nominally complying with the SCO requirements. It is suggested that SCO lanterns could be graded for this purpose into two types:

Situation	Intensity at 90^o (max)	Pos^n of 1.2 MHI	Comment
Light Surrounds	0.6 MHI	78^o - 84^o	Current Requirement
Dark Surrounds	0.15 MHI	78^o - 84^o	Suggested Modification

Increased Illumination.

Since some glare is unavoidable in practical economical installations, a large component of revealing power will be by reverse silhouette, especially if the value of background luminance is low. If the general illumination is raised in the installation this component will be enhanced, in addition the general luminance level will rise which in turn will, by Fig. 2.2 and Fig. 6.3, enhance contrast sensitivity and improve visual performance. Lighting engineers may easily increase illumination by a factor of two approximately by increasing the wattage of the lamps in the lanterns, e.g. from 250 watt MBF (12,000 lamp lumens) to 400 watt MBF (21,000 lamp lumens).

The revealing power for the backgrounds in installation with increased illumination is shown in Fig. 6.5. The curves have been displaced to the left by halving the new values of background luminance so they may be compared with installations in which the illumination has remained the same. Doubling the illumination in the installation with originally a glare level of 0.04ft L(0.14cd/m^2) raised the revealing power to that of an installation that has a glare level of 0.03ft L (0.1cd/m^2), i.e. doubling the illumination has the same effect as cutting the glare by 0.01ft L(0.03cd/m^2).

Doubling the illumination in the installation with a glare level of originally 0.03ft L(0.1cd/m^2) raises the revealing power to nearly that in a cut-off installation. Thus the use of lanterns at the extreme low end of the SCO range with double the light output (and double the glare) will give the same effect as using CO lanterns. However, this simple increase in the use of power will be a much more economical proposition than the increase in use of power <u>and</u> the increase in amount of lighting equipment associated with CO lighting.

CHANGES IN LIGHT DISTRIBUTION.

The lanterns used in the installations discussed above release a considerable component of their light towards the house side and so onto the surrounds. Examinations of iso candela diagrams suggest that this component is about 50 per cent.

In Chapter 3, it was shown that detailed attention through specific quantification was being paid to the carriageway luminance and the control of discomfort glare. With the advent of the more compact high pressure sodium source lantern designers may be tempted to consider only the distribution of light in the vertical plane and to concentrate light on the carriageway to the detriment of the surrounds.

It would be a pity if lack of specific quantification through the imprecise nature of this aspect of road lighting led to retrograde modifications of the azimuthal light distribution. Appraisals of new lanterns designed under the impetuses mentioned above should include the component of light flux falling on the road surrounds and the effectiveness with which it is used.

In Fig. 6.6 the general effects of changing that part of the light distribution which illuminates the roadway edges is explored in order to give guidance on future lantern design. Increased illuminance of the road surrounds and objects on the road edge, both together and separately, have been considered whilst holding the level of glare constant to that of the best current SCO lanterns. This implies that the azimuthal distribution has a sharp cut-off along the road edge as well as the normal vertical runback. As before the curves have been moved to the left where applicable.

Where different amounts of light are arranged to fall on backgrounds and objects, the biggest improvement arises where the backgrounds are made brighter than the objects. Revealing power is greater in this case than in the current cut-off lanterned installation. This arrangement implies a peak in the azimuthal distribution directed along the house side in the direction of traffic onto the backgrounds.

On the other hand, enchancement of light on the object only, by restricting the increase of light in the azimuthal distribution to only the road verge immediately abutting the kerbline improves seeing radically where the surrounds have a very low luminance. This is effected by increasing the reverse silhouette component; at other luminances revealing power is unimproved or worse.

Where the illuminance of both object and surrounds is doubled, revealing power is raised to between that of a current cut-off and glare free installation. This appears to be the most promising approach in the development of design.

MODIFICATION OF THE SURROUNDS.

Some lighting codes, e.g. of Australia and Great Britain, recognise the importance of the surrounds to the roadway, even to the point of expressing the pious hope that artificial light coloured backgrounds will be used to enhance visibility. This analysis does underline the correctness to this attitude and show that visibility will be enhanced if the relative contrast between object and background are altered. This is difficult to achieve and normally road lighting engineers have to take the situation as they find it.

It is probably unrealistic to expect small business and private householders to be acquainted with these aspects of lighting and take remedial action if necessary. However, it is not unreasonable to expect awareness and co-operation in large public and private activities. Public housing estates and utilities should have light coloured facades, walls and fences where these abutt roadways. Where trees are planted or issued by local government for road beautification they should have light coloured foliage if possible. Data presented in table 11.5 shows that the luminance factors of foliages can vary over a range of 4 to 1. One Australian road authority has examined native plants on this basis for their suitability for road side planting (6.2).

REFERENCES.

6.1 Harris, A. T., and Christie, A. W., The revealing power of street lighting installations and its calculation, Trans. Illum. Eng. Soc. (Lond), Vol. 16,No. 5, 1951.

6.2 Ford , F. F., Landscaping: reflective barriers, Aust. Rd. Res. Bd., Vol. 3, No. 3, 1967.

	Background	Luminance ft-L	Revealing Power
Pavement	maximum luminance range	0.8 — 0.23	100 — 98
	average luminance range	0.33 — 0.14	100 — 85
	minimum luminance range	0.19 — 0.06	93 — 65
Surrounds	painted wood house walls and fences	0.44 — 0.10	100 — 77
	brick and unpainted wood	0.15 — 0.01	87 — 20
	bushes	0.05 — 0.003	56 — 20

Table 6.1. Revealing power of backgrounds in installations designed to the Australian Code of Practice. The luminances are based on measurements described in chapter 4.

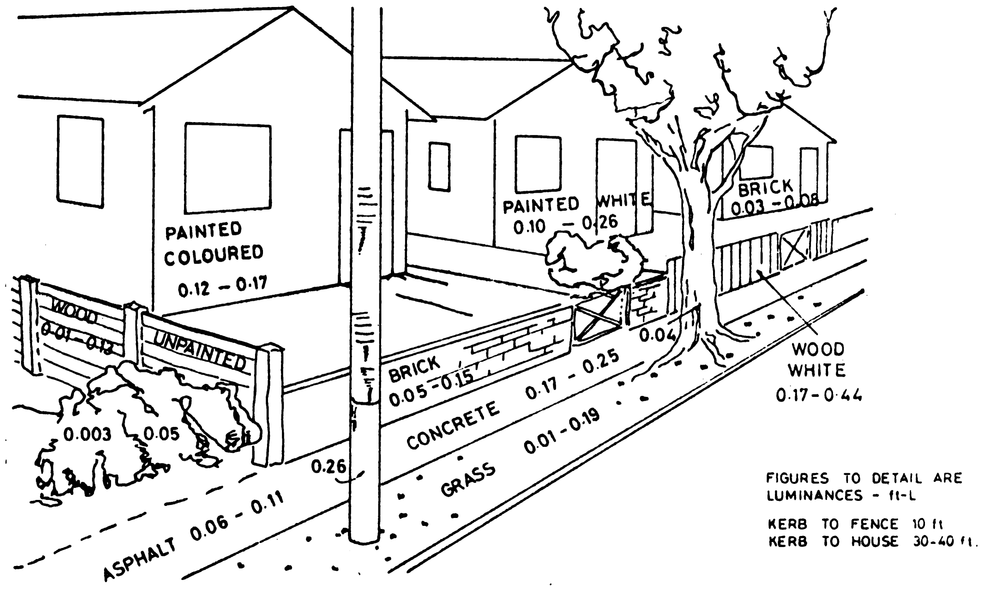

Fig. 6.1. The range of luminances of the surrounds to the carriageway met with in streets lighted to the Australian Code of Practice.

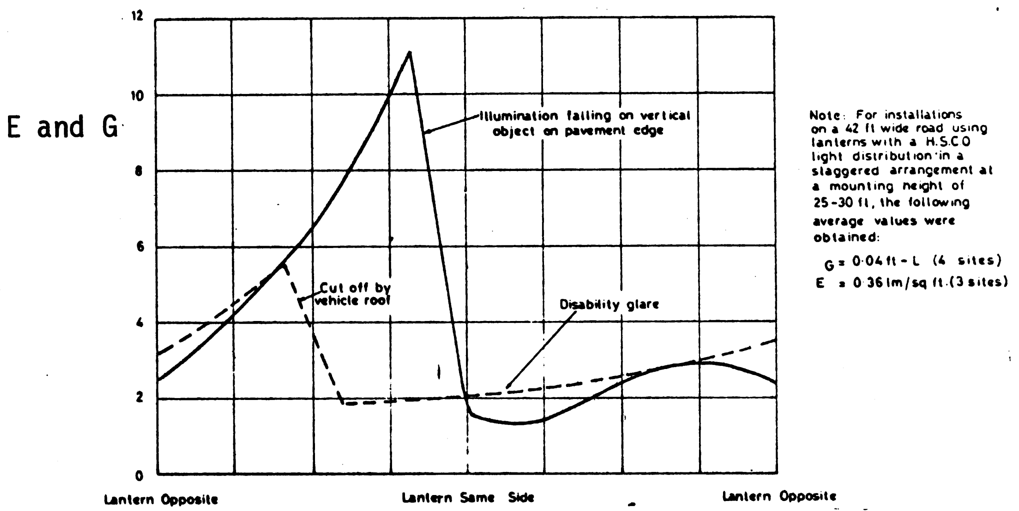

Fig. 6.2. Cyclic variation of object illumination E and glare G in street lighting installations, both in arbitrary units.

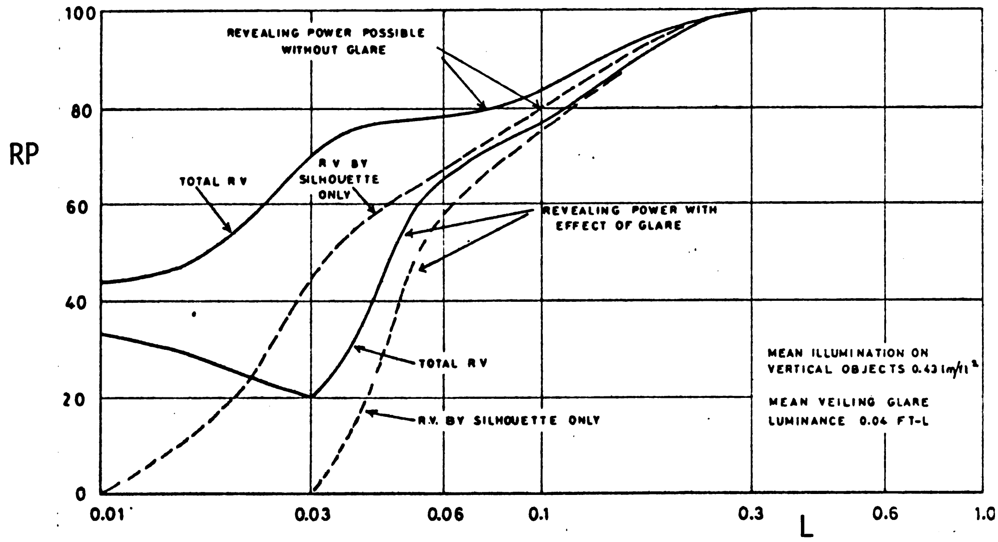

Fig. 6.3. The variation of revealing power RP with background luminance L(ftL) in a lighted street, with and without the effect of glare. The silhouette components are shown separately by the dashed lines.

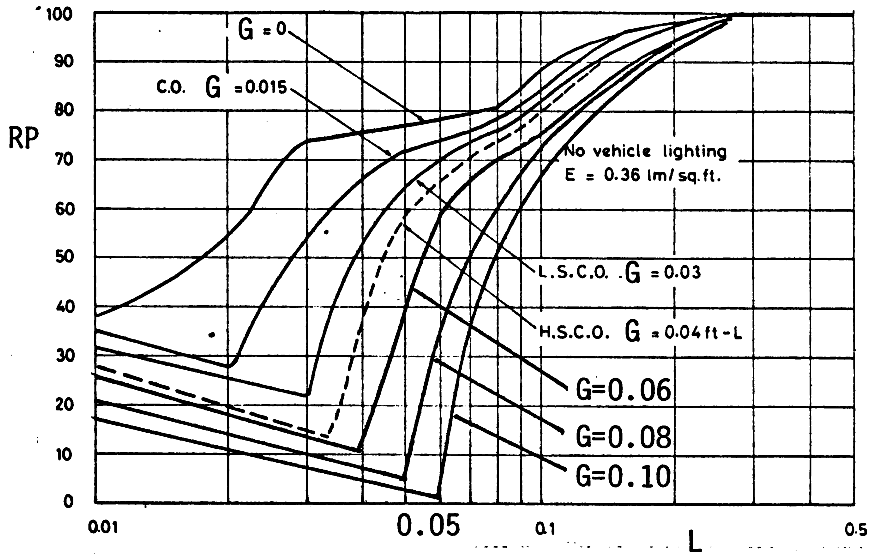

Fig. 6.4. The effect on the revealing power RP of backgrounds of luminance L(ftL) of different values of veiling luminance G.

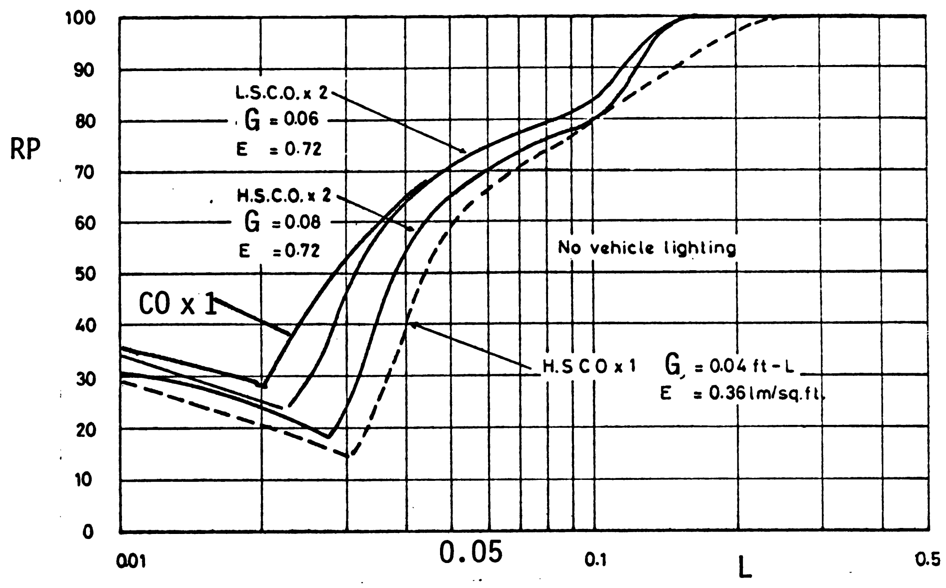

Fig. 6.5. The effect on revealing power RP of backgrounds of luminance L(ftL) of increasing the light output twofold for two types of semi-cut-off lanterns.

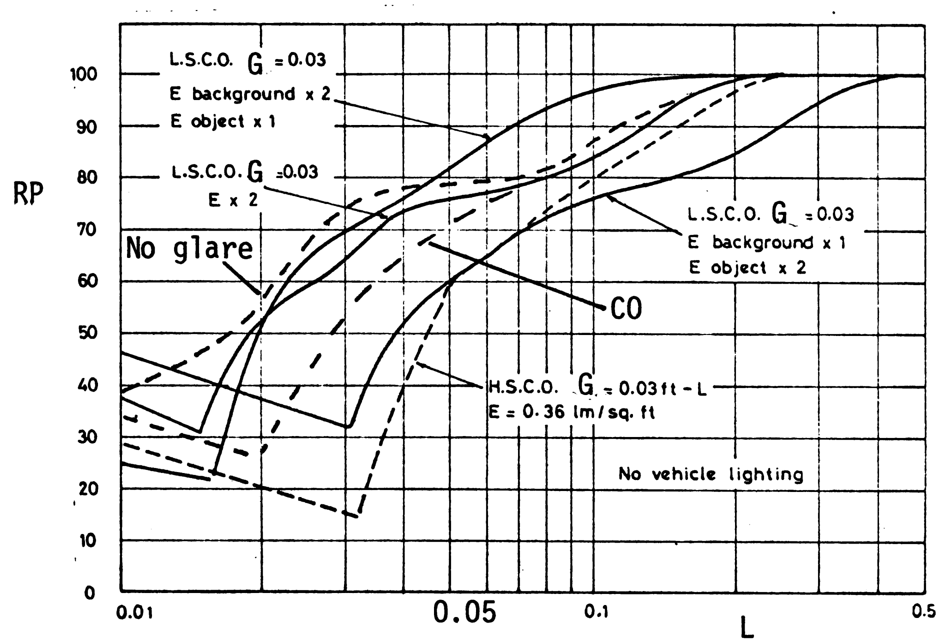

Fig. 6.6. The effect on revealing power RP of backgrounds of luminance L(ftL) of increasing illumination and backgrounds differentially, whilst restricting glare.

PART THREE

VEHICLE HEADLIGHTING

In the dark a glimmering light often sufficies for the pilot to find the pole star and set his course.

METASTASIO, ACHILLE.

"At night, with headlighting we see chiefly by light from the headlamps reflected back from the road and objects thereon. The problem becomes that of providing sufficient light from the headlamps to illuminate any hazard encountered to a brightness which will serve to attract attention and to reveal the nature of the hazard accurately and in time. No wonder motor-car headlighting has been termed the perfect problem for research in seeing."

VAL. J. ROPER AND E. A. HOWARD, Seeing with motor car headlamps, 1937.

CHAPTER 7

A REVIEW

INTRODUCTION.

This chapter reviews headlighting practice, the reasons why headlighting does not afford good visibility in the manner of streetlighting and discusses the inherent limitations which inhibit improvements. The headlighting system considered here consists of those lights prescribed and whose form is controlled by government regulation for illuminating the way ahead under normal conditions and when other road users are met. It does not include long range driving lamps or fog lamps.

Other lamps such as front and rear markers, stop and signal lamps on vehicles provide sources of formal information. Headlamps reveal informal information such as the carriageway, its surrounds and other non-self luminous objects.

THE HEADLIGHTING SYSTEM.

Conventional headlighting systems produce two kinds of beam:*

(i) the upper beam for open road driving and during the initial stages of vehicle meetings;

(ii) the lower beam for the closing stages of vehicle meetings.

This division arises as a compromise between providing high intensities for long seeing distances and the necessity to reduce glare to a tolerable level. Night traffic usually permits only limited use of the upper beam and the lower beam is the driving beam in most situations.

Night traffic situations vary in complexity:

(i) Open Road: this is the least complex situation,

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* The beam used for open road driving will be called the upper beam and that used in vehicle meeting situations the lower beam. Other names given in the literature to the two beams are driving, main and meeting, dipped, respectively.

sufficient light is needed, such that objects in the path of the vehicle can be recognised at distances greater than the stopping distance of the vehicle and to reveal abrupt changes in road direction at a sufficient distance to allow for any changes in speed necessary. This situation calls for a beam giving high luminous intensities along the carriageway axis. Light on the sides of the road is also necessary to facilitate vehicle positioning, by reference to the immediate carriageway surrounds, and for the early detection of persons or animals likely to encroach on the carriageway. Limitations on luminous intensity of the upper beam is desirable to control discomfort glare at the start of a protracted vehicle meeting situation.

(ii) Single vehicle meeting situation: it is a normal requirement that at the closing stages of vehicle meeting the lower beam is used to reduce discomfort to a tolerable level. However, disability glare and reduced object illumination causes visibility distance to be less than for the open road situation.

Safe driving at the same speed now depends on the short term memory of what has been seen ahead with the upper beam. It depends also on immediate recovery of the open road visibility upon reverting to the upper beam after the vehicles have passed. The lower beam is used mainly to illiminate the near side of the road to facilitate positioning of the vehicles.

(iii) Multiple vehicle meeting situations: often on major rural traffic routes and most urban routes there is a continuous flow of traffic and the low beam is in continuous use.

The lower beam must now illuminate all the sources of information in situations where it is the only form of lighting. Seeing distances of objects are shorter than would be obtained in open road situations. Therefore, a lower speed of travel must be expected in this situation than that possible in the open road situation.

THE UPPER BEAM.

It is obviously desirable that the intensity of the upper beam should be sufficient to make objects visible from a distance commensuate with the speed of travel. It is most likely that intensities from present day lamps derive from what is practicable with conventional equipment.

Upper Beam Intensity Values.

The American SAE specification J579a limits the total straight ahead intensity from upper beams to 75,000cd whereas the British BS AU40 Part 4 has no limit. Conventional lamps of 200mm diameter and a rating of 12v 60w give a combined intensity of about 100,000cd. This figure can be easily boosted to 200,000cd with the use of quartz halogen sources. There are proposals to increase the SAE limit and to introduce a 300,000cd maximum in United Nations protocols on vehicle design. The situation gives rise to several questions: should there be a limit on upper beam intensity, because it is used in the initial stages of vehicle meetings? what is the relationship between intensity, visibility distance and discomfort?

Visibility Distance.

Reference has been made in Chapter 1 to the poor visual performance in terms of contrast sensitivity, at light levels associated with vehicle lighting. In order to raise the luminance of objects and backgrounds to levels at which they can easily be seen large forward beam intensitites are necessary. These arise because to reach the required illuminance the beam intensity is proportional to the square of the distance the object is ahead. (This is unlike the requirement of street lighting where the illuminance is essentially constant through the installation). The beam intensity requirement is increased above this simple relationship since the angular sizes of objects become progressively smaller as the required visibility distance increases and smaller objects require higher luminances to be seen than larger ones.

The data of Jehu (7.1) show how beam intensity requirements grow as the required visibility distance is increased. The data were derived from controlled field studies to be described below when considering the lower beam and are illustrated in Fig. 7.1. Starting at a modest 500cd the visibility distance of an objeet of side 0.45m and luminance factor (β) of 7 per cent is about 30m. In order to double this distance the beam intensity needs to be quadrupled; in order to double the distance again the intensity has to be increased by a further factor of ten. Thus to increase seeing distance from 30m to 120m (X4) the intensity had to be increased from 500cd to 20,000cd (X40).

The reported seeing distances with current upper beams (100,000cd) add weight to the notion of a drastically decreasing rate of return for increasing beam intensity (7.2). A man sized object (larger than the object used above) could be seen from 200m if lightly clothed (β = 15%, lighter than object above) and from only 80m if the clothing was dark (β = 1%). One may reasonably surmise that any, even large, increases over current upper beam intensities will yield negligible increases in seeing distance.

Discomfort.

The distances reported above refer to the open road. There is evidence that drivers dip their lights to the lower beam in the very early stages of vehicle meetings to alleviate the discomfort caused by the upper beam intensity. This is in spite of the fact that visibility distance during a meeting using upper beams can be marginally greater than that using lower beams. See Table 7.1 (7.3, 7.4).

Dipping occurs before disability glare has increased from the upper beam to such an extent that seeing is curtailed to that which is experienced on lower beams (7.4). In Australia the upper beam may be used, by regulation, to within 180m (600ft)of an approaching vehicle, if the other driver has not already dipped his lights. At intercar distances greater than this there is a seeing distance advantage in using upper beams rather than using lower beams, especially if the lateral separation exceeds 8m, as it could in a divided highway (7.3).

Data from the USA (7.5) suggest that the vast majority of drivers dip their lights at intercar distances greater than 180m. Observations at 14 sites showed 75% of all vehicles travelled on lower beams. Of nearly 3000 vehicles observed on high beam 82% dipped in deference to an opposing vehicle. The distribution of the intercar distances on dipping is shown in Fig. 7.2. The mean distance was 520m. About 85% dipped at distances greater than 180m.

Discussion.

It appears that drivers use a criterion of comfort rather than visibility in operating their lights during vehicle meetings. The unrestricted intensity of high beams could increase discomfort and force drivers to dip their lights at undesirabledistances apart to gain relief even on divided roads. Against this is to be weighed a problematic increase in visibility distance on the open road. The upper beam could become virtually useless. Even its present restricted use, which can afford short spells of long distance seeing to aid the short term memory and allows safe high speed driving where road and traffic conditions permit, would not be possible. The upper beams could become a long range driving beam that has to be switched off directly another vehicle comes into view, for use on a few lightly trafficked roads.

There appears to be little quantative data on seeing and discomfort associated with upper beam intensity on which to base rational decisions. Therefore, this aspect of headlighting has been selected for a more detailed examination, which is described in Chapters 8 and 9.

THE LOWER BEAM.

The next and major part of this review concerns the lower beam. There has been a continuous and substantial investigation since the advent of the motor vehicle into the properties of the lower beam and its improvement in terms of providing good visibility distance with a minimum of glare. This has encompassed both conventional and polarised lighting: it will be seen that there has emerged a rather complete understanding of the interplay of parameters which effect performance.

The review will start by considering general requirements and design of lower beams then proceed to examining the relationship between beam intensity, visibility distance and glare, factors which degrade performance, the importance of aiming and concludes by looking at the possibilities of improvements including the use of polarised light.

General Requirements.

A lower beam has to fulfil the following requirments:

(i) it must reveal objects on the road sufficiently far away to give the driver time to stop or to avoid them;

(ii) it must reveal enough of the road markings and of the edges of the road to show the driver where he is in relation to the kerb and to other vehicles, and

(iii) it must not cause glare. The first and third requirements conflict, and all lower beams are compromises between the requirements of visibility and lack of glare. A driver is not usually conscious of the lack of seeing distance and judges a lower beam mainly by how far it fulfils the second and third requirements of good position-keeping and lack of glare. Only when seeing distances become very short, as in severe conditions of glare, is a driver likely to notice how restricted is his range of view (7.6). In addition the headlight acts as a marker of a moving car to pedestrians. It must also adequately illuminate retro-reflectorised signs.

Detection of Objects.

Much of the research has been directed to aspects of the detection of objects. An object may be detected by the light of headlamps in two ways - by direct seeing as on the open road, when the object appears brighter than its background, or by silhouette seeing when it appears dark against the light background of the road surface illuminated by the approaching vehicle. In the situation when two vehicles meet, both kinds of seeing occur, silhouette seeing being more frequent for objects at the centre and off side of the road and direct seeing for those on the near side and directly in front of the vehicle.

Silhouette seeing is generally regarded as less important to safety than direct seeing. Silhouette seeing depends upon brightening the road surface and since surfaces vary, it is therefore less reliable than direct seeing; when roads are wet, the beam reflected from the road surface may become a streak and hardly any silhouette seeing is possible. It is least effective for objects on the near side of the road, where danger is most likely to arise. A further consideration is that to be seen at all in silhouette, a pedestrian must step into the roadway before the other vehicle passes. Nevertheless, silhouette seeing may be of great assistance when vehicles are, say, 60 - 120m apart, that is, just at the time when direct seeing is poorest (7.6). Johansson and Rumar have experimentally determined the limitations of silhouette seeing and the factors effecting it (7.7).

Geometry of a Vehicle Meeting Situation.

Fig. 7.3 shows the geometry of the simplest conditions, those of a straight and level road. OL and OR are the left and right hand kerbs of a 30ft(9m) wide road and the human figures are 6ft(1.8m) tall. The intensities which determine visibility distance are contained within the rectangle ABCD. The intensities which determine glare lie along the line OG, the path followed by the oncoming driver's eyes. For good visibility the intensities near to BO must be as high, and those along OG as low as possible. In addition for general comfort in driving and vehicle positioning light has to be widely spread across the road.

The difficulty in obtaining a high ratio of intensities in the two direction will be appreciated when it is noted the angular height of the rectangle is only about 1.6 degrees. For good visibility distance and low glare the intensity must decrease rapidly between two points, the first 1° below the horizontal and the second about 3° to the right and 0.25° above the horizontal (7.6).

Superimposed on the roadway is the isocandela diagram of a lower beam, which attempts to conform with the principles given above: it will be shown later that pedestrians in fairly dark clothing will be seen by direct vision at a distance of about 60m only. Limitations in optical design preclude the complete elimination of light in directions which give rise to glare whilst still providing high illuminating intensities.

Bases of Headlamp Design.

In the process of optimising beam performance by making the ratio of illuminating to glare intensities as high as possible two rather distinct design methods have resulted - the American/British and the European.

The American/British System.

In this system transverse filaments are mounted at and above the focus of a parabolic reflector (Fig. 7.4a). By means of prisms and flutes which comprise the lens, the lamp designer treats the light from each part of the reflector separately deflecting rays in unwanted directions downwards or to the side; the lens is tailored to suit the reflector so that the light is sent where it is required. The lamp can be aimed with the upper beam switched on by reference to the beam hot spot; the filament producing the lower beam is offset which ensures that the peak intensity of the lower beam is directed along the nearside of the road (7.8). However, the trend in recent regulations and specifications is to aim the lamp using the lower beam pattern. All-sealed units can be aimed by mechanical aimers using the aiming pads on the lens of the units as a datum. These pads are aligned to the beam during manufacture.

The European System.

In this lamp a parabolic reflector is fitted with a bulb with an axial filament, the rear end only of which is at the focus of the reflector (Fig. 7.4b). This arrangement produces a circular patch of light made up of a series of images of the filament radiating from its centre. The images which are likely to cause glare, namely, those in the top half of the patch, all come from the bottom half of the reflector. If this is screened a semi-circular patch is produced with a very sharp transition from light to dark at the top edge; such an arrangement is said to have a sharp cut-off.

In practice, the reflector is not screened, instead a small hood below the low beam filament is used to intercept the light before it reached the reflector. The hood is so shaped to allow the cut-off to be lifted on the near side to allow additional light in that direction. This will be referred to as the asymmetrical beam; early lamps produced a symmetrical cut-off right across the beam. The lamp is normally aimed on the lower beam using the sharp cut-off as a datum (7.8).

Lamp Construction.

European lamps are normally semi-sealed units; the filaments are contained in a separate glass bulb, which has a prefocus flange to locate it accurately in the reflector housing. British lamps, originally of a semi-sealed construction are now of an all-sealed, all-glass construction, as are American ones, whereby the filament supports are sealed into the reflector and the reflector and lens form a large bulb envelope. This type of construction excludes completely dirt and moisture and reduces the loss in efficiency due to blackening of the bulb envelope. On the other hand, filament failure means complete unit replacement.

The development of the quartz halogen bulb has brought promise of improved headlamp design though increased light output for unit electrical input, longer filament life and maintenance of light output through life and smaller filaments which could improve optical control of light.

Early halogen bulbs could only employ one filament but double filament bulbs are now made. Recently all-sealed units operating on the European beam principle have been produced commercially which use the halogen cycle.

Beam Distribution Requirements.

Standards giving light intensities at nominated test points are:

U.S.A.:S.A.E.	J579a
U.K.:B.S.	AU40 Parts 3 and 4.
Europe:	Inland Transport Committee of the Economic Commission for Europe, ECE Regulations 1 and 2.

Fig. 7.5 shows the beam diagrams measured by the writer, of two

commercially available lower beams (a) SAE/BS 7 in.sealed 50w set with aiming plane vertical, and (b) European $5\frac{3}{4}$ in. semi-sealed tungsten halogen 55w set with cut-off 1 in 100 down. The lines represent the average paths of the drivers' eyes and of the roadway 3m to the nearside of the centre line of a car, for a lateral separation of approaching cars of 3m. The points on the lines represent distances ahead and intercar separations respectively of 50, 100 and 200m. The closeness of the intensity contours denotes the sharpness of cut-off. Road and object illumination is slightly better for beam (a) but glare is less for beam (b). Beam (b) gives increased glare with very little difference in object illumination over the European beam using a conventional bulb.

Further improvements in beam (b) can only come by raising the area of much higher maximum intensity whilst keeping the glare constant or decreasing it. This will give rise to manufacturing, aiming and maintenance problems: it can be seen that directions of light giving rise to illumination and glare are separated vertically by only small angles. It can be seen that the light available to illuminate retro-reflective traffic signs is less with beam (b) than with (a).

VEHICLE HEADLAMP PERFORMANCE.

There are two different designs of lower beam and the following questions can be posed:

(i) how far can a driver see with them?

(ii) is one type of beam significantly better than the other?

(iii) what is the relationship between object illumination and glare?

Road Tests.

Although the basic relationships between visual performance and lighting parameters are well known (see chapter 1), road tests overcome the uncertainty of applying laboratory data to road conditions. Fig. 7.6

shows the general nature of data obtained by Roper (7.9) where two vehicles started from opposite ends of a test track along which objects had been placed and the drivers signalled when they could see them.

When the distance between the vehicles is large the object is seen directly as a light object against a darker background. The seeing distance is much less than the distance between the vehicles and diminishes as the vehicles approach one another. Before the vehicles meet and pass, the seeing distance reaches a minimum after which it increases more rapidly than it diminished, particularly after the vehicles have passed and there is no glare. When, instead of seeing the object directly by the light of his own lamps, a driver sees it silhouetted against the patch of road lit by the approaching vehicle, the seeing distances are often much greater than for direct seeing. Objects on the nearside of the road are less frequently seen in this way than objects in the middle or to the offside. The seeing distance will depend on road width (the glare will decrease as lateral separation of vehicles increase), the size and reflecting properties of the object and the speed of the vehicles. Roper established the way seeing distances decline with vehicle speed and driver inattention. He demonstrated (7.10) as others did later (7.2, 7.6, 7.11 7.12) that seeing distances could be less than the stopping distance at legal speeds.

Swedish investigators at the University of Uppsala have used standard road tests to investigate basic principles of headlighting, polarised light and to compare different beam types, particularly halogen against conventional (7.11, 7.13, 7.14). Hemion and his associates, in the U.S.A., have used road tests in a recent reassessment of polarised lighting (7.4, 7.15).

Comparisons Between American/British and European Beams.

In 1949 international tests, similar to those described above, were carried out in Holland on behalf of the CIE (Commission Internationale de l'Eclairage) to compare the performance of the then current American and European (symmetrical beam) lamps. Some results are shown in Fig. 7.7. It will be noted that the results are scattered and this scatter is likely to mask any differences due to beam type. In fact, little difference in the two types of beam was found; seeing distances with both could be very low.

The only agreement to come out of the tests was that more light was needed along the nearside (hence the appearance of the European asymmetric beam); no agreement was reached on the degree of glare control (beam cut-off) necessary and no universal agreement has been reached subsequently.

A Standard Method of Comparison.

Full scale road tests are costly and tedious and the variability of results is likely to mask differences due to beam distribution. To overcome this probelm and to enable the effect of lamp misaim and road curvature on performance to be estimated the Transport and Road Research Laboratory of Great Britain obtained basic data relating seeing distance to illuminating and glare intensities (i.e. independently of beam design). The Laboratory used the set-up which is shown in Fig. 7.8. The observer was required to signal when he detected the shape of a simple object 0.46m high (the CIE tests showed that the small object was seen at distances only slightly less than those for a tall object 1.5m high.) The luminance factor was 7%, that of medium grey cloth. The headlamps, providing the sources of illumination and glare, had extremely uniform distributions, so that the preset values were maintained while approaching the target (7.1, 7.12).

The general results are shown in Fig. 7.1 and replotted in Fig. 7.9.

This shows that there is a sharply diminishing increase in visibility distance for increasing object illumination and a modest amount of glare causes a drastic reduction in visibility distance.

With the aid of beam distributions such as shown in Fig. 7.10 and the Hollady-Stiles disability glare effect formula, discussed in Chapter 2, the basic data can be extrapolated to predict the performance of any beam under road conditions (7.1). (The method yields results very comparable with the CIE results, both in shape of seeing distance curve and absolute values). It can be seen in Fig. 7.10 that there is a gradual diminishing of visibility of the near side object as the vehicles approach. For the centre of the road object there is a catastrophic drop in visibility as the cars pass one another.

Results of Comparisons.

A general comparison of results obtained for the two basic lower beam systems is given in Fig. 7.10 (7.16). Minimum seeing distances for a standard object by direct seeing are about 60m and 20m for nearside and centre of the road positions of the object respectively. Although seeing distances are greater for the British beams in the earlier stages of a vehicle meeting the minimum distances obtained with them are less than those obtained with the European beam.

Calculations show (7.12, 7.16, 7.17, 7.18):

(i) Current lamp designs do give greater seeing distances than obsolescent designs i.e. asymmetrical European better than symmetrical, all-sealed British better than semi-sealed.

(ii) The variation in seeing distance of the nearside object over all current designs is about ±7.5%, the European asymmetrical and the American 4 lamp ($5\frac{3}{4}$ ins) beams give equal results bettered only by that for the American 4 lamp (7 ins).

(iii) The variation in seeing distance of the centre object is about ±10%, the European system gives superior results to the American/British system.

(iv) British beams tend to give lower distances than their American equivalents.

What is striking about these results is not only the little difference in seeing distances between beam types but the shortness of those distances. These low values have been validated in road tests, results of which are given in Table 7.1. The investigators concerned remark that these distances are often less than the stopping distances for the legal speed limits and that probably drivers consistently over-drive their lights (7.5, 7.11).

Road tests with the latest lamp development, the quartz halogen lamped European beams, do not give longer distances than those obtained with conventional lamped ones. (7.14) This is despite the expected better light control, discussed above, leading to decreased glare and increased illuminating intensities.

The Effects of Misaim on Performance.

The minimum seeing distances occurring in a vehicle meeting when the lamps of one vehicle are tilted up slightly ($+\frac{1}{2}^{o}$) and the lamps of the other vehicle are tilted down ($-\frac{1}{2}^{o}$) have been calculated (7.17). Whereas the earlier European lamps were affected by misaim more than the earlier British ones, the effect is now more nearly equal. It amounts to a reduction of about 25% in seeing distance.

The Effects of Horizontal Road Curvature on Performance.

The calculations of seeing distance have been extended to roads having a noticeable curvature (Radius - 450m). Performance obtained with the beam from the semi-sealed British unit has been compared with that of symmetrical European beam (7.19). In the early stages of a vehicle meeting the British beam gave higher seeing distances for the nearside object on the inside of the bend than on the straight road. However, the minimum seeing distance for this situation and the outside of the bend one were less than obtained for the straight road condition. The European beam was judged to be inferior to the British beam because of low seeing distances, in general, in the early stages of meeting and, in particular, for the nearside object on the inside of the bend.

This inferiority probably does not apply to the current asymmetric European beam where the sharp cut-off has been lifted on the near side to provide additional object illumination in this direction.

Seeing Distances with Mixed Systems.

The results above are for meeting situations in which the vehicles are equipped with similar lamps. However, meeting situations arise where one driver will be using the European system and the other the American/British system. The glare intensity from the first system is about one quarter that of the second, hence it would be expected that the seeing distance of one driver would increase at the expense of that of the other driver.

Calculations showed that a driver using the lower beam from semi-sealed British lamps could expect a general improvement in minimum seeing distances in this type of situation, from 14 per cent for the near side object to 24 per cent for the centre of the road object. The seeing distances given by the European (symmetrical) beam are correspondingly reduced by 12 and 16 per cent respectively. (7.17).

However, both the symmetrical European and British semi-sealed units have been improved. For both systems the disability glare values have been reduced by about one third. But whereas the American/British illuminating intensities have been increased two fold those for the European system have increased four fold (7.12, BS AU40, 3 and 4).

Thus, although the driver using the current design of the European system will still be at a disadvantage, the degree will be less than before.

Driver Appraisal Tests.

Appraisal tests, carried out by the RRL on behalf of the CIE, showed that the drivers in general preferred the British type of lamp to the European. Reasons given were, less glare particularly from wet roads, better illumination of the road edge, better silhouette seeing, less fluctuations in glare and forward visibility due to vehicle motion (7.8). It should be noted the symmetrical European beams were used; many of the causes for unfavourable comment should have been eliminated by the introduction of the asymmetrical beam with its increased light along the near side and increased spread across the road.

A working party in the U.K. after seeing demonstrations of the current lamps could not come to any agreed decision. On the open (unlit) road the prevalent view was that the American/British beam was preferable as its aiming was less critical and the contrast between upper beam, especially if it employed a halogen source, and the lower beam was less marked. On lighted streets opinion was much more divided (7.20).

The protagonists of the quartz halogen lamped European beam, whilst admitting that it has little or no superiority in seeing distance, claim that the greater light output improves ease of perception in the areas of the road lighted by the beam (7.21). This may be true but it could be assumed that the sharper cut-off gives rise to a rather disconcerting demarkation on the road between the light patch and the rest of the dark road. Appraisals in street lighting, referred to in Chapter 3, showed observers to give a poor rating to installations in which severe luminance gradients existed along the carriageway.

Recently, Schmidt-Clausen investigated headlamp discomfort glare in a model. Glare appraisal was related to glare illuminance, road luminance and the number and position of glare sources (7.43).

Most tests appear almost stylised in that only two-vehicle meetings are ever considered; the prevalent situation of meeting continuous streams of vehicles is ignored. Since the nominal glaring intensities of the European beam are only about ¼ those of the American/British beam, both the disability and discomfort glare might be less in real situations involving the meeting of a stream of European beams than in those involving American/British ones.

However, discomfort is related not only to the intensity of light from lamps but also to their area. Recent work described in Chapter 13, showed that observers rated small sources on vehicles to be brighter than larger ones, even though the light intensity directed towards their eyes was the same in both cases.

Thus, European beams can appear, as substantiated by inspection, extremely bright at certain points in the meeting situation because the whole area of the reflector is not fully flashed. The high directional intensities now produced in the nearside uplift of the beam are derived from a small area of the reflector visible to the oncoming driver.

FACTORS DEGRADING HEADLAMP PERFORMANCE.

In-service Lamp Performance.

In preceding sections the design of headlamps and their performance has been discussed. The figures of seeing distance deduced are those for lamps correctly aimed and maintained and mounted at a standard height. That in-service lamp performance may fall considerably short of that predicted on this basis is illustrated by the two following tests.

Swedish Tests.

In these tests 413 drivers volunteered to participate in their own cars. Each driver's task was to drive his car towards a stationary car, both cars with lower beams (probably European symmetrical beams) and to brake as soon as he discovered the dark clothed dummy placed in the middle of the lane beside the meeting car. The median seeing distance was 23m and the 10th percentile was 15m. The short distances and large variation were attributed mainly to the varying conditions of the headlights which include misaiming, voltage losses, bulbs blackening, production inconsistencies (7.11).

British Tests.

Measurements with a photoelectric device were made of the glaring intensities from vehicles as they travelled along. (7.18). The relevant results shown in Fig. 7.11. Those for modern headlamps suggest that there has been an improvement over the years, possibly associated with compulsory testing. Nonetheless, nearly one half of the results lie outside the limits within which correctly functioning lamps would lie. More than half these lamps outside the limits were too glaring.

More recently Yerrell carried out an extensive survey of the in-service performance of headlights in Great Britain and in Continental Europe (7.22). He used photoelectric devices to measure the glaring and illuminating intensities emanating from vehicles as they passed through various test sites. The results are given in Table 7.2. About 75% of the values of glaring intensities are greater than the expected value as derived from beam specifications. The mean glaring intensities, experienced in three Continental countries, were more than ½ rather than the expected ¼ of those experienced in Great Britain. The difference between glare experienced in one of the Continental countries and Great Britain was negligible. It does not therefore seem that the situation has improved with time.

Lamp Aim.

The TRRL, some fifteen years ago, measured the aim of the lights of vehicles stopped at random at a roadside check point (7.6). The relevant results, those for the aim of the upper beam of British semi-sealed units, are given in the following table:

Sample	Mean Aim	Standard Deviation of aim about the Mean
180	0.7° down	1.1°
	0.2° right	1.4°

More recently Parsons (7.23) checked the aim of modern all–sealed units on a sample of 164 cars, in New South Wales, Australia. He found the mean aim to be 0.4° down and 0.14° left with a standard deviation of 1.1° and 1.3° respectively. Thus the standard of aim does not appear to have improved over the years.

Loading.

Even if the lamps are correctly aimed for one condition of loading, the aim is likely to change with changes of load.

Some time ago the TRRL showed that most cars of the day tilted upwards by less than 0.5° on the application of full load. The effect of front seat passengers was small, most of the tilting was caused by rear passengers and loads in the boot. Some small cars tilted by 0.75°. Vans and lorries tilted by between 1° and 1.5° although the tilt in articulated and multi-axle lorries did not exceed 0.5° (7.6).

The advent of the minicar and softer suspensions has increased the susceptibility of cars to tilt on loading. This is shown in Table 7.3 which contains results of measurements made by the writer on the range of vehicles produced by one manufacturer.

The seriousness of these potential misalignments of headlamps can be gauged from the following findings:

A driver's seeing distance in a vehicle meeting situation on an unlit road is reduced by 25% if the opposing drivers headlamps are tilted upwards by 1°. If, in addition, the drivers own headlamps are 1° too low the total loss in seeing will be 45% (7.24). Any potential differences in seeing distances due to beam design can be, and probably are now, largely nullified by poor aiming standards.

Production Tolerances.

Where both beams are derived from the same lamp, the lamp is often aimed by reference to the hot spot of the upper beam. The accuracy of the aim of the lower beam will be influenced by tolerances in lamp production. In one investigation 40 complete British semi-sealed units were taken off a production line at random. It was found that if the headlamps were adjusted so that all the lower beams had the same horizontal intensity, the aim of the upper beam had a variability in the vertical with a standard deviation of 0.35^{o} (7.25). Another report (7.26) suggests that production tolerances in the manufacture of all-sealed units resulted in a standard deviation in vertical aim of 0.15^{o}, i.e. sealed units are an improvement in this regard.

More recently the writer has measured the tolerances in samples of all-sealed units, both new and used: the results are shown in Table 7.4. The units were aligned to a photometric bench using the aiming pads on the front surface of the lamps. The values of glare and illumination are quite variable although largely within the limits of the relevant specifications, BS AU40, Part 4 and SAE J579a. Although the glaring intensities appear higher for the used units than for the new ones this difference is not statistically significant. Thus used units appear to maintain their beam photometric characteristics in use. Thus the aiming pads may be used to mechanically align new and old units alike without reference to their beam characteristics.

Results of further measurments by the writer, given in the following table, show that the difference in parallelism between the aiming and seating planes of light units is small. Thus burnt out units may be replaced with reasonable assurance that the replacement units will be correctly aimed, providing the aiming adjustment in the lamp housing is not tampered with on replacement, and the lights were aimed correctly initially.

DIFFERENCE IN PARALLELISM BETWEEN
AIMING AND SEATING PLANES OF
ALL-SEALED UNITS, IN MINUTES OF ARC

	Mean	St. Dev.	95% limits about mean
Horizontal	2	7	±13
Vertical	11	8	±15

Sample size 26 using units of various wattages and from various sources.

Lamp Voltage.

Changes in voltage across the filament of the lamp will result in changes of directional intensity in the lamp beam. A one per cent change in voltage will give a 3 to 4 per cent change in light output. Tests (7.26) have shown that a range of filament voltage of about 3.0 volts may be expected in cars fitted with compensated voltage regulators and 2.0 volts in those fitted with current regulators. These variations of voltage may be expressed in terms of variation in aim; it has been calculated that variations of 2 volts and 3 volts are equivalent to aiming variations of the British semi-sealed unit, the standard deviations of which are 0.13^{o} and 0.22^{o} respectively.

THE IMPORTANCE OF AIMING HEADLAMPS.

It has been shown in preceding sections that lower beam performance is dependent on the ratio of glare to object illuminating intensities and the actual value of the illuminating intensity. Calculations and measurements under in-service conditions have shown that actual performance is dependent on lamp aiming and is likely to become critically so if lamps are further developed along conventional lines. This section will deal with a study of the standard of aim required for a given level of seeing and a given lamp design, and the methods available to achieve this standard of aim.

Relation Between Seeing, Lamp Design and Aim.

When two vehicles, taken at random, are approaching one another and when the design of the beams and standard of accuracy of aiming are known, it is possible to calculate the probabilities that glaring and illuminating intensities will have any chosen value and hence calculate the probability of the minimum seeing distance falling short of any arbitrary distance. Harris (7.27) has made such calculations basing his method on the layout in Fig. 7.8 where the light is assumed to originate from a single lamp on each vehicle, and on the data in Fig. 7.1.

Further, to make the analysis manageable the beam distribution has been simplified, in a reasonable manner, such that it is assumed that the light intensity increases n times for every degree downwards and that the intensity straight ahead is 3000cd . Typical values of n , the cut-off factor, in the region near the horizontal at the time ranged from 2.0 to 2.6 for the British semi-sealed unit, 2.3 to 3.8 for American sealed lamps and 2.3 to 3.6 for the European lamp. At angles just below the horizontal the cut-off factor rises to about 10 for the European beam.

Some of his results are presented in Fig. 7.12. These show that if seeing distances less than 100 ft (30m) are to form 5 per cent or less of the total, then n and σ (the standard deviation for vertical aim) must be given by points on or to the left of curve A. If σ just exceeds 1.2° it becomes possible, but a very sharp cut-off (n greater than 8) is required. If σ is less than 1° it is possible to obtain the low probability with values of n as low as that for the British semi-sealed lamp or even lower. Curve B for 150 ft (45m) is similar but more demanding both as regards aim and sharpness of cut-off. Curve C for 200 ft (60m) calls for a still sharper cut-off and a standard of aiming so high that lamps would probably have to be re-adjusted whenever the number of passengers in the back seat of a car was changed.

The relationship between lower beam cutoff, standard of aim and glare is shown in Fig. 7.13. The curve is that for which the probability of the glaring intensity exceeding three times the nominal straight ahead intensity is not greater than 1 in 20. The present standard of aim ($\sigma = 1^{\circ}$) is satisfactory, on this basis, for current SAE/BS beams (n = 3) but the standard for current European beams (n = 15) needs to be nearer $\sigma = 0.5^{\circ}$ for similar performance.

It is an important question whether improvements in aim and cut-off necessary to achieve improved seeing distances can be made without running into serious trouble from discomfort due to high intensities. An improvement in aiming diminishes the probability of high glaring intensities but the effect of cut-off is more complicated. If the cut-off is made sharper, high intensities are made more probable and low ones less probable. However, if, as a result of sharpening the cut-off and improving the aim, the performance of beams is improved as regards seeing distance, it will also be improved in relation to glaring intensities.

This suggests that, apart from intermittent dazzle due to the pitching motion of the vehicles, questions of intensity and comfort can be subordinated to questions of visibility. It is the intermittent dazzle, however, which probably sets a limit to the sharpness of cut-off than can be used (7.27).

Methods of Aiming and Their Accuracy.

Various devices exist to aid the aiming of headlamps. Since the aim of the lower beam is critical it is preferable that it is this beam from the lamp that is aimed and preferably checked photoelectrically for glaring intensity level. Lamps of the European system can easily be aimed visually on a graduated screen using the lower beam cut-off as a reference. However, the more fuzzy lower beam of the American/British lamp is harder to aim visually. Where the two beams, upper and lower, are derived from the same lamp the upper beam may easily be aimed visually on a screen using the hot spot as a reference. The lower beam is then assumed to be correctly aimed because of regulated relative positioning of the lower beam filament during production (the production tolerances have been discussed in the previous section).

However, the use of separate lamps in the 4 lamp system to produce the different beams has made the aiming of the lower beam less easy by this means; the supplementary upper beam derived from the Type 2 lamp has no well defined hot-spot. Replacement units, for the conventional 4 lamp system, are being marketed using single filament halogen bulbs. In this system the lower beam unit must be aimed by reference to the lower beam.

Sealed units of the American/British system have aiming pads in the form of three glass flats built into the front of the glass. These flats define a reference plane, relative to which the unit filaments are positioned during manufacture. By a simple mechanical device the lamp may be aimed without switching on the unit. The success of this sophisticated but simple procedure depends on close production tolerances.

Various devices exist to aid the aiming of headlamps. They vary in complexity, from a device which relies solely on photoelectric measurements and utilizes a four element bridge network to a shadow casting device. The TRRL has made extensive checks on the accuracy of beam setting equipment (7.12).

Vertical Aim.

All equipments use the floor as a reference plane so that the absolute accuracy depends both on the inherent accuracy of the instrument and the quality of the floor. Characteristics of instruments may be compared by obtaining the accuracy of repeat lamp settings. Results show that the variation in settings made visually using the sharp cut-off European low beam is about the same as that made using the British high beam; less variation is made using photoelectric instruments. However, the maximum variation in setting or measuring vertical aim is only about $\pm 0.2^{o}$.

Horizontal Aim.

This is more difficult to determine than vertical aim because there is no ready-made reference plane. The horizontal aim of the headlamps of a vehicle should be parallel to the direction of the travel of its rear wheels when on a flat surface. It is assumed that this direction which is called the mean wheel axis is midway between the separate directions taken up by the undistorted rims of the rear wheels. None of the equipment examined used this reference axis but were aligned to the vehicle using either the body, the rear wheels and the front wheels or the headlamps themselves as a datum. Results show that these procedures can introduce aiming errors of $\pm 0.75^{o}$, which can be reduced to $\pm 0.25^{o}$ if either the rear wheels or headlamp is used as a datum. In addition to this, results of repeated settings show that horizontal aim cannot be determined to the same accuracy as vertical aim. In most favourable circumstances a setting variation of about $\pm 0.5^{o}$ occurs; in unfavourable circumstances the accuracy may be reduced to $\pm 1.25^{o}$.

Variation of Aim Due to Vehicle Loading.

After the lamps have been correctly set, the greatest variation in lamp aim will probably be caused by the tilting effects of loading. Various automatic mechanical, electro-magnetic and electro-hydraulic correction devices have been discussed: one such device working off the depression of the vehicle suspension is fitted to a currently available model of car. A simple device whereby the motorist can correct the aim by turning a calibrated knob has been described (7.16). The most sophisticated method at present under development would be to use a photo-electric device to aim the headlamps with reference to the oncoming vehicle lamps (7.28). Since the angles involved are small, the devices must be sensitive and accurate. It seems to be accepted that the success of any lamp improvements relying on sharpening the beam cut-off depends on maintenance of aim, through an automatic levelling device.

THE IMPROVEMENT OF HEADLAMP PERFORMANCE.

Whilst there has been a great deal of research and development in the headlamp field, performance still leaves much to be desired. Data in Fig. 7.14 suggests that whilst some improvement in lower beam performance has been made, the most recent modifications have yielded only small gains. Particularly, the results for the $5\frac{3}{4}$ ins diameter four lamp system are disappointing. The potential gains in light control appear to have been largely sacrificed, in the interests of space reduction, by reducing the unit diameter from 7 ins to $5\frac{3}{4}$ ins. A better four headlamp arrangement would be provided by using a 7 in diameter lamp for the lower beam and in fact this arrangement is being now used on some vehicles. It has been shown that results from the quartz halogen lamped European beam also have been disappointing in that no radical increases in visibility distance have been attained.

Improvements to the Conventional Lamp.

The possibility of further improvements to the lower beam may be assessed using Fig. 7.9, in which the data contained in Fig. 7.1 has been replotted. This set of curves is the most significant one in headlamp design and possibly the most neglected. It clearly demonstrates the implicit limitations in beam design and performance. It can be seen that modest seeing distances can be achieved by many combinations of illuminating and glare intensities, of which those represented by two lamp designs are but two cases. However, at higher values of seeing distance the curves are closer together. Large increases in illuminating intensity, the glare illumination ratio remaining the same, result in very small improvements in seeing with increased discomfort. This suggests that it is glare control rather than increases in illuminating intensities which will result in improvements.

The present American $5\frac{3}{4}$ in lamp gives an illuminating intensity of about 8000 cds. and a glare to illuminating intensity ratio of about 0.1 for conditions of minimum seeing. It was stated above that a limit has been reached in glare control in this type of lamp, hence merely increasing light output of the lamp would result in little improvement in seeing but in an aggravation of discomfort glare.

The present asymmetric European beam results in an illuminating intensity of about 4250 cds. and a glare-illumination ratio of about 0.05. Thus, the illuminating intensities in this beam may be increased four fold (by the use of high wattage halogen bulbs) whilst only increasing the glare to that produced by the present American/British beam. The data in Fig. 7.9 suggests that this radical change in light output will result in an improvement of about 10% in seeing distance.

If better optical control of the light is achieved using the halogen bulb (this has yet to be demonstrated) and the glare illumination ratio is halved, an improvement of 25% is possible, i.e. the minimum near side seeing distance will be increased from 60m to 75m. However, it is doubtful whether better optical control is feasible; the potential advantage of using the relatively smaller filament of the halogen bulb must be largely offset by the increase in its size necessary to accommodate the increase in wattage. Indeed it bears repeating that performance from this type of lamp has been disappointing to date.

If this type of beam is to be used it has been shown that its performance becomes very sensitive to in-service factors of which initial aiming and subsequent maintenance of aim are the most important. Overall it is not unreasonable to suggest that exploitation of the conventional low beam has reached its limit and indeed present trends could make the night road situation worse and not better. Further improvements could possibly come through changes to the other elements of the road environment or the use of unconventional headlighting systems.

FACTORS OTHER THAN LAMP DESIGN.

Road Design.

The lateral separation of vehicles reduces the adverse effects of glare. However, it has been shown that a separation of 40m is necessary before open road conditions prevail (7.3). This figure is about twice the median width estimated to be effective in combating cross median accidents and thus is hardly an economic proposition. On narrow medians plantations of shrubs or anti-glare fences can be used to inhibit glare. Criticism of a fence in use in the U.K. has been the loss of daylight amenity (7.29) and data from the U.K. and the U.S.A. raises the conflict as to whether such a fence increases or decreases accidents (7.30).

Motorways, Freeways, Turnpikes.

Roads of the expressway type are different from the ordinary traffic route in as much as the opposing traffic has a greater lateral separation. An investigation has been made on the effect of lateral separation, on both straight and curved roads, on headlight performance (7.3). The following conclusions were reached:

(i) Using lower beams the lateral vehicle separation must be at least 7.5m for there to be a negligible effect on seeing;

(ii) Using upper beams the lateral vehicle separation must be at least 20m in order to reduce the discomfort glare to a tolerable level;

(iii) For this separation seeing distances obtained with upper beams will be greater in general than those obtained with the lower beam, although in some situations (observer on the inside of the bend) there will be little difference;

(iv) To render the effect of glare from upper beams on seeing negligible the lateral separation should be 40m.

This would suggest that the upper beam cannot be used for expressway driving. For faster driving, however, something better than the conventional lower beam is being sought to provide adequate vision without glare. The turnpike lamp, giving a beam midway between the upper and lower beam, is being considered especially in the U.S.A., the advent of which might result in the six headlamp system, (although, since the open road condition is becoming less and less frequent, the upper beam may in fact be regarded as obsolete).

Jones (7.28) has made an on-paper study of the potential of such a beam. Provided that the lateral separation of vehicles is 7.5m useful increases in seeing for straight road situations can be attained. However, on bends (r = 900m) seeing is not much better than with the conventional lower beam. Of course, drivers of vehicles equipped only with the lower beam will be adversely affected when meeting the turnpike lamp. None of this takes into account the effect of streams of vehicles on seeing and the increased discomfort glare that is implicit in the turnpike lamp design. Jones does point out that the degree of improvement achievable seems disappointingly small.

Vehicle Design.

The positions of both headlamps and drivers eyes influence seeing. Since the illumination light from the lower beam is normally directed down, the lamp mounting height will determine its reach along the road. Reference to Fig. 7.3 indicates that glare will be reduced as the vertical separation of lamp and eyes increases. Taking a standard height for the lamps, lorry drivers will suffer less glare than car drivers.

Data (7.15) show that both the overall height of cars and driver eye height have decreased over the years, presumably in the interest of low silhouette styling. Calculations indicate that because 3m in seeing distance is lost for every 25mm the headlamp is lowered, seeing distances have been reduced by 18m over the years (7.31).

Object Reflecting Properties.

The seeing distance comparisons described above utilize objects with luminance factors of 7%: the TRRL standard object was medium grey. To improve direct seeing distances it would be advantageous to have pedestrians in as light a clothing as possible. A pre-war survey of clothing showed that 75% of articles had luminance factors of 10% or less; changes of fashion and road safety campaigns do not appear to have changed this state of affairs.

SEEING DISTANCES OF OBJECTS OF DIFFERENT LUMINANCE FACTORS

Subject	Clothing	Seeing Distance (m)	Conditions of Test
Male Pedestrian	Dark (1%)	35	Lower beam 2 vehicle meeting at 64k/h on 9m carriageway. Object on N.S. opposite opposing vehicle
	Light coat (15%)	60	
	Dark with reflectorized cuffs	200	
Male Cyclist	Dark (1%)	16	
	Light coat (15%)	60	

The use of retro-reflective material (the light is preferentially reflected back along the direction of the incident light) increases detection distance. A pedestrian wearing reflectorized cuffs is detected at six times the distance that he would have been without the cuffs (7.2).

UNCONVENTIONAL HEADLIGHTING.

Colour.

Nearly all countries use white, the notable exception being France. The writer has reviewed extensively literature on visual performance and colour (7.32). He concluded that no significant gain could be made by the exclusive use of either white or yellow light. The only demonstrable superiority was that discomfort glare appeared less from yellow light.

Both visibility distance and driver appreciation tests have been carried out using sets of lamps in which the only difference was to colour of light emitted; one emitted white and the other yellow. Visibility distances for yellow light were slightly but not significantly longer than those for white light. In the appreciation tests the observers, who were accustomed to driving with white light, preferred the white beam. The majority consistently found under conditions of high and low glare that the yellow light was less glaring than white although they judged the difference to be small. This suggests that the glare problem cannot be overcome by merely changing the colour of the light (7.33).

Polarised Light.

The data discussed above suggests that there cannot be any major improvements in seeing during vehicle meetings and that seeing distances will never approach those pertaining to open road conditions whilst conventional means are used. It is possible by means of a polarised system of lighting (Fig. 7.15) to all but eliminate glare, the main inhibitor of forward visibility.

Land, the inventor of the sheet polariser, described the system nearly thirty years ago (7.34) but it was Jehu of the TRRL who made a thorough analysis of the system over a decade ago (7.12, 7.35, 7.36). Taking into account losses at the analyser due to depolarisation of the light reflected from objects, the use of a polariser and an analyser reduce the effective beam intensity to about 1/5 of the initial unpolarised beam. The apparent glaring intensity of the oncoming polarised beam however, is reduced to at least one hundredth of this. The nett gain is that the glare/illumination ratio is reduced drastically.

Calculations show that polarisation existing head-light upper beams would provide seeing distances of about 90m for both drivers in a meeting (Fig. 7.16). Depending on the polarised beam intensity and the efficiency of polarisation even longer distances can be achieved (Fig. 7.17). This radical improvement would be achieved at the expense of seeing on the open road which would drop to 0.75 of its former value if the visor was used all the time and 0.85 if the visor was not used on the open road.

Provided that the driver was content with this small loss in seeing on the open road the system would virtually become a single beam system which has always been the ideal of the headlamp designer (7.36).

However, although in driver appreciation tests there was an over-whelming majority preferring the polarised beam rather than the convention-al lower beam, adverse comments were made on poor road illumination, loss of silhouette seeing, and the loss of warning of the approach of vehicles over crests and around bends by illumination of the atmosphere.

Recently there has been a renewal of interest in plarised headlight-ing. It is becoming realised that the limit has been reached with conventional means and the situation is still unsatisfactory on the many miles of intercity traffic routes not lit and unlikely to be lit by fixed lighting. Hemion and his associates have carried out extensive field trials for the U.S. Government (7.15). They have confirmed the improvements predicted by Jehu: see Fig. 7.18. The Swedish investigators at the University of Uppsala have made further field trials, especially to find the effects of toughened glass windscreens on a polarised lighting system (7.13).

The unsatisfactory nature of sheet polarisers has been tackled by research workers of lighting companies. Much higher efficiencies are claimed for a system employing a polarisation by reflection system (7.37). Fig. 7.19 shows the complexity of the light unit. Work has been recently described by which polarised light is produced on the initial reflection of light from the lamp filament by the lamp reflector (7.38). Increased efficiency of polarisers and increased light output from the quartz halogen lamp could be used to overcome many of the adverse comments on earlier systems.

It is obvious that to be successful the system has to be universally adopted with close government supervision over a carefully prepared changeover period. There will be little incentive for individuals to fit it since the initial benefit will not be obvious, they will still suffer glare from the many conventional lamps. Those using conventional lamps will experience increased glare from the more intense polarised lamps. Proposals for the change over period have been made in the U.K., Sweden, U.S.A. and Germany based on polarising either the present lower or upper beams and on different strategies to be used by drivers depending on whether he or the opposing vehicles has to system or not (7.36, 7.39, 7.40, 7.41).

Ultimately a single pair of lamps would provide the one and only combined driving and meeting beam for all the situations referred to above save one, that of the lighted urban street. The writer thinks that implementation would be satisfactorily made if after a certain date all new vehicles were fitted with polarised headlamps and that existing vehicles be fitted with an analyser. Thus the driver of an old vehicle would not suffer during meetings with new vehicles. Drivers of old vehicles would continue with their present practice of dipping their lights on meeting vehicles, so that new vehicle drivers would not suffer during meetings with unpolarised lights.

The other main road user is the pedestrian: he should not be made uncomfortable by the presence of what would amount to upper beams in his environment, i.e. city centres and urban routes. Since more and more contiguous miles are being lit to a high standard of street lighting, a town driving beam (described in Part 4) can be safely used. Therefore, in lighted town streets the motorist would "dip" his polarised lights to a town beam.

Obviously costs will be great. However, it has been seen that conventional headlighting could become costly if automatic aiming devices become universal. It has been calculated that the annual cost of a polarized headlighting system in the U.K. would be 15 million pound, about half the sum annually expended on public lighting (7.41). Hemion has estimated that it would cost $14 billion to introduce the system into the U.S.A. over a three year period. This sum would be justified economically if the system reduces accidents by 6% (7.39).

DISCUSSION.

The comprehensive survey above has been presented since it becomes obvious on studying the literature that enough is known about the mechanics of vehicle lower beam headlighting to come to definite conclusions, without further investigational work. Certainly technical solutions to problems can be refined but the basic data needed to evaluate these solutions are available. Much work has been done in trying to develop headlighting such that seeing is sufficiently good that vehicular traffic may proceed by night with the same speed and degree of safety as by day. Since the accident rate is higher by night than by day it may be supposed that this has not yet been achieved.

Probably the most neglected data are those in Fig. 7.1 giving the relationship between seeing distance, illumination and glare. These data predict limitations to conventional lighting and one should not be surprised at the poor results given by the latest "improvements" in vehicle headlighting, technically excellent though they may be as hardware. It should be recognised that the conventional lower beam has been exploited to the limit but that seeing distances in vehicle meeting situations are extremely low. So low that Hemion concluded that 60% of all vehicles observed were travelling at speeds in excess of those considered safe, echoing the sentiments of other investigators in the past.

Indeed the situation is being reached in which the employment of new lamps with extremely sharp cut-off beams can be considered a retrograde step. They rely, for their performance, on a level of in-service maintenance which is not available. To overcome this, probably costly and complex automatic aiming devices will have to be installed on vehicles with the possibility of a dubious return.

To make the lighting task easier it would be desirable to alter the environment in which it has to work. However, lighting considerations play little part in the design of roads and vehicles now and there has been little success in persuading pedestrians to wear light coloured clothing: it would appear to be unrealistic to expect much difference in the future.

It can be reasonably concluded that the present limitations of vehicle headlights will not be appreciated by road users and therefore their behaviour cannot be expected to be easily altered to mitigate the effects of these limitations.

Therefore, any attempts to improve the situation must be based on exploiting lamp technology in ways which involve road user co-operation as little as possible and largely accept the road-vehicle environment as it is.

Three strategies are proposed to improve the situation, two short term and the other long term. These are certainly applicable to Australia being as it is an island continent and hence more master of its own destiny, although decisions about motor vehicles are becoming increasingly an international matter.

Night Speed Limits.

It can be shown there is a limitation to the distance objects may be seen, especially in vehicle meeting situations. There is therefore, a safe speed of progress but since drivers are largely unaware that they cannot see, or if they are aware, they largely ignore the risk, this speed is often exceeded. Again one class of objects, pedestrians, are largely unaware that they cannot be seen.

Therefore, it would appear that the desirable speed of travel, ie., that largely conditioned by road construction and the amount of traffic, is not compatible with the safe speed of travel. The problem could be tackled by the introduction of a realistic differential night speed limit based on the minimum visibility distances of objects and the ability of driver-vehicle combinations to avoid them. It could be argued that this safe speed would probably be so low as to be unbelievable and unacceptable and, therefore, even if legislated, would be largely disregarded and so be unenforceable. On the other hand, it is known that to a certain extent speed limits are self enforceable, in that once a speed limit is introduced the average speed drops (7.42).

It is traffic engineering practice to warn motorists of hazardous conditions, both permanent and transient and suggest safe speeds. These are road deficiencies and road works, susceptibility to flooding and icing, possible presence of pedestrians and animals. Even conditions which might be thought to be obviously hazardous to motorists such as fog, are now brought to their notice. Thus, it seems that it is not unreasonable to warn motorists of the dangers of darkness, in a similar manner.

Table 7.5 shows the stopping distances from various speeds published by two Australian State Government organisations. There are considerable discrepencies between the values caused by differences in the values assumed for reaction time and vehicle braking efficiency.

The ability of vehicles to stop is demonstrated in Fig. 7.20, which shows the results of measurements on a random sample of cars in the United Kingdom taken a decade ago. This suggests that there is a large range of performance. These figures do not take into account the reaction time of the driver: again there will be a range of performance.

If the safe speed is based on avoidance rather than stopping, it can be a little higher. Grime (7.6) has suggested that in order to avoid objects the seeing distance needs to be twice the velocity of travel in metres per hour. He assumes a lateral vehicle movement of 1 metre and a lateral acceleration of 0.25g, which would be a rather violent manoeuvre.

If a reasonable reaction time is allowed (say 2s) on top of the data given in Fig. 7.20, it will be seen that the first set of stopping distances given in Table 7.5 are the most realistic. In the standard headlamp comparison set up of Jehu the object along the near side of the road will be seen at about 60m and that on the centre line of the road will be seen at 20m distance. Data from field trials give visibility distances at which pedestrians and cyclists are seen of 15m to 80m depending on the lightness of their clothing. From these considerations, it is suggested that a 60 km/h day speed limit for urban areas should be reduced to 50 km/h or below at night. Consideration of the rural road situation suggests a reduction of a day limit of 100km/h to one of 80km/h at night.

Beam Distribution.

It is the writer's view that the relevant authorities should maintain the status quo in conventional headlighting. Specifications should be modified so that extremely sharp cut-off lamps are not permitted. The cut-off should be commensurate with the present standard of aiming. Sharper cut-off will lead to a deterioration of present conditions unless automatic devices are fitted to vehicles. In the writer's opinion, the cost of such devices and the further development of conventional lighting would be better spent on perfecting and introducing polarised lighting.

Long Term.

Many countries, including Australia, have long lengths of inter-city and interstate roads, for which there is little hope of installation of fixed lighting. However, something drastic needs to be done to improve safety and comfort on these roads at night. The ideal solution for these situations is polarised lighting. Definite plans should be made now for its orderly introduction. This should stimulate industry into a development programme.

The writer visualises a simple lighting system of a single beam high intensity polarised headlighting system for rural roads with a town beam for urban traffic routes lit with high quality fixed lighting. A third beam modelled on the present low beam might be necessary for use in residential areas. Here high intensity polarised lights will be objectionable to pedestrians and the town beam will not provide sufficient light to compliment residential fixed lighting for good visibility. The vehicle headlighting system would be controlled automatically by a photoelectric device.

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Source	Conditions	Visibility Distance (m.) Open Road Upper Beam	Open Road Lower Beam	Vehicle Meeting Upper Beam	Vehicle Meeting Lower Beam
U.S.A.(1)	Sign — white paint arrow 2 m. from N.S. lane edge	260	130	150	105
	Pedestrian — 2 m. high 17% reflection, 0.6 m. from N.S. lane edge	235	115	80	80
	Line — 30 m. yellow reflectorised no overtaking line	105	65	45	40
Sweden(2)	Pedestrian 5% reflection	60	—	—	25
	Pedestrian 25% reflection	200	—	—	40
Sweden(3)	Pedestrian 4% reflection			23 (median) 15 (10th percentile)	
U.K.(4)	Pedestrian				
	1% reflection	80	50	—	35
	15% reflection	200	80	—	60
	Cyclist				
	1% reflection	—	30	—	16
	15% reflection	—	75	—	60

Notes

(1) 20 drivers of general public (17-54 years, male and female). 2 lane road at 88 km/h, correctly set lamps. 50% of drivers gave detection distances less than given values. Experimenters concluded distances less than stopping distances from legal speed limits.

(2) Controlled field tests.

(3) 400 general public drivers in own vehicles. Experimenters concluded that safe driving speed should be between 25 km/h and 50 km/h.

(4) 1 driver in controlled field trial on 2 lane road at 64 km/h. The experimenter concluded that dark clothed pedestrians were a safety hazard.

Table 7.1. Detection distances of common objects with various headlight combinations.
(After Hemion, Johansson & Rumar, MacNeill)

Country	Number of Readings	Values from cumulative frequency diagrams			Expected value	
		Lower Quartile	Median	Upper Quartile	from beam spec.	from beam diagram
U.K.	1342	710	950	1280	1600	700
Belgium Netherlands Germany	1295	370	520	740	375	375
France	377	520	680	990	375	375

Table 7.2. Measured glare values from oncoming vehicles on some European roads, 1971.

(After Yerrell)

Car type	Loading condition			
	1	2	3	4
Mini (Suspension 1) (Sample of 4)	0.2	0.9	1.0	2.4
Mini (Suspension 2) (Sample of 4)	0.3	0.7	0.7	1.6
Small (Suspension 1) (Sample of 2)	0.5	1.1	1.1	1.8
Medium (Suspension 1) (Sample of 4)	0.6	1.2	1.3	1.8

Loading condition (1) = Driver + petrol.
(2) = Driver + petrol + luggage.
(3) = (2) + 1 front passenger.
(4) = (3) + 2 rear passengers.

Weights: Occupants 80 kg
Petrol 30 kg (15 kg Mini)
Luggage 55 kg (40 kg Mini)

Table 7.3. Tilting up, in degrees, of headlamps on vehicle loading.

Speed km/h	Stopping Distance (m) 1	2
48	52	32
64	79	50
80	115	73
96	158	97
112	212	130

Criterion 1 $D = 2.5v + \frac{v^2}{2gf}$, where f is coefficient of friction for clean wet bituminous or concrete surfaces and reaction time is 2.5 secs. (Source: National Association Australian State Road Authorities.

Criterion 2 $D = 1.0v + \frac{v^2}{2a}$, where $a = 0.5g$ and reaction time is 1.0 sec. (Source: N.S.W. Department of Motor Transport.)

Table 7.5. Stopping distances from various speeds used by two government agencies.

Units	Test Point	Mean	St. Dev.	95% limits
New (Sample of 11)	½° U 1° R (a)	695	115	469 – 922
	Straight ahead (b)	2,180	580	1,030 – 3,330
	1½° D 2° L	17,900	2,400	13,100 – 22,700
	Maximum	20,600	2,500	15,700 – 25,500
Used (Sample of 7)	½° U 1° R	819	178	471 – 1,170
	Straight ahead	1,760	560	660 – 2,860
	1½° D 2° L	15,600	3,100	9,500 – 21,600
	Maximum	18,900	2,700	13,600 – 24,200

Notes

(1) Units all-sealed 12V 75/50W BS/SAE.
(2) New units obtained 6 ex-factory, 5 ex-retailer.
(3) Used units obtained ex-motor vehicle manufacturer — all units used in excess 300 hrs.
(4) All units tested at 12.8V and no allowance made for small variations in wattage.
(5) The intensity results for used units are not significantly different, using Student's-t test, from those for new units. Measurements were also made on the direction of maximum intensity. The mean vertical directions were not significantly different whereas the mean horizontal directions were (at the 2% level), for the two samples.
(6) Spec. requirements (a) 800 cd max.
(b) 10,000 cd min.

Table 7.4. Lower beam intensities (cd) from new and used headlamp units.

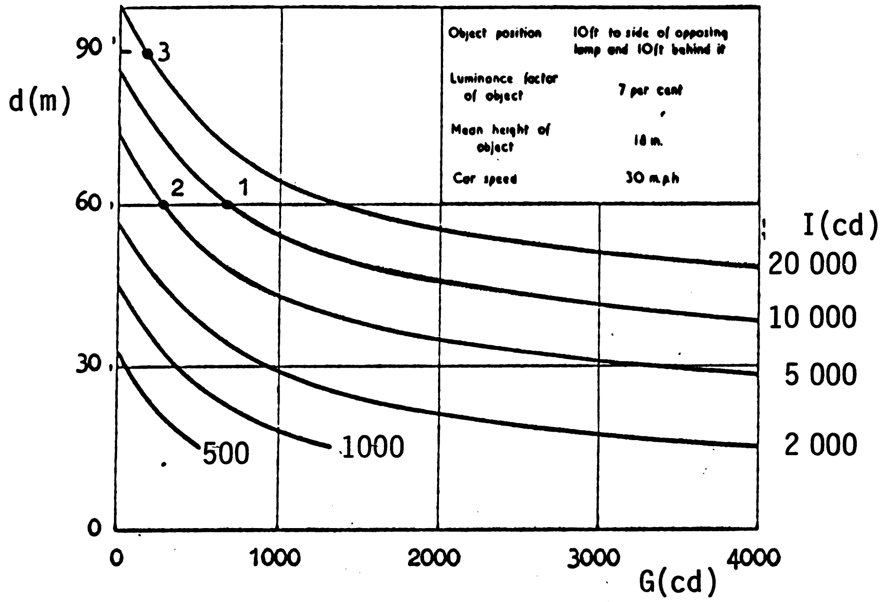


Fig. 7.1. The basic relationship between seeing distance (d), glare (G) and intensity directed towards the object (I) in a standard situation. (Present lower beams work at points 1 (SAE/BS) or 2 (European); to improve they need to work at point 3.)

(After Jehu)

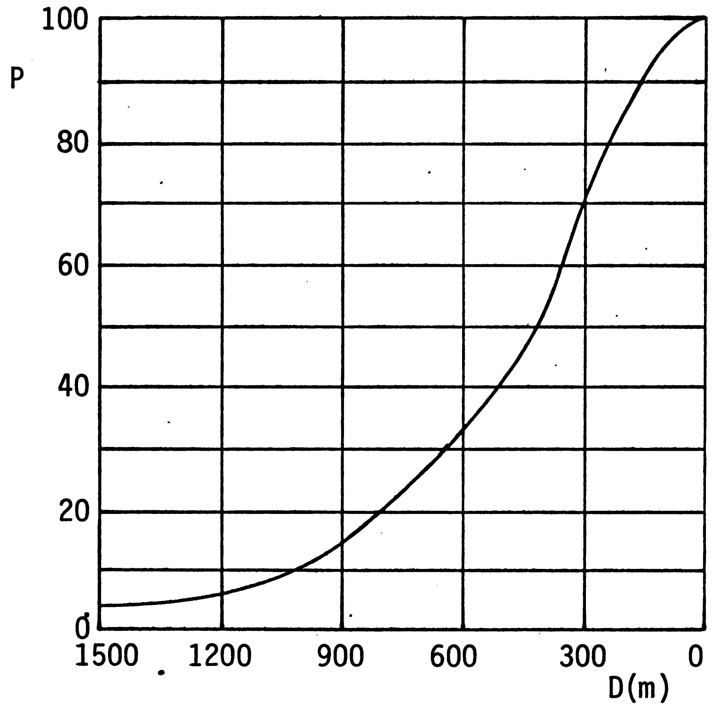


Fig. 7.2. Percentage of drivers (P) dipping their lights at less than the intercar distance (D).

(After Hare & Hemion)

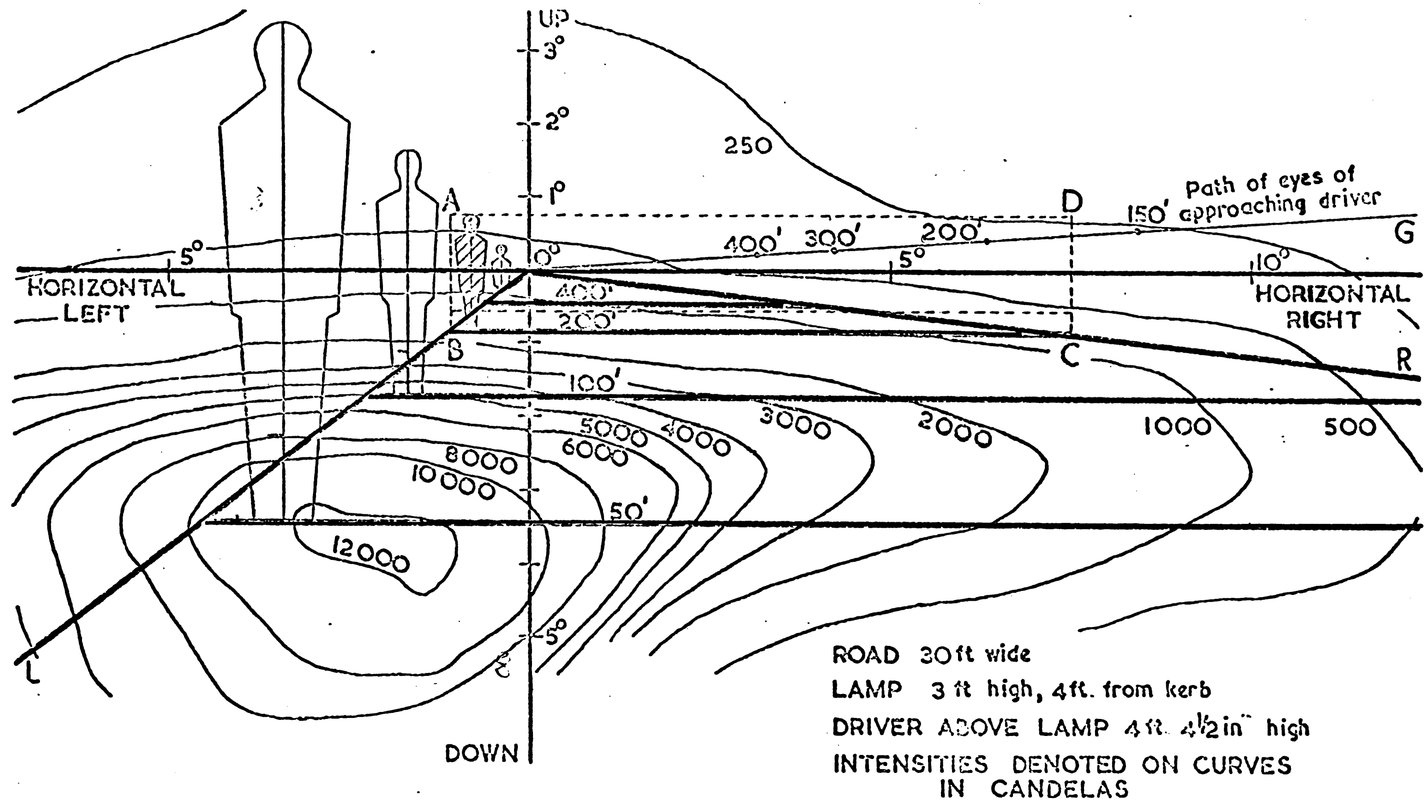
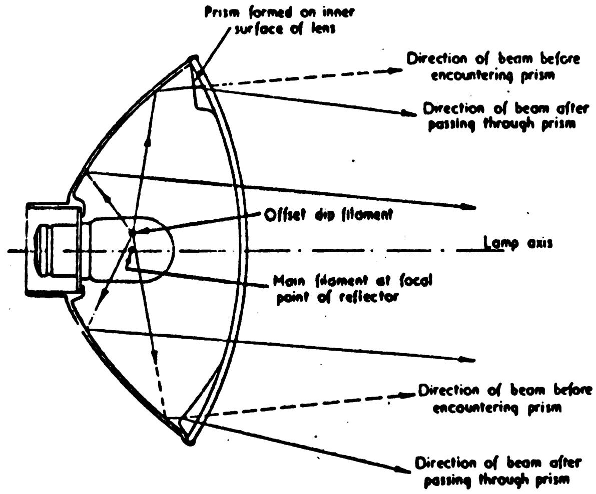


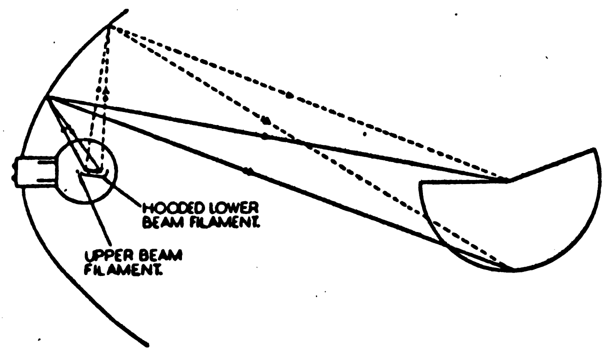
Fig. 7.3. Geometry of headlighting problem on a straight road: intensities in the beam in relation to the road, a 6 ft man at various distances and an approaching driver.

(After Harris)



(a) American/British

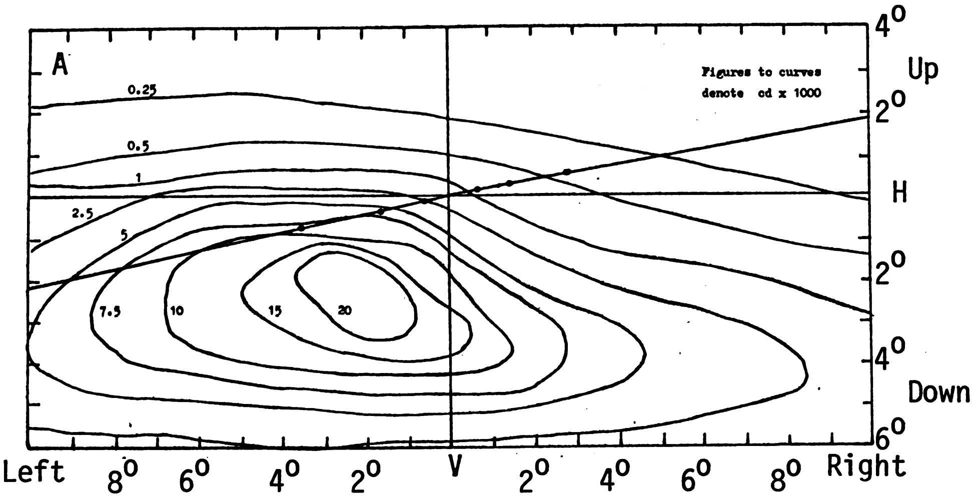
(After Moore)



(b) European

(After Jones)

Fig. 7.4. American-British and European headlamp optical systems and the formation of the lower beam.



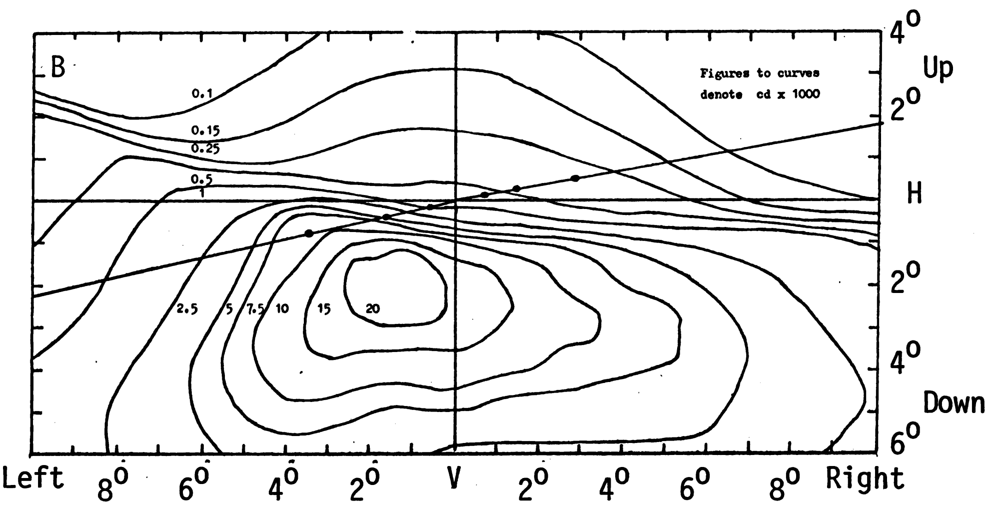


Fig. 7.5. Beam diagrams of two lower beams: (A) SAE/BS 7 in. 50W with aiming plane vertical, and (B) European $5\frac{3}{4}$ in. 55W tungsten halogen with cut off 1 in 100 down. The lines represent the mean paths of the oncoming driver's eyes for a lateral separation of 3m between the approaching cars and the roadway edge 3m to the N.S of centre line of a car. The points are for intercar distance and distance ahead respectively of 50, 100 and 200m.

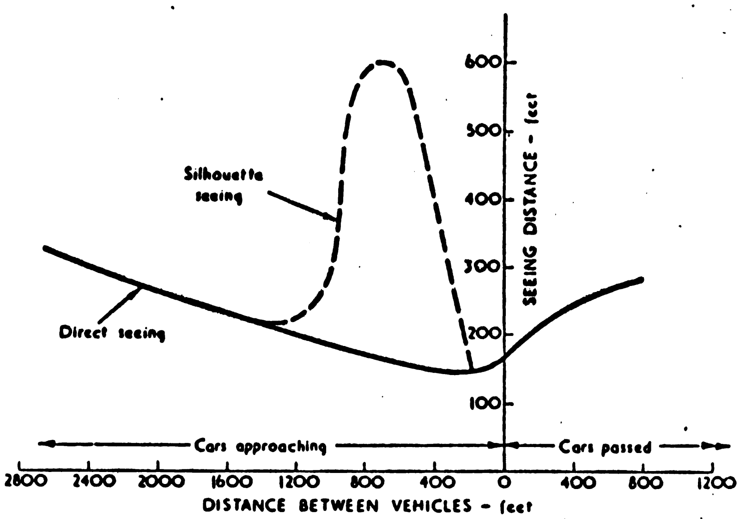


Fig. 7.6. Seeing distance as a function of distance between vehicles.

(After Roper)

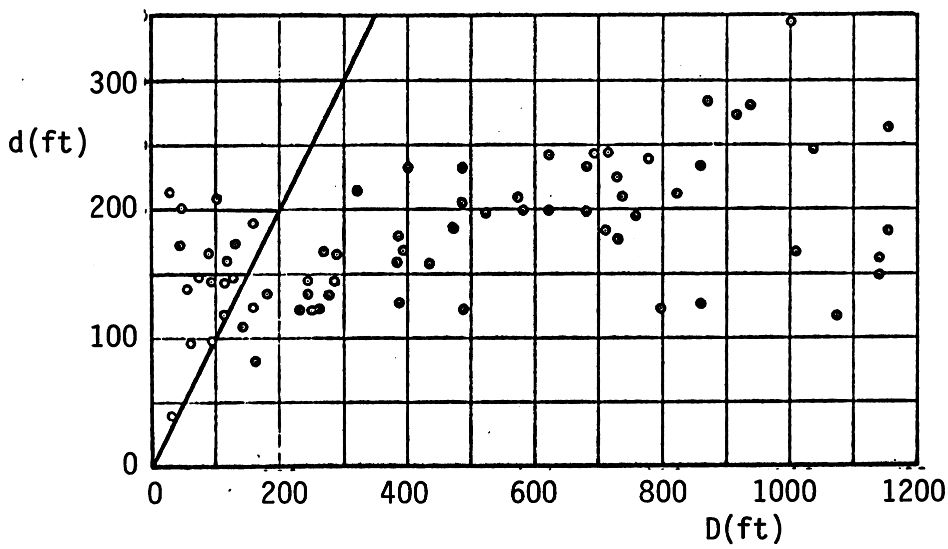


Fig. 7.7. Measured seeing distances (d) at various intercar distances (D), for a small object on the nearside of the road with opposed American lower beams, obtained in international comparison tests.

(After HMSO)

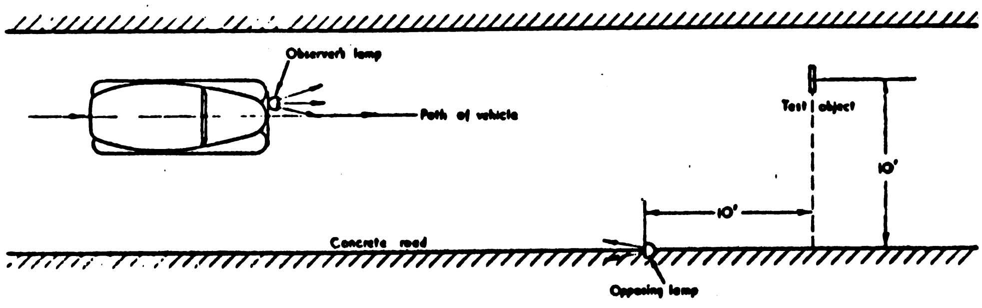


Fig. 7.8. Layout of the standard visibility test used by Jehu. (After Jehu)

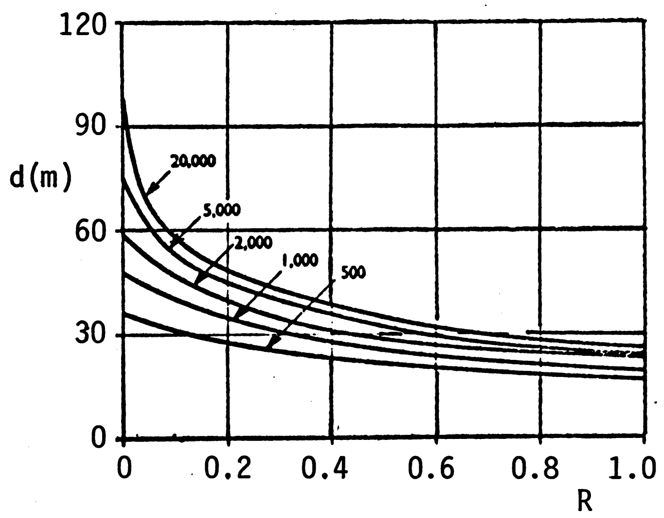


Fig. 7.9. Seeing distance (d) as a function of the ratio (R) of the glaring intensity to that directed towards the object. Figures to curves give intensity (cd) directed towards object. (After Grime)

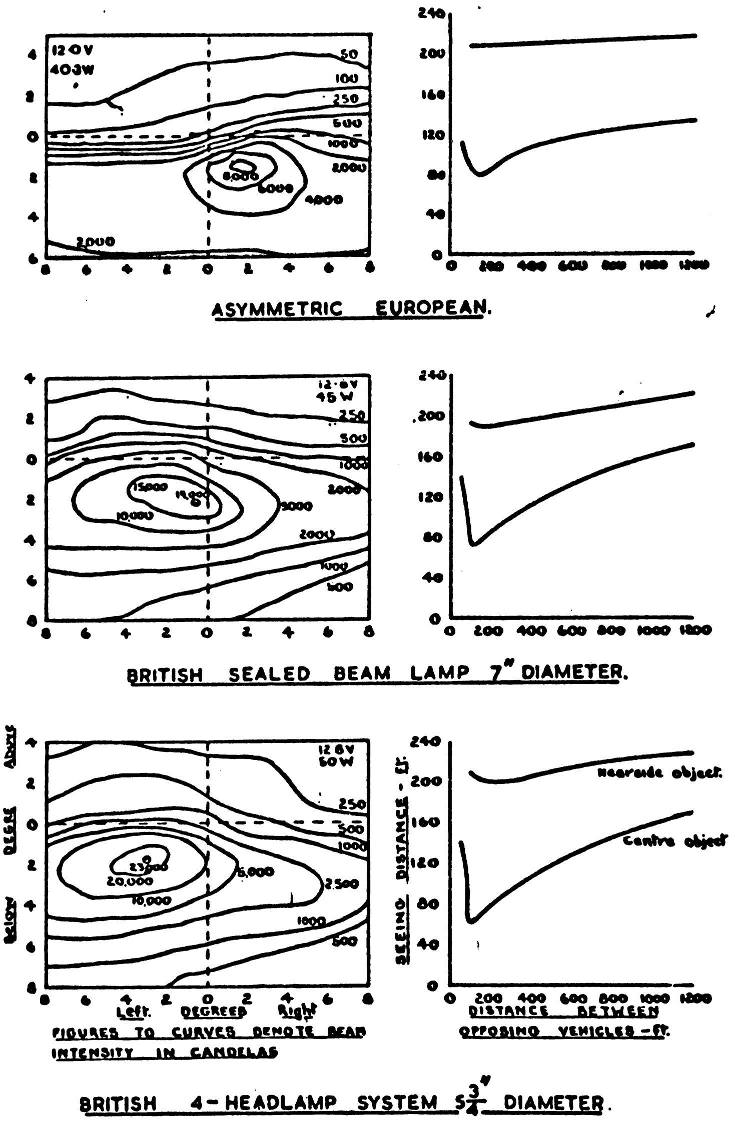


Fig. 7.10. Lower beam distributions from modern headlamps and direct seeing distances on a straight road using them opposed by similar lamps correctly set. Distances refer to a standard object 18 in. high and 7% reflectance.

(After Fosberry & Moore)

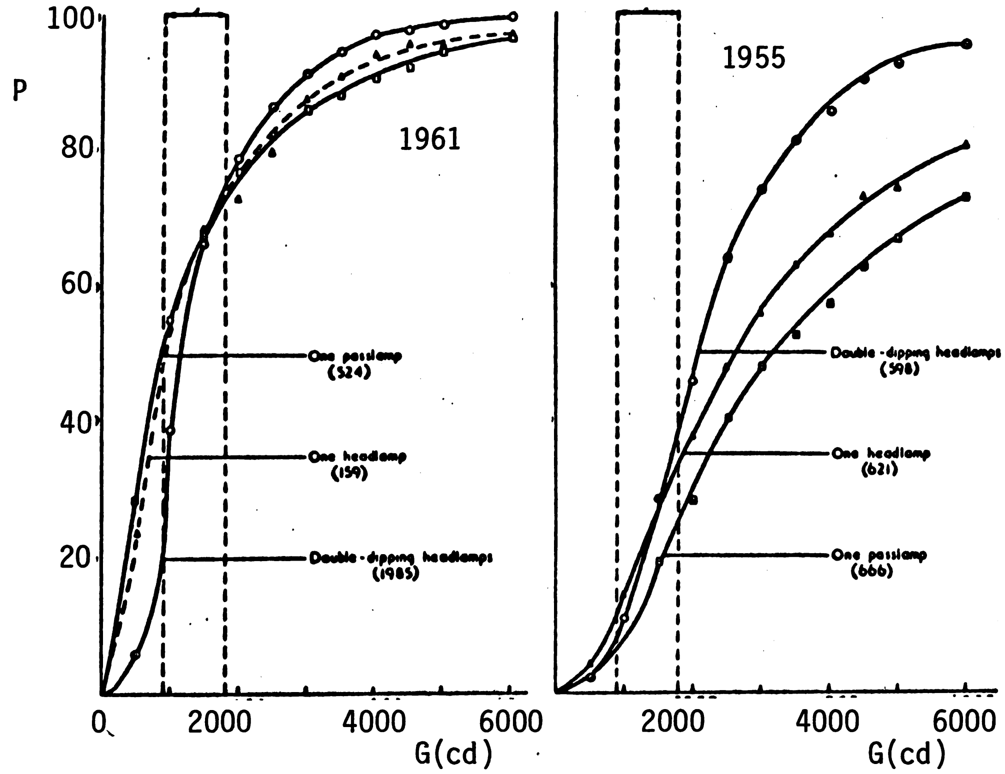


Fig. 7.11. The percentage (P) of vehicles giving less than the glare (G), in two surveys. The desirable limits are marked.
(After Jehu)

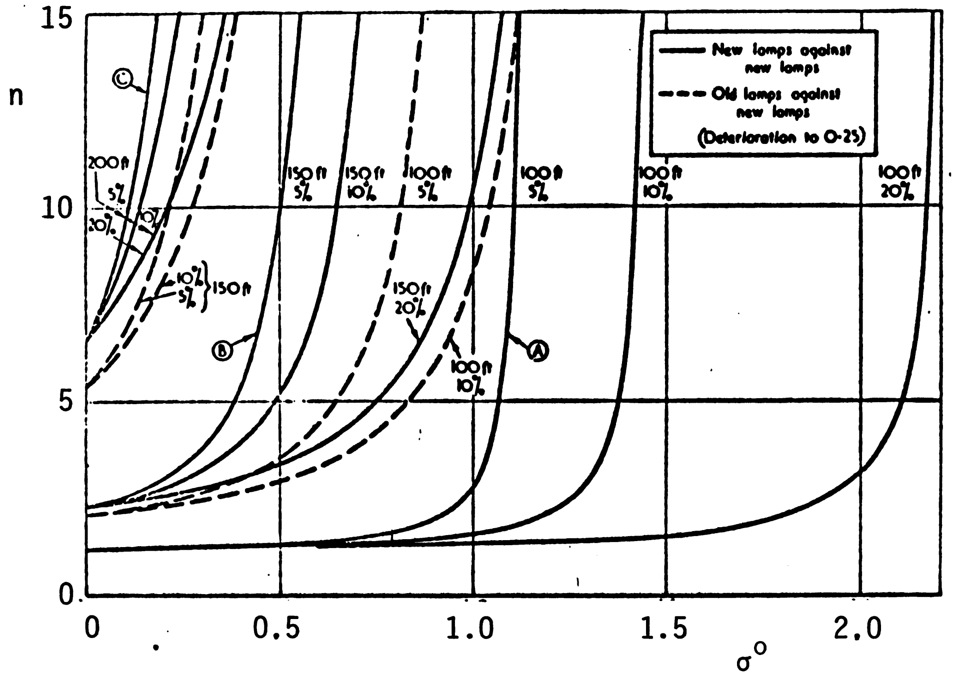


Fig. 7.12. Relationship between sharpness of beam cut off (n) and standard of aim (σ) for given probability of given minimum seeing distance, the values of which are given on curves.
(After Harris)

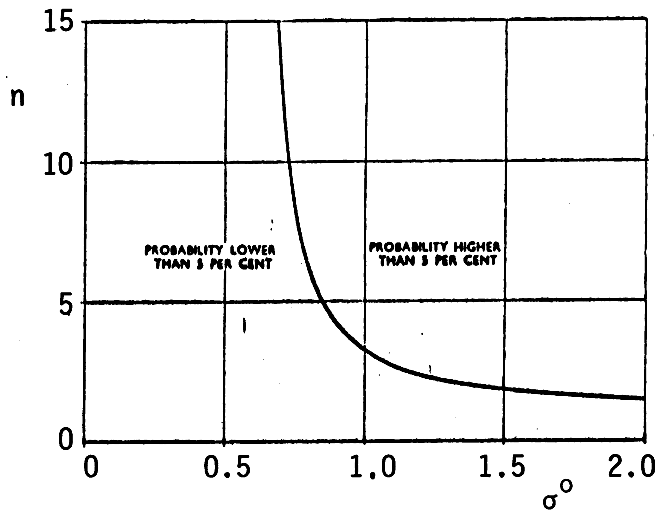


Fig. 7.13. The relationship between standard of aim (σ) and beam cut off (n), so probability of glaring intensity exceeding 3 times nominal straight ahead intensity is restricted to 5%.
(After Harris)

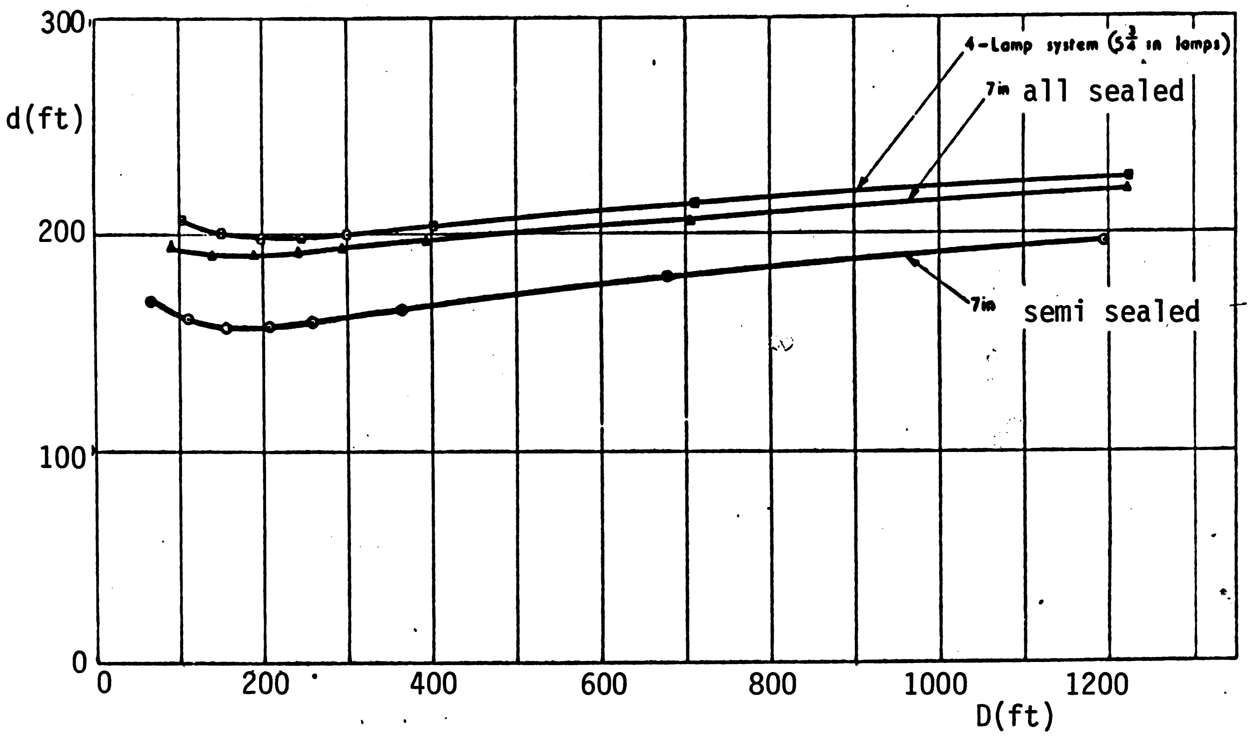


Fig. 7.14. Seeing distance (d) with intercar distance (D) of nearside object with British lower beams.
(After Jehu)

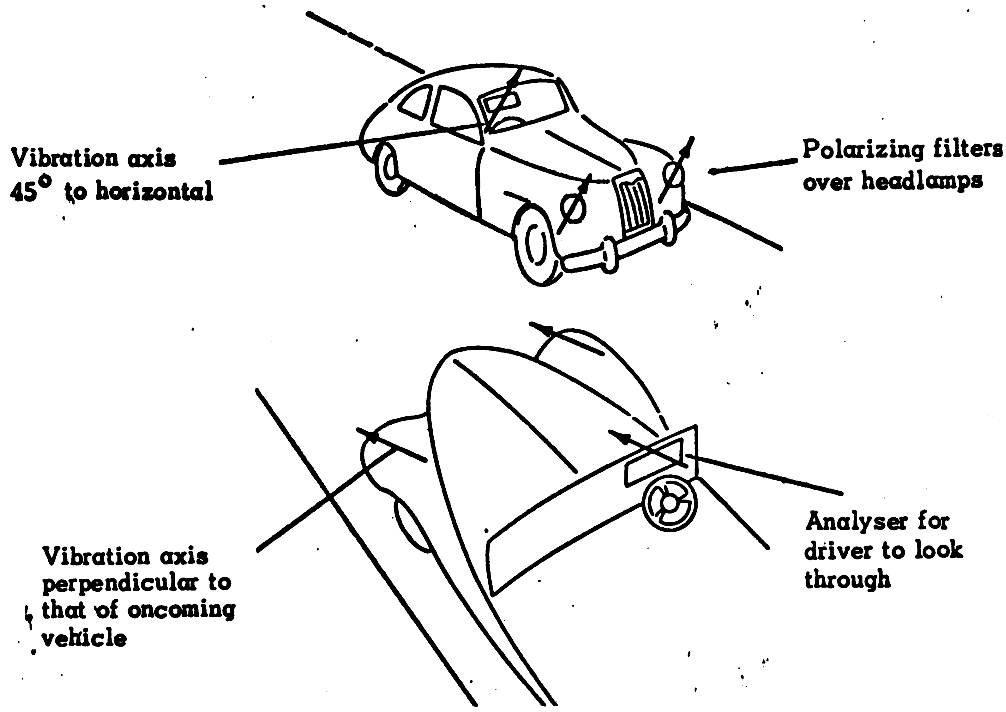


Fig. 7.15. The polarised headlight system. (After Jehu)

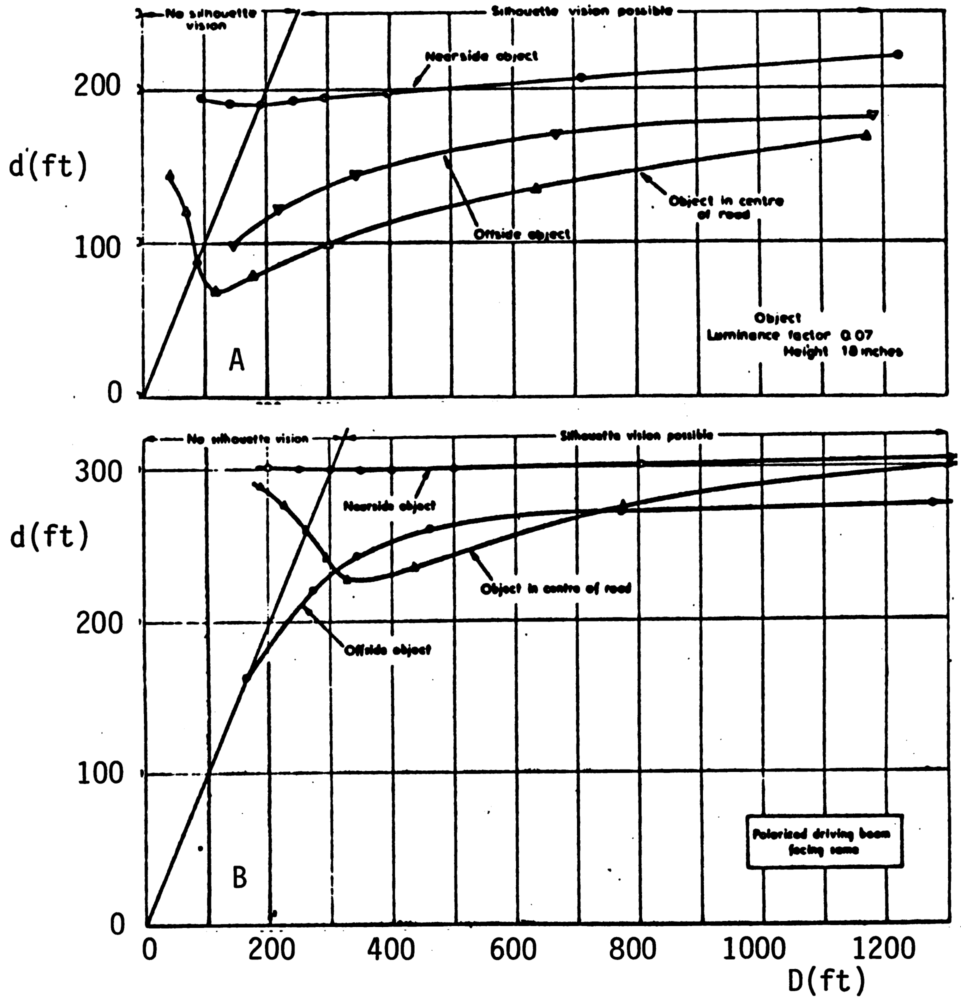


Fig. 7.16. Comparison of seeing distances (d) obtained with lower beam (A) with those for polarised upper beam (B). (After Jehu)

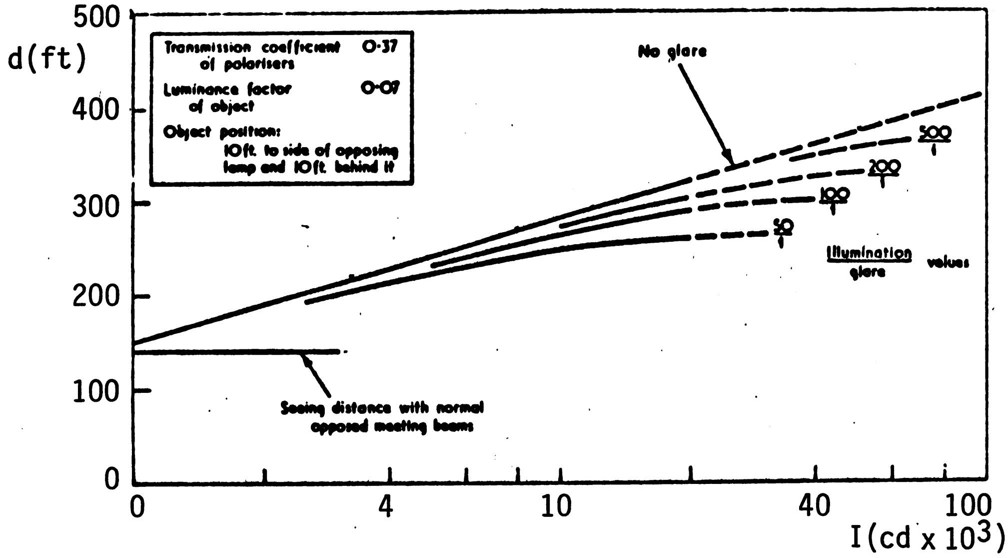
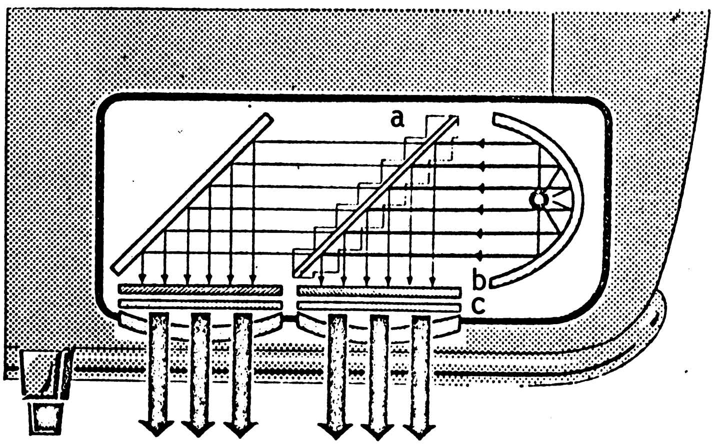


Fig. 7.17. Relationship between seeing distance (d) and effective beam intensity (I) for polarised systems of various illumination/glare ratios.

(After Jehu)



The Bosch polarised headlamp system consists of three components:
(a) Beam splitting multiple layer polariser. This produces a transmitted beam and reflected beam which are approximately equal in intensity and polarised with the planes of polarisation at right angles. The polarising plate is bounded by two series of prisms to provide a more convenient angle of maximum polarisation (Brewster's angle).
(b) Half wave plates to rotate the planes of polarisation so that they are both at 45° to the horizontal.
(c) Polarising filter to improve the degree of polarisation

Fig. 7.19. The Bosch polarised headlamp system.

(After Davey)

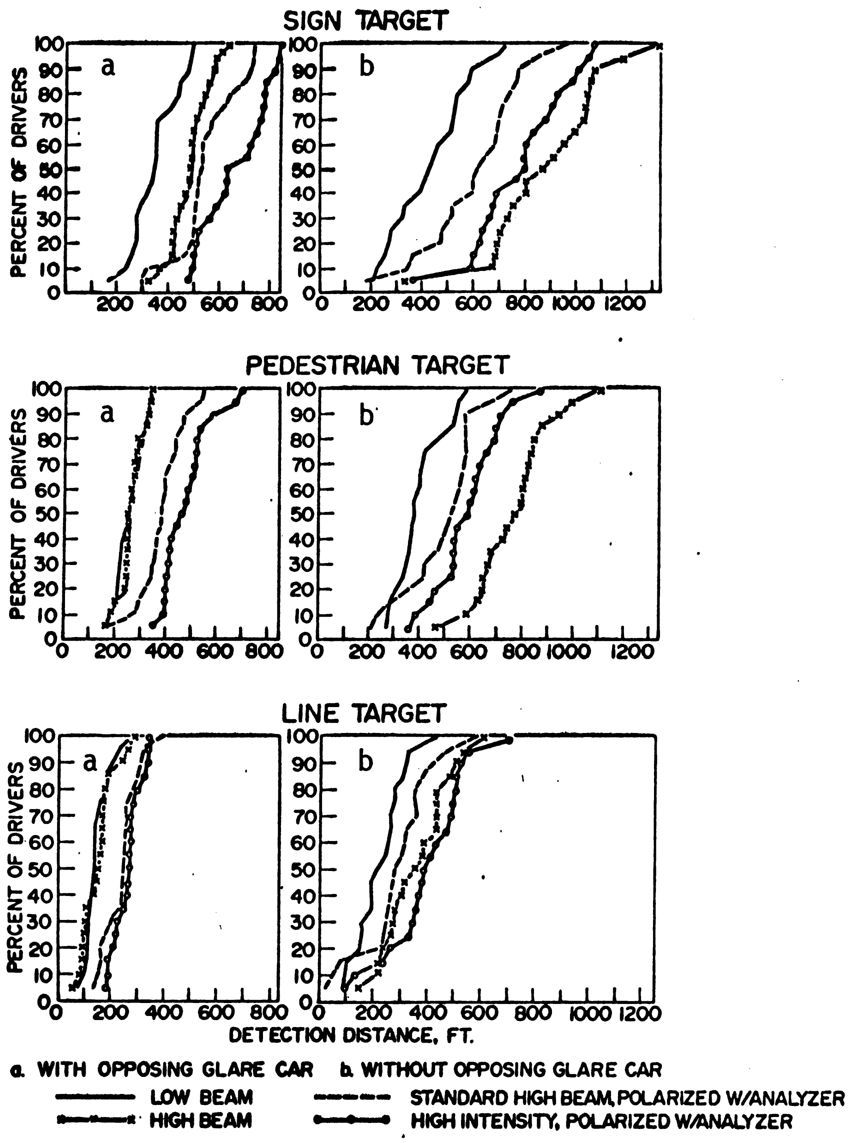


Fig. 7.18. The percentage of drivers recording less than the given detection distances, for various targets and beam systems. (After Schwab and Hemion)

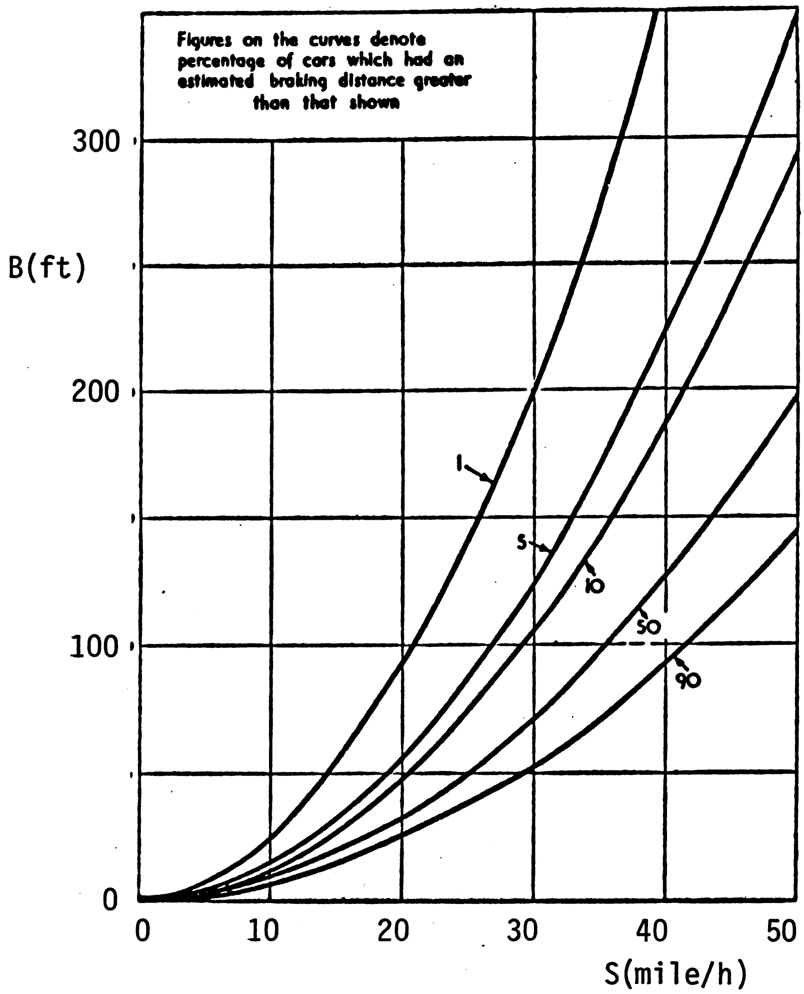


Fig. 7.20. Braking distance (B) from different speeds (S) of a random sample of cars in use.

(After HMSO)

CHAPTER 8

SEEING DISTANCE WITH UPPER BEAMS

INTRODUCTION.

In the previous chapter evidence was presented which suggested that there is a sharply diminishing return in increased seeing distance for increases in upper beam intensity. This probably results from two main effects: as the object to be seen is further away the beam intensity needs to be increased in proportion to the square of distance to maintain the same illuminance, but the illuminance also needs to be increased to compensate for the smaller angular size of the object.

In particular, it was suggested that the proposed increase in total upper beam intensity from the current level of 100,000 cd to around 300,000 cd would result in a negligible increase in seeing distance. In this chapter an analysis is made of the interconnection between seeing distance, beam intensity and object size and contrast.

METHOD.

The method of calculating seeing distance has been developed fully in Chapter 2. It makes use of the relationship between background luminance, object size and the necessary contrast between the object and background developed by Blackwell. In order that the laboratory data shall be more representative of practical situations, the necessary contrasts have been increased by a factor of 10, as shown in Fig. 8.1.

In order to determine the contrast and hence beam intensity using equations 2.7 and 2.8 it is necessary to assume representative values for the luminance factors of the object and background and for the linear size of the object.

Parameter Values.

The following range of values has been considered:

Linear size (diameter) of the object: 0.23m, 0.45m, 0.91m.

Luminance factor of object: 0.15, 0.07, 0.04, 0.02.

Luminance factor of background: 0.03.

The size range encompasses the object size (0.23m) used in an Australian road design criterion for sight distance (8.1), the size of object (0.45m) used by Jehu in his seeing distance investigations and a larger object, approaching pedestrian size. The object luminance factors range from those for dark to light objects and include that (0.07) of the object used by Jehu. The luminance factor of the background is that determined by the writer for an asphaltic concrete surface for headlighting. The measurements are described in the Appendix. This value is similar to those for foliage, reported in Table 11.5.

The contrasts between object and background are, by equation 2.7:

Luminance factor of object (β_o)	Contrast
0.15	4.00 (Object lighter than road)
0.07	1.33 (Object lighter than road)
0.04	0.33 (Object lighter than road)
0.02	0.33 (Object darker than road)

These values are marked in on Fig. 8.1: the necessary background luminances, in order to see objects with these contrasts are read off for each angular object size. The equivalent distance away for each linear size of object is deduced and the necessary beam intensity calculated from equation 2.8.

RESULTS.

The results in terms of plots of seeing distance against beam intensity, for the various object sizes and contrasts, are shown in Fig. 8.2. Very large increases in beam intensity (I) have to be made for small increases in seeing distance (d): very approximately the curves are of the form:

$$I = cd^4$$

where c is a constant depending on object size and contrast. As object size and contrast decreases so the necessary beam intensity increases.
Comparison with Road Tests.

Seeing distances for a range of beam intensities have been measured in field tests by Jehu; the data is shown in Fig. 7.1. The relevant parameters were object luminance factor 0.07 and size 0.45m diameter: the luminance factor of the road surface is unknown. The measured seeing distances for the beam intensity range investigated (500 to 20,000cd) are plotted in Fig. 8.2b. The agreement between these distances and the calculated ones for the conditions, object luminance factor 0.07 and object size 0.45m is reasonably good (8.2).

Reference to Table 7.1 shows that the distance at which light and dark clothed pedestrian objects were seen with current upper beams in field experiments were 200 - 235m and 60 - 80m respectively. For similar conditions, the calculated data give values of about 270m and 100m, again there is reasonable agreement.

Very recently Helmers and Rumer (8.3) of the University of Uppsala measured object visibility for a range of high beam intensities (29,000 to 260,000 cd). The relevant parameters were object luminance factor 0.045, object size 1.0m high by 0.4m broad, roadway luminance factor 0.033. Their results are plotted in Fig. 8.2c. In this case the agreement between their results and the calculated ones for the conditions, object luminance factor 0.04 and object size 0.91m, is not so good. The Swedish data has the same form as the calculated data, the points lying parallel to the calculated curve for the object. The points are displaced upwards by 1/3 of a log unit, i.e. the Swedish distances are about twice those that are predicted by calculation.

The Swedish distances are puzzlingly high: when compared to other data in Table 7.1 it is to be expected that the distances would more likely apply to a light object and that the dark object actually used would yield distances about half the values of those quoted.

One explanation is that the report of the Swedish trials speaks of object detection whereas, the data of Jehu, at least, are based on recognition of the object. In addition the Swedish trials employed multiple objects. Thus the Swedes were alerted to objects appearing which they only had to detect. Data based on recognition and less alert observers would be expected to be more conservative and more realistic of the driving task.

Thus the calculation method and the major assumption of the relevance to road conditions of laboratory data with a field factor of X 10 is largely validated. Moreover, a general relationship between parameters over a large range of values has been established by this method. This would be extremely tedious to do by field measurements.

IMPLICATIONS TO ROAD TRAVEL.

The data in Fig. 8.2 can be used to determine the intensities required in order that objects may be seen from the distances required to stop a vehicle from given speeds. The distances required, taken from an Australian road design manual (8.1) are:

Speed (km/h)	Stopping Distance (m)
80	115
96	158
112	212

These intensities requirements are given in Table 8.1.

The safe speed of travel on the open road at night depends very much on what objects are likely to intrude into the path of the vehicle. It would be judicious to assume that small and/or dark objects are likely to be encountered. In Australia macropods are common on rural roads at night. Thus with current high beams (100,000cd) the safe speed of travel at night is about 80 km/h.

HEADLAMP DESIGN.

It has been mentioned in Chapter 7 that the introduction of the quartz halogen source into headlighting could see increases in upper beam intensities. The present beam intensity of about 100,000cd could easily be increased to about 250,000cd, i.e. X 2.5. (The SAE <u>maximum</u> is 75,000 but there is a proposal for a 300,000 cd maximum in the UN protocols on vehicle lighting.)

The figures in Table 8.1 suggest that even this large increase will not have any appreciable effect on visibility conditions:

(i) for each 16 km/h increase in speed a four times increase in beam intensity is necessary to see the larger lighter objects at sufficient distance; for the smaller darker objects a seven times increase is necessary;

(ii) each time the object dimension or luminance factor is halved a seven to ten times increase in beam intensity, depending on speed, is necessary.

In Table 8.2 the seeing distance increases are given for the intensity increase of 2.5 times for various objects. These increases in distance range from 17 per cent for the small dark objects to 23 per cent for the large and/or light objects. The Swedes found that on increasing the beam intensity from 87,000 to 260,000 they realised a 22 per cent increase (8.3).

DISCUSSION.

This analysis confirms the supposition made earlier that large increases in beam intensity yield small increases in seeing distance. A possible increase of X 2.5 gives an increase in seeing distance of about 20 per cent. Reference to the stopping distances given above suggests that the best that can be said about this increase is that it will further ensure the safety of those travelling at a reasonable night speed (80 km/h). It will do little to improve the safety of those who wish to travel at speeds over 100 km/h. At these speeds the stopping distances increase much more rapidly than in proportion to speed; the small increase in seeing distance is equivalent to a negligible increase in safe speed.

Increased beam intensity could well given drivers a false sense of security and induce them to drive at even more unsafe speeds than they do now since the luminance of the scene close to the car will be very noticeably raised. This could lead to false assumptions about improved seeing distance ahead of the vehicle.

REFERENCES.

8.1 NAASRA, Policy for geometric design of two lane rural roads, 3rd ed, National Association of Australian State Road Authorities, Sydney, 1967.

8.2 Jehu, V. J., A method of evaluating seeing distances on a straight road for vehicle meeting beams. Trans Illum. Eng. Soc. (Lond), Vol. 20, No. 2, 1955.

8.3 Helmers, G. and Rumar, K., High beam intensity and obstacle visibility, Report 150, Dept. Psychology Uni. Uppsala, 1974.

APPENDIX 8.1
THE DETERMINATION OF THE LIGHT REFLECTING PROPERTIES OF ASPHALTIC CONCRETE USING A SIMULATED HEADLIGHTING CONFIGURATION

The sample of asphaltic concrete was that which had been used to obtain reflection characteristics for street lighting purposes referred to in Chapter 3. In this series of measurements a headlighting configuration was simulated by illuminating the sample surface with a slide projector (approx. CIE Illuminant A) and viewing the sample with a Pritchard Spectraphotometer. The projector and photometer were on the same side of the sample and at a distance of about 3m from it. Their horizontal separation was 2.4°. The angle between the horizontal and the direction of illumination (α) was varied between 0.5° and 5° and the angle (θ) between the horizontal and the direction joining the photometer to the centre of the sample was varied between 1° and 6°.

In order to improve the resolution of the measurement of these angles the projector lens and photometer objective lens were both stopped down to subtend 0.5° at the sample. The field aperture of the photometer was 1° in horizontal and 6' in vertical, so the photometer viewed only the central area of the sample.

The illuminance and luminance of the sample were determined absolutely by comparing the readings obtained on the sample with those obtained using a standard lamp illuminating a standard reflecting surface.

RESULTS.

The luminance factors for different values of α and θ are shown in Fig. 8.3. For ease of further calculation, luminance factor is defined as the luminance (in apostilbs) per unit illuminance (in lux), measured in a plane perpendicular to the incident beam.

It can be seen that for each value of (θ) the luminance factor rises for increasing α, sharply at first and then more slowly, tending to a common value. At the smaller angles of α and θ there is shielding of parts of the surface by projecting surface aggregate, which probably accounts for the shape of the curves.

The values of luminance factor for the driver-vehicle-road configuration at various distances ahead are given in Table 8.3. It appears that the luminance factor applicable to this configuration is largely independent of the distance ahead of the road surface. However, the measurement set up restricted the effective distance ahead to about 75m, a value at the lower end of the range of interest. At greater distances the angles involved become so small as to prevent simulation with the laboratory apparatus. Thus a value of luminance factor of 0.03 was assumed to be representative of the situation considered: this value was similar to that derived in a spot measurement during the Swedish field trials.

Object Luminance Factor	Object Size (m)	Light Intensity (cd) Required for Various Speeds (km/h) 112	96	80
0.15	0.91	2.4×10^4	5.6×10^3	1.7×10^3
	0.45	2.2×10^5	4.5×10^4	1.1×10^4
	0.23	2.1×10^6	3.5×10^5	7.1×10^4
0.07	0.91	2.0×10^5	4.5×10^4	1.1×10^4
	0.45	2.2×10^6	3.5×10^5	7.1×10^4
	0.23	2.2×10^7	3.5×10^6	6.0×10^5
0.04 and 0.02	0.91	2.1×10^6	4.6×10^5	1.1×10^5
	0.45	1.0×10^8	8.5×10^6	1.3×10^6
	0.23	Not detectable	Not detectable	3.2×10^7

Table 8.1. The luminous intensity required to be directed towards an object so that it will be seen at a sufficient distance in order to stop from a given speed.

Luminance factor of object	Size of object (m)	Seeing distance (m) 250kcd beam	100kcd beam	Ratio
0.15	0.91	350	284	1.23
	0.45	221	182	1.21
	0.23	146	121	1.21
0.07	0.91	229	188	1.22
	0.45	146	121	1.21
	0.23	100	83	1.20
0.04 and 0.02	0.91	136	111	1.23
	0.45	86	73	1.18
	0.23	57	48	1.17

Table 8.2. Seeing distances for two beam intensities for various objects.

Configuration	Distance Ahead (m.)	θ^o	α^o	Luminance Factor β
Eye height — 1.22 m.	73	1	0.6	0.025
Lamp height — 0.76 m.	**37**	**2**	**1.2**	**0.029**
(Car)	24	3	1.8	0.028
	12	6	3.6	0.028

Table 8.3. The reflecting properties of an asphaltic concrete surface for various driver-vehicle-road configurations.

θ = vertical angle between line of sight and direction of travel

α = vertical angle between incident light and direction of travel

θ & α are essentially in the same vertical plane and on the same side of the normal to the road sample under test.

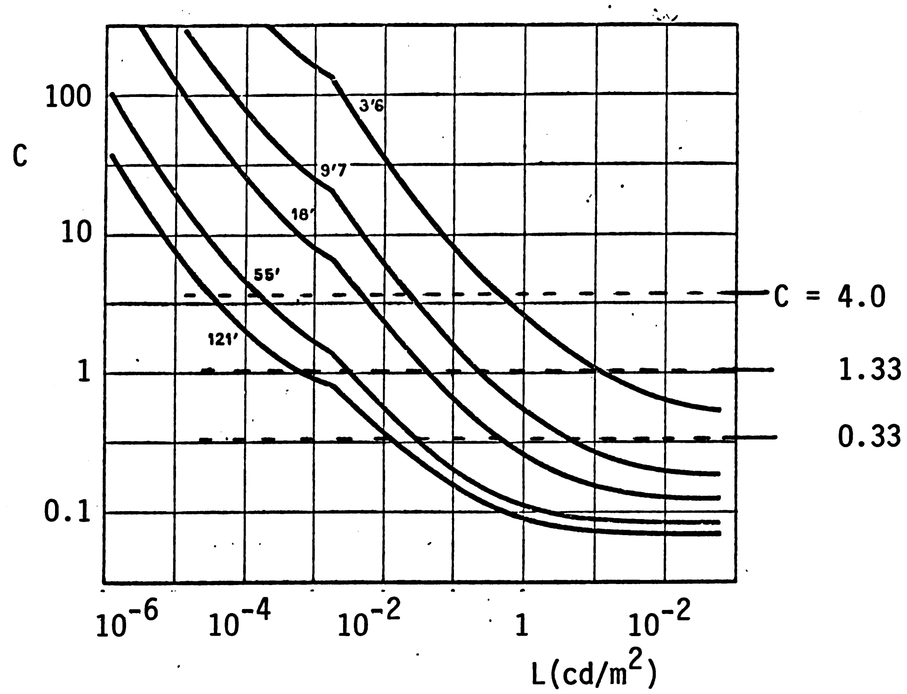


Fig. 8.1. The necessary contrast (C) required to see objects in headlights with road luminance (L). Those marked are used in the calculations.

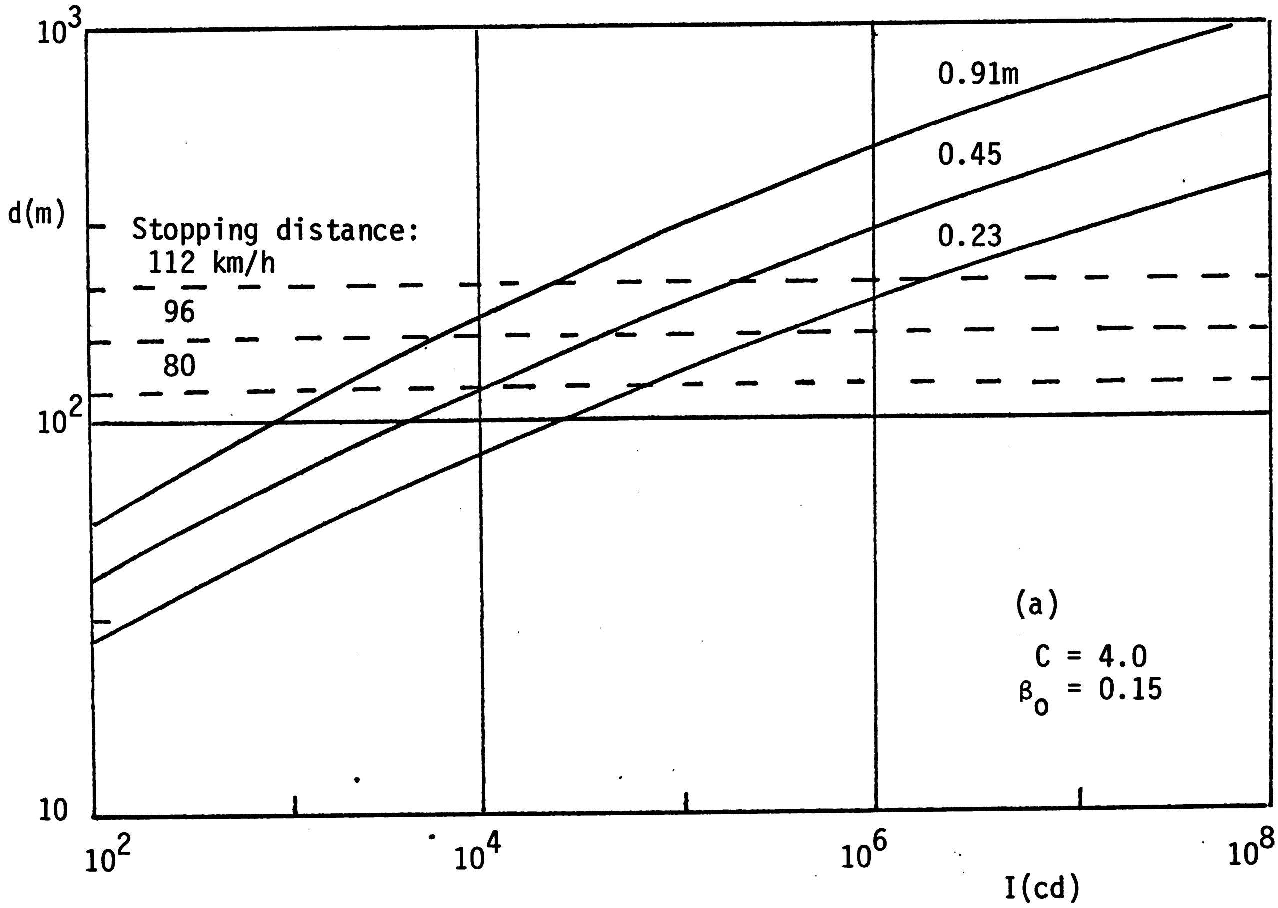


Fig. 8.2a. Seeing distance (d) with beam intensity (I) for various objects.

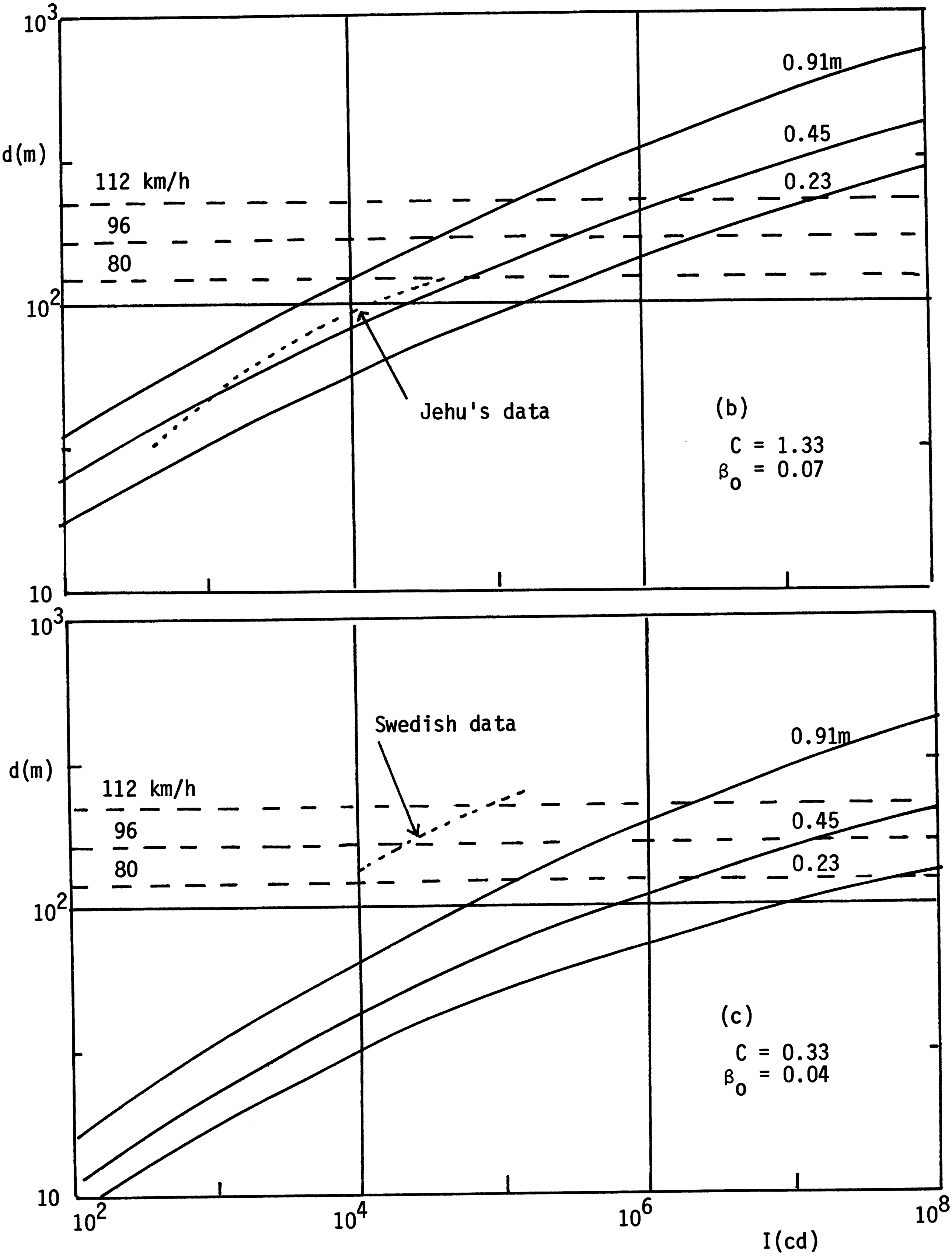


Fig. 8.2b,c.Seeing distance (d) with beam intensity (I) for various objects.

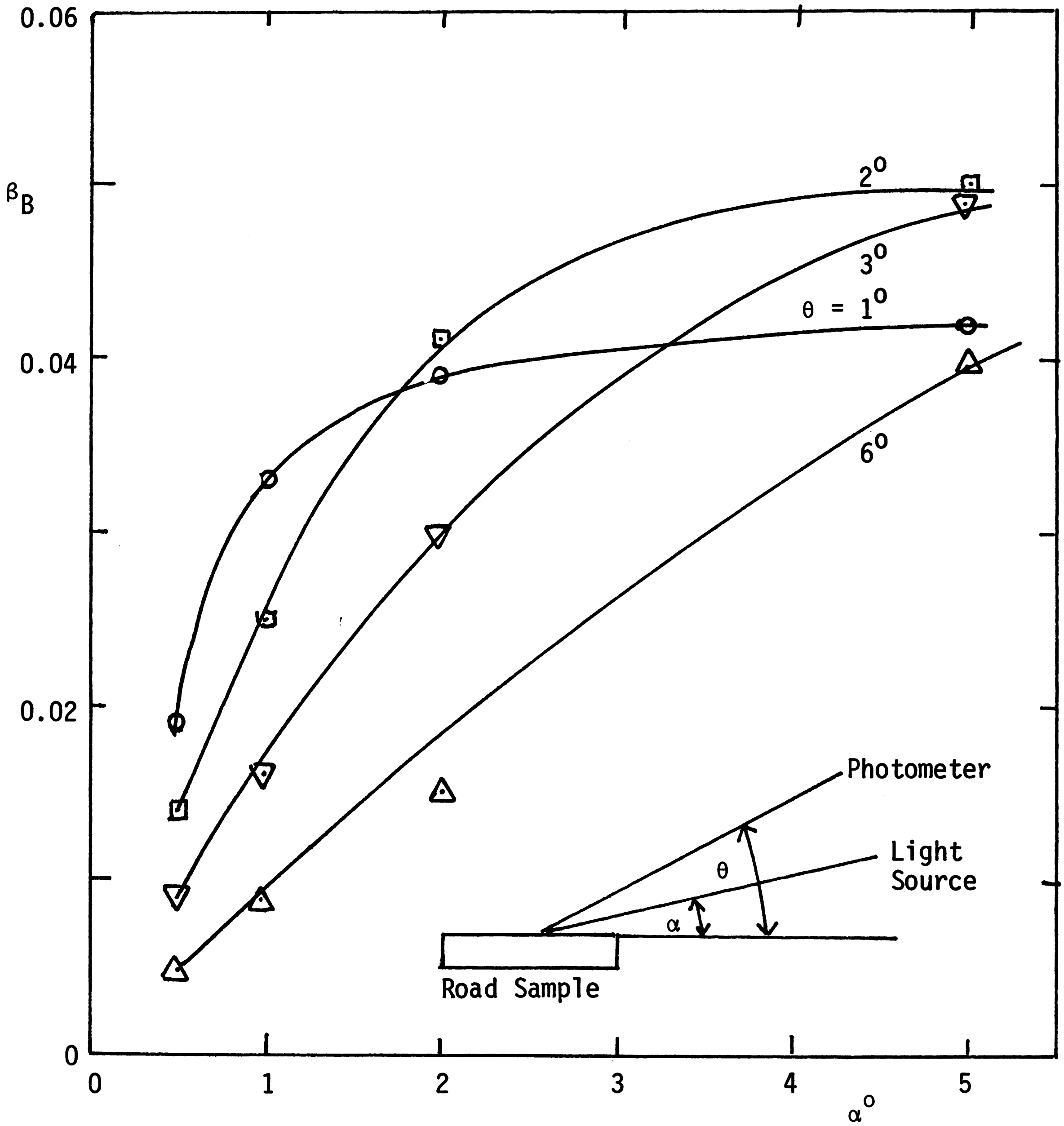


Fig. 8.3. The reflecting properties of a sample of asphaltic concrete road surface using a headlighting configuration. The luminance factor β_B is the luminance (apostilbs) per unit illuminance (lux) measured in plane normal to the incident light.

CHAPTER 9

APPRAISALS OF UPPER BEAM

INTRODUCTION.

In Chapter 8, it was shown that negligible increases in seeing distance were obtained on the open road for very large increases in upper beam intensity. In Chapter 7, evidence was given that drivers dip their headlights in the very early stages of vehicle meetings to avoid discomfort.

It was suggested that increases in upper beam intensity will result in drivers dipping their headlights at even greater distances so making the upper beam less useful than now.

This chapter describes some appraisals of upper beams of different intensity. Subjects were asked to rate vehicle meeting situations, in which the upper beam was used, on a semantic scale.

TEST PROCEDURE.

The Track.

Two cars were driven towards each other with about 3m lateral separation along a bitumen surfaced track. The track had a straight section of about 1,000m; on a loop at either end the cars could turn and lamp intensities changed, with the cars facing away from one another. The track had rough edges marked with white posts at about 60m intervals. The surrounds to the track were dark. The situation simulated a country road where two approaching cars would come round bends to meet on a straight portion of road.

Rubber cones were placed on each side at the track midpoint and at 90m and 180m from it in each direction. The outer and inner sets of cones were equal to twice and once respectively the minimum intercar distance at which dipping is required by Australian state government traffic regulations.

Lamps.

Each car was fitted with three pairs of lamps positioned across the vehicle front so that the centre of each lamp was the same height from the ground and the horizontal distance between centres of each pair was the same:

- (i) the normal 7in (175mm) diameter 12v 75w/50w units to SAE/BS design giving upper and lower beams;
- (ii) a pair of 6in (150mm) diameter 55w quartz halogen units giving single beam;
- (iii) a pair of 8.5in (215mm) diameter 100w units giving a single beam;

The suppliers stated that with the car engine running the combined straight ahead intensity from each pair would be 100,000cd (upper beams), 250,000cd and 500,000cd respectively. The beams from the last two lamps were pencil beams with little spread of light across the road. In order to obtain a fourth upper beam intensity of 50,000 cd it was intended to dim the normal upper beams. This was not possible at the time of the tests and this intensity was obtained by switching out the left 7in diameter unit. A fifth intensity of 5,000 cd was obtained from the lower beams of the normal units. Besides being used as "upper beams" on some runs, the normal lower beams were used whenever any of the upper beams were dipped.

Subjects.

The 12 subjects were males with ages from 25 to 55 years; three were policemen, 2 were professional drivers, and 7 were from five different organisations.

Test Runs.

Each vehicle contained three subjects and an experimenter. The experimenter in one car told the driver if and when to dip, taking his cue from the marker cones; the driver in the other car dipped in response to the first car. Vehicle meeting speeds were about 65km/h and trial runs were performed to accustom subjects to the procedure and range of test conditions. Experimenters at each loop were in radio contact with one another to make sure runs were being made in the correct sequence and to see the cars started at the same time. That the cars did start off at the same time and that each maintained the same speed was verified by noting that the cars passed each other at the mid-point cones placed at the side of the track.

The following 12 test conditions were used:

Total straight ahead intensity - cd.	Distance apart of vehicles on dipping to beams with 5000 cd. straight ahead.		
	No Dipping	180m	360m
5,000	YES	-	-
50,000	YES	YES	-
100,000	YES	YES	YES
250,000	YES	YES	YES
500,000	YES	YES	YES

Three runs for each condition enabled each of six subjects to drive once and be a passenger twice for each condition. A total of 36 randomised runs constituted one series. The time for this series was about two hours with a break halfway. A second series was run the next evening with six different subjects. Both evenings were dry and clear.

Questionnaire.

After each run the subjects answered four questions on a preprinted sheet about their experience during the vehicle meeting, i.e. during the whole time the vehicles were approaching each other. They were asked to rate their experiences on a semantic scale:

(i)	Glare experienced	1. Intolerable	2. Uncomfortable
		3. Noticeable	4. Imperceptible
(ii)	Visibility of track details	1. Good	2. Fair
		3. Poor	4. Bad
(iii)	Difference in road brightness between upper and lower beams	1. Very marked	2. Marked
		3. Slight	4. Unnoticeable
(iv)	Overall assessment of lighting conditions.	1. Acceptable	2. Not acceptable

RESULTS.

The subject responses have been treated as a group, giving 36 responses for each test condition. Those for the 50,000 cd beam intensity have been omitted since the use of only one headlight unit is rather artificial and is different from the other test conditions. Also omitted are the responses to the question on the difference in road brightness between upper and lower beams, since there was doubt as to the subjects interpretation; it is possible that some assessed the lamp brightness rather than road brightness.

The group responses remaining are given in Table 9.1. An increasing number of the superior ratings of comfort from glare, of visibility and of acceptability of the situation, experienced during the vehicle meetings, have been given as the upper beam intensity decreases and the inter car distance on dipping increases. In order to bring this out more clearly the superior ratings of "imperceptible" and "noticeable" glare have been grouped together as "satisfactory" and are shown in Fig. 9.1. Similarly, ratings of "good" and "fair" visibility have been grouped together under "satisfactory" and are shown in Fig. 9.2. The "acceptable" ratings for the overall assessment are shown in Fig. 9.3. In each case the data points appear to be best linked by straight lines and these have been drawn in by eye.

Glare.

If the current lower beams are used throughout a vehicle meeting 97% of responses are in the satisfactory rating. If current upper beams (100,000 cd) are used only 60% of ratings will be satisfactory if the inter car distance on dipping is 180m. In order to elicit 95% of satisfactory ratings it appears, from Fig. 9.1, that the intercar distance must be over 400m. In other words even with the current system the minimum intercar distance on dipping of 180m, specified by regulation, needs to be more than doubled. This is based on the reasonable design objective of a 95% satisfactory rating of restriction of glare, no worse than would be experienced if only lower beams were used throughout the meetings.

The data in Fig. 9.1 suggest that there is no reasonable intercar distance for dipping that will yield a 50%, much less 95%, of satisfactory ratings for the higher intensity beams.

Visibility.

The visibility assessment yielded more satisfactory ratings than did the glare assessment, for any given set of conditions. For an intercar distance of 180 m the current system yielded 85% of satisfactory ratings, with an intercar distance of about 300m this increased to 95%. If lower beams are used throughout a vehicle meeting there is 89% of satisfactory ratings. Thus the use of upper beams can improve visibility assessment over that of lower beams provided the intercar distance on dipping is greater than the specified minimum.

The data in Fig. 9.2 suggest that 50% of satisfactory ratings will be elicited in a system using an upper beam intensity of 250,000cd if the intercar distance on dipping is about 250m. However, it appears again there is no reasonable distance that will give rise to a response of 95% satisfactory ratings.

Overall Assessment.

The data in Fig. 9.3 show the number of acceptable responses to fall in between the numbers of satisfactory responses to the glare and visibility appraisals. At an intercar distance of 180m there are 77 per cent acceptable responses to the current system; an intercar distance of about 350m yields a 95 per cent level of response.

The data suggest that 50 per cent of acceptable ratings will be elicited by a system using an upper beam intensity of 250,000 cd if the intercar distance on dipping is about 400m; no reasonable distance will give rise to 95 per cent of acceptable ratings.

DISCUSSION.

In spite of its brevity, done as it was to provide ready information for a committee, the investigation has yielded positive insights into the glare experienced from upper beams during vehicle meetings. More data would have added to the precision of the analysis but several conclusions can be reached with confidence:

(i) with the <u>current</u> headlighting system a considerable number of responses will rate glare restriction during a vehicle meeting less than satisfactory, if the intercar distance on dipping is the minimum specified by regulation;

(ii) in order to obtain a 95 per cent level of satisfactory glare restriction responses to the <u>current</u> system the minimum intercar distance on dipping prescribed by regulation should be doubled. From data presented in Chapter 7 it is probable that the majority of motorists dip at a greater distance:

the revision of the regulation would impress on the minority the need to dip their lights at a reasonable distance away from oncoming vehicles;

(iii) increases in upper beam intensity over the current level discussed in Chapter 7, will necessitate the beams being dipped directly another vehicle is met, if a 95 per cent satisfactory glare restriction rating is to be maintained.

In coming to these conclusions greatest weight has been given to the glare appraisals. It was noted that drivers tended to make a trade off between glare experienced and visibility when giving an overall assessment of the lighting conditions. The task of glare assessment is probably a more definite one and is more reliably carried out than that of visiblity where no distance measurements are involved. It is probable that drivers do not realise how little visiblity varies ahead as the beam intensity increases; their judgements could be made on the amount of foreground illumination. However, all this is really of little moment since the trade off is insufficient to materially alter the conclusions.

LAMP DETAILS		GLARE EXPERIENCED				MEETING VISIBILITY				OVERALL	
INTENSITY (cd)	DIPPING DISTANCE (m)	INTOL. (1)	UNCOMF. (2)	NOTIC. (3)	IMPERCEPT. (4)	GOOD (1)	FAIR (2)	POOR (3)	BAD (4)	ACCEPT. (1)	UNACC. (2)
500,000	0	21	13	2	0	1	9	11	15	6½	29½
	180	19	12	5	0	3	10½	8½	14	7½	28½
	360	14	17	4	1	3	11	12	10	10	26
		54	42	11	1	7	30½	31½	39	24	84
250,000	0	23	11	2	0	3	10	7	16	6½	29½
	180	13	19	4	0	4	9½	12½	10	12	24
	360	10	16	9	1	2	23	8	3	17	19
		46	46	15	1	9	42½	27½	29	35½	72½
100,000	0	2	22½	8½	3	5	17	11	3	19½	16½
	180	2	15	16	3	9	23½	1½	2	30½	5½
	360	0	4	23½	8½	9	26	1	0	35	1
		4	41½	48	14½	23	66½	13½	5	85	23
5,000	0	0	1	8	27	18	14	4	0	34	2

Note: The "½" in some entries is given because one subject, contrary to instructions, split his assessment between ratings.

Table 9.1. Subject responses to lighting conditions.

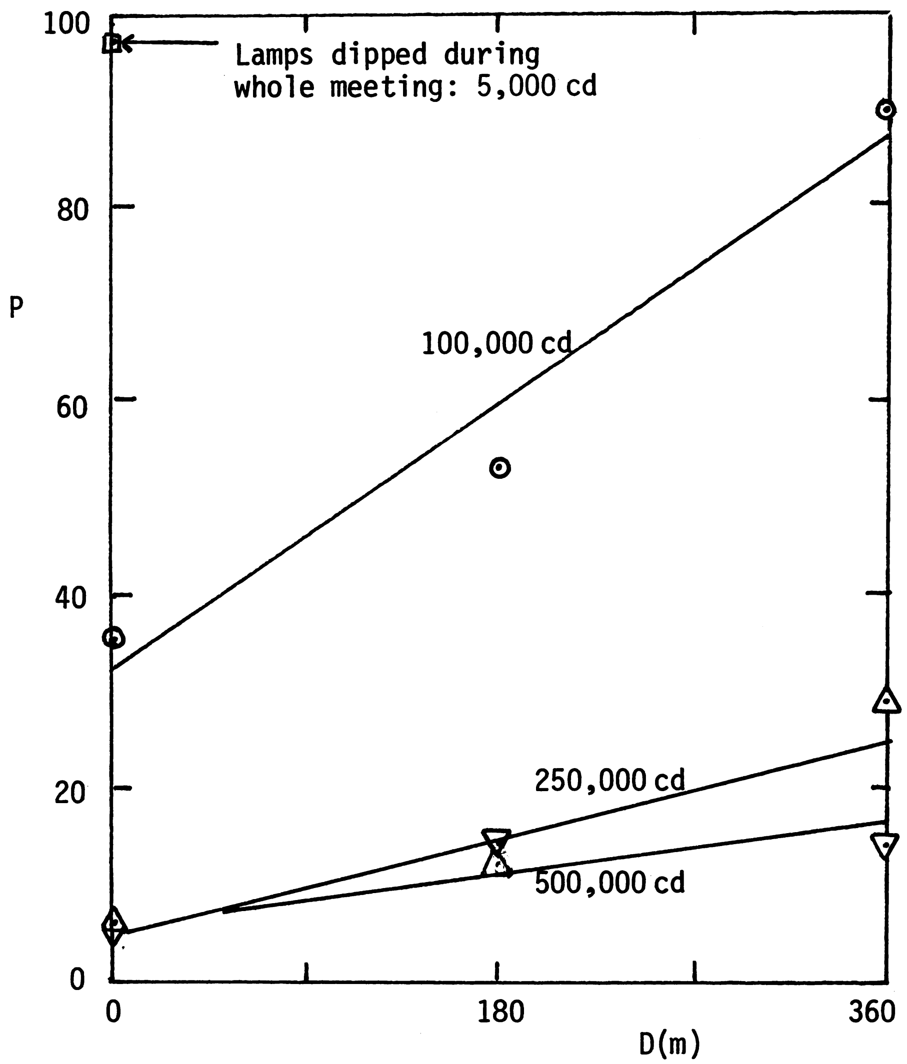


Fig. 9.1. Percentage (P) of satisfactory responses to glare experienced during vehicle meeting for different intercar dipping distances (D) and upper beam intensities.

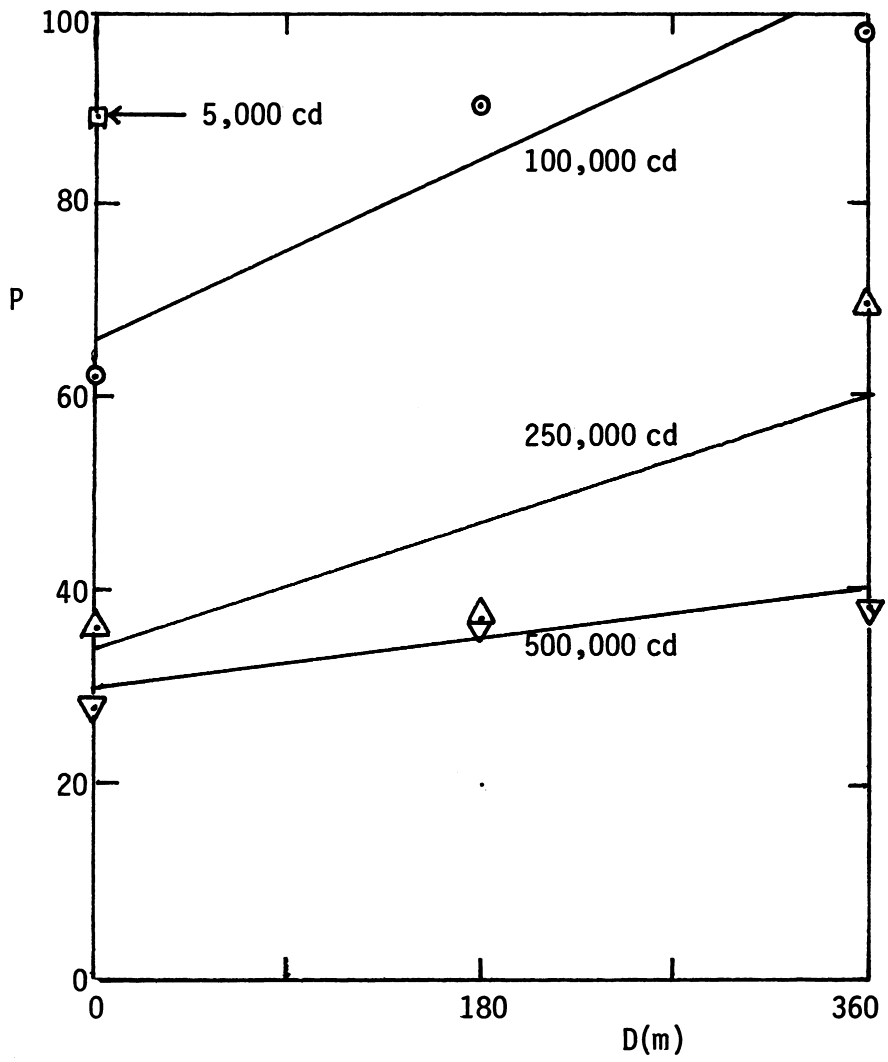


Fig. 9.2. Percentage (P) of satisfactory responses for visibility experienced during vehicle meetings for different intercar dipping distances (D) and upper beam intensities.

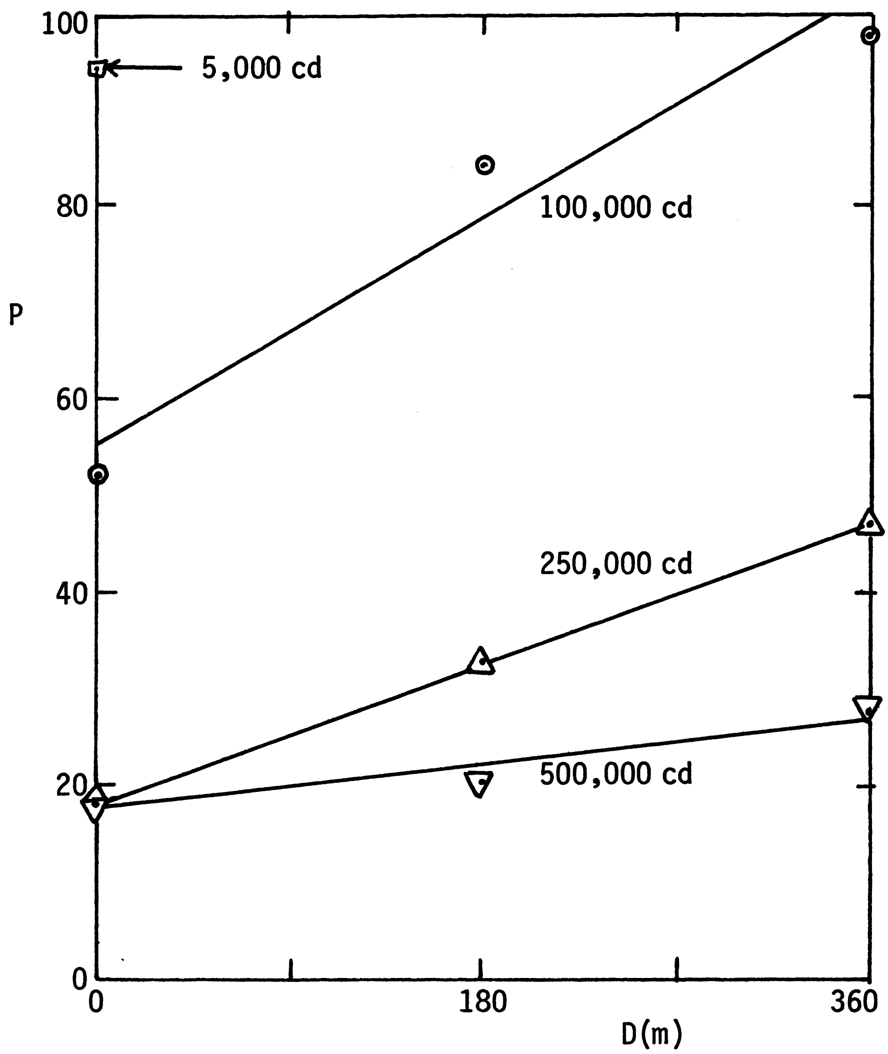


Fig. 9.3. Percentage (P) of acceptable responses for overall assessment of lighting conditions during vehicle meetings for different intercar dipping distances (D) and upper beam intensities.

PART FOUR

THE STREET AND VEHICLE LIGHTING INTERFACE

Light seeking light doth light of light
beguile.

SHAKESPEARE, LOVE'S LABOUR'S LOST

The light that never was on sea or land,
The consecration, and the Poet's dream.

WORDSWORTH, ELEGIAC STANZAS

CHAPTER 10

A REVIEW

THE STREET AND VEHICLE LIGHTING INTERFACE.

Up to now the two lighting modes, street and vehicle lighting have been considered separately. Each suggests itself as the logical means of lighting in specific situations: vehicle headlighting for rural roads and intercity freeways, street lighting for urban traffic routes. However, much overlap occurs especially in the city. Most urban roads have some form of street lighting, the level of which covers a wide range from main traffic route lighting through to footpath lighting. Some lighting and safety experts state that motorists should use the lower beam headlight at all times, regardless of the level of street lighting, in order to ensure uniformity of lamp usage, a conspicuous marker of moving vehicles and the use of headlights on the poorer lighted residential streets. Others, whilst agreeing that it is necessary to supplement footpath lighting, say that headlights are undesirable and even harmful under traffic route lighting because of the glare produced.

This dichotomy is reflected in national practice. In some countries such as the U.S.A. and Australia the use of the lower beam is mandatory on all urban roads whereas in Great Britain and Europe the decision whether to use lower beams or marker lights is left to the motorist. For example, in Great Britain the motorist has to evaluate the legal requirement that headlights must be used at night except on roads lit by a system of street lighting in which the lanterns are not more than 200 yds (183m) apart (10.1), the quasi-legal advice to use lower beam headlights in built up areas unless the street lighting is so good that they are not needed (10.2), the accepted community behaviour of the particular area of the country and lastly, perhaps, a safety campaign aimed at changing these mores (10.3).

All motorists, whether allowed a choice or not, may not be equipped with the optimum form of lighting anyway, since it has been suggested that vehicles should be fitted with a town beam, of intensity between that of the present marker light and lower beam, that would act as a conspicuous marker of moving vehicles without giving rise to glare (10.4, 10.5). The road research group S2 of the Organisation for Economic Co-operation and Development (OECD) has identified the question of the use of headlights in street lighting as one requiring urgent research and international co-operation (10.6).

THE EXTENT OF THE STREET AND VEHICLE LIGHTING INTERFACE.

This aspect of lighting is associated with a large proportion of road use and traffic accidents. For example, from data of Dunn and Hutchings (10.7), it can be deduced that of all the vehicle distance travelled in Great Britain on major and classified roads, roughly one half occurs in urban areas, i.e. on roads likely to have traffic route lighting. Some 50% of this traffic occurs daily during the hours of darkness during February with the figure for August being about 17%.

Christie (10.8) shows that in Great Britain 35% of accidents occur in the hours of darkness. Of this proportion 72% occur on urban roads, i.e. this aspect of lighting is associated with 25% of all road accidents. There is evidence that both casualty accidents and distance travelled at night are increasing, relative to the day values, the former at a greater rate than the latter (10.9).

The limitations of vehicle headlights have been discussed in Chapter 7 and the superiority of street lighting has been shown in Chapter 3 in regard to vision and in Chapter 1 in regard to night accident reduction. However, desirable traffic route lighting is a relatively large public cost and its use can only be justified on a cost benefit basis where traffic volumes are sufficiently large. Thus, vehicle lighting must remain the primary mode of lighting even on many miles of urban roads. There remains the problem of how best to organise the street and vehicle lighting interface.

Indications come from the literature on whether any departure from present practice is necessary and in what manner. Information is available on the requirements of a vehicle marker light for use in traffic route lighting, the effect of lower beams on vision and accidents in lighted streets and on the design of a town beam.

THE REQUIREMENTS OF A VEHICLE MARKER LIGHT.

Both motorists and pedestrians require information about the position and relative velocities of other road users together with the road layout and any hazards on it. Such information may come from the vehicle itself, by its change in apparent size during movement, for which two widely separated marker lights can give a good clue. Other information comes from the position of the object under observation relative to the carriageway and its surrounds. Detail, particularly of pedestrians, can give clues as to subsequent gross changes in velocity. Thus the nature of the information is both formal, such as obligatory vehicle lighting, and informal, such as the background of the road, illuminated by street lighting.

If the basic psycho-physical data of Blackwell (10.10) is examined it can be seen that for an object to be detected, its luminous contrast with its surrounds needs to be only a few percent for surround luminances met within lighted streets. However, these data apply to laboratory conditions and a 50% probability of seeing. If certainty of seeing is required under practical conditions field factors must be applied to the basic data. These field factors have been the subject of a number of investigations and by using a realistic value of 10 the lighting requirement for vehicle front marker lights may be indicated for the following conditions:

Background luminance: $1\ cd/m^2$

Distance ahead : 100m

Diameter of markers : 40mm or 175mm (the approximate size of present day marker and headlights).

The required contrasts for the two sizes of markers are then 20 and 1 respectively yielding intensity values of 0.025cd for a marker about the size of present side lights and 0.05cd for one the size of the present standard headlamp. On this basis the present international standard (10.11) intensity requirement of 4cd min. along the axis of a marker light is quite adequate and the 500cd or so obtained from a lower beam headlight is a very excessive value.

Several factors can increase the value of this simple requirement. If the observer is not looking directly towards the marker the intensity must be raised if his attention is to be attracted to it. From investigations into traffic signal lantern intensity requirements, the writer found that the factor was $\theta^{4/3}$, where θ is the angle between the direction of the signal and the line of sight (10.12). For $\theta = 10^{\circ}$ the factor will be about 20 and if $\theta = 20^{\circ}$ the factor rises to about 50. The necessary contrast increases with the observer age. Whilst the contrast multiplier remains at one up to about forty years, it increases to two by sixty years and to three by seventy years (10.13). The necessary contrast will be increased if there are bright lights in the field of view. Light from these glare sources will be scattered in the eye and produce a luminous veil which will raise the effective luminous level of the field of view. The luminance of this veil can be calculated from the value of lighting parameters pertaining to the situation, and it has been shown that the light from a stream of lower beam headlights can raise effective background luminance to three or more times its actual value (10.14). The necessary eontrast and hence the intensity of any marker light in this traffic stream will be increased accordingly. Again old people will suffer more from the effects of glare than young people; the writer has shown that calculated veiling luminance of a sixty year old observer would be three times that of a twenty year old (10.15).

Thus, basic data on visual processes suggest that to be adequate marker lights on vehicles still do not need to be very bright. Even for old people not looking directly at lights a few candelas would suffice, which is much less than the intensity of a lower beam. However, a uniform system is necessary since low intensity markers could be lost among lower beam headlights.

THE EFFECT OF LOWER BEAMS ON VISION IN LIGHTED ROADS.

The use of lower beams under traffic route lighting may not only mask marker lights but can lower visibility of objects and detail in the whole visual field. Non luminous objects such as pedestrians, in general, have less contrast with their surrounds than will luminous objects, and an observer's ability to see them will be more impaired by disability glare. The glare effect, discussed in Chapter 2, depends on the observer's line of sight relative to the direction of the oncoming lights. As the number of vehicles increases and as the driver looks across the road to the off-side kerb the glare arising from the vehicle lighting can exceed that from the street lighting by a factor of 10 or more (10.14). Turner (10.14) analysed the effect of lower beams on the visibility of objects on the carriageway and concluded they have an adverse effect. The Dutch Safety Research Organisation (SWOV) (10. 5) concluded that the European lower beam or E beam, which gives less glare than the British type, causes an unacceptable degree of glare which adversely effects seeing.

Thus the use of lower beams in good street lighting could veil objects and detail in the road scene. For instance, pedestrians are not always viewed under the best circumstances against the relatively bright road surface on the near side of the vehicle. They often have to be viewed coming from the off-side and against the relatively dark surrounds to the road. Jacobs (10.16), from films taken in lighted streets, deduced that on nearly 90% of occasions pedestrians were first seen against the surrounds to the road carriageway and in 28% of cases pedestrains were crossing from right to left with opposing vehicles present. As this study was carried out in London where the vast majority of car drivers use marker lights, the ability to see these pedestrians was not impaired. Ability could have been impaired, however, in a city where lower beam headlights were compulsory.

Faulkner and Older (10.17) carried out a field experiment to test the effect of various types of headlighting on seeing by drivers in an experimental street lighting installation. They found that the distances at which a target was detected and recognised were shorter when using the normal British lower beam than when using marker lights, for some object positions along the centre of road adjacent to or beyond the oncoming car. They also made a less extensive comparison of the effects of the British lower beam and a town beam (the lower beam reduced to about 1/10 intensity) on the visibility of objects on the near side or off-side of the road as well as along the centre. As before, visibility along the centre was adversely affected by the use of lower beams. Along the nearside detection distances were the same with the two beam types; however, recognition distances were less with the lower beams in use. For the off-side position there was a catastrophic fall in visibility when the object was close to the oncoming car and lower beams were used.

EFFECT OF LIGHTING ON CROSSING THE ROAD.

SWOV have observed the performance of young pedestrians (25 - 35 years) crossing the road under different experimental lighting conditions. It was found that the decision whether to cross the road was not related to the intensity of the approaching cars' lights (the values used were 0.3cd - 300cd) and the level of street lighting. However, the results suggested that the closeness of the highest intensity lights is overestimated. They concluded that any influence by the intensity of vehicles' lights on decisions to cross the road is likely to result from the simultaneous presence of vehicles carrying lights of very different intensities and from a masking effect of lower beam headlights on marker lights. From his observations on pedestrian behaviour in lighted roads, Jacobs concluded that vehicle lighting had no signficant effect on how far ahead of the car or how quickly pedestrians crossed the road or on the proportion of these stepping into the road who actually crossed in front of the car.

COMFORT ON URBAN ROADS.

Besides the visibility aspect of vision there is also the comfort aspect. Vehicle headlighting is an attempt to make a compromise between producing light to see by and keeping glare, both of the disability and discomfort kinds, to a tolerable level. It is known that visibility distances can be greater if drivers use their high beams throughout a vehicle meeting situation. Headlights are dipped because the discomfort of high beams is intolerable. A great deal of research has gone into relating visual comfort to street lighting parameters (10.18) but without the presence of vehicle lighting. Street lighting engineers have placed increasing merit on the limitation of the release of light from street lighting lanterns, in those directions that will give rise to glare, in order to obtain a comfortable visual environment. It is often claimed that a comfortable environment, besides being intrinsically desirable, is an efficient environment but it is difficult to justify this formally.

While lower beam headlights give out similar intensities to street lighting lanterns in those regions of the beam which are likely to contribute to discomfort, they are likely to give rise to a greater degree of discomfort since there are often more in the field of view and they are closer to the line of sight.

A TOWN BEAM.

In order to provide an improved marker light of a moving vehicle without causing either discomfort or disability glare both SWOV (10. 5) and Jehu (10.4) have proposed the use of a town driving beam of intensity between the present headlight and marker lights. Jehu has suggested that the present headlight be used dimmed to about 1/10th of its intensity when proceeding along in traffic route lighting. The objection to this system is that the motorist is faced with another decision to make and another switch to actuate. However, Sabey (10.19) has described a photoelectric device which senses the level of street lighting and sets the intensity of the headlights accordingly. It is completely automatic and has a fast response time to the sudden drops in level of lighting that would occur in going from traffic route installations into residential footpath lighting.

THE EFFECT OF VEHICLE LIGHTS ON URBAN ACCIDENTS.

The real effect of this problem on system efficiency should be reflected in accident statistics. The installation of good street lighting has the same general large beneficial effects regardless whether traffic uses lower beams, as in the U.S.A. and Australia or marker lights as in Great Britain (10.20, 10.21, 10.22). Thus the effects of vehicle lighting on accidents in areas of traffic route lighting, must be small. Several studies have been made to elucidate this point. A safety campaign was run in Birmingham during the winter 1962 - 1963 to persuade drivers to use lower beams in all lighted streets instead of side lights only. The campaign was repeated in the winter 1963 - 1964 and in other cities. The casualty accident data has been analysed by comparing campaign cities with similar non-campaign cities (10.3). The indications are that in Birmingham there was a reduction in pedestrian accidents, but an increase in non-pedestrian accidents. In the other campaign cities all accidents appeared to increase. The report notes that during the first campaign in Birmingham the increased useage of lower beams had a beneficial effect on safety in poorly lit streets. However, the effect in well lit streets was less beneficial and possibly harmful. The use of control areas in the analysis reduce somewhat the effect of extraneous influences, but it is interesting to note that Birmingham was carrying out a large programme of relighting both traffic and residential roads, lighting which could be expected to have had a beneficial effect on pedestrian safety.

A campaign for purely scientific purposes was organised in Holland (10.5). The campaign, in Utrecht during the winter of 1964 - 1965, raised the useage of lower beams there from 35% to 80% (useage in Birmingham rose to 50%). Accident patterns were compared with three control cities, one with an already similar high useage of lower beams and two with very low useages. It was found that campaign had no demonstrable influence on road safety in Utrecht. There were indications that as the percentage of lower beam headlights increases there is less accident risk to these drivers and a greater risk for marker light drivers. In two of the control cities and in Utrecht it was found that the risk of accident involvement was less than would be expected from their proportion in the traffic. In one city the number of accidents involving vehicles with lower beams and pedestrians was smaller than would be expected from the proportion of dipped headlight equipped vehicles. The report concludes that the study points to the need for uniform lighting system so that marker lights are not masked by lower beams and that present marker lights are inadequate under some circumstances.

Where the motorist has a choice, the lighting mode used is likely to be variable. Cooper (10.23) showed in seven cities surveyed that the useage of lower beams varied between 39% and 77% in poor street lighting, between 7% and 46% in medium street lighting and between 5% and 48% in good street lighting. In six cities an increasing percentage of drivers used their headlights, as the street lighting became poorer. However, in Birmingham, which had been subjected to the campaigns encouraging headlamp useage at all times after dark, a constant level of useage, of about 50% was recorded.

FUTURE TRENDS IN HEADLIGHTING.

Whilst traffic route lighting will be extended and refined it is unlikely that lighting levels will be increased dramatically to the point where the lower beam becomes purely a conspicuous marker light without any overtones of glare. The level of street lighting is dictated largely by what the community is prepared to pay and it seems illogical to increase the present level, which is effectively paid for by the savings in accidents.

On the other hand, vehicle lighting is undergoing a period of extensive development. The present British lower beam is being displaced by the European sharp cut-off beam. In theory the intensities giving rise to glare from this beam should only be about 1/4 those from the British beam. Although the SWOV report suggested from the results of an analytical study that even this glare level could adversely affect vision in a lighted street, Faulkner and Older could not detect this effect in their field trials.

However, as shown in Chapter 7, headlamp performance is very susceptible to aiming tolerances, and loading of vehicles. Yerrell (10.24) has made a survey of the glaring intensities experienced at sites on

British and Continental roads. He found that the mean glaring intensities experienced in three Continental countries were more than 1/2, rather than 1/4, those experienced in Great Britain. The difference in glare experienced in another Continental country and Great Britain was negligible.

In addition the quartz halogen light source is being commercially exploited and sharp cut-off beams are coming onto the market with higher intensities in directions close to the horizontal. Thus, the glaring intensities from European lamps can be expected to increase when this type of source comes into common use. Harris (10.25) has shown theoretically that as the beam cut-off increases, the standard of aiming must be improved in order to restrict the proportion of glaring lamps to given value. With modern car suspensions, the amount of upward tilt of headlamps is substantial when design loads are carried. Hignett (10.26) has shown that the glare from a small car fitted with European meeting beams can increase to a level of intolerable glare through misaim on loading.

DISCUSSION.

This review suggests, from basic visual considerations and field trials, that the use of lower beam headlights can impair vision in streets lit to traffic route standard. The accident data suggest a small but adverse effect on system efficiency. This indicates that it is undesirable to require the blanket use of lower beams in order to secure their use on unlit or poorly lit streets. On the otherhand, the general consensus of opinion appears to be that the present marker lights are inadequate, although the data suggest that intensities as high as those from the lower beam are unnecessary.

However, in Chapters 4 and 6 it was shown that whilst lit traffic routes can have a high carriageway luminance, their immediate surrounds may be dark. It has been argued that these surrounds need to be well lit also, since many objects, such as pedestrians, are viewed against them.

Since the lower beam is asymmetric towards the kerb side, it could well be thought of as overcoming this deficiency of streetlighting. This point is systematically analysed in the next chapter, using the methodology developed in Chapter 2.

There has been little systematic work to establish the luminous requirements of a light that is an adequately conspicuous but glare free marker. Chapter 12 describes a field trial to test the response of road users to a town light, devised from the conventional lower beam headlight. Chapter 13 describes a series of field tests to establish the optimum size and intensity of the town light.

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CHAPTER 11

VISUAL PERFORMANCE IN STREETLIGHTING: THE INFLUENCE OF VEHICLE HEADLIGHTING

INTRODUCTION.

Streetlighting is the primary mode of lighting urban traffic routes, generally giving conditions for good visibility. In the design of this lighting, engineers place much store in the restriction of glare to achieve this and, on the otherhand, vehicle headlighting has limitations, one of which is that of relatively poor glare restriction. Notwithstanding, vehicle headlights on lower beam are used in street lighting. It has been pointed out in the previous chapter that the glare from vehicle headlighting can inhibit visibility on streets with fixed lighting.

There is one aspect where street lighting does not always perform satisfactorily, that is in showing up objects along the road edge when viewed against dark surrounds. It may be thought that in this situation vehicle lighting helps, in that the lower beam is directed along the near side and will illuminate these objects. This proposition is explored in this chapter, using the methods already explained and used in Chapters 2 and 6.

SITUATION DESCRIPTION.

The situation to be considered will be that where two vehicles are meeting, each using lower beams of the same design on a straight road also lit by street lights. In viewing their left hand pavement edges, the geometrical relationship of the drivers to their vehicles, the road and objects on the edge of the pavement are as shown in Fig. 11.1. The large range of relative positions possible has been restricted by using the following values:

distance apart of vehicles (d_v)	50ft- 750ft(15 - 230m)
lateral separation of vehicles (S_v)	10ft, 15ft, 20ft(3 - 6m)
distance ahead of the object (d_o)	150ft, 300ft, 450ft(45 - 135m)
lateral separation of vehicle and object (S_o)	20ft— $\frac{S_v}{2}$
lateral separation of object and background (S_b)	10ft(3m)

The values of d_o require comment. The concept of revealing power does not include the notion of visibility distance, but is concerned rather with whether backgrounds at indeterminate distances can reveal large objects viewed against them. However, if their revealing power is inadequate, there is concern as to whether objects can be seen at a safe distance away. A safe distance is usually taken as being the stopping distance required at a given vehicle speed. Safety literature suggests that under ideal conditions the stopping distance from 35 m/h (now 60 km/h), the urban speed limit, will be about 150ft(45m). However, there will be a distribution of speeds, driver reaction times and braking efficiencies and some stopping distances will be much higher.

Grime (11.1) suggests that in order to take avoiding action, a seeing distance of at least twice the vehicle velocity, in feet, is necessary. Thus, it is reasonable for a motorist to expect to see objects about 300ft (90m) away so as to avoid violent changes in lateral and longitudinal velocity.

LIGHTING PARAMETERS.

The luminances of the backgrounds, due to street lighting, have been measured and found to be in the range of 0.01ftL to 0.5ftL (0.03 - 1.7cd/m^2), as referred to in Chapter 4. The light from vehicle headlights may raise the background luminance and this can be calculated. The visibility of a particular object viewed against a background of given luminance will be determined solely by the illumination falling on it and the glare. The values from the two sources of lighting are additive and individually they are as follows:

Street Lighting.

It was shown in Chapter 6 (Fig. 6.2) that both the illumination and glare from an installation vary cyclically. It is permissible to use average values as the variation is not great. These values were derived from photometric measurements and are those used in Chapter 6, viz:

illuminance	0.36 lm/sqft (4.0 lux)
disability glare (veiling luminance)	0.04ft L (0.14 cd/m^2)

Vehicle Lighting.

The contributions made by the lower beams to objects illumination and glare have been calculated. Mean values cannot be used because of the great variation. As will be seen below, the glare values will vary over a range of 100:1 depending on the relative positions of the vehicles and the line of sight and it is thus more convenient to calculate these than to obtain them by direct measurement. Similarly, the illumination on the object will be related to the inverse square of the distance. The vehicles have been assumed to be fitted with the British-made 7 in diameter two lamp all sealed system. This is the type of lighting fitted to the large majority of currently sold vehicles. Fig. 11.2 shows the measured distribution of directional intensisites from one such lamp, conforming to the photometric requirements of B.S.A.U. 40, Part 4, which are similar to those of S.A.E. J579a. An increasing number of vehicles in Australia are being fitted with sharp cut-off E beams. As discussed in Chapter 7, glare and illumination will be less than with the BS/SAE beam and the resultant visibility will be much the same in the two cases.

Illumination.

Since it has been assumed that the object centre height is the same as the headlamps, the average illuminating intensities will, on the beam diagram, be along the line 0^{o} up/down, 0^{o}left to left over the range of 1^{o} L to 6^{o} L. The contours are very flat over this region, therefore, there will be little variation in the directional illuminating intensities for the range of situations to be studied. For each correctly aimed lamp a value of directional intensity of 5000 cd has been assumed. The illuminance of objects is then, very nearly,

$$\frac{10,000}{d_o^{2}} \text{ lm/sq.ft.}$$

These values are given in Table 11.1

Glare.

The path of the driver's eyes relative to the oncoming lights can be drawn on the beam diagram by plotting a pair of values of $\emptyset_H$ and $\emptyset_V$ for a particular d_V and joining this point to the origin. Each lamp and value of S_V must be treated separately. Values of glare intensity directed towards the driver's eyes can be read off for particular values of $\emptyset_H$ i.e for particular values of d_V, the vehicle separation. The glare illumination is obtained, very nearly, by dividing by d_V^{2}. Finally, the disability glare is found from equation 2.2, where θ is taken as, very nearly, $\emptyset_H + \alpha_H$. Values of disability glare are given in Table 11.2. For ease of analysis, the multiple values have been reduced to single representative values for each situation and these are given in Table 11.3.

Misaim of Lamps.

The data presented so far are for correctly aimed and maintained lamps on straight level roads. Whilst it can be largely assumed that street lighting lanterns are properly installed and maintained, the same cannot be assumed about vehicle headlamps. It was shown in Chapter 7 that vehicle headlighting performance is very dependent on the standard of aim. The standard deviation of aim for lamps mounted on Australian cars is 1.1^{o} vertically and 1.3^{o} horizontally. Passengers in the rear of a car can tilt the lamp up by up to 2^{o}. Deviation from the ideal condition can also arise from voltage variation, dirt, deterioration, production tolerances, road curvature and grade. These can be thought of in terms of lamp misaim which will affect glare and illumination values. In order to describe the effect on visibility of lamp misaim lighting parameters have been calculated for misaims of $\pm\frac{1}{2}^{o}$ and $\pm 1^{o}$ and these are shown in Table 11.1 and 11.3.

Traffic Stream.

The general situation may be extended to a single vehicle meeting a traffic stream. It is assumed that only the light from the single vehicle contributes to the illumination of object and background. However, the glare will be increased as shown in Table 11.3. These values were based on correctly aimed lamps, a vehicle headway of 60ft(18m) and only the off side headlamp being visible for vehicles 200 ft(60m) away or more. A vehicle gap of two headways was assumed at d_o = 150ft(45m) and d_o = 450ft(135m) for each situation respectively, which a pedestrian might be expected to use in order to cross the road.

Luminance of the Backgrounds.

The headlights will illuminate the backgrounds to the object as well as the object. This illuminance was found to be significant only when the object is close to the approaching vehicle, as shown in Table 11.4. The additional luminance of the background over that produced by the street lighting was calculated from the illuminance estimated from the isocandela diagram, and the reflecting properties of surround materials given in Table 11.5, which are based on field measurements.

RESULTS.

Object on Pavement Edge, Viewed Directly.

In Fig. 11.3, the necessary luminance factors required for objects to be adequately seen have been plotted against background luminance. For the object positions d_o = 450ft and d_o = 300ft the increases in glare and illuminance have both contributed to poorer silhouette seeing. Increases in reverse silhouette seeing, made potentially possible by increased object illumination, have been largely offset by increases in glare. The further away the object the greater the glare experienced (for d_o = 450ft a single vehicle produces the same glare as is produced by a whole street lighting installation) and the lower the object illuminance. Thus for distances greater than 450ft the presence of vehicle lighting has an entirely adverse effect. However, at short distances, d_o = 150ft, reverse silhouette seeing is considerably enhanced but at the expense of silhouette seeing.

The data in Fig. 11.3 has been used to compute the revealing power of the backgrounds, which are shown in Fig. 11.4. Since the pedestrian has clothing which is more likely to be dark, the general effect of vehicle lighting on the revealing power (RP) of backgrounds against which objects at 450ft and 300ft away will be viewed is adverse. For low values of luminance (L = 0.01 - 0.03ft L) the values of RP are not very different whereas for values of luminance greater than 0.03ft L the values of RP are less than with those for street lighting only, especially in the range L = 0.04 - 0.07ftL. The minimum RP value has been depressed by 50 per cent. For d_o = 150ft the RP values have increased substantially for the low values of L, but have decreased for the higher values of L. The minimum RP value has been increased by 70 per cent.

The curve for d_o = 150ft as shown in Fig. 11.4 cannot strictly be compared with the one for street lighting alone. Whereas the illuminance from the headlights will not alter materially the background luminance for situations d_o = 450ft and 300ft, reference to Tables 11.4 and 11.5 shows that this is not so for situation d_o = 150ft. Thus, for example, the RP values for L = 0.2ftL and L = 0.02ft on the d_o = 150ft curve should be compared with say, the RP values for L = 0.15ftL and L = 0.01ftL on the street lighting only curve. Thus both the adverse and beneficial effects are not as large as might be indicated in Fig. 11.4 except in the region L = 0.04 - 0.07ftL where the curves are steep.

Effect of the Lateral Separation of the Vehicles.

As the lateral separation of the vehicles increases, θ increases and hence the disability glare will decrease. Fig. 11.5 shows that this decrease in disability glare reduces the adverse effects of vehicle lighting without further enhancing the beneficial effects. For a two-vehicle meeting on a 40ft carriageway with both vehicles travelling along the centre of their respective lanes, there would probably be a beneficial effect on visibility using vehicle lighting for the situation d_o = 150ft. For d_o = 450ft there would probably be a marked adverse effect only for visibility against backgrounds of L = 0.04 - 0.05ft L.

Effect of a Stream of Vehicles.

The situation considered above involved the meeting of one approaching vehicle. If a stream of vehicles is met the glare experienced will rise. Its effect on the necessary values of object luminance factors are shown in Fig. 11.6. At d_o = 450ft both silhouette and reverse silhouette seeing are severely affected. At d_o = 150ft seeing of objects against backgrounds of high luminance is hardly affected but silhouette seeing in the range L = 0.04 - 0.07ftL is further reduced and some of the increases of reverse silhouette seeing for low values of L will be nullified.

Effect of Misaimed Lamps.

The results presented above have been for those situations involving vehicles fitted with correctly aimed lamps. Fig. 11.6 shows how the necessary values of object luminance factors are influenced by lamp misaim. The worst situations have been explored. The single approaching vehicle lights are tilted up so producing increased glare, and the lights of the observer's vehicle are tilted down. At d_o = 450ft the effect of increasing glare is pronounced, the pairs of curves separate as the misaim increases, and both silhouette and reverse silhouette seeing are further adversely affected.

At d_o = 150ft it is the fall in object illuminance that has most affect, the pairs of curves involving vehicle lighting move towards the position of the curves for street lighting only. With increasing misaim, the gain in reverse silhouette seeing afforded by the use of vehicle lighting, is increasingly nullified. For a misaim of 1^o down seeing is the same as with no vehicle lighting.

If it is assumed that only the lights of the approaching vehicle are misaimed the results will lie between those for the all correctly aimed lamps and those for the traffic stream. For the situation d_o = 450ft, the position is still that both direct and reverse silhouette seeing will be adversely affected. At d_o = 150ft the increased glare will affect silhouette seeing in the range L = 0.04 - 0.07ftL and reverse silhouette seeing for low values of L. The magnitude of the effect will depend on the amount of misaim and will have a limiting value similar to that obtained for the traffic stream situation.

Effect of Looking Straight Ahead.

So far in the analysis, it has been assumed that the observer is looking in the direction of the object. However, in scanning the field of view, the observer will at times be looking in directions such as straight ahead when the angle (θ) between this direction and the direction of the oncoming vehicle lights will be small. The disability glare will be greater in these cases than those involving looking directly at the objects. Thus the glare from oncoming vehicles may be expected to reduce the alerting capacity of objects appearing in the peripheral field. For situations d_o = 150ft to 450ft and the observer looking straight ahead the object will be eccentric to the line of sight by 1^o to 6^o. It is known that equation 2.2 will apply for these conditions (11.2).

Since, as in Fig. 11.1, $\theta = \phi_H$ the value of disability glare will be markedly dependent on both d_V and s_V. As an example the disability glare from correctly aimed lamps for s_V = 15ft is given in Table 11.2. The effect of this glare on the visibility of an object 450ft ahead in the early stages of a meeting, can by reference to Table 11.3, be likened to the effect produced by lamps tilted up 1^o (S_V = 10ft, d_o = 450ft). In the later stages of meeting the effect can be likened to that of correctly aimed lamps (S_V = 10ft, d_o = 450ft). From Fig. 11.6 it can be seen visibility is more adversely affected than if the object was viewed directly.

Similarly the effect on an object 150ft ahead, in the early stages of a meeting can be likened to that of a stream of vehicles (S_V = 10ft, d_o = 150ft) and in the later stages to that of lamps tilted up $\frac{1}{2}^o$. Reference to Fig. 11.6 shows that in the early stages of meeting, visibility is worse than if the object is viewed directly. Much of the improvement gained for low values of L is nullified. The adverse effect will be greater as S_V decreases and less as S_V increases.

DISCUSSION.

The presence of vehicle lighting (lower beams) in street lighting installations generally adversely effects visibility, especially for the background luminance range L = 0.03 - 0.07ft (0.1 - 0.25cd/m^2), because of the additional glare. It is only when a driver is looking directly at an object 150 ft(45m) away during the meeting with a single vehicle that the additional illumination provided by vehicle lighting is of any use. Reverse silhouette seeing is enhanced for backgrounds of luminance L = 0.01-0.035ft L(0.03 - 0.12 cd/m^2) and the minimum RP is raised from 15 per cent to nearly 30 per cent. Possible loss of silhouette seeing is largely nullified because of the increase in background luminance.

The effects of misaim of lamps and multiple vehicle meetings will make inroads into this gain in visibility and so visibility in directions further down the road will be further worsened.

It has been shown by Turner (11.3) that visibility of objects viewed against the pavement is adversely affected by vehicle lighting. The pedestrian after being viewed against the road surrounds will, in crossing the road, be viewed by the oncoming traffic against the pavement. It would therefore appear that vehicle lighting does have, overall, severe adverse affects on the visibility potential of street lighting installations designed to the requirements of the Australian Code of Practice.

In Chapter 6, the possibilities of improving visibility in situations with dark surrounds by modification to street lighting practice was discussed. It was shown that doubling the wattage of lamps used in SCO lanterns with good glare restriction improved visibility. The improvement is as much as in the one case where vehicle lighting is beneficial. This improvement however is maintained <u>throughout the installation</u> along the pavement edge and without adverse effects on visibility of objects viewed against the pavement.

REFERENCES.

11.1 Grime, G., The performance of headlamp meeting beams, Proc. Inst. Mech. Engrs. (Auto Div.), Vol. 3, 108, 1954 -55 .

11.2 Adrian, W., The influence of disturbing lights on the extrafoveal perception of the human eye, Lichttechnik, Vol 13, Nos. 9, 10 and 11, 1961.

11.3 Turner, H. J., The interaction between fixed lighting and vehicle headlights, Aust. Rd Res., Vol. 2, No. 3, 1965.

Distance of Object Along Pavement (ft)	Illumination (lm/sq. ft)			
	Street lighting	Vehicle lighting		
		Correctly aimed	Lamps down 1/2°	Lamps down 1°
150	0.36	0.44	0.22	0.09
300	0.36	0.11	—	—
450	0.36	0.05	0.025	0.01

Table 11.1. Illumination falling on object, used in calculations.

d_v (ft)	$d_o = 450$ ft			$d_o = 300$ ft			$d_o = 150$ ft			$d_o = \infty$
	$s_v = 10$ ft	$s_v = 15$ ft	$s_v = 20$ ft	$s_v = 10$ ft	$s_v = 15$ ft	$s_v = 20$ ft	$s_v = 10$ ft	$s_v = 15$ ft	$s_v = 20$ ft	$s_v = 15$ ft
50	0.029	0.011	0.003	0.024	0.010	0.003	0.015	0.007	0.002	0.013
100	0.041	0.015	0.008	0.032	0.013	0.007	0.017	0.008	0.005	0.024
150	0.043	0.022	0.012	0.030	0.017	0.010	0.013	0.009	0.007	0.040
200	0.039	0.021	0.014	0.026	0.016	0.011	0.011	0.008	0.007	0.047
300	0.036	0.021	0.014	0.022	0.014	0.010	0.008	0.006	0.005	0.061
500	0.024	0.019	0.014	0.014	0.012	0.010	0.005	0.004	0.004	0.094
750	0.017	0.013	0.012	0.009	0.008	0.008	0.003	0.003	0.003	0.103

d_v = distance apart of vehicles
s_v = lateral sparation of vehicles
d_o = distance of object along pavement edge

Table 11.2. Disability glare (ftL) from headlights in two vehicle meetings for some situations.

d_o (ft)	s_v (ft)	Street Lighting	Disability Glare (ft-L) Vehicle Lighting			
			Correctly aimed	Lamps up 1/2°	Lamps up 1°	Stream of vehicles
450	10	0.04	0.04	0.055	0.11	0.29
	15	0.04	0.02			
	20	0.04	0.015			
300	10	0.04	0.03			
	15	0.04	0.015			
	20	0.04	0.01			
150	10	0.04	0.015	0.02	0.027	0.067
	20	0.04	0.007			

Table 11.3. Disability glare values used in calculations.

Distance Away of Object d_o (ft)	Lateral Separation of Vehicle and Object $= 20 - \frac{s_v}{2}$ (ft)	Distance Away of Background (ft)	Background Illumination* (lm/sq ft)
150	15	250	0.16
	12.5	270	0.14
	10	300	0.11
300	12.5	540	0.035
450	12.5	810	0.015

* Measured on plane perpendicular to the line joining the background to the midpoint between the lamps

Table 11.4. Illumination falling on backgrounds from headlights.

Type of Background		Luminance Per Unit Illumination†	Luminance When Illuminated From 150 ft ($s_v = 15$ ft) (ft — L)
Foliage 8 sites	mean	0.033	0.005
	min.	0.013	
	max.	0.054	
Brick 6 sites	mean	0.15	0.024
	min.	0.066	
	max.	0.20	
Wood 3 sites	mean	0.26	0.042
White painted surface	max.	0.33	0.052

* Measured in the field with a Pritchard Spectrophotometer and a known illumination, simulating the set up shown in *Fig.* 11.1. Laboratory tests on a limited range of background types showed that the reflecting properties were largely independent of α_H.

† Measured on plane perpendicular to the line joining the background to the midpoint between the lamps. in ftL per lm/ft^2.

Table 11.5. Reflecting properties of backgrounds and their luminance when illuminated by headlights.

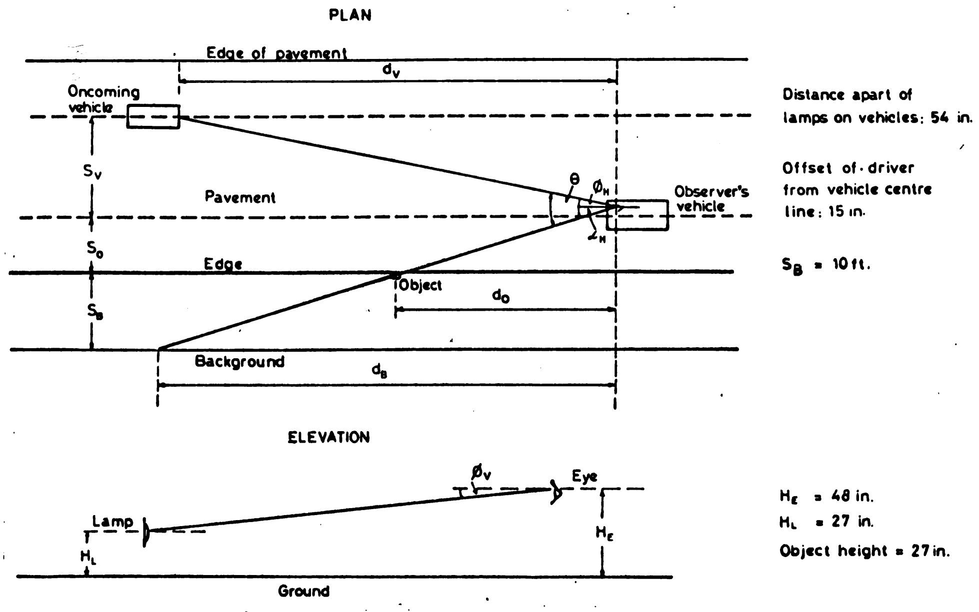


Fig. 11.1. Layout of important quantities in a vehicle meeting necessary to calculate glare and illuminance values.

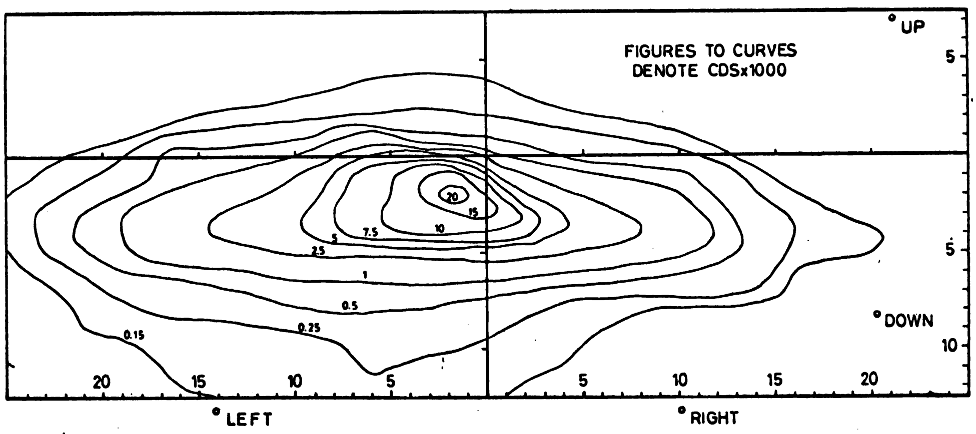


Fig. 11.2. Lower beam diagram for one 12V 60W/45W 7 in. all-sealed headlamp run at 12.8V.

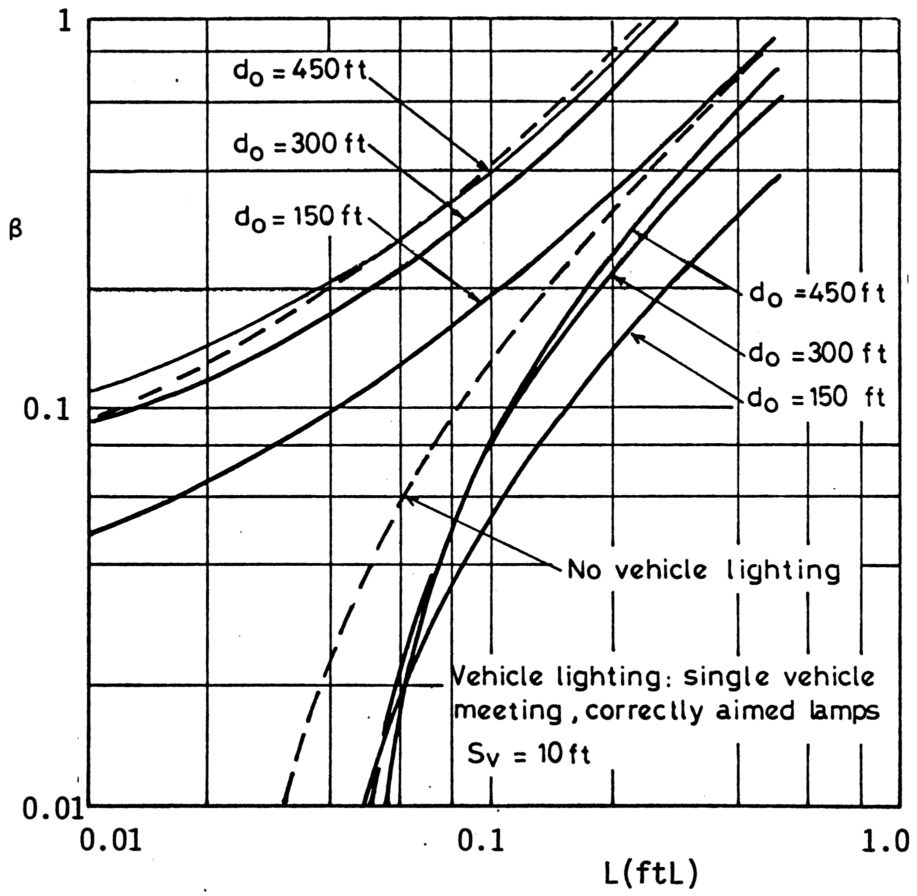


Fig. 11.3. Necessary luminance factor (β) for objects to be adequately seen against a streetlighting background of luminance L, with and without headlights.

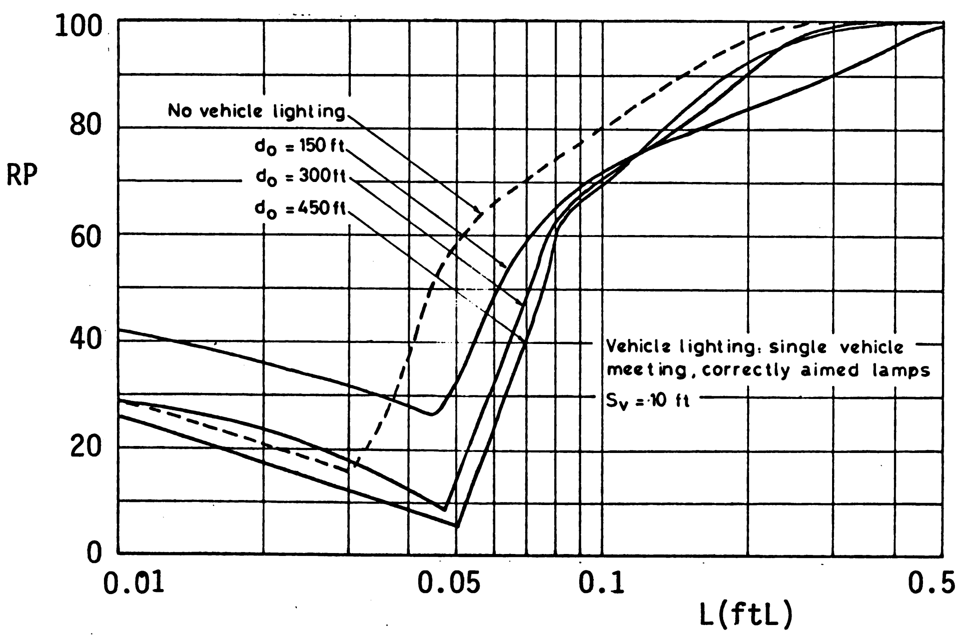


Fig. 11.4. Revealing power (RP) in street lighting with and without vehicle lighting.

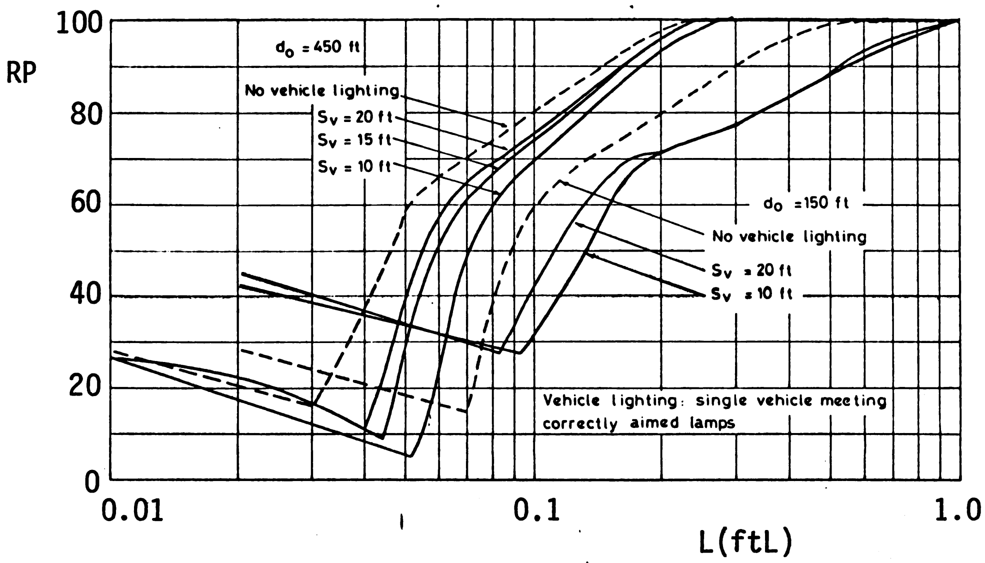
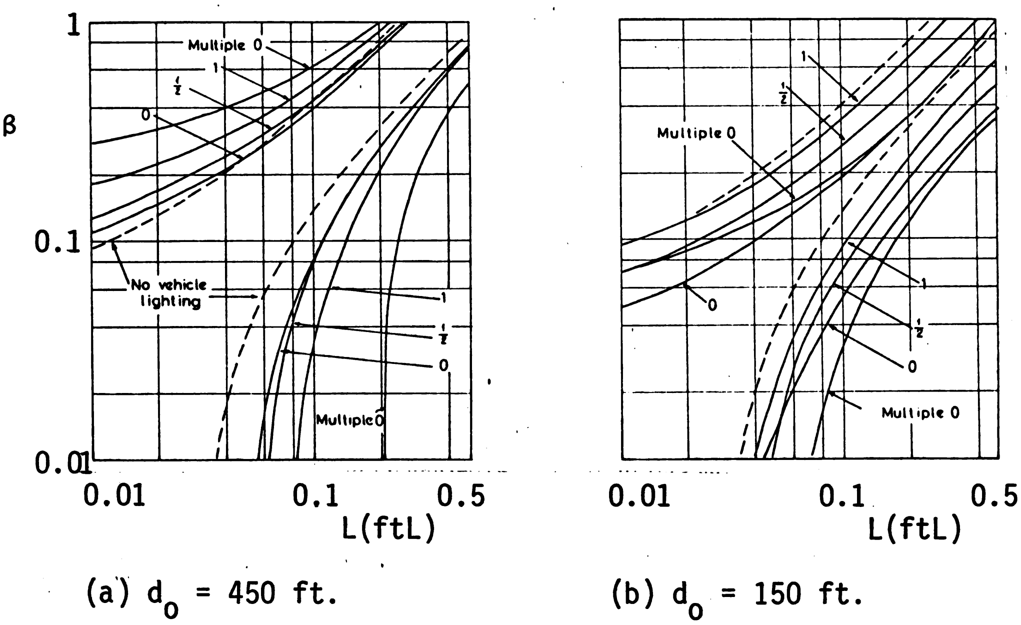


Fig. 11.5, The effect of lateral vehicle separation on revealing power. (The curves for d_o = 150 ft have been displaced to the right for clarity.)



(a) d_o = 450 ft.

(b) d_o = 150 ft.

Fig. 11.6. The effect of lamp misaim and multiple vehicle meetings on the necessary luminance factor (β) for objects to be seen adequately against background (L). (Figures to curves give misaim in degrees.)

CHAPTER 12

ROAD USER REACTION TO A TOWN BEAM

INTRODUCTION.

In Chapter 10 it was suggested that vehicles should be fitted with a town beam, for use in traffic route lighting, of intensity between that of the present marker light and lower beam headlight. This would act as a conspicuous but glare free marker of moving vehicles.

Two field investigations into the town beam will be described in the next two chapters. Whilst the concept is not new, there is a lack of systematic investigation into necessary photometric attributes of the town beam and the reaction to it of road users. Its British proposers concentrated on the practicalities of its implementation and control after only a limited field trial. The British in their trial used a town beam consisting of the conventional lower beam reduced to one tenth of its original intensity. The Dutch investigators concluded that a glare free conspicuous marker light should have an intensity of 30 - 50 cd.

In the investigation on road user reaction to be described now, the town light was obtained by dimming the conventional lower beam to one tenth intensity. This figure was adopted because a large reduction in intensity is required to give a noticeable reduction in glare. To reduce disability glare to the level of the European beam a reduction in beam intensity to 1/4 - 1/5 is necessary and to reduce the apparent headlight brightness by two just noticeable difference steps requires a reduction to approximately 1/10. The glare intensity will be reduced to about 50 to 100cd for oncoming motorists and to about 100 - 250 cd for pedestrians on the same side of the road as the oncoming vehicle, as shown in Fig. 12.1.

THE INVESTIGATION.

The aims of this investigation were to establish whether road users, both drivers and pedestrians, thought the town beam to be superior to the conventional lower beam headlight and to find the bases on which they made their decisions within a realistic but controlled traffic environment.

EXPERIMENTAL PROCEDURE.

The traffic environment was of three vehicles driven by the subjects (observer cars) meeting a traffic stream of six vehicles approaching in the opposite direction. The two sets of vehicles were to meet and pass at one of two locations (meeting places):

(a) on the crest and bend of the road;

(b) on a straight section of the road.

And under two headlighting conditions:

(a) using normal lower beam of the British/American type currently used in Australia; and

(b) using experimental town beam.

The experiment was carried out on two nights with twelve subjects each night. Each night was divided into two stages. In stage 1, six of the subjects were paired off to act as drivers, the other six were to act as pedestrians. Stage 2, except for a different order in the schedule of runs, was the same as for stage 1, but with the subject's functions being reversed.

Each stage was divided into two sub-stages. In sub-stage 1, one each of the three pairs of driver subjects actually drove for six consecutive runs, whilst the three others of the pairs acted as front seat passengers. Sub-stage 2, except for different order in the schedule of runs, was the same as sub-stage 1, but with driver and passenger reversing functions.

A run was defined as a traversal of one length of the road used in the experiment. The schedules of runs were the order and way in which the runs were made. Controlled changes in the schedule were made to cancel any order effects. This was done by adopting a ABBA design on the two factors: meeting place and state of headlights. The three observer cars were rotated after two consecutive runs, to cancel for vehicle position effects. For an example of schedule of runs for one sub-stage see Appendix 12.1.

At the end of each six consecutive runs, a questionnaire was administered to drivers, passengers and pedestrians through which they gave their appraisal of comfort and visibility. At the end of each sub-stage a special detection run was made to find out whether a vehicle on town beam would be noticed amongst a stream of vehicles on lower beam. Again a questionnaire was administered to all subjects. The subjects were unaware of the specific contents of a questionnaire until it was administered. Each was completed strictly without reference to either fellow subjects or preceding questionnaires.

Before the start of each evening's proceedings the subjects assembled in a hall on site to be briefed. They were informed of the run procedure and told that they were to compare two systems of car headlighting for use in well lighted streets, to find out if there were any basic differences and if so to what degree. They were told they would be asked questions on visibility and comfort. However, the concept of a town beam and lighting practice was not mentioned. It will be noted that the questionnaire refers to bright and dim systems of lighting. This differentiation was not mentioned until this stage, at which point all, but one apparently, of the subjects were aware of the most obvious difference between the two beams. The subjects were told not to discuss their reactions with fellow subjects and to direct any procedural queries to the experimenters. Any discussion on the experiment, its aims and subject comment was deferred until the completion. After briefing, the subjects had several trial runs to become familiar with experimental procedure.

Subjects.

Nineteen male and five female subjects were used in the experiment. Their ages ranged from 19 to 54 years of age. Four of the subjects were involved in street lighting and worked for Electricity Authorities but not at a decision making level, four were professional drivers for a motor car manufacturing company and the sixteen others were private citizens who, however, were connected as colleagues, friends or relations of the experimenters.

Vehicles.

Nine vehicles in all were fitted with the town beam. The three subject cars were all late model station wagons. The traffic stream cars were comprised of two sedans, two station wagons, one panel van and one utility.

Test Site.

The site selectedwas a 1 km length of Telegraph Road, Pymble, Sydney. The carriageway, two way, 13m wide, is fully kerbed and guttered and heavily lined with trees. The street is lighted to the minimum level of SAA Street Lighting Code. A map of the site is given in Fig. 12.2

Vehicle Lighting.

The vehicles were fitted with current all sealed headlight units of British/American design.

The town beam intensity setting was accomplished using a variable resistor in series with the headlight lower beam filament. The resistor was adjusted in position with the headlights on and the engine running using a modified and calibrated commercial beam setter. A simple toggle switch was used to by-pass the resistor for normal lower beam. The lamps were aimed so that the hot spot of upper beams were aimed 1/2^{o} down with the vehicles loaded. The marker lights were disconnected on those vehicles which normally showed them when the headlights were in operation.

Questionnaires.

An examination of the night road situation suggested that the following aspects be investigated:

(a) relative comfort of a stream of town beams compared with the conventional lower beams;

(b) vision ahead and behind;

(c) visibility of 1 town beam amongst stream of lower beams;

(d) relative ease in assessing crossing the road; and

(e) preference for one system by pedestrians and drivers.

Questionnaires based on these aspects, which were administered to the subjects, are contained in Appendix 12.2.

RESULTS.

The results of the questionnaires are given in Table 12.1 in terms of the number of subjects (out of 24) having a given opinion based on the answers to the first administration of the questionnaires. It was found that drivers and passengers answered in an essentially similar manner. The second administration of a questionnaire yielded almost identical responses to the first, showing the consistency of subject responses. There was no significant order effect in being first a driver, as against a pedestrian. A meeting place analysis revealed an almost duplication of results, except for the one question on glare experience discussed in the next paragraph.

Drivers' Visibility.

A majority of subjects (15/25) thought that the visibility of pedestrians was better with one system of headlighting than with the other. Twelve out of the fifteen thought that this difference was marked or very marked. However, the fifteen were split 8/7, lower to town beam, in their estimation of which system gave the better visibility This non-significant result is consistant with the findings of Chapter 11 that during vehicle meetings with conventional lights visibility will be generally adversely affected by headlamp glare, except that it may be enhanced in the final stages by increased illumination. It is to be expected then that drivers would have different preferences, based on these two factors; however, it should be noted that a conclusion in Chapter 11 was that overall visibility in lighted streets was adversely affected by vehicle lighting.

In looking across to the right hand side of the road, and thus beyond the lights of the oncoming vehicles, a non-significant majority of subjects (14/24) thought visibility was better. Of these, thirteen thought the difference in visibility was marked or very marked. From studies of Turner it would be expected that visibility in this region of the road would be badly affected by disability glare from the lower beam.

Drivers' Comfort.

Twenty-three out of the twenty-four subjects noticed the difference in brightness of the two systems of headlighting. Twenty-two subjects thought the difference was marked or very marked. However, there was nearly a 50/50 split as to whether glare (discomfort) was present in any of the runs, although for two thirds of those who experienced glare, it was marked or very marked.

Using the Fisher exact probability test, a further analysis differentiating between meetings on the crest and straight, showed the following opposite trend in glare experienced:

MEETING PLACE	GLARE	NO GLARE
Crest	16	8
Straight	9	15

This reversal of opinion is just not significant at the 5 percent level. This suggests that drivers from past experience will tolerate a large degree of glare, perhaps called by the layman excess brightness, without saying lights are glaring, whilst still suffering discomfort. They will tolerate a steady stream of lower beams, but not a sudden encountering of the same lights as happens on the crest (and also on the curve) in a road. A driver question using the word comfort may have elicited a more definite opinion, as in the case of the pedestrian question.

Seventeen subjects thought rear vision comfort was much better with the town light. The difference in comfort was either marked or very marked. This result was just not significant at the 5 percent level.

Pedestrians.

Most pedestrian subjects (23/1) felt more comfortable when facing the town beam than with conventional lights. Crossing the road was thought by eighteen subjects to be easier with one of the two systems. However, the 13/5 split for town over lower beams is not significant. This is consistent with the results of British work which suggests that pedestrian behaviour in crossing the road is independent of lighting.

Detection of town light.

In the two special runs each night where only one town light was showing in the traffic stream, 2/3 of the road users detected the presence of one set of different headlights. However, the other eight although not detecting the position of the odd car most probably still saw it. A question on the number of vehicles passed would have been more fruitful in finding out whether a vehicle using the town beam would be lost in a stream of conventional lights.

Overall Preferences.

Questionnaires 5 and 6 asked the subjects to make preferences for one system of headlighting or the other, for the conditions of the trial: first an overall preference (Q5), secondly and thirdly, a preference made from a driver's and pedestrian viewpoint respectively (Q6). The overall preference favoured the town light by a majority of 17 to 7. This is just not significant at the 5 percent level. However, both the remaining preferences again in favour of the town light, were significant with majorities of 18 to 6. Of the seven subjects preferring the lower beam in questionnaire 5, one changed his driver preference and one changed his pedestrian preference in questionnaire 6 to town beam.

Sub-group Analyses.

Several other analyses were performed on the data. The twenty-four subjects were sub-divided into groups according to the following attributes: age, sex, wearing glasses and occupation. Sex and the wearing of glasses had no significant effect on the answers given. For the age analysis, the group was divided into three age groups: 20 - 29, 30 - 39, 40 - 60. There was no significant differences between answers given by the three groups on all butone question. For rear vision comfort there was a 9:2, 7:1, 1:4 yes/no vote for it being greater with one system of headlights. Combining the two lower age groups and comparing with the 40 - 60 group the 16/3 to 1/4 contrast is significant at the 5 percent level, using the Fisher exact probability test. This may be due to ageing effects in the eye that possibly bring about a diminution in the sensitivity of detecting differences in glare and the older group may have found the town beam glaring in this situation.

The occupation sub-grouping comprised three groups:

(1) professional drivers;

(2) people concerned with street lighting; and

(3) private citizens.

There was a 4/0, 0/4, 3/13 lower/town beam overall preference for each of the three groups respectively. Group one shows a 2 percent significant opposite trend to both the other two groups individually and when combined. This significant contrast also shows up in the preferences from a drivers and a pedestrian viewpoint as well as in the overall preference:

GROUP	OVERALL	DRIVER	PEDESTRIAN
1	4/0	4/0	3/1
2	0/4	0/4	1/3
3	3/13	2/14	2/14

This opposite trend on the part of professional drivers may be attributed to a conservative attitude towards conventional and long established vehicle lighting practice.

DISCUSSION.

Previously, it has been demonstrated that street lighting of the appropriate standard alone provides adequate visibility on traffic routes. Use of the conventional lower beam can adversely affect both visibility and comfort. Its replacement by some other form of lighting which is glare free but acts as a conspicuous marker of a moving vehicle has been suggested. A group of 24 road users, as a whole, preferred the use of a town beam (conventional lower beam reduced to 1/10 intensity) to the conventional lower beam in a well lighted street. The preference appears to be based on comfort considerations rather than on ones of visibility, and suggests that road users are critical of the use of lower beams in well lighted streets. This result gives support to the concept of vehicle lighting designed specifically for use on lighted traffic routes.

APPENDIX 12.1

Night : 1
Stage : 1

SCHEDULE OF RUNS

Run Number	Positions of the 3 observer cars			Driver	State of Headlights	Meeting Place	Starting end for observer cars
Trial	1	2	3	1	B	S	P.H.
Trial	1	2	3	2	B	C	M.V.
1	3	1	2	2	B	S	P.H.
2	3	1	2	2	D	S	M.V.
3	2	3	1	2	D	S	P.H.
4	2	3	1	2	B	S	M.V.
5	1	2	3	2	B	S	P.H.
6	1	2	3	2	D	S	M.V.
Administer Questionnaires 1 and 3							
7	3	1	2	1	D	C	P.H.
8	3	1	2	1	B	C	M.V.
9	2	3	1	1	B	C	P.H.
10	2	3	1	1	D	C	M.V.
11	1	2	3	1	D	C	P.H.
12	1	2	3	1	B	C	M.V.
Administer Questionnaires 1 and 3							
13	3	1	2	1	*	S	P.H.

Administer Questionnaires 2 and 4
Administer Questionnaires 5 and 6 (after stages 1 and 2).

NOTES

1, 2, 3	The three observer cars
B	Lower beams
D	Town beam
S	Straight section of Telegraph Rd
C	Crest section of Telegraph Rd
M.V.	Pacific Highway end of Telegraph Rd
P.H.	Mona Vale Rd end of Telegraph Rd
*	3rd stream car on D lights, the remainder of all cars on B lights

APPENDIX 12.2

QUESTIONNAIRE 1 — DRIVERS AND PASSENGERS

1. Was there a noticeable difference in brightness between the two systems of oncoming headlights used in the last six runs?
   i) Yes
   ii) No

   If yes, was the difference
   i) very marked
   ii) marked
   iii) hardly noticeable
2. Did you experience glare during any of the six runs?
   i) Yes
   ii) No

   If yes, was the glare
   i) uncomfortable
   ii) noticeable
   iii) just perceptible
3. Was there a noticeable difference in your ability to see on the right hand side of the road, immediately beyond the oncoming cars, with the two lighting systems?
   i) Yes
   ii) No

   If yes, was the difference
   i) very marked
   ii) marked
   iii) hardly noticeable
4. During the actual meeting with the oncoming cars, was there any difference in the visibility of pedestrians, on the left hand side of the road, with the two lighting systems?
   i) Yes
   ii) No

   If yes, with which system was visibility better
   i) Bright
   ii) Dim

   and was this difference
   i) very marked
   ii) marked
   iii) hardly noticeable
5. Did you notice any difference in comfort when using the rear vision mirror with the two lighting systems?
   i) Yes
   ii) No

   If yes, with which system was comfort greater
   i) Bright
   ii) Dim

   and was this difference
   i) very marked
   ii) marked
   iii) hardly noticeable

QUESTIONNAIRE 2 — DRIVERS AND PEDESTRIANS

1. In the stream of traffic you have just passed, did you notice a car with different lighting from the rest?
   i) Yes
   ii) No

   If yes, in what position in the stream of cars was it?
   i) 1st
   ii) 2nd
   iii) 3rd
   iv) 4th
   v) 5th
   vi) 6th

QUESTIONNAIRE 3 — PEDESTRIANS

1. Was it easier to make up your mind to cross the road with one system of headlights?
   - i) Yes
   - ii) No

   If yes, with which system
   - i) Bright
   - ii) Dim

   and was this difference in ease
   - i) very marked
   - ii) marked
   - iii) hardly noticeable
2. Did you notice any difference in your general comfort when looking at the oncoming traffic, with the two lighting systems?
   - i) Yes
   - ii) No

   If yes, was the difference
   - i) very marked
   - ii) marked
   - iii) hardly noticeable

QUESTIONNAIRE 5 — TO ALL

1. Which of the two systems of car lighting did you prefer tonight?
   - i) Bright
   - ii) Dim

QUESTIONNAIRE 6 — TO ALL

1. As a driver, which system did you prefer?
   - i) Bright
   - ii) Dim

   Is this preference?
   - i) Strong
   - ii) Medium
   - iii) Mild
2. As a pedestrian, which system did you prefer?
   - i) Bright
   - ii) Dim

   Is this preference?
   - i) Strong
   - ii) Medium
   - iii) Mild

Questionnaires 1 and 3

Question.	Yes (1)	No	Very Marked	Marked	Hardly Noticeable	Statistically Significant (3)
Questionnaire 1						
1. Brightness difference	23	1	9	13	1	Yes
2. Glare experienced?	12	12	3	5	4	No
3. Diff. in visibility of r.h.s. road?	14	10	4	9	1	No
4. Diff. in visibility of pedestrians?	8L/7T	9	1	11	3	No
5. Comfort using rear vision mirror?	1L/16T	7	6	11	0	Just Not
Questionnaire 3						
1. Diff. in ease of crossing road	5L/13T	6	2	11	5	No
2. Diff in comfort	23	1	10	10	3	Yes

Questionnaires 2 and 4

Question	Yes	No	Right Car	1 Car Out	More than 1 Car Out	Statistically Significant
Town beam detected in traffic stream	16	8	11	4	1	No

Questionnaires 5 and 6

Question	Town Beam (2)	Lower Beam	Statistically Significant
Overall preference	17	7	Just not
Driver preference	18 (8 : 9 : 1)	6 (3 : 2 : 1)	Yes
Pedestrian preference	18 (7 : 7 : 4)	6 (3 : 3 : 0)	Yes

Notes: (1) L = lower beam, T = town beam.

(2) Strong : medium : mild.

(3) The data in terms of two classes were analysed statistically using the Binomial Probability test. A split 18/6 corresponds to a 2 per cent probability that it occurred by chance, 17/7 to p=6 per cent and 16/8 to p=15 per cent. A value of p=5 per cent or less is usually taken to indicate a significant result.

Table 12.1. Analysis of results.

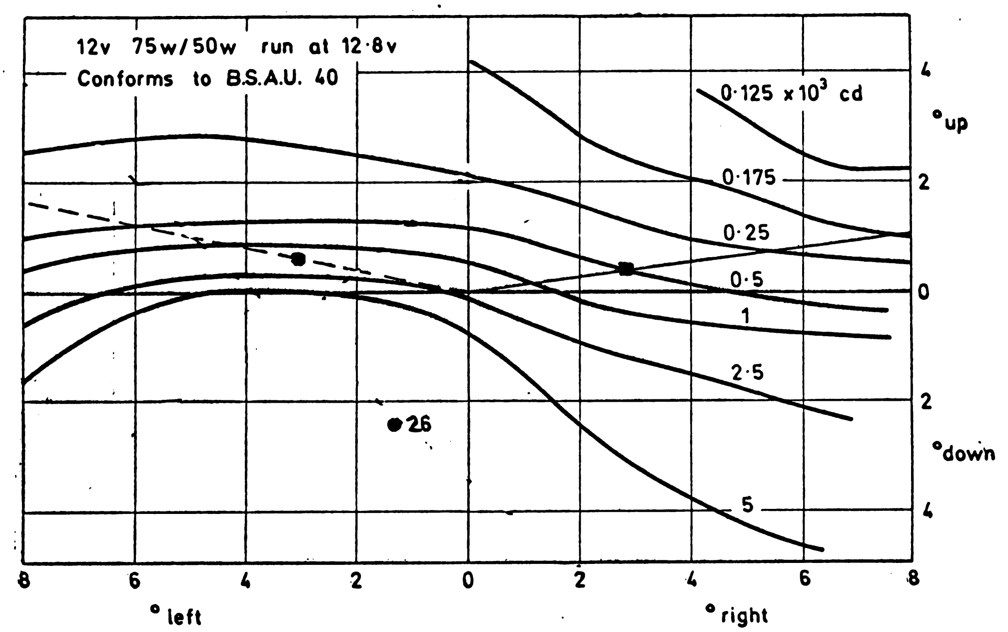


Fig. 12.1. Lower beam from one BS headlamp. The dotted and full lines show approx. paths of the eyes of facing pedestrians on N.S kerb and of motorists respectively as car approaches : the squares give distance of 100m. With beam dimmed the values will be 1/10.

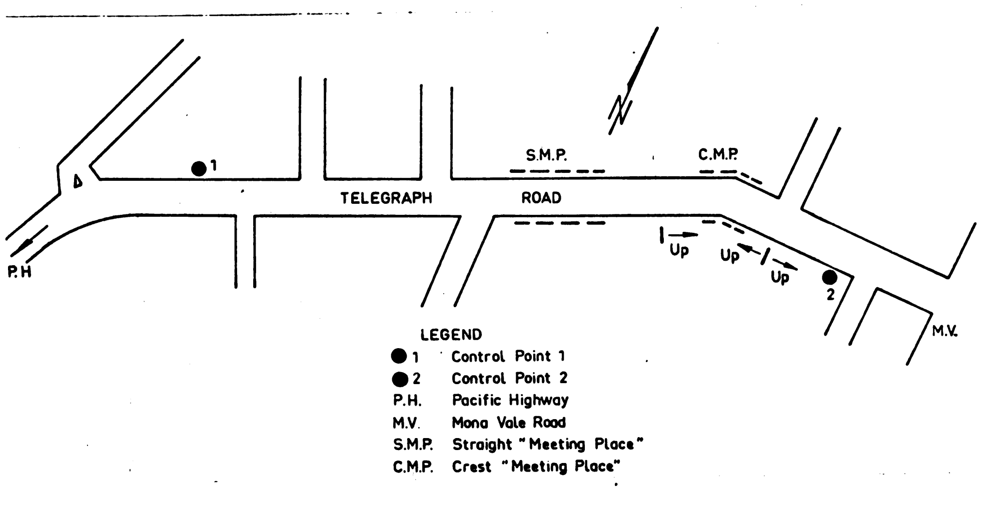


Fig. 12.2. Details of test site. The two streams of vehicles were controlled from points 1 and 2 by means of a radio link. The vehicles were started from each end with a predetermined interval so they met at S.M.P. or C.M.P. with no other vehicles intruding into the run.

CHAPTER 13

THE LUMINOUS INTENSITY REQUIREMENTS OF A TOWN BEAM

INTRODUCTION.

The concept of a town beam for use in traffic route lighting was validated by the results of the investigation described in the previous chapter. A single intensity and size of lamp (the lower beam headlight reduced to 1/10 intensity) was used. This chapter describes an investigation to see if this arrangement yields the optimum parameters for a town beam.

EXPERIMENTAL PROCEDURE.

An appraisal and subjective rating method was used by observers who appraised a range of marker lights on a car in several lighted streets, in terms of conspicuity and discomfort,caused by glare. In order that a large range of lighting conditions could be appraised several times, by as many people as possible under street conditions, the majority of datawere collected with observers stationary at the kerb-side, as pedestrians, viewing a single static experimental car. In the investigation described in Chapter 12, no differences were found in the overall appraisals of pedestrian and driver subjects for a limited set of lighting conditions. The effects of movement and number of the test vehicles on appraisals were tested by some observations on one and then three moving cars.

Vehicle Lights.

A car was fitted with new 12v 75w/50w British sealed beam head-lamps, in front of which were mounted slide holders to take screens to alter the circular area and light intensity of the headlights. The area could be varied over a range of 10 to 1 in 3 steps and the intensity with each step over a range of 10^5 to 1 in 8 steps. The range of intensities covers those of poor marker lights to full headlights. These details are

are shown in Table 13.1

The intensities were computed from isocandela diagrams obtained from one headlamp with the various screens in position run at the working voltage and the geometry of the experimental site. On site the car engine was run at a constant fast idling speed and the voltage across the lamps was monitored. The lamps were masked so that only light through the test apertures was visible. For the semi dynamic observations two other vehicles were modified similarly.

Test Sites.

At the test sites, for the static observations, the car was placed close to the kerb at the middle of a lighting span. The observers were stationed 100 m in front of the car in a close group along the kerb. This distance was chosen as being representative of that which people require in order to cross the road under urban traffic conditions (13.1, 13.2). The disability glare that a driver experiences in vehicle meeting is at a maximum at about this distance away from the oncoming car, especially for small lateral separations of the two traffic streams (13.3). For the observations of moving cars a section of dual carriageway was used as a loop. The lights were set on the opposite carriageway to the subjects and the test vehicles turned into the subjects carriageway about 250 m in front of them. The vehicles approached at about 50 km/h and turned off again adjacent to the observation position.

The street lighting at the static test sites, one of residential and two of traffic route standard, gave a range of average road carriageway luminance of 20 to 1 in three steps. The surrounds to the carriageway at the two sites of lowest carriageway luminance were dark but those at the site of highest carriageway luminance were light, due to the unobstructed proximity of the houses to the road. The fourth site, used for observations of moving cars had a high carriageway luminance but dark surrounds. The details of each of the sites are given in Table 13.2

Subjects.

All the subjects were unpaid volunteers, and included students and members of the research, academic, technical and administrative staff of a University Department and their relations and friends. Altogether 35 subjects participated in the five experimental sessions, attending from one to four times. They included 26 males and 9 females of whom 16 wore glasses and their average age was 29 years within a range of 22 - 58 years, with only two over 40 years. Only one of the subjects had a formal interest in public lighting. It was not possible to match the groups attending each session; the details of each subject group are given in Table 13.3.

Experimental Sessions.

In each of the three static experimental sessions the 24 combinations of light size and intensity were each presented for 10 seconds in a random order, which was replicated three times. In addition, each session started with five practice presentations and each replication contained a dummy presentation when no light was shown. In the sessions with moving cars there were two replications of the lighting presentations when one car was involved and one replication when three cars were used.

The sessions were conducted after the evening peak hour traffic, starting at 20.00 hours. The presentations were made so that no other vehicle was between the experimental car and the observers. The experimenters were in radio touch with the observers to ensure that their recording kept in step with the order of presentation. Each session took one hour to complete. The weather was cold, extremely so in the first three sessions and in the last three sessions the road was damp and there was slight mist.

Questionnaire.

At the start of each session the subjects were briefed and during the sessions they recorded their appraisals on a preprinted sheet. The appraisal took the following form (see Appendices 13.2, 13.3):

Conspicuousness:

Qu. 1. Did you detect the lights? Yes/No.

Qu. 2. Were the lights at least adequately conspicuous to indicate the presence of a car, under these conditions? Yes/No.

Qu. 3. Give the degree of conspicuousness experienced on the scale 1 to 6. Poor conspicuity should rate a low number and good conspicuity should rate a high number. The following descriptions have been associated with the numbers:

1	2	3	4	5	6
Barely detectable Very indistinct	Indistinct Not very noticeable	Detectable Noticeable	Distinct Clear	Very clear Very distinct	Outstanding Very striking

Brightness:

Qu. 4. Were the lights too bright under these conditions? Yes/No.

Qu. 5. Give the degree of brightness experienced on the scale 1 to 6. Low brightness should rate a low number and high brightness should rate a high number. The following descriptions have been associated with the numbers:

1	2	3	4	5	6
Very Dim Very Dull	Dim Dull	Diffuse Not very bright	Bright Uncomfortable	Glaring Very uncomfortable	Intolerable Unbearable

RESULTS.

The Yes/No Questions 1, 2 and 4.

All the light intensities presented were detected except in a few acknowledged cases of error in presentation or recording. An example of the pattern of yes/no responses to the questions concerning the adequacy of conspicuousness and the brightness is given in Table 13.4. It can be seen that at high and low values of light intensity there is unanimity of response but near the middle of the range there is uncertainty both within individuals and the group. Although the uncertainty exists at different points within the intensity range for different observers, this uncertainty does not appear to depend on the personal attributes of the subjects listed or on learning or fatigue effects. The results for each group of observers were taken together in order to determine group consensus for the intensity levels which produce given percentages of response.

The cumulative frequencies of response to each of the yes/no questions for each size of light in each experimental session were plotted as standard deviations about the 50% level against the logarithm (base 10) of the light intensities. In order to extend the available data the first 0% and 100% response at either end of the normally useable range of responses was assigned a value of 1% and 99%. Thus the expected log normal distributions of responses are transformed into a linear relationship with the light intensity.

Examples of the data treated in this way are shown in Figures 13.1 and 13.2. The line of best fit was calculated for each data set and the results of this analysis are shown in Appendix 13.1 It can be seen that in all cases there is a linear correlation between frequency of response and light intensity, expressed in the manner explained above, statistically significant to the 5% level or better. In addition, these correlations explain, in all cases, 90% or over of the observed variability within each data set.

Deduced from the correlation for each data set were the values of intensity giving the threshold or 50% probability of response and a higher probability value more realistic of the traffic situation, i.e. 95% finding the light "adequate" and 5% finding it "too bright". These values are given in Table 13.5. The 50% intensity values for "adequate" conspicuity and "too bright" are about 10cd and 1000cd respectively, i.e. difference of about 100 times. However, for the 95% probability of "adequate" and 5% probability of "too bright" this difference disappears and the intensity values overlap at about 100cd.

The 20 to 1 range in average road luminance appears to have almost no practical effect on the light intensity requirements. The threshold intensity for the adequate criterion increases by a factor of about 2 only in going from the darkest to the lightest road, but this effect is lost at the 95% level. Whilst intensity values for too bright are lower for the Croftdown Road session (dark) than those for the Wolverhampton Road session (light) the values for all the other sessions do not appear to fall into any systematic pattern. There appears to be no effect on the results with the movement of the vehicles or the increase in their number.

Since these factors have little influence on the intensity values, log mean intensity value for all the sessions taken together is shown for each source size in Table 13.6. The size of the source has a marked and consistent effect on the results. The subjects appear to find the larger source more conspicuous than the smaller whereas they find the smaller source brighter and more discomforting than the larger, as shown in Fig. 13.3. This result implies that brightness and conspicuity are not linked in a simple manner. It is well established that as the illumination at the eye increases from a source it will appear brighter but that for any given illumination (or intensity for a constant distance) a smaller source will appear brighter and more discomforting than a large one (13.4). It now appears, however, that the smaller source is also less conspicuous; thus brightness and conspicuity appear not to be the same attribute of a luminous source. General inquiries showed that road users preferred those marker lights which were incorporated with the headlamps unit, giving a large luminous area on the vehicle.

The Numerical Scaling Questions 3 and 5.

An example of the pattern of the number scaling responses is given in Table 13.7. It can be seen that scale value increases as the light intensity increases both for individuals and the group as a whole. The variation in scale response over the three repetitions of a particular light intensity is large and for an individual it can be 2 units and for the group it can be 3 units i.e. over half the total scale. The average response values, representing the group consensus, were plotted against the logarithm (base 10) of the light intensities for each size of light for each session. Since the scaling appeared to be insensitive to source size a single curve was drawn through the combined data for each session. Examples of this data are shown in Figures 13.4 and 13.5.

It might have been expected that whilst the brightness response continued to rise with intensity and to tail off with the largest values of intensity, the conspicuity response would rise sharply at first and tail off at more moderate intensity values, i.e. a light would reach maximum conspicuity before reaching maximum brightness. A plot of mean conspicuity appraisals against mean brightness appraisals, shown in Figure 13.6, only gives a hint of this; at the centre of the scale the two appraisals are different by about half a unit.

Verbal Descriptions.

In order to obtain an association of scale numbers with verbal descriptions of lights most of the subjects were asked to assign a number to lists of words descriptive of conspicuity and brightness. The numbers of subjects making various assignments are shown in Appendix 13.2. If the closest semantic descriptions are allied to numbers it can be seen that as regards conspicuity, the mean intensity values giving rise to a rating of 2.5 (perceptible), 3.5 (noticeable) and 4 (distinct) are 5, 17 and 410cd respectively. Thus the intensity giving rise to the 50% response level to the "adequate conspicuity?" has a connotation of perceptible rather than distinct. The actual values for each session are given in Table 13.8. However, the 95% response level to the same question, of about 100cd, would give a rise to a group consensus scale value of 3.5, which is approaching the connotation of distinct.

As regards brightness, a mean scale value of 4(bright) is evoked by an intensity of 1,900cd. For a scale value of 4.5 (uncomfortable, disturbing) an intensity of 4,700cd is required. The actual values for each session are also given in Table 13.8. These intensities are in good agreement with the intensity which gave rise to a 50% response level to the "too bright?" question. The 5% response level to the same question, of about 100cd, would correspond to a scale value of

3 which is one unit below any connotation of brightness, and hence possible discomfort.

DISCUSSION.

It was found that the intensity requirements for a town beam are largely independent of observer attributes, the luminance of the road surface and its surrounds and the number and movement of the vehicles. However, the results suggest that conspicuity and brightness are different attributes of a light. Whilst both increased with increasing luminous intensity the observers found, for a given intensity, that a larger source was the more conspicuous but that a smaller was the more discomforting.

The optimum vehicle lighting for urban traffic routes appears to be a town beam, based on the size of the present lower beam headlight, giving a straight ahead intensity of 80cd. This intensity is similar to that experienced from the current British American lower beam dimmed to 1/10 its intensity, that was used in the investigation described in Chapter 12. If the light is based on the present usually small diameter marker light this value needs to be doubled to give adequate conspicuity but then about one observation in twenty will find this light too bright.

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APPENDIX 13.1

Correlations between frequency of response and light intensity, for various experimental conditions.

(1) CONSPICUITY $x = \log_{10}$ light intensity

y = frequency of "no" responses in standard deviations about the 50% level.

University (1 static car)		
178mm light	$y = 0.55 - 1.11x$	
$n = 4$	$r^2 = 0.940$	SL = 5%
102mm light	$y = 0.59 - 1.01x$	
$n = 4$	$r^2 = 0.924$	SL = 5%
56mm light	$y = 0.78 - 0.95x$	
$n = 5$	$r^2 = 0.995$	SL = 0.1%
Croftdown Road (1 static car)		
178mm light	$y = 1.11 - 1.45x$	
$n = 4$	$r^2 = 0.998$	SL = 0.1%
102mm light	$y = 1.01 - 1.28x$	
$n = 5$	$r^2 = 0.985$	SL = 0.1%
56mm light	$y = 1.36 - 1.25x$	
$n = 5$	$r^2 = 0.997$	SL = o.1%
Wolverhampton Road (1 static car)		
178mm light	$y = 1.89 - 1.85x$	
$n = 4$	$r^2 = 0.980$	SL = 1%
102mm light	$y = 2.10 - 1.33x$	
$n = 4$	$r^2 = 0.901$	SL = 5%
56mm light	$y = 1.98 - 1.55x$	
$n = 4$	$r^2 = 0.982$	SL = 1%
Pebble Mill Road (1 car moving)		
178mm light	$y = 1.22 - 1.53x$	
$n = 4$	$r^2 = 0.951$	SL = 5%
102mm light	$y = 1.71 - 1.99x$	
$n = 4$	$r^2 = 0.999$	SL = 0.1%
56mm light	$y = 1.86 - 1.69x$	
$n = 4$	$r^2 = 0.910$	SL = 5%

Pebble Mill Road (3 cars moving)

178mm light		$y = 1.28 - 1.58x$	
	$n = 4$	$r^2 = 0.910$	SL = 5%
102mm light		$y = 1.54 - 1.96x$	
	$n = 4$	$r^2 = 0.990$	SL = 1%
56mm light		$y = 1.99 - 1.95x$	
	$n = 4$	$r^2 = 0.999$	SL = 0.1%

(2) BRIGHTNESS $x = \log_{10}$ light intensity

y = frequency of "yes" responses in standard deviations about the 50% level.

University (1 static car)

178mm light		$y = 2.33x - 8.60$	
	$n = 4$	$r^2 = 0.994$	SL = 1%
102mm light		$y = 1.25x - 4.38$	
	$n = 5$	$r^2 = 0.968$	SL = 1%
56mm light		$y = 1.12x - 3.85$	
	$n = 4$	$r^2 = 0.999$	SL = 0.1%

Croftdown Road (1 static car)

178mm light		$y = 1.35x - 4.11$	
	$n = 5$	$r^2 = 0.944$	SL = 1%
102mm light		$y = 1.44x - 4.22$	
	$n = 5$	$r^2 = 0.943$	SL = 1%
56mm light		$y = 1.55x - 4.47$	
	$n = 4$	$r^2 = 0.998$	SL = 0.1%

Wolverhampton Road (1 static car)

178mm light		$y = 1.98x - 6.89$	
	$n = 5$	$r^2 = 0.995$	SL = 0.1%
102mm light		$y = 1.45x - 4.69$	
	$n = 5$	$r^2 = 0.952$	SL = 1.0%
56mm light		$y = 1.34x - 4.42$	
	$n = 5$	$r^2 = 0.996$	SL = 0.1%

Pebble Mill Road (1 car moving)

178mm light	$y = 1.20x - 4.03$	
n = 5	$r^2 = 0.947$	SL = 1.0%
102mm light	$y = 1.44x - 4.55$	
n = 5	$r^2 = 0.950$	SL = 1.0%
56mm light	$y = 1.20x - 3.96$	
n = 5	$r^2 = 0.980$	SL - 1.0%

Pebble Mill Road (3 cars moving)

178mm light	$y = 1.69x - 6.25$	
n = 5	$r^2 = 0.947$	SL = 1.0%
102mm light	$y = 1.86x - 6.42$	
n = 5	$r^2 = 0.930$	SL = 1.0%
56mm light	$y = 1.41x - 4.49$	
n = 5	$r^2 = 0.988$	SL = 1.0%

APPENDIX 13.2

SUBJECTIVE APPRAISAL

As the light flux reaching the eyes from a source increases, it reaches the threshold necessary for perception and then the source becomes progressively brighter until it becomes so bright as to cause discomfort. Many investigations have been carried out in order to relate the subjective degree of discomfort glare to the lighting parameters i.e. illumination at the eyes, source size and position and general light adaptation level.

For these experiments, in the street and interior lighting context, various systems have been used to represent the subjective response to glare (i) Multiple limits, e.g. "just intolerable", "just uncomfortable", "satisfactory", "just not perceptible" (Hopkinson); (ii) Single limit e.g. "borderline between comfort and discomfort" (Guth); (iii) Multiple classification e.g. "unbearable", "disturbing", "just admissible", "satisfactory", "unnoticeable" (de Boer). In addition a numerical scale can be given to the classification, on the assumption that the descriptions represent equal intervals of sensation, so that mathematical analysis may be facilitated. Indeed the numerical scale has been used without verbal description.

Since the main purpose of this investigation was to find the ideal lighting parameters which gave a conspicuous but glare free marker, it was decided to use mainly the single limit system. However, since the intensity of the experimental lights was not continuously variable but was presentable in discrete steps the subjects were forced into a Yes/No choice of two classes either side of the single limit. Thus the two main questions posed became:

(i) Were the lights at least adequately conspicuous?
(ii) Were the lights too bright?

Since the two vehicle lighting modes, side and dipped lights, are apparently not the ideal solution to the problem it was decided to ask the subjects to place all the test lights on a scale, in order that other practical lighting conditions could be rated with respect to the ideal solution.

Although conspicuity and brightness must be related in that, in general, a bright light is a conspicuous light it was considered that conspicuity and brightness did not form one continuum and are separate attributes of a source. As the light intensity increases above a certain level the conspicuity may not increase whereas the brightness and discomfort may well continue to do so. The appraisal of brightness and conspicuity may be made differently; whereas brightness is known to be inversely related to source size, conspicuity may be related to source size in a different way.

It was decided to use a six point numerical classification, which gives a manageable number of choices without chance of a central tendency. Also included with each numerical classification were descriptions of subjective responses that could be associated with the scale. Thus the two classifications were:

(i) Conspicuousness

1	2	3	4	5	6
Barely detectable Very indistinct	Indistinct Not very noticeable	Detectable Noticeable	Distinct Clear	Very clear Very distinct	Outstanding Very striking

(ii) Brightness

1	2	3	4	5	6
Very dim Very dull	Dim Dull	Diffuse Not very bright	Bright Uncom-fortable	Glaring Very uncom-fortable	Intolerable Unbearable

It will be noted the discomfort is included in a brightness scale and is not classified by itself. This is so the discomfort responses will be made within the context of the whole range of brightness of lights that is found on the road and not within a preconceived ideal range. If conspicuity is maximal before discomfort with increasing light intensity then the conspicuity scale is more sensitive than the brightness one.

The association of scale numbers with descriptions was derived from a questionnaire in which subjects were asked to assign a number to lists of words, as shown in Tables 13.9, 13.10. Originally "not seen" was included in descriptions of conspicuity but since to be conspicuous a light must be seen and other descriptions of low conspicuity were often given a rating of one,the description "not seen" was deleted from the conspicuity classification. Some difficulty was found in associating descriptions with the middle of the scale. English adjectives seem to be made up of combinations of opposites i.e. the words "very indistinct", "indistinct", "distinct", "very distinct", do not form a continuum but rather fall into two opposite groups. The average ratings for definite discomfort "uncomfortable" "very uncomfortable" "unbearable" fall well into the top half of the brightness scale. Words giving a connatation of slight discomfort such as "disturbing" and "distracting" do not have an unambiguous meaning as shown by the diversity of ratings.

Description	1	2	3	4	5	6	Average
			Scale number				
Gleaming			8	11	8		4·00
Fuzzy	3	16	8				2·19
Brilliant			1	7	11	8	4·96
Dull	6	21					1·78
Very uncomfortable				2	16	9	5·26
Unbearable						26	6·00
Bright		1	6	14	6		3·93
Intolerable						27	6·00
Uncomfortable			1	9	16	1	4·63
Glaring				8	12	7	4·96
Very dim	26	1					1·04
Dazzling				5	11	11	5·22
Very bright			2	7	16	2	4·67
Dim	4	23					1·85
Disturbing			3	10	11	3	4·52
Very glaring				2	11	14	5·44
Very dull	25	2					1·07
Very disturbing				3	12	12	5·33
Distracting		1	4	10	11	1	4·26
Pale	2	19	6				2·15
Intense			3	11	10	3	4·48
Diffuse		12	13	2			2·63
Blazing				3	13	11	5·30
Vivid			4	10	10	3	4·44
Hazy	1	15	10	1			2·41
Not very bright	1	8	11				2·50

Table 13.9. Scaling words descriptive of degree of brightness.

Description	1	2	3	4	5	6	Average
			Scale number				
Barely detectable	9	18					1·67
Distinct			5	15	7		4·07
Detectable	1	9	14	3			2·70
Conspicuous			1	9	14	3	4·70
Clear			5	16	6		4·04
Very noticeable			1	4	16	6	5·00
Indistinct	4	14	9				2·19
Striking				1	16	10	5·33
Not seen	26						1·00
Easily seen			4	12	11		4·26
Outstanding					7	20	5·74
Very conspicuous					5	21	5·81
Imperceptible	23	4					1·15
Very clear				7	11	9	5·07
Very distinct				2	17	8	5·22
Very indistinct	9	17					1·65
Perceptible	3	9	10	5			2·63
Very easily seen				6	13	8	5·07
Very striking					5	22	5·81
Noticeable		2	14	11			3·33
Not very noticeable	2	17	8				2·22
Feint	8	17	2				1·78

Table 13.10. Scaling words descriptive of degree of conspicuity.

APPENDIX 13.3

This appendix contains

(i) the preliminary letter sent to subjects telling them of session details, the format and the object of the investigation,

(ii) the session briefing, and

(iii) the appraisal report form.

(i) PRELIMINARY LETTER TO SUBJECTS

Headlight Appraisals

Dear

You kindly agreed to take part in my lighting investigation. The particulars are:

Date - Time -

Place -

Please do not park you car on the test site; I suggest -

If the test is doubtful through rain or fog on the evening please phone me at home (429 4571) after 5.30 p.m. or at the University before 5 p.m. If you have any difficulties in transport etc., please let me know.

The object of the investigation is to see if it is possible to improve the design of lights on the front of vehicles. At present, in lighted streets the driver has a choice of using side lights or headlights, to indicate his presence to other road users. It is the opinion of some that side lights are insufficiently conspicuous but that the headlight, whilst conspicuous, could be uncomfortably bright. The solution may be a headlight designed specially for use in towns.

You will be asked to look at a series of lights on a stationary or on a moving vehicle. You will be asked to judge the conspicuousness and the brightness of the lights from a position on the kerb and to record your judgements on a form. The detailed procedure and form will be explained at the site.

Thank you

A. Fisher

Internal ext.5285
External ext. 454

(ii) ON-SITE BRIEFING READ OUT BY THE EXPERIMENTER

The object of the investigation is to see if it is possible to improve the design of lights on the front of vehicles. At present, in lighted streets the driver has a choice of using side lights or headlights to indicate his presence to other road users. It is the opinion of some that side lights are insufficiently conspicuous but that the headlight, whilst conspicuous, could be uncomfortably bright. The solution may be a headlight designed specially for use in towns.

The lights of the vehicle facing you will be switched on at regular intervals for a short time. Whilst the lights are on please appraise their conspicuousness and their brightness as a road user under these ambient conditions. Then answer the following questions on the form each time the lights are switched off by circling your appraisal and keeping in numerical step with the radio sequence.

Conspicuousness

Qu.1. Did you detect the lights? Yes/No.

Qu.2. Were the lights at least adequately conspicuous to indicate the presence of a car, under these conditions? Yes/No.

Qu.3. Give the degree of conspicuousness experienced on the scale 1 to 6. Poor conspicuity should rate a low number and good conspicuity should rate a high number. The following descriptions have been associated with the numbers:

1	2	3	4	5	6
Barely detectable Very indistinct	Indistinct Not very noticeable	Detectable Noticeable	Distinct Clear	Very clear Very distinct	Outstanding Very strikin

Brightness

Qu.4. Were the lights too bright under these conditions? Yes/No.

Qu.5. Give the degree of brightness experienced on the scale 1 to 6. Low brightness should rate a low number and high brightness should rate a high number. The following descriptions have been associated with the numbers:

1	2	3	4	5	6
Very dim Very dull	Dim Dull	Diffuse Not very bright	Bright Uncom-fortable	Glaring Very uncom-fortable	Intolerable Unbearable

Appraise and mark each question "conspicuousness" and "brightness" separately. Consider the lights only as an onlooker and not as a driver behing them. It is not a competition and there are no right or wrong answers; all your own work, please.

(iii) APPRAISAL FORM (The subjects also had a copy of the appraisal questions.

HEADLIGHTING INVESTIGATION

Name: Sex: Glasses worn: Age:

Date: Position on road:

Run No.	Conspicuousness			Brightness	
	Qu.1 Seen?	Qu.2 Adequate?	Qu.3 Degree?	Qu.4 Too bright?	Qu.5 Degree?
1.	Yes/No	Yes/No	1 2 3 4 5 6	Yes/No	1 2 3 4 5 6
2.	Yes/No	Yes/No	1 2 3 4 5 6	Yes/No	1 2 3 4 5 6
3.	Yes/No	Yes/No	1 2 3 4 5 6	Yes/No	1 2 3 4 5 6
4.	Yes/No	Yes/No	1 2 3 4 5 6	Yes/No	1 2 3 4 5 6
5.	Yes/No	Yes/No	1 2 3 4 5 6	Yes/No	1 2 3 4 5 6
6.	Yes/No	Yes/No	1 2 3 4 5 6	Yes/No	1 2 3 4 5 6
7.	Yes/No	Yes/No	1 2 3 4 5 6	Yes/No	1 2 3 4 5 6

↓

etc., to run No.80.

Circular Size diameter in mm.	Beam	Screen	Intensity (cd) towards subjects (each light)
178	High	-	53,000
	High	N.D.filter	14,000
	High	N.D.filter	4,000
	Low	N.D.filter	1,500
	Low	N.D.filter	240
	Low	Diffuser	9.5
	Low	Diffuser	2.4
	Low	Diffuser	0.75
102	High	-	37,000
	High	N.D.filter	10,000
	High	N.D.filter	2,800
	Low	N.D.filter	550
	Low	N.D.filter	110
	Low	Diffuser	6.1
	Low	Diffuser	1.6
	Low	Diffuser	0.50
56	High	-	5,500
	High	N.D.filter	1,500
	High	N.D. filter	430
	Low	N.D.filter	160
	Low	N.D.filter	30
	Low	Diffuser	2.4
	Low	Diffuser	0.60
	Low	Diffuser	0.19

Note : (i) Due to variations in aiming, voltage regulation and observer position the maximum variations in intensity will be within $\pm$ 25% of those stated.

Table 13.1. Details of lights used in experiment.

	Road name	Road type	Lantern arrangement	Lantern type	Road luminance
1	University	Residential Single Carriageway	Single Side H = 4 m S = 33 m W = 5 m	Post top 32 watt Fluorescent	Av = 0·06 cd/m² — Dark Surrounds
2	Croftdown Road	Traffic route Single Carriageway	Staggered H = 9 m S = 28·5 m W = 10 m	C.O. Reflector 250 watt MBFU	Av = 0·25 cd/m² Max/Min = 3 Dark Surrounds
3	Wolverhampton Road (A.4123)	Traffic route Dual Carriageway Narrow Median	Opposite H = 10 m S = 46 m W = 15 m	S.C.O. Refractor 135 watt SOX	Av = 1·35 cd/m² Max/Min = 3 Light Surrounds
4	Pebble Mill Road	Traffic route Dual Carriageway Wide Median	Single Side H = 9 m S = 27 m W = 7 m	C.O. Reflector 400 watt MBFU	Av = 1·2 cd/m² Max/Min = 1·5 Dark Surrounds

Note: H, S and W, refer to the height and spacing of lanterns and widths of road between kerb lines respectively.

The first three sites were used for static observations, the last for those with moving cars.

Table 13.2. Details of test sites.

Session		Number of subjects	Age Mean	Age Range	Male/Female	Glasses/ Unaided vision
Site 1.	Static	12	26	23–31	8/4	8/4
Site 2.	Static	12	32	22–58	9/3	4/8
Site 3.	Static	13	30	23–58	11/2	7/6
Site 4.	Moving	13	31	22–58	11/2	7/6
Site 4.	Moving	11	30	22–58	8/3	3/8

Table 13.3. Details of subject groups.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	% No Responses
Age	48	29	25	24	22	26	25	25	35	58	29	34	
Sex	F	M	M	M	M	M	M	F	F	M	M	M	
Glasses	-	-	YES	-	-	YES	-	YES	-	-	-	YES	
Increasing Intensity in eight steps ↑	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	- Y Y	Y Y Y	Y Y Y	- Y Y	Y Y Y	Y Y Y	0
	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	0
	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	0
	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y N Y	Y Y Y	N - Y	Y - Y	Y N Y	8.9
	Y Y Y	Y Y Y	Y Y N	Y Y N	Y Y Y	Y Y Y	Y Y Y	Y N N	Y Y Y	N N Y	N Y N	Y N N	27.8
	N Y N	N N N	Y N N	Y N N	Y N Y	N N N	N N N	N N N	Y Y Y	N N N	N N N	N N N	77.8
	Y N N	N N N	N N N	N N N	N N N	N N N	N N N	N N N	N Y N	N N N	N N N	N N N	94.4
	N - N	N - N	N - N	N - N	N - N	N - N	- - N	N - N	N - N	N - N	- - N	N - N	100

Table 13.4. The pattern of yes (Y) and no (N) responses to the question "was the light adequately conspicuous". (For 3 repetitions of 8 intensities presented at random; the dashes are lapses in presentation or response. Site: Croftdown Road. Light size: 56mm dia.)

Site	Light size (mm dia)	Conspicuity % finding I value 'Adequate' 50%	95%	Brightness % finding I value 'Too Bright' 50%	5%
University (1 static car)	178	3	100	4800	960
	102	3	170	3300	160
	56	7	370	2800	93
Croftdown Road (1 static car)	178	6	83	1100	68
	102	6	120	850	60
	56	13	270	740	66
Wolverhampton Road (1 static car)	178	11	85	3300	430
	102	38	680	1700	130
	56	19	210	1900	120
Pebble Mill Road (1 moving car)	178	6	76	2300	96
	102	7	50	1400	100
	56	13	120	2100	89
Pebble Mill Road (3 moving cars)	178	7	71	5200	530
	102	6	43	2800	360
	56	11	76	1500	100

Table 13.5. Values of light intensity (Icd) evoking a given level of response.

Light size (mm dia)	Conspicuity % finding I value 'Adequate' 50%	95%	Brightness % finding I value 'Too Bright' 50%	5%
178	6	82	2900	270
102	8	120	1800	140
56	12	180	1600	91

Table 13.6. Intensity requirements (Icd) for each light size, averaged over all sessions, to evoke a given level of response.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	Average Value
Increasing intensity in eight steps ⟶	5 6 4	4 4 5	5 5 5	4 5 4	5 6 5	5 5 5	- 5 6	5 4 4	6 5 5	- 4 4	4 5 5	5 6 5	4.85
	4 2 4	5 3 4	4 4 5	3 4 4	5 5 4	6 5 4	5 5 5	5 4 3	5 5 5	5 4 4	4 4 4	5 4 5	4.33
	4 4 4	2 3 4	4 4 4	3 4 4	5 4 3	4 5 4	5 4 4	3 3 3	5 6 5	3 4 4	4 3 2	4 3 5	3.86
	3 3 3	4 4 4	4 4 5	4 3 4	4 4 4	4 3 5	4 4 4	4 2 3	4 4 5	4 - 3	4 - 4	4 3 3	3.76
	4 3 4	4 3 3	3 4 3	5 3 3	3 3 4	4 4 3	3 3 3	3 2 2	3 4 4	2 3 3	2 3 3	3 2 2	3.14
	2 3 2	2 2 3	2 3 1	3 2 2	3 2 2	2 2 2	3 2 3	2 2 1	3 3 2	2 2 2	1 2 1	2 2 2	2.14
	3 2 2	2 2 3	2 1 1	2 2 2	2 1 2	2 1 1	1 2 2	2 2 2	2 2 2	1 2 2	1 2 2	2 2 2	1.83
	1 - 2	1 - 2	1 - 1	2 - 2	1 - 1	2 - 1	- - 2	1 - 1	1 - 2	1 - 1	- - 1	1 - 2	1.36

Table 13.7. The pattern of responses to placing a light on a scale of conspicuousness. (Experimental conditions as in Table 13.4.)

Site	Conspicuity scale			Brightness scale	
	2·5	3	4	4	4·5
University	3·0	10	280	2500	6300
Croftdown Road	3·5	14	450	2000	4500
Wolverhampton Road	8·0	25	500	2500	4500
Pebble Mill Road	6·0	22	450	1000	4000
Mean I	5·0	17	410	1900	4700

Table 13.8. Values of light intensity (Icd) evoking the given scale values of conspicuity and brightness.

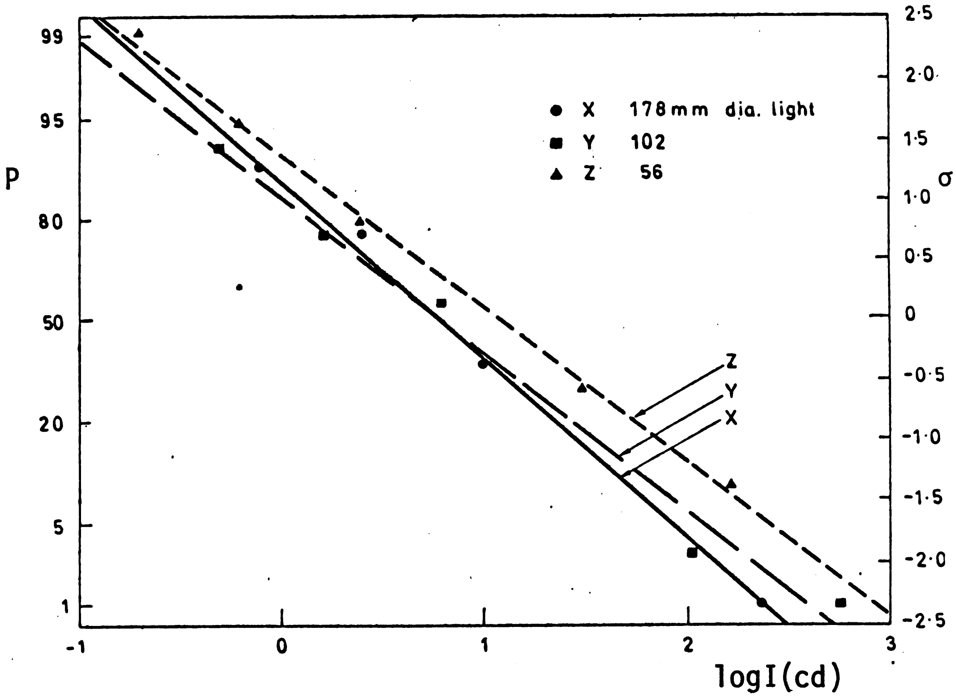

Fig. 13.1. Percentage probability (P) and its standard deviation (σ) of a "NO" response as to a light of intensity (I) being adequately conspicuous: Croftdown Road site.

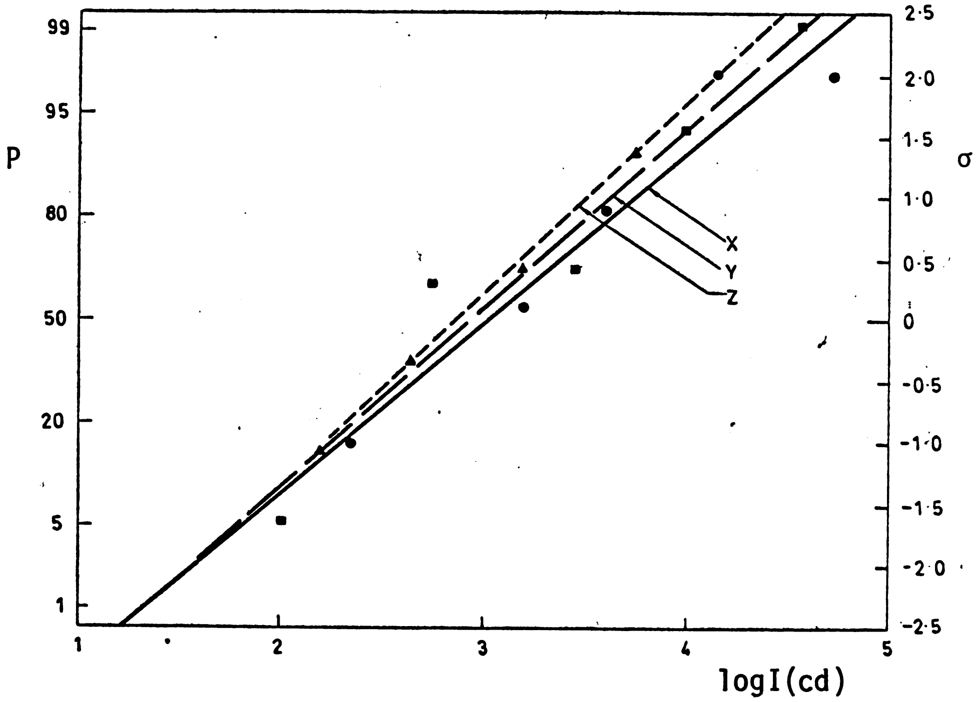

Fig. 13.2. Percentage probability (P) and its standard deviation (σ) of a "YES" response as to a light of intensity (I) being too bright: Croftdown Road site.

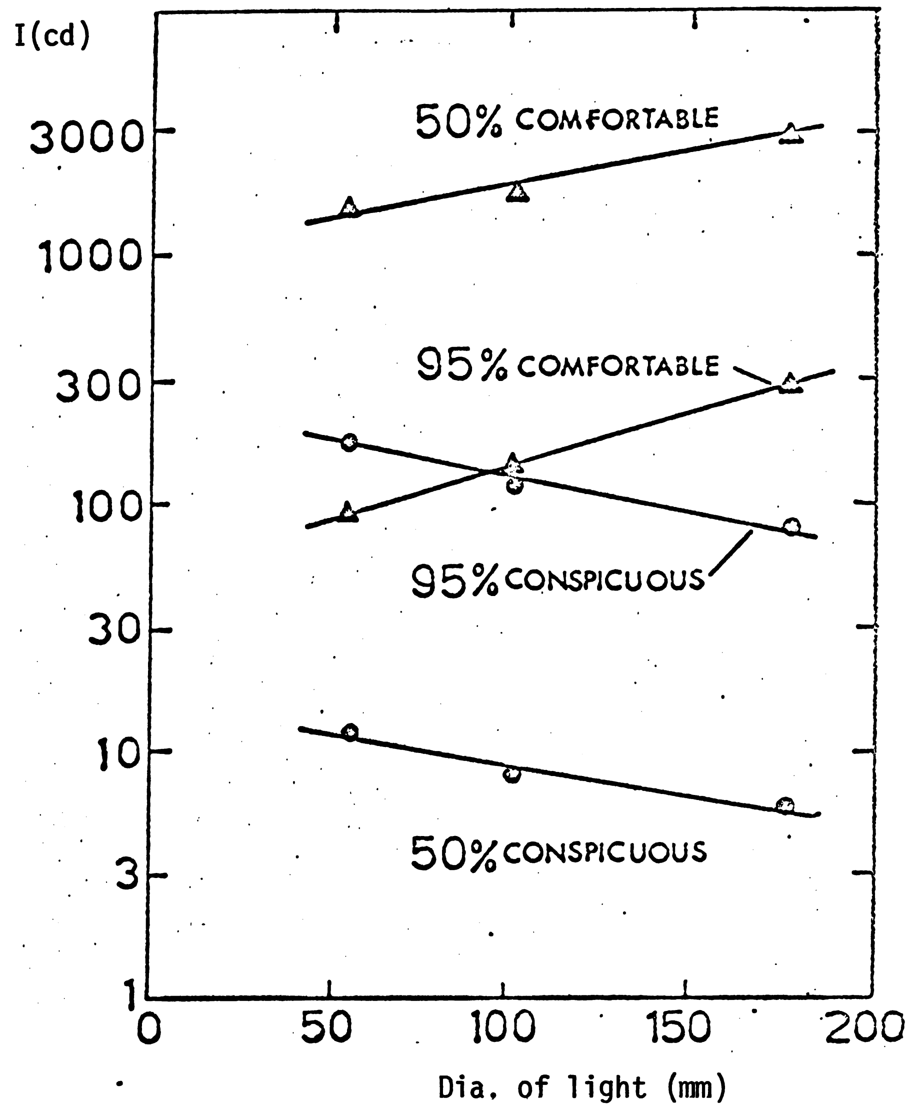

Fig. 13.3. The relationship between the intensity of a light (I) and its size for a given subjective response.

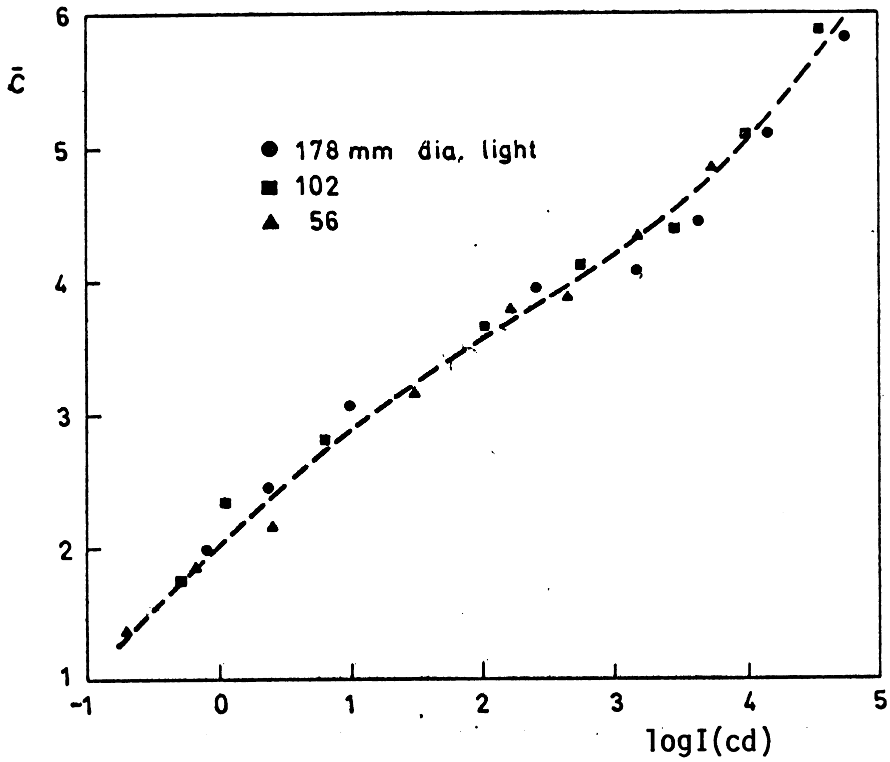

Fig. 13.4. Mean group appraisal rating of conspicuity ($\bar{C}$) for lights of intensity (I): Croftdown Road site.

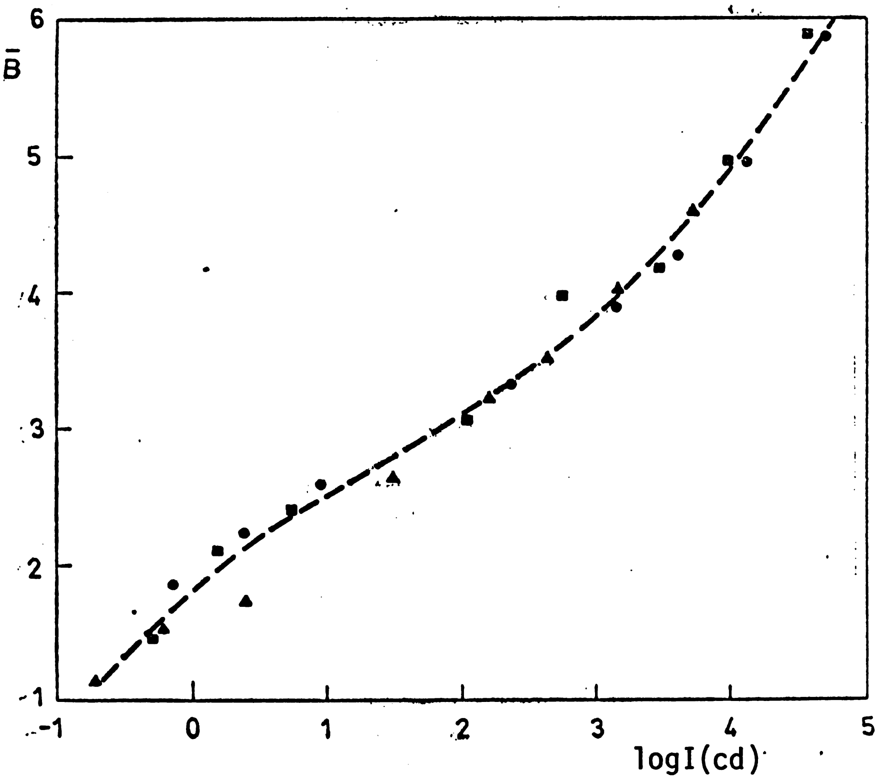

Fig. 13.5. Mean group appraisal rating of brightness ($\bar{B}$) for lights of intensity (I): Croftdown Road site.

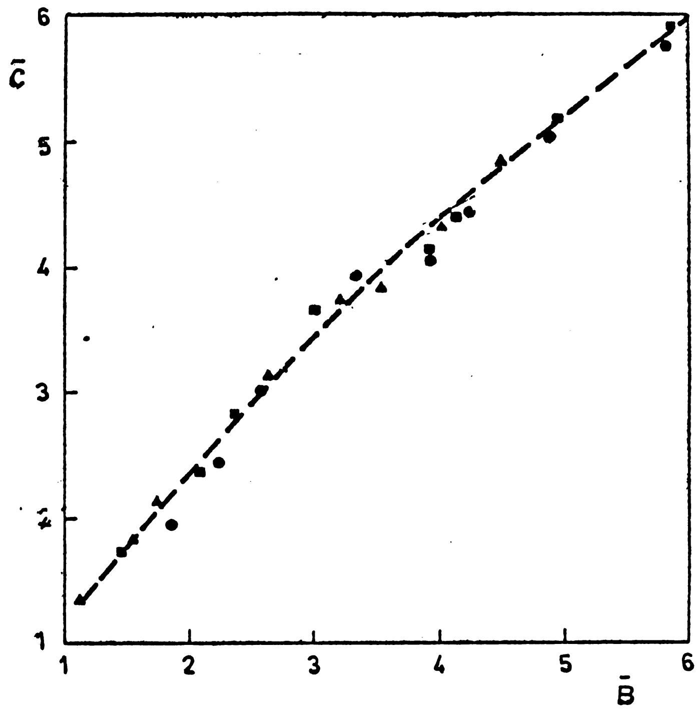

Fig. 13.6. The variation of mean group appraisal rating of conspicuity ($\overline{C}$) with mean group appraisal rating of brightness ($\overline{B}$): Croftdown Road site.

CHAPTER 14

CONCLUDING SUMMARY

The thesis opened by making the hypothesis that the intrinsic low light level at night leads to poor visual performance in individuals which is responsible for poor task or driving performance. Poor individual performance is then reflected in lower traffic system efficiency which can be improved if the light level is raised. It was shown that the accident rate is higher by night than by day but this can be mitigated by the provision of good street lighting.

It is argued that detailed lighting requirements can only come from the analysis of individual visual and task performance. The importance of informal information, the plethora of detail in the scene which supply subtle cues necessary for driving, as well as formal information, such as signals, signs and markings, is stressed. However, in general, standard visual tasks are used in investigations to typify the visual task.

It has been shown that basic data on two aspects of vision, contrast sensitivity and disability glare, can be used to explore specific problem areas in detail. In arriving at lighting attributes it is necessary to place these in the context of one or other of the two established modes of lighting roads: street lighting or vehicle headlighting.

Review of street lighting research and practice shows that the mechanisms and necessary attributes of street lighting are well established. A modest level of lighting, in terms of road surface luminance of about 1 cd/m^2, provides satisfactory visual conditions provided luminance uniformity and glare restriction are good. A survey of installations designed to the then Australian Code of Practice, involving detailed field measurements, showed that design objectives were in general being realised. Some recommendations on upgrading practice have been incorporated in the subsequent revision of the Code, AS 1158, Part 1.

Two problem areas were established for analysis: it was found that the surrounds to the carriageway against which objects can be viewed are often dark and that high values of disability glare occurred in some installations. The relationship between visibility, background luminance and glare was analysed and a combination of low background luminance and glare was shown to seriously affect visibility expressed in terms of revealing power. Recommendations are made on installation design employing lanterns emitting a significant component of light onto the surrounds and with good glare control.

In order to assist lighting equipment manufacturers and lighting engineers to understand the disability glare requirements of lanterns, a relationship between glare and parameters of the lantern light distribution has been developed. The same parameters I_{80} and I_{88} that are used in the international method of assessing discomfort can be employed. Values of the parameters are suggested for degrees of glare control.

From the review of vehicle headlighting the conclusion is reached that conventional lighting has been exploited to the full, but visibility is still poor and uncomfortable. Lack of a break-through results from basic vision and engineering constraints.

It is suggested that further technical innovations, such as sharp cut-off lower beams, could exacerbate the situation because of in-service degrading factors. It is recommended that the status quo is maintained in conventional lighting. Radical improvement on otherwise unlit non-urban roads can only come about by unconventional means, polarised headlighting.

One innovation is an increase in intensity of upper beams. The hypothesis is made that any increase will make this beam virtually unusable in traffic because of the discomfort to oncoming drivers in the early stages of vehicle meetings. Field trials have given a relationship between comfort rating of a vehicle meeting, upper beam intensity and the intercar distance on dipping of lights. The data show observers to be critical of present upper beams if dipping is carried out only at the minimum intercar distance allowed by law. With increased intensity the discomfort rating rises dramatically, indicating either lights will be dipped when vehicles are a great distance apart or, if not dipped, that they will cause great discomfort.

In addition it is shown that seeing distance (d) is related to upper beam intensity (I) approximately by the expression $I = kd^4$. Thus practical increases in beam intensity will give little increase in seeing distance, when the upper beam can be used, to off-set a large increase in discomfort in vehicle meetings. Thus there is an upper limit to visibility distance with headlights (even using polarised lights), constrained by the limits of the human visual system. The safe speed of driving needs to be tailored to this fact.

The two lighting modes interact on urban roads: a review suggests that the use of headlights in good street lighting is an inefficient way of providing marker lights on moving cars. Headlights produces discomfort glare which street lighting engineers take pains to avoid in designing street lighting. Visibility and safety is probably impaired.

An analysis of the visibility of objects viewed against road surrounds shows that glare from vehicle headlights affects visibility in general. The additional illumination improves visibility marginally when the vehicle is close to an object.

Allowing street lighting to be the lighting mode, then moving vehicles need to have a conspicuous glare free marker: a town beam. Observers had a significant preference for a town beam after observing it and normal lower beam headlights in a simulated traffic stream. Further appraisals of a range of lighting parameters showed, using a 50% observations satisfied criterion, that a light must be less than about 1000cd so as not to cause discomfort and above about 10cd to be conspicuous. For 95% of observations to be satisfactory the light had to be about 100cd to be both conspicuous and comfortable.

However, area of the source has an effect: with equal illuminance at the eye a small bright source is judged more discomforting but less conspicuous than a larger less bright source. The optimum town beam is a light the size of present headlights with a straight ahead intensity of 80cd.

The ideal lighting for night road use appears to be good street lighting for urban areas, with vehicles using town beams, and polarised headlights for rural roads. There is sufficient knowledge on the human visual system and its lighting needs at night, on the mechanisms and necessary attributes of lighting equipment to state this with confidence. However, ideal lighting needs a planned government-industry approach, a national lighting programme for its implementation. The alternative is a continuation of the present piece-meal approach using current equipment but hopefully with a greater realisation of the limitations of the system and an attendant lowering of expectations of the level of road service at night.