THE RELATION BETWEEN LIGHTING PARAMETERS AND TRANSPORTATION PERFORMANCE

R-78-6

D.A. Schreuder

Voorburg, 1978

Institute for Road Safety Research SWOV, The Netherlands

ABSTRACT

Lighting for road traffic is utilitarian in essence. Its technical requirements (geometry and photometry) must therefore be based on its function for road traffic: safety, speed and comfort, taking costs into account. The paper deals with the relationship between these requirements and these functions. Emphasis is placed on safety; comfort in a further consideration. As regards safety, the chain between costs and effectiveness (i.e. transportation performance or accident reduction) will be split in its elements. Each element can be studied separately, the chain to be followed from both ends: the supply side and the demand side. Costs lead at the supply side to the supplied conspicuity level whereas the accident reduction leads to the conspicuity level required. Future recommendations will have to ensure that the level supplied always exceeds the level required.

The approach presented in the paper - the functional approach - promises results, in contrast to the traditional approach that considers only the visibility of a standard task, defined *a priori*. The reason is that these *a priori* tasks have no demonstrable relationship to the actual driving task in real traffic situations.

Further detailed research is still required.

1. INTRODUCTION

Road lighting is expensive, regarding both costs and energy. Therefore these costs should be justified by benefits. Thus, road lighting is considered as utilitarian. Benefits are considered to be found in four slightly overlapping domains:

- road traffic and transportation performance
- public safety
- amenity
- aesthetics.

This paper will be restricted to the traffic and transportation performance.

In the past road transportation was viewed upon from the economic viewpoint alone; so, the cost-effectiveness considerations were simply a matter of book-keeping. Recently, however, it has been realised that road transportation has an extremely wide impact on the community. The function of various facilities - amongst which road lighting - is to ensure that the transportation can take place optimally. The function is usually described as allowing the road user to reach his destination safely, speedily, comfortably, and with minimum costs. Thus, cost-effectiveness considerations - also those for road lighting - are more complicated than book-keeping only. It is usually assumed - be it without scientific ground - that all requirements as regards road lighting for safety, speed and comfort are similar, and they increase in that order in respect to their severity. Thus, safety can be considered as the basic aspect, the others only increasing the load on the lighting.

The effectiveness of road lighting installations as compared with no lighting at all can be estimated on the basis of traffic accident studies. Usually they are of the before - and - after study type: the number of accidents before the installation of the road lighting is compared with the number of accidents after installation, appropriate correction being made for variations in travel, weather, other alterations on the road etc. As a result of methodological restrictions, the number of investigations that yield valid data is relatively small, but they all suggest a reduction of some 30% in night-time accidents. (1, 2, 3, 4, 5, 6, 7, 8, 9, 10.) This holds for "good" lighting installations as compared with very little lighting or no lighting at all. In order, however, to find out how good the lighting should be in order to be considered as "good" in cost-effectiveness consideration, this approach does not give useful results. The reasons for this are that only in a few cases the change in lighting installations proves to be applicable in before - and - after studies, that the number of accidents is too small and their registration not accurate enough to permit a rigorous statistical treatment, and - probably most important - the effectiveness of lighting seems to depend not only on the lighting level, but also on the type of road and traffic. Therefore, for a more detailed study, also more detailed methods have to be applied, in order to be able to compare lighting installations of different quality levels in terms of their accident reduction potential. As will be indicated in this paper, such a more detailed study will require the subdivision of the problem in a set (a chain) of sub-problems. This chain is indicated in Figure 1; the separate elements of this chain will be described in detail in the Sections 3 and 4 of this paper. Further study areas pertain to including driving comfort and transport aspects.

It should be pointed out that this approach is not a very recent development. However, the pionier work of Dunbar (11), Smith (12) and Waldram (13) passed unnoted, and usually - if considered at all - the aim of road lighting was supposed to be as closely to daylight as possible. The more recent "functional approach" aims at a more realistic view (14, 15). Furthermore, the fundamental work of Hopkinson (16) on discomfort effects should be mentioned.

2. THE ANALYSIS OF THE PROBLEM

Depending on whether the problem is to design or assess lighting installations one of the following questions should be asked:

- which are the requirements on lighting and installation parameters (and thus what are the costs) of a lighting installation that ensures a certain effectiveness (to be expressed in terms of accident reduction).

or:

- what is the effectiveness of a lighting installation that shows certain characteristics as regards the lighting and installation parameters (and thus as regards costs).

Clearly, these two questions indicate two approaches of the problem, which can be described aptly as related to "demand" and "supply". Equally clearly, lighting installations can be qualified only as "adequate", "good" etc. if the supply equals or exceeds the demand.

There are many ways to improve night-time traffic. Road lighting, amongst them, centres on the fact that nearly all information needed for participating in traffic (as driver, as well as pedestrian) is of visual origin. Therefore it seems natural to use the visual information supplied and required respectively as the main concept. As in most cases the visual information is related to the degree in which objects are conspicuous, it is suggested that the amount of visual information is expressed in levels of conspicuity.
In this way, the cost-effectiveness-assement is split up in two main problem areas
a) how is the supplied conspicuity level related to the lighting and installation parameters?
b) how is the demanded (required) conspicuity level related to the travel performance (e.g. to be expressed in terms of accidents or accident reduction)?

These two problem areas are connected by the requirement for "adequate" lighting: the supply should be equal or larger than the demand. See again Figure 1.

It should be noted that in the above it is assumed that the actual costs of a specific lighting installation, of which the installation parameters are known, can be calculated.

3. THE RELATION BETWEEN LIGHTING AND CONSPICUITY

This relation is in fact the "supply" part of the total chain. This part, again, can be subdivided in a number of separate steps. For our considerations, we will use the installation parameters as a starting point, taking into account that usually the actual costs can be assessed when the installation parameters are known. See (b) and (a) in Figure 1.

The installation parameters represent the actual lighting installation. They include the geometry (spacing, mounting height, road width, overhang, arrangement) the lamp/lantern characteristics (I_{80}, I_{88}, luminous flux, LSI etc.) and the road surface characteristics (such as q_o and x_p; q_o, S_1, S_2; or probably other characteristics). In most cases, all data are available, and usually they will be available even before the actual realisation of the installation.

When the installation parameters are known (or are selected) it is possible, on the basis of the systems and programmes as proposed by the CIE (17) to perform the next step: the assessment of the lighting parameters. The general system is worked out in detail in the CIE Publication No. 30 (18). This requires a complete information as regards the light distribution (I tables) and of the reflection properties of the road (R tables) and, of courese, of the other data.

It has been argued that a lighting installation can be described by a number of lighting (or photometric) characteristics, viz.: the average road surface luminance and its uniformity, the Glare Control Mark, the Threshold Increment and the visual guidance (18, section 2). To a certain extent, when setting up these characteristics, visibility and driving performance aspects have been taken into account. Therefore, it is to be expected that a further and more systematic consideration of these aspects requires an adaption (extension, change) of these characteristics. Furthermore, dynamic aspects have not been fully taken into account.

The photometric characteristics represent an intermediate step between the installation and the conspicuity. For this purpose they can serve rather well, although in essence they are not a homogenous set: the Treshold Increment is exclusively a matter of visual performance; the luminance and the uniformity combine aspects of visual performance and visual comfort; the G mark is exclusively a matter of visual comfort (by definition) and the visual/optical guidance is a matter of traffic performance combined with visual comfort. In the past, however, the criteria have been considered to a certain extent as having a basic function of their own. Apart from the theoretical shortcomings in this view, and from the rigidity in lighting engineering they sometimes provoke, the major draw-back of this way of looking at the matter is in the fact that the criteria are usually considered as independent factors each of which calls for its own minimum value. Thus, the CIE Recommendations state that for a particular type of road L_{av} should exceed 2 cd/m^2, and the uniformity should be better than 0.4 and G should exceed 6 and TI should be lower than 10%. A more fundamental approach, allows for investigations of the type: "if G is 8, and the uniformity 0.6; it is allowed-possible-adviseable- to decrease the minimum for L_{av} to 1.8; or 1.5; or 1.0?" Obviously, answers to questions like that are important for practical lighting design. (See e.g. 3, 19).

The lighting parameters are considered to describe the visual environment in adequate detail in order to assess the visibility. (The visual quidance and the G-mark play no part in this.) This statement, although plausible, requires further confirmation. It depends on the desired accuracy in how far the statement can be applied. As a first approximation, the average road surface luminance is sufficient for many types of problems, as it usually approaches the level of adaptation fairly well. On the other hand, for the description of the visual environment as prevailing in actual traffic, the characteristics quoted above are not sufficient: dynamic effects are not included, nor glare for other light sources and the influence of the luminance of the surrounds of the roads (shoulders, sidewalks) on the adaptation level is not fully known. Thus, results from this approach can be applied for a restricted group of traffic situations only. This should be kept in mind when the findings for e.g. busy town streets are to be applied on rural motorways. It is precisely to handle these hereto unknown factors, that the approach from the "demand" side is being developed.

When the visual environment is defined, the visibility can be assessed directly on the base of the system adopted by the CIE (20). The validity of the approach is assessed by a great number of investigations (3, 21, 22, 23, 24, 25, 26, 27, 28). Although some discrepancies did show up, in general there seems to be a good agreement between the actual measurements and the theoretical framework that is developed primarily on the basis of laboratory experiments.

However, this approach to arrive at a set of requirements for road lighting installations that ensure a pre-selected degree of road traffic and transport performance has come to a complete dead-end. Although the visibility can be assessed to a very precise degree, the results are of no practical value.

Visibility can be assessed only for a distinct object. Furthermore, the appropriate definition of the concept "visibility" itself includes implicitely aspects of the task of the observer. It is customary to make certain assumptions in these two respects (usually the object is taken as a small cube or something similar, and visibility is taken as to be equivalent to threshold perceptibility). The results of this exercise are inconclusive for matters regarding road safety; this results from the fact that from the visibility and lighting studies there is no possibility to find out whether the assumption are in any way related to what is relevant in traffic. The only thing that emerges is the suspicion that the visibility as defined in this way has, in fact, very little to do with traffic. Therefore, "field factors" amounting to a factor ten to thirty are included. These field factors actually reflect the common sense and the experience of the investigator, both as lighting designer and as a road user. This again explains why actual road lighting installations usually perform quite well (as may be seen from the studies on accidents statistics as quoted earlier) although the fundamental questions were not answered at all. However, the foregoing also explains that important but rather precise questions like the minimum required levels of luminance for motorways (1 or 2 cd/m^2) cannot be answered, and that new developments, for which no experience does exist, can be perfected only by means of very expensive and very time-consuming trials.

As a summing up: the selection of (sets of) standard visual tasks <u>a priori</u> is useless, and selection on the basis of visibility considerations is dubious. The first does not give any information that can be applied with good confidence in road situations; the other, representing in essence a circular argument, only serves to hide the real problems behind a curtain of beliefs and assumptions. The <u>only</u> valid basis for definition of "standard" visiual tasks is the actual requirement in road traffic.

The way-out of this impasse is suggested to be the functional approach. This will be a major part of future research in this field. In essence, it consists of considering the "demand" side of the conspicuity level. (It may be noted here in passing that the term conspicuity level is preferred to the term visibility, in order to indicate the fact that one of the major problems at hand is to find the aspects of visibility that are really relevant for road traffic).

4. THE RELATION BETWEEN CONSPICUITY AND ROAD SAFETY

As indicated earlier, of all benefits of road lighting, only the road traffic and transportation performance is considered in this paper, and from this only the road safety expressed in accident reduction potential. Now, a further restriction will be introduced: furtheron we will deal exclusively with drivers of vehicles (or passenger cars) when the "users" of the lighting are considered - users meaning here those individuals that use the lighting in order to improve their possibilities for observation in the road. Thus, pedestrians are considered as "objects" and not as road users. All these restrictions are not of a fundamental value. They are introduced only to reduce the size of the discussion; all arguments, and all conclusions, can be restated in such a way that they include other types of benefits, other criteria of quality of travel, and other road users - the common idea being the fact that in all cases the lighting serves a well defined purpose, and is therefore utilitarian.

The benefits of road lighting as regards car drivers can be expressed in the number of accidents that are prevented by the lighting. This has looseley been described as the accident-reduction potential of the lighting. More precisely, these benefits could be expressed as $N = f(Q)$ where N is the number of accidents still occurring and Q the quality of the lighting. It is the first research item to define Q in such terms that this function can be applied.

As indicated earlier, this functional relationship cannot be established directly from accident statistics. Not only the description of Q is lacking; in order to approximate a function relationship, the "steps" in Q should be small, and thus the differences in consecutive steps in N.

This holds even more if one looks for the minimum admissable value of Q. For this, the relationship is usually taken as having an asymptote N_∞ in N for high Q. The minimum admissable value of Q is that value where $(N - N_\infty) < \varepsilon$, ε being small, and in magnitude depending on the amount of social concern. This implies that when $N = f(Q)$ is not known as a real (continuous) function, it should at least be known in steps smaller than ε . This is illustrated in Figure 2. The establishment of this (quasi-)function directly from accident statistics data requires an enormous experimental effort. The reason for this is, that accidents, being occurrences that happen relatively seldom, can be described by a stochastic process (a Poisson-distribution which can be approximated by a normal distribution). Now, in order to distinguish between two normal distributions that differ only slightly in their mean values (the step ε) the samples to be taken must be large. The length of road network available for the experiments is very large as well. This makes it virtually impossible to perform this analysis within a reasonable time and costs budget.

As a possible way out of these difficulties, it is suggested to split up the relationship between conspicuity and road safety in a number of separate steps, as indicated in Figure 1. It is suggested to include the (analysis of the) driving task as one of the intermediate steps. As has been argued in other places in great detail (29, 30, 31, 32) the driving task can be described in an hierarchy of decision processes. See Figure 3. The hierarchical level that is of most importance for our subject is the lower, in which the manoeuvres are described. Thus, the actual handling of a vehicle can be described as a series of manoeuvres, each of which is performed after a decision to do so, a decision which is based amongst other things on the (visual) information regarding the oudside world. For each manoeuvre there can be defined a "space" required for the adequate performance of the particular manoeuvre; furthermore, the available "space" can be defined as well. "Space" should be understood here in a very general sense; the space is determined not only by the border of the roadway, but by the manoeuvrability of the vehicle, the ability of the driver, the presence and the manoeuvres (actual of planned) of other road users, the visibility, the meteorological conditions, the skidding resistance of the road surface etc.

The actual extent of the space (both the required and the available space) is unknown. The driver has to base his decision to undertake a certain manoeuvre, or not, on the estimations he makes regarding the extent of the space. It may be assumed that the estimation of the required space is not a visibility matter but rather a matter of the amount of confidence in road-holding of the vehicle, driving ability of the driver, etc. The estimation of the available space, however, is clearly a matter of visibility. Now, there are three possibilities: the actual extent A of the available space is larger/smaller/equal than the estimated extent A'. A more detailed consideration leads to the preference for A'=A. Thus the lighting should be so that A can be estimated correctly.

Vaguely, this idea is behind the requirement that the visibility distance of objects must be at least equal to the minimum stopping distance. However, if one selects a visual task that corresponds to an object for which the driver really has to stop - e.g. a truck parked on the roadway - the visibility distance becomes unrealistic large. Furthermore, trucks have signalling lights or at least reflectors. Therefore, one usually selects a very small object (the notorious 20 x 20 cm^2 dull grey box) which, however, is not a thing drivers usually have to stop for. This precisely is the impasse we indicated in an earlier section: the way-out is the consideration that there are many objects that can present themselves and that there are a number of possible manoeuvres from which the driver has to select one, after he had the opportunity to see, and recognise the object, and has had the opportunity to make an assessment of the pro's and con's of the different manoeuvres. And it is the analysis of the driving task that permits us to state which are the possible manoeuvres under certain circumstances and which is the most appropriate. For the different manoeuvres and for the different conditions under which they have (may have) to be performed, the required space to manoeuvre can be assessed, taking into account the actual or the average value of vehicle performance, road characteristics and driver ability. Taking into account the characteristics of the object that requires this particular manoeuvre, the visual environment can be described that will enable the actual or the average driver really to observe the object. This visual environment corresponds with the "demand" side, with the required conspicuity level. Now, finally, the lighting installation should be such that the "demand" does not exceed the "supply".

In this way the "chain" of installation parameters to road traffic and transportation performance is complete. It should be noted, however, that in the analysis given above, specific aspects of vision and lighting come only in the last two steps! A major part of the future research mentioned in this paper is on the programme of the CIE Technical Committee TC 4.6 on Road Lighting.

5. CONCLUSIONS

The effectiveness of good road lighting as compared with no lighting at all can be decided from the result of traffic accident studies. When one seeks to know how good is "good" in this respect, accidents are not frequent enough and not recorded accurately enough to proceed in the same way. The chain between costs and transportation performance is split up in smaller parts; the costs (and the installation parameters closely related to them) stand for the "supply" side and the road traffic and transportation performance (and the accident reduction potential, closely related to this) forms the "demand" side. For good road lighting, the supply should equal or exceed the demand.

The chain is followed, starting from both sides simultaneously. The supply side gives the supplied conspicuity level; the demand side leads to the required conspicuity level. Again here, the supply should equal or exceed the demand.
The supplied conspicuity level can be derived from the installation parameters by means of well-established methods. A similar derivation of the required conspicuity level from the traffic and transportation performance requires further research. The traditional method, where one or maybe two standard visual tasks are postulated as being representative for driving, is completely unsatisfactory and may even lead to erroneous results.

REFERENCES

(1) Street lighting and accidents. Publication No. 8. Paris (1960) Commission Internationale de l'Eclairage CIE.

(2) CORNWELL, P.R.; G.M. MACKAY. Lighting and road traffic (I). Traffic Engng. & Control (1972) 142-144.

(3) DE BOER, J.B. ed. Public lighting. Eindhoven (1967) Centrex.

(4) DUFF, J.T. Road lighting and accidents. Report to CIE TC 4.6. (Not published).

(5) BOX, P. Relationship between illumination and freeway accidents. Illum. Engng. 61 (1971) 365-393.

(6) Lighting, visibility and accidents. Paris (1971) Organisation for Economic Co-operation and Development.

(7) BOER, J.B.; SCHREUDER, D.A. New developments in road and street lighting with a view to road safety. In: Intertraffic '72. Amsterdam (1972) RAI.

(8) TAN, T.H. Wegverlichting in de praktijk (The practice of road lighting). In: (33).

(9) FISHER, A. Road lighting as an accident counter measure. In: (10).

(10) Measures of road lighting effectiveness. Symposium 1977, Karlsruhe. Paris (1977) Commission Internationale de l'Eclairage CIE.

(11) DUNBAR, C. Necessary values of brightness contrast in artificially lighted streets. Trans. Ill. Engng. Soc. (London) 3 (1938) 187.

(12) SMITH, F.C. Reflection factors and revealing power. Trans. Ill. Engng. Soc. (London) 3 (1938) 196-200.

(13) WALDRAM, J.M. The revealing power of street lighting installations. Trans. Ill. Engng. Soc. (London) 3 (1938) 173.

(14) SCHREUDER, D.A. Road lighting and traffic safety; a functional approach. Lux No. 57 (1970) 146-147; 256-263.

(15) SCHREUDER, D.A. A functional approach to lighting research. Tenth International Study Week in Traffic and Safety Engineering. Rotterdam (1970) World Touring and Automobile Organisation OTA.

(16) HOPKINSON, R.G. Discomfort glare in lighted streets. Trans. Illum. Engng. Soc. (London) 5 (1940) 1-24.

(17) Recommendations for the lighting of roads for motorized traffic. Publication 12-2. Paris (1977) Commission Internationale de l'Eclairage CIE.

(18) Calculation and measurement of luminance and illuminance in road lighting. Publication No. 30. Paris (1976) Commission Internationale de l'Eclairage CIE.

(19) ENZMANN, E.; W. ADRIAN. The influence of glare on visual performance and lighting parameters on roads of equal luminance uniformity. In: (10).

(20) An unified framework of methods for evaluating visual performance aspects of lighting. Publication No. 19. Paris (1972) Commission Internationale de l'Eclairage CIE.

(21) DE BOER, J.B. Fundamental experiments on visibility and admissible glare in road lighting. Stockholm (1951) Commission Internationale de l'Eclairage CIE.

(22) DE BOER, J.B. et al. Appraisal of the quality of public lighting based on road surface luminance and glare. Brussels (1959) Commission Internationale de l'Eclairage CIE

(23) WALTHERT, R. Zur Bewertung der Leuchtdichteverteilung beleuchteter Strassen (The assessment of the luminance distribution in lighted streets). Thesis, University Karlsruhe (1973).

(24) BLACKWELL, O.M. & H.R. BLACKWELL. A proposed procedure for predicting performance aspects of roadway lighting in terms of visibility. Journ. IES (1977) 148-166

(25) BLACKWELL, H.R. & O.M. BLACKWELL. A basic task performance assessment of roadway luminous environment. In: (10).

(26) GALLAGHER, V.; P.G. MCGUIRE. Contrast requirements of urban driving. Special Report 156. Washington, D.C. (1975) TRB.

(27) KETVIRTIS, A.; P.J. COOPER. Detection of critical-size object as criteria for determining driver's visual needs. TRB 56th Annual meeting. Washington, D.C. (1977) TRB.

(28) ECONOMOPOULOS, I. Relationship between lighting parameters and visual performance in road lighting. In: (10).

(29) ASMUSSEN, E. Beleid onderbouwd (Support to policy). In: SWOV-congres Toekomst in veiligheid (Proc. SWOV-congress Future in Road Safety). Publ. 1976-4N. Voorburg (1976) Institute for Road Safety Research SWOV

(30) GRIEP, D.J. Analysis of the driving task: System-analytical points of view. Paper presented to OECD Symposium "Road user perception and decision making", Rome, 13-15 november 1972. Voorburg (1972) Institute for Road Safety Research SWOV

(31) SCHREUDER, D.A. De rol van functionele eisen bij de wegverlichting (The role of functional requirements for road lighting). In: (33)

(32) SCHREUDER, D.A. Signaleren in het wegverkeer (Signals in road traffic). Electrotechniek 55 (1977) 254-275

(33) Wegontwerp en wegverlichting tegen de achtergrond van de verkeersveiligheid (Road design and road lighting in relation to road safety). Den Haag (1974) Het Nederlandsche Wegencongres.

Figure titels

Figure 1

A chain of sub-problems linking the costs and the road traffic and transportation performance

Figure 2

A qualitative indication of the relationship between the number of accidents N and the quality of the road lighting Q

Figure 3

A systematic framework for the driving task in terms of a hierarchy of decision making processes

"supply"	[a]	costs
	[b]	installation parameters
	[c]	lighting parameters
	[d]	supplied conspicuity level
"demand"	[4]	required conspicuity level
	[3]	manoeuvre behaviour
	[2]	accident reduction capacity
	[1]	road traffic and transportation performance

$$[a] \leftarrow [b] \rightarrow [c] \rightarrow [d] \rightarrow$$

$$\leftarrow [4] \leftarrow [3] \leftarrow [2] \leftarrow [1]$$

<u>Figure 1</u>.

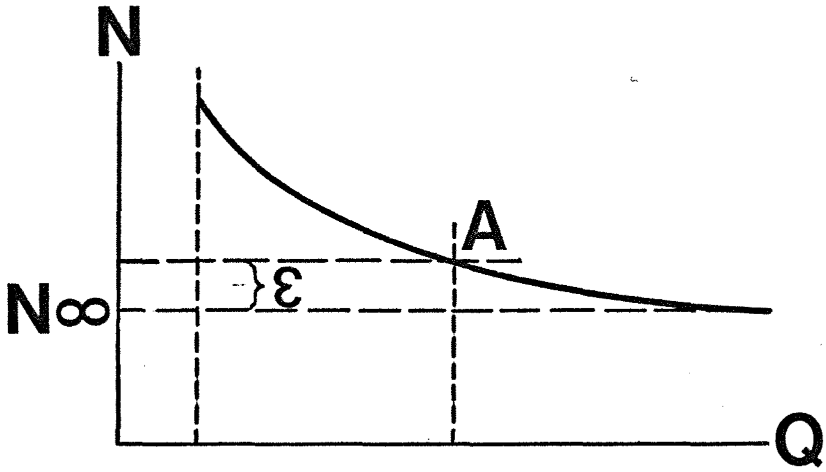

Figure 2.

individual behaviour	collective behaviour
selection of motive	trip generation
selection of destination	trip distribution
selection of mode of transport	modal split
selection of route	assignement
selection of manoeuvre	traffic flow

Figure 3.