Relation Between Lighting Parameters and Transportation Performance

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The relation between the technical requirements for road-traffic lighting (geometry and photometry) and the functions of safety, speed, comfort, and cost is examined. Emphasis is placed on safety considerations. The "chain" between cost and effectiveness (i.e., transportation performance or accident reduction) is broken down into its elements. Each element can be studied separately, and the chain can be followed from both sides—supply and demand. On the supply side, cost leads to the conspicuity level provided; on the demand side, accident reduction leads to the conspicuity level required. Future recommendations must ensure that the level provided always exceeds the level required. The functional approach presented here promises results. It contrasts with the traditional approach, which considers only the visibility for standard tasks defined a priori—tasks that have no demonstrable relation to the driving task in real traffic situations. It is concluded that further detailed research is required.

Road lighting is expensive in terms of both money and energy. Therefore, these costs should be justified by benefits. Road lighting is thus considered utilitarian. Its benefits are found in four slightly overlapping areas: (a) road traffic and transportation performance, (b) public safety, (c) amenity, and (d) aesthetics. This paper is restricted to road traffic and transportation performance.

In the past, because road transportation was viewed from the economic viewpoint alone, cost-effectiveness considerations were simply a matter of bookkeeping. Recently, however, it has been realized that road transportation has an extremely wide impact on the community. The function of various facilities, such as road lighting, is to ensure that such transportation can function optimally. The function is usually described as allowing the road user to reach his or her destination safely, speedily, comfortably, and at minimum cost. Thus, cost-effectiveness considerations, and those for road lighting, are more complicated than bookkeeping only. It is usually assumed that all road-lighting requirements for safety, speed, and comfort are similar, increasing in that order in respect to their severity. Thus, safety can be considered the basic aspect and the others as only increasing the load on the lighting.

The effectiveness of road-lighting installations compared with no lighting at all can be estimated on the basis of traffic accident studies. Usually they are of the before-and-after type: The number of accidents before the installation of road lighting is compared with the number of accidents after installation, and appropriate correction is made for variations in travel, weather, and other changing factors on the road. 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 percent in nighttime accidents attributable to lighting (1, 2, 3, 4, 5, 6, 7, 8). This holds for "good" lighting installations compared with very little lighting or no lighting at all. However, to find out how good lighting should be in order to be considered good in considerations of cost-effectiveness, this approach does not give useful results. The reasons for this are that (a) the change in lighting installations proves to be applicable in before-and-after studies in only a few cases, (b) the number of accidents is too small and their registration not accurate enough to permit a rigorous statistical treatment, and, probably most important, (c) 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, more detailed methods must be applied so that lighting installations of different quality in terms of accident-reduction potential can be compared. Such a detailed study requires the subdivision of the problem into a set (a chain) of subproblems. This chain is shown in Figure 1; the separate elements of the chain are described in detail in this paper. Further study areas pertain to including driving comfort and transport aspects.

This approach is not a very recent development. However, the pioneer work of Dunbar (9), Smith (10), and Waldram (11) passed unnoted, and usually—if it was considered at all—the aim of road lighting was supposed to be to approximate daylight as closely as possible. The more recent functional approach aims at a more realistic view (12, 13). The fundamental work of Hopkinson on discomfort effects (14) should also be mentioned.

ANALYSIS OF THE PROBLEM

One of the following questions should be asked, depending on whether the problem is to design or to assess lighting installations:

1. Which are the requirements on lighting and installation parameters (what are the costs) of a lighting installation that ensures a certain effectiveness (to be expressed in terms of accident reduction)?
2. What is the effectiveness of a lighting installation that shows certain characteristics in relation to lighting and installation parameters (and thus costs)?

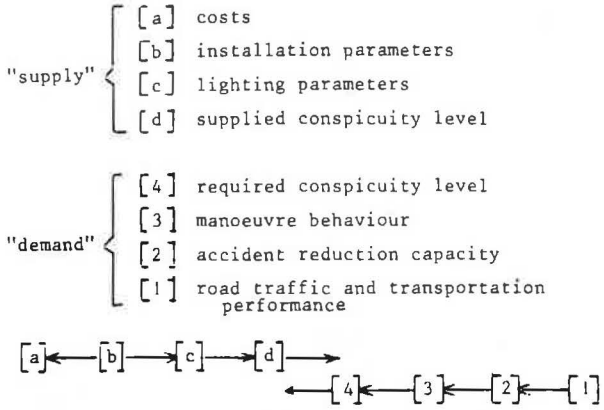
Clearly, these two questions indicate two approaches to the problem that can be described as related to demand and supply. Equally clearly, lighting installations can be qualified as adequate or good only if the supply equals or exceeds the demand.

There are many ways to improve nighttime traffic conditions. Road lighting centers on the fact that nearly all information needed for participating in traffic (as driver or pedestrian) is of visual origin. Therefore, it seems natural to use the visual information supplied and required as the main concept. Because in most cases visual information is related to the degree to which objects are conspicuous, it is suggested that the amount of visual information should be expressed in levels of conspicuity.

In this way, the assessment of cost-effectiveness is split into two main problem areas:

1. How is the supplied conspicuity level related to lighting and installation parameters?
2. How is the demanded (required) conspicuity level

Figure 1. Chain of subproblems linking costs to road traffic and transportation performance.



related to travel performance (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 to or larger than the demand (Figure 1). (It is assumed above that the actual costs of a specific lighting installation, for which the installation parameters are known, can be calculated.)

RELATION BETWEEN LIGHTING AND CONSPICUITY

The relation between lighting and conspicuity is in fact the supply part of the total chain. This part can be subdivided into a number of separate steps. Installation parameters are used here as a starting point in view of the fact that actual costs can usually 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 geometry (spacing, mounting height, road width, overhang, and arrangement), lamp or lantern characteristics (I_{80}, I_{88}, luminous flux, large-scale integration), and road surface characteristics (such as q_o and x_p; q_o, S_1, S_2; or other characteristics). In most cases, all data are available; they will usually be available even before the installation becomes reality.

When the installation parameters are known (or selected), it is possible on the basis of the systems and programs proposed by the International Commission on Illumination (CIE) (15) to perform the next step—the assessment of the lighting parameters. The general system has been worked out in detail by CIE (16). This requires complete information on the lighting distribution (I tables), the reflection properties of the road (R tables), and, of course, other data.

It has been argued that a lighting installation can be described by a number of lighting (or photometric) characteristics such as the average road surface luminance and its uniformity, the glare control mark, the threshold increment, and the visual guidance (16, section 2). To a certain extent, visibility and driving performance have been taken into account in setting up these characteristics. Therefore, it is to be expected that a further and more systematic consideration of these aspects requires adaption (extension or change) of these characteristics. Furthermore, dynamic aspects have not been fully taken into account.

Photometric characteristics represent an intermediate step between the installation and conspicuity. For this purpose, they can serve rather well although in essence they are not a homogeneous set: The threshold increment is exclusively a matter of visual performance, luminance and uniformity combine aspects of visual performance and visual comfort, the G mark is exclusively a matter of visual comfort (by definition), and 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 to have a basic function of their own. Apart from the theoretical shortcomings of this view and the rigidity in lighting engineering they sometimes provoke, the major drawback of this way of looking at the matter is that the criteria are usually considered as independent factors, each of which calls for its own minimum value. Thus, CIE recommendations state that, for a particular type of road, L_{av} should exceed 2 cd/m^2, the uniformity should be better than 0.4, G should exceed 6, and TI should be lower than 10 percent. A more fundamental approach allows for investigations of the following type: If G is 8 and the uniformity 0.6, is it allowed or possible or advisable to decrease the minimum for L_{av} to 1.8 or 1.5 or 1.0? Obviously, answers to such questions are important for practical lighting design (3, 17).

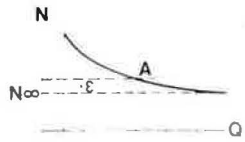
Lighting parameters are considered to describe the visual environment in adequate detail to assess visibility (the visual guidance and the G mark play no part in this). This statement, although plausible, requires further confirmation. How far the statement can be applied depends on the accuracy desired. As a first approximation, the average road surface luminance is sufficient for many types of problems since it usually approaches the level of adaptation fairly well. On the other hand, for the description of the visual environment in actual traffic conditions, the characteristics given above are not sufficient: Dynamic effects are not included, and glare for other light sources and the influence of the luminance of the surrounds of the roads (shoulders and sidewalks) on the adaptation level are not fully known. Thus, results from this approach can be applied only for a restricted group of traffic situations. This should be kept in mind when, for example, the findings for busy urban streets are to be applied on rural motorways. It is precisely to handle these hitherto unknown factors that the approach from the demand side is being developed.

When the visual environment is defined, visibility can be assessed directly on the basis of the system adopted by CIE (18). The validity of the approach has been assessed in many investigations (3, 19, 20, 21, 22, 23, 24, 25, 26). Although some discrepancies did show up, in general there seems to be good agreement between the actual measurements and the theoretical framework that is developed primarily on the basis of laboratory experiments.

However, this approach to arriving at a set of requirements for road-lighting installations that ensure a preselected degree of road traffic and transport performance has come to a complete dead end. Although 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 of visibility implicitly includes 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 equivalent to threshold perceptibility). The results of this exercise are inconclusive in relation to road safety because it is impossible to find out from the visibility and lighting studies whether the assumptions are in any way related to what is

Figure 2. Qualitative indication of the relation between number of accidents N and quality of road lighting Q.



relevant in traffic. The only thing that emerges is the suspicion that visibility, defined in this way, has in fact very little to do with traffic.

Therefore, "field factors" of from 10 to 30 are included. These field factors actually reflect the common sense and the experience of the investigator both as a 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 accident statistics quoted earlier) although the fundamental questions were not answered at all. It also explains why important but rather precise questions like the minimum required levels of luminance for motorways (1 or 2 cd/m^2) cannot be answered and why new developments for which no experience exists can be perfected only by means of very expensive and time-consuming trials.

In summary, selecting (sets of) standard visual tasks a priori is useless, and selecting them on the basis of visibility considerations is dubious. The first does not give any information that can be applied with 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 only valid basis for the definition of "standard" visual tasks is the actual requirement in road traffic.

The functional approach is a possible way out of this impasse. 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 (the term conspicuity level is preferred to the term visibility because one of the major problems at hand is to find aspects of visibility that are really relevant to road traffic).

RELATION BETWEEN CONSPICUITY AND ROAD SAFETY

As indicated earlier, of all the benefits of road lighting only road traffic and transportation performance are considered in this paper, which results in road safety being expressed as accident-reduction potential. A further restriction is now introduced: Drivers of vehicles (or automobiles) are considered to be users of road lighting—users meaning here those individuals that use the lighting to improve their possibilities for observation on the road. Thus, pedestrians are considered as objects and not as road users. All these restrictions are not of 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 for automobile drivers can be expressed in the number of accidents that are prevented by the lighting. This has loosely 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. The first research task is to define Q in such terms that it can be applied.

As indicated earlier, this functional relation cannot be established directly from accident statistics. Not only the description of Q is lacking; to approximate a function relation, the "steps" in Q, and thus the differences in consecutive steps in N, should be small. This holds even more if one looks for the minimum admissible value of Q. For this, the relation is usually taken as having an asymptote N_∞ in N for high Q. The minimum admissible value of Q is that value where $(N - N_\infty) < \epsilon$, ϵ being small and depending in magnitude 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 shown in Figure 2. The establishment of this (quasi-) function directly from accident statistics 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 that can be approximated by a normal distribution). 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 also large. This makes it virtually impossible to perform this analysis within reasonable time and cost limits.

As a possible way out of these difficulties, it is suggested that the relation between conspicuity and road safety be broken up into a number of separate steps, as shown in Figure 1. It is also suggested that the analysis of the driving task be included as one of the intermediate steps. As has been argued in other places in great detail (27, 28, 29, 30), the driving task can be described in the hierarchy of decision processes given below:

Individual Behavior	Collective Behavior
Selection of motive	Trip generation
Selection of destination	Trip distribution
Selection of mode of transport	Modal split
Selection of route	Assignment
Selection of maneuver	Traffic flow

The hierarchical level of most importance here is the lower one in which the maneuvers are described. Thus, the actual handling of a vehicle can be described as a series of maneuvers, each of which is performed after a decision to do so, a decision based among other things on (visual) information about the outside world.

The "space" required for the adequate performance of each maneuver can be defined, as can the available space. Space should be understood here in a very general sense; it is determined not only by the border of the roadway but also by the maneuverability of the vehicle, the ability of the driver, the presence and the maneuvers (actual or planned) of other road users, visiblity, meteorological conditions, the skidding resistance of the road surface, and other factors. The actual extent of both the required and the available space is unknown. The driver has to base the decision whether or not to undertake a certain maneuver on estimations of the extent of the space. It may be assumed that the estimation of the required space is not a matter of visibility but of confidence in the road-holding capability of the vehicle, the driving ability of the driver, and so on. The estimation of the available space, however, is clearly a matter of visibility. There are three possibilities: The actual extent A of the available space is larger than, smaller than, or equal to the estimated extent A′. A more detailed consideration leads to the preference for A′ = A. Thus,

the road lighting should be such that A can be estimated correctly.

This idea is, in a vague way, 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 unrealistically large. Furthermore, trucks have signal lights or at least reflectors. Therefore, one usually selects a very small object—e.g., the notorious 20- by 20-cm^2 dull grey box (not an object drivers usually have to stop for). This is precisely the impasse indicated earlier.

The way out is the consideration that there are many objects that can present themselves and that there are a number of possible maneuvers from which the driver has to select one after he or she has had the opportunity to see and recognize the object and has had the opportunity to make an assessment of the pros and cons of the different maneuvers. It is the analysis of the driving task that permits one to state which are the possible maneuvers under certain circumstances and which is the most appropriate. For the different maneuvers and for the different conditions under which they have (or may have) to be performed, the required space to maneuver can be assessed by taking into account the actual or the average value of vehicle performance, road characteristics, and driver ability. By taking into account the characteristics of the object that requires the particular maneuver, the visual environment can be described so as to enable the actual or the average driver to really observe the object. This visual environment corresponds with the demand side, with the required conspicuity level. Finally, the lighting installation should be such that demand does not exceed supply.

In this way, the chain that links 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 are involved only in the last two steps. A major part of the future research mentioned in this paper is on the schedule of the CIE Technical Committee on Road Lighting.

CONCLUSIONS

The effectiveness of good road lighting compared with no lighting at all can be determined from 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.

The chain between costs and transportation performance is split up into smaller parts; the costs (and the installation parameters closely related to them) stand for the supply side, and road traffic and transportation performance (and accident-reduction potential, which is closely related) form the demand side. For good road lighting, the supply should equal or exceed the demand. The chain is followed by starting from both sides simultaneously. The supply side gives the supplied conspicuity level; the demand side leads to the required conspicuity level. Again, the supply should equal or exceed the demand.

The supplied conspicuity level can be derived from installation parameters by means of well-established methods. A similar derivation of the required conspicuity level from traffic and transportation performance requires further research. The traditional method, in which one or maybe two standard visual tasks are postulated as being representative for driving, is completely unsatisfactory and may even lead to erroneous results.

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Abridgment

Reanalysis of California Driver-Vision Data: General Findings

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Early studies of the relations between driver vision and accidents were contradictory in their findings, largely because of the small sample sizes used. However, in 1967 and 1968, Burg (1, 2) published the findings of a study in which visual measurements made on over 17 500 California drivers were compared with their 3-year driving records, which included over 5200 accidents. It remains to a considerable extent the most comprehensive study of driver vision yet accomplished.

Taking the driving population as a whole, Burg found very weak but statistically significant correlations between various vision scores and driving records. The vision test that best predicted accidents proved to be a nonstandard one—dynamic visual acuity (DVA), in which the observer had to resolve detail in a rapidly moving acuity target; however, by itself, DVA remained a poor predictor of a driver's accident rate. This and other general findings of Burg's study reflected both the multicausal nature of traffic accidents and the need to develop tests of visual perception that are more relevant to the driving task than the classical tests of vision (which were largely devised for reading purposes).

Vision standards for driver licensing require not only the selection of valid visual characteristics to be tested but also the establishment of valid cutoff scores as criteria for passing or failing. To date there has been virtually no research into the latter problem, and this study was conducted with this need in mind. This paper summarizes the major findings of the study and is taken from a more detailed report (3).

The study explored in depth the implications of Burg's data for driver-vision standards and concentrated on determining whether certain subgroups of the driving population displayed stronger relations between vision and driving than did others. Preliminary work suggested that analysis of older drivers rather than of those with poor vision was most likely to show these stronger relations. Therefore, in the main analyses, the sample was divided into four age groups: under age 25, ages 25 to 39, ages 40 to 54, and over age 54.

VISION TESTS

The vision tests used by Burg included the following:

1. Static visual acuity (SVA)—binocular distance acuity measured by using the Bausch and Lomb Ortho-Rater (F-3 test) and, for a subsample of the total population, a Snellen chart;
2. Dynamic visual acuity (DVA)—the ability to perceive a series of rapidly moving (Ortho-Rater) checkerboard acuity targets projected on a cylindrical screen at two angular rotation speeds: 90°/s and 120°/s;
3. Low-light recognition threshold—the threshold amount of light required to recognize familiar targets;
4. Glare recovery—the length of time taken by the subject to reattain the low-light recognition threshold after exposure to 5-s glare; and