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## ABSTRACT

In usual low-land situations, the adaptation of the visual system of drivers/observers follows without an appreciable adaptation lag the changes in the luminance of the immediate surround.
This luminance may be assessed by adding the intrinsic luminance of the actual objects which are observed and the veiling luminance caused by scatter of light in the media in between.
In tunnel lighting practice, only the scatter in the eye, in the windscreen of the car, and in the atmosphere need to be taken into account. For all practical day-time conditions, the required luminance in any portion of the tunnel can be assessed as being a constant fraction of this sum-luminance; the fraction being determined by the traffic situation.

This system is applied in several new and renovated tunnels in the Netherlands. The high values of the luminance in the threshold zone are arrived at by applying louvres that are not sun-tight, and by artificial light. New design principles of the louvres are introduced, based on psychological studies; this involves the shape, dimensions, colour scheme, materials and marking, aimed at an optimal guidance and a minimal disturbance of the drivers.

Special points are the development of a computer programme for the calculation of the veiling luminance, the measurements of windscreen cut-off and the classification and characterisation of short tunnels.

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## SYMBOLS

a factor of proportionality
a" factor of proportionality
$\alpha \quad$ cut-off angle (degree)
$\tau \quad$ overall reaction time ( sec )
C contrast (intrinsic contrast)
$C^{\prime} \quad$ visible contrast
C" threshold contrast
d distance to the tunnel (m)
$d_{a} \quad$ distance of adaptation point to tunnel portal (m)
$d_{s} \quad$ safe stopping distance ( $m$ )
D throughlook
$\theta$ angle between glare source and line of sight (degree)
$E_{e} \quad$ illuminance at the eye (lux)
$\mathrm{E}_{\mathrm{h}} \quad$ horizontal illuminance (lux)
$\mathrm{E}_{\mathrm{p}} \quad$ perpendicular illuminance (lux)
f field factor
$l_{\text {th }} \quad$ length of treshold zone (m)
$L_{o(d)}$ average luminance within a cone with an apex of $2 \times 10^{\circ}$ around the line of sight at a distance $\mathrm{d}\left(\mathrm{cd} / \mathrm{m}^{2}\right)$
$L_{1} \quad$ luminance of the (uniform) surrounding field ( $\mathrm{cd} / \mathrm{m}^{2}$ )
$L_{1}^{\prime} \quad$ equivalent luminance of the standard field ( $\mathrm{cd} / \mathrm{m}^{2}$ )
$\mathrm{L}_{2} \quad$ luminance in the tunnel entrance ( $\mathrm{cd} / \mathrm{m}^{2}$ )
$\mathrm{L}_{3} \quad$ luminance of object $\left(\mathrm{cd} / \mathrm{m}^{2}\right)$
$\mathrm{L}_{\mathrm{A}} \quad$ adaptation luminance $\left(\mathrm{cd} / \mathrm{m}^{2}\right)$
$L_{a d e f}$ adaptation deficiency ( $\mathrm{cd} / \mathrm{m}^{2}$ )
$L_{a t(d)}$ atmospheric scatter at distance $d\left(c d / m^{2}\right)$
$\mathrm{L}_{\mathrm{d}} \quad$ disturbing luminance ( $\mathrm{cd} / \mathrm{m}^{2}$ )
$L_{e} \quad$ eye scatter ( $\mathrm{cd} / \mathrm{m}^{2}$ )
$L_{o f}$ luminance open field ( $\mathrm{cd} / \mathrm{m}^{2}$ )
$L_{w(d)}$ vehicle windscreen scatter at distance $d\left(c d / m^{2}\right)$
$L_{w, 1} \quad L_{w}$ damage and dirt
$L_{w, 2} \quad L_{w}$ other sources
$\Delta \mathrm{L} \quad$ luminance difference ( $\mathrm{cd} / \mathrm{m}^{2}$ )
p probability of detection
p $p^{\prime}$ p"factors of proportionality
$P_{\text {adef }} L_{\text {adef }} / L_{1}^{\prime}$
$q$ retardation ( $\mathrm{m} / \mathrm{sec}^{2}$ )

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\rho reflection factor
R coefficiënt of retroreflection (cd/m
vo speed (m/sec)
V
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## FOREWORD

The following report is the result of a study that has been made by the Institute for Road Safety Research SWOV on request of the Locks and Weirs Division of Rijkswaterstaat (Ministry of Traffic and Waterways). An earlier form of this study was prepared to the Lux Europe conference held in 1985 in Lausanne, Switzerland. A summary has been published afterwards (Schreuder \& Oud, 1985).

The theoretical part of the study was made by the first author. The second author contributed the material for the sections that describe the experiments in real tunnels and the computer programme. The latter will be published separately in the future.

## 1. INTRODUCTION

Tunnels for road traffic have been built for a long time. Only in the 'twenties of this century they were used on a large scale for motor traffic. Only then one began to feel the need for adequate lighting. In the beginning, efforts were concentrated on the lighting of the tunnel interior; the entrance did get only some additional lamps to serve as a "threshold". When speeds and intensities of motor traffic increased in the late 'forties and the early 'fifties, this trend was reversed: the major emphasis was placed on the lighting of the tunnel entrance; usually, one did take the extreme of the unfavourable conditions as a criterion (e.g. full summer shunshine on light concrete structures). One might call these two steps the first and the second generation of traffic tunnel lighting respectively. The considerations of the second generation stood as a cornerstone for the recommendations for tunnel lighting of the CIE and for the many ensuing national codes and standards. In the 'sixties and the early 'seventies a great surge of motorisation coincided with a deep-felt consideration with environmental aspects of life; this resulted in the need to construct a great number of tunnels all over the world. And the economic recession in general and the soaring energy prices required a very stringent restriction of running costs of tunnels, particularly of lighting installations. Many of the related problems have been solved in the following years by the efforts of the practical engineers engaged in the design and operation of these many new tunnels. As a point of fact, it was proven that quite acceptable tunnel lighting installations could be designed, in spite of the fact that they did not conform to the CIE-standard. This curious phenomenon of course raised the question whether the CIE-recommendations really are realistic. As was shown, they are. However, they are not completely relevant any more for the present situation of the late seventies and the eighties (Schreuder, 1980). So a practical way of lighting did present itself, the "third" generation, that, however, did lack a theoretical support. It is the aim of this paper to present a number of considerations on which such a theoretical structure for the third generation lighting could be based. These considerations, this system of lighting, has been applied to a number of new and renovated tunnels in the Netherlands with a certain degree of success: a number of good and economically acceptable lighting installations has been designed.

The geographic and the geological situation of the Netherlands determine to a large extent the main aspects of the traffic: the major waterways are running east-west, and the major rail and road connection are northsouth. This obviously requires a number of major crossings; as the waterways often carry sea-going vessels, bridges are not always feasible. Thus, one might find a large number of tunnels in the Netherlands where roads and waterways of the highest importance intersect, particularly in the Western part of the country. Typically, the tunnels are of intermediate length (about one kilometre in length) and carry very heavy road traffic: they are four or six, sometimes eight lane highways. And finally the tunnels are not bored but sunk in a cut, dredged in the bottom of the water. So, the tunnels can be wide and shallow, and do not dip very deep underground; they usually have a rectangular cross-section. In this way, these Dutch tunnels differ markedly from the circular, bored undersea and mountain tunnels that are often constructed in other countries. Although the system to be presented here is designed more in particular for the Dutch conditions, the results are applicable in a more general way.

Usually, the lighting design of tunnels is based on requirements of visibility; i.e. one requires that a specific object is visible to an approaching car driver in time to avoid a collision with this object. Obviously, this represents an important aspect of the "driving task" (or the "seeing task") of a driver. Recent study did, however, suggest that an even more important aspect is the task to keep course. The second task (subtask) represents the requirement to reach the destination of the trip, the first to arrive without collisions. It seems that in the past an undue emphasis was placed on the second sub-task: it has been stated that avoiding obstacles is the first priority for the driver and that providing the possibilities to do so was the first priority for the lighting. As may be seen from the following these considerations determined to a large extent the way the third generation lighting is designed; so at the moment the theoretical fundament for the third generation lighting is beginning to take shape, a fourth generation lighting based on more modern considerations of the behaviour of the human operator in road traffic is beginning to evolve!

## 2. THE BASIC FORMULA

The major visibility problem in tunnels is the daytime entrance, particularly for tunnels for motorized traffic. The visual system of an approaching driver is adapted to an average, overall luminance $\mathrm{L}_{\mathrm{of}}$ of the open field. When the tunnel has no lighting, the entrance presents itself as a "black hole" in which no details can be seen. The approaching driver is required, however, to be able to see into the tunnel even before he has reached the portal. A certain level of lighting is required in the tunnel entrance. This is conventionally indicated with $\mathrm{L}_{2}$, assuming that the lighting conditions in the tunnel entrance can adequately be described by only one level of luminance: that of the road surface andor the tunnel walls. We disregard for the moment the important question as to which of the two is the most important. Reference should be made to the work of the CIE-PIARC joint Technical Committee on tunnel lighting. The problem is to establish the minimum value of $\mathrm{L}_{2}$ for different prevailing values of $\mathrm{L}_{\mathrm{of}}$. This is needed for two rather distinct purposes: for the design of the tunnel lighting installation, and for the adjustment of the tunnel lighting to changes in the surroundings (of $\mathrm{L}_{\mathrm{of}}$ ). According to the traditional viewpoints the requirements will be expressed in the visibility of specific objects. It is custumary to take small objects and consider the detection (the threshold of being "just visible") as a criterion. It has been shown that even for objects that are small in terms of traffic engineering, the detection is governed primarily by the contrast between the object and its direct background; dimensions, shape, colour and "internal contrasts" play only a minor role in the detection (Schreuder, 1964; De Boer (ed.), 1967). It should be pointed out that for the recognition of the object those factors are very important (Schreuder, 1985a).
The contrast of the specific object can under the relevant conditions be expressed as follows
$C=\frac{L_{2}-L_{3}}{\mathrm{~L}_{2}}$
where $C$ is the contrast as would be measured at the location of the object (intrinsic contrast); $L_{2}$ and $L_{3}$ are the luminance of the background and the object itself.

The object that is supposed to be in the tunnel near the entrance must be visible from a considerable distance; the distance is usually taken as the safe stopping distance - some 150 m . It should be noted in passing that this distance may be considered as adequate for emergency stops, but it is not long enough for manoeuvres in normal traffic (Schreuder, 1981).

From a distance the contrast of the object seems to be different. The visible (virtual or extrinsic) contrast is indicated by $\mathrm{C}^{\prime}$. Two factors account for this difference. Both are the result of the fact that the luminance $L_{2}$ in the tunnel entrance may at day be considerably lower than the surrounding luminance: $\mathrm{L}_{2} \ll \mathrm{~L}_{\mathrm{ov}}$. In the field of view of a car driver approaching the tunnel, the tunnel entrance itself will usually be centered in the field of view, even when the usual amount of eye-movements are taken into account (Schreuder, 1971; Narisada \& Yoshikawa, 1974). By consequence, the - brighter - surround is more in the periphery of the field of view. Now, areas of high brightness influence the perception in dark areas; the two factors that account for that are relevant here. The first is the influence from areas with high retinal illuminance on areas with lower illuminance; a neural interaction. The second is the stray light that is caused by the bright areas. All these influences are added-up to a "disturbance" that may be described as a veil covering the (relevant part of) the field of view, and that may be expressed in luminance terms (Schreuder, 1981). This disturbing luminance will be designated by $\mathrm{L}_{\mathrm{d}}$. To all luminances the "disturbance" $\mathrm{L}_{\mathrm{d}}$ must be added. The contrast therefore seems to be reduced.
$C^{\prime}=\frac{\left(L_{2}+L_{d}\right)-\left(L_{3}+L_{d}\right)}{L_{3}+L_{d}}=\frac{L_{2}-L_{3}}{\bar{L}_{3}^{-}+L_{d}} ;$ thus, $C^{\prime}=\frac{L_{2}}{L_{2}^{-}+L_{d}} C$
As $\mathrm{L}_{\mathrm{d}}>0, \mathrm{C}^{\prime}<\mathrm{C}$. This implies that the intrinsic contrast C must be greater than the threshold value that corresponds to the fact that the object is "just visible", if the object should visible as well under the practical situation. In order that the object is "just visible" under such practical situations (again a threshold value) the intrinsic contrast must be greater than the "intrinsic threshold". This point is of particular interest, because it is not possible to measure C' directly. However, we may measure the threshold under idealized laboratory situations. The contrast value corresponding to this threshold is called C". And we may define a "field factor" $f$ that relates $C^{\prime}$ to $C$ ". So we may define $f=$
$C^{\prime \prime} / C^{\prime}$, so that $C^{\prime}=f C^{\prime \prime}$. If we measure $C^{\prime \prime}$ and if we know $f$ we may assess $C^{\prime}$. We will come back to the field factor $f$ (See Sec. 3.4).

From $C^{\prime}=\mathrm{fCl}^{\prime \prime}$ follows:
$\mathrm{fC}^{\prime \prime}=\frac{\mathrm{L}_{2}}{\mathrm{~L}_{2}+\mathrm{L}_{\mathrm{d}}} \mathrm{C}$
$\left(\mathrm{L}_{2}+\mathrm{L}_{\mathrm{d}}\right) \mathrm{fC} \mathrm{Cl}^{\prime \prime}=\mathrm{L}_{2} \mathrm{C}$
$L_{2}=\frac{L_{d} f C^{\prime \prime}}{C-f C^{\prime \prime}}$
In this way $L_{2}$ can be assessed if $L_{d}$, $f$ and $C^{\prime \prime}$ are known and if a value of $C$ is chosen. It should be pointed out that in reality the value of the contrast of real objects in real tunnels obviously follows from the characteristics of those objects (size, shape, reflection factors, colours) and of the lighting installation (colour of the light, luminance and luminance distribution). As, however, the occurrence of objects cannot be predicted, one has to make a choice as regards the object (now a hypothetical one) that is considered to represent all dangerous obstacles that may be uncountered in tunnels. And the contrast of that hypothetical object against its background $L_{2}$ (or rather the luminance of the object $L_{3}$ ) is chosen in such a way that the majority of dangerous obstacles can be considered as being represented. Obviously, this procedure is a weak point of this type of assessment of the visibility (Schreuder, 1984; Padmos, 1984a).
The expression (1) is the basic formula for tunnel entrance lighting. Before we may try to apply it, we have to establish the different factors.

## 3. THE QUANTIFICATION OF THE BASIC FORMULA

### 3.1. The threshold value C"

The threshold of the contrast sensitivity is the basis for the CIE-system as explained in Publication CIE 19/2 (CIE, 1981). A convenient representation of the data as relevant for tunnel entrance lighting is given by Adrian \& Eberbach (1969), see Figure 1.
From the data it can be derived that for the range of adaptation luminances between 1 and $10^{4} \mathrm{~cd} / \mathrm{m}^{2}$ the logarithm of the threshold luminance difference $\Delta L$ is proportional to the logarithm of the adaptation luminance $L_{A}\left(\Delta L_{s}\right.$ and $L_{u}$ respectively in Figure 1). For $100 \%$ probability of perception, free view and an object of $7^{\prime}$ (corresponding with 20 cm at 100 m ) the expression follows:
$\log \Delta L=0.75 \log L_{A}-1$
$\log \Delta \mathrm{L}-\log \mathrm{L}_{\mathrm{A}}=-0,25 \log \mathrm{~L}_{\mathrm{A}}-1=\log \mathrm{C}^{\prime \prime}$
For $L_{A}=1000 \mathrm{~cd} / \mathrm{m}^{2}$, the result is $\mathrm{C}^{\prime \prime}=0.0177$.

### 3.2. The disturbing luminance $L_{d}$

$\mathrm{L}_{\mathrm{d}}$ consists of two major components. The first is related to the fact that the adaptation of the visual system is not instantaneous: it takes some time to adapt from one level to another - both for increasing as for decreasing luminance; there may be some deficiency. Schreuder (1981) indicates that this deficiency may be expressed in luminance terms: $\mathrm{L}_{\mathrm{adef}}$ (adaptation deficiency).
The second component is the straylight. Apart from the eye scatter ( $L_{e}$ ), in the practice of tunnel lighting we have to acknowledge two more sources: the atmosphere ( $\mathrm{L}_{\mathrm{at}}$ ) and the vehicle windscreen ( $\mathrm{L}_{\mathrm{w}}$ ). Vos and his collaborators studied these factors in detail (Vos, 1983, 1984; Vos \& Padmos, 1983; Padmos, 1984; Padmos \& Alferdinck, 1983, 1983a). We will discuss these four factors separately.

### 3.2.1. The adaptation deficiency $L_{\text {adef }}$

The existence of an adaptation deficiency is very easy to observe; it is, however, difficult to measure and to explain.

For intermediate values of the adaptation luminance ( $10<\mathrm{L}_{\mathrm{A}}<1000$ $\mathrm{cd} / \mathrm{m}^{2}$ ) the adaptation deficiency may be disregarded. This follows from measurements represented in Figure 2 (Schreuder, 1964), where the time that elapsed between a sudden reduction of the luminance in the field of view and the disappearance of disturbing (subjective) after-images is plotted against the magnitude of the sudden reduction with the starting luminance level as a parameter. For $10<\mathrm{L}_{\mathrm{A}}<1000$ the "adaptation time" is small ( $L_{b}$ in Figure 2). For low values, it may have considerable influence as is shown by a.o. Rinalducci (1972). These and other measurements are summarized by Schreuder (1964, 1971, 1973, 1983). These effects follow from the well-known neurophysiological characteristics of the visual system as explained by Schreuder (1981). However, it is not easy to explain the fact that at higher levels of the adaptation luminance ( $\mathrm{L}_{\mathrm{A}}$ $>3000 \mathrm{~cd} / \mathrm{m}^{2}$ ) the adaptation deficiency increases very rapidly and becomes the predominant factor at a luminance of about $10,000 \mathrm{~cd} / \mathrm{m}^{2}$. The traditional theories of bleaching of visual pigments do not explain the rapid detoriation of the visual system at high luminance values. As all experiments regarding the bleaching of visual pigments have been made with small fields of vision and as in tunnel lighting practice the relevant field of vision is very large (approaching a half-sphere) we might suspect an overwhelming influence of the periphery of the retina on the foveal discrimination. There are no experimental data to support this suggestion. It is a curious effect, however, that in this range a factor of only three in the luminance causes the visual system to break down completely, whereas in other luminance ranges a factor of three in the adaptation causes effects that only can be detected by refined measuring systems.
One may conclude to two things:

- firstly, when in the day-time the adaptation level is below some 3000 $\mathrm{cd} / \mathrm{m}^{2}$ the adaptation deficiency may be disregarded ( $\mathrm{L}_{\text {adef }} \simeq 0$ ); - secondly, for higher luminances (e.g. sun on snow) the adaptation deficiency is predominant.

These conclusions result in a considerable discrepancy between the approach followed here and the traditional approach that is followed a.o. in the Recommendations of the CIE (CIE, 1973; see also Schreuder, 1964). In the traditional approach, the adaptation deficiency was considered to be the most important factor that determined the required tunnel entrance luminance level. As for the highest practical luminance value the resul-
ting ratio between $L_{2}$ and $L_{o v}$ was found to be about 0.125 (Schreuder, 1964), it was assumed that the tunnel entrance luminance level should be always $0.125 \mathrm{~L}_{\mathrm{ov}}$ (or more). This is the origin of the CIE rule-of-thumb $L_{2} / L_{\text {ov }} \sim 0.1$. In view of the more modern considerations, this value should be restricted only to the area where it was found in actual experiments (for $L_{o v}=8000 \mathrm{~cd} / \mathrm{m}^{2}$ or more) but not for lower values of $\mathrm{L}_{\mathrm{ov}}$. This point is particularly of interest if the entrance lighting is made by artificial light. In the case of daylight screens, where $L_{2}$ is in a first approximation proportional to $\mathrm{L}_{\mathrm{ov}}$, the discrepancy is less importance. It should be noted that daylight screening was considered most economic way of tunnel entrance lighting at the time the CIE-recommendations were drafted.

### 3.2.2. The ocular straylight $\mathrm{L}_{\mathrm{e}}$

The light scatter in the eye hase been studied in great detail, as it is the major contributing factor to glare. Vos (1984) summarized all the available material, and concluded that the ocular straylight can be assessed by a relatively simple equation:
$L_{e}=a E_{e}\left(\frac{1}{\theta^{2}}+\frac{1}{\theta^{3}}\right)$
where $E_{e}$ is the illuminance at the eye (lux) and $\theta$ the angle between glare source and line of sight (degrees). For young adults a equals to about 10; for 70 year old persons a equals to about 20 . This equation may be used for $0.1<\theta<100$ and for point sources and for areas (where an appropriate summation must be applied).

Vos (op. cit.) does not indicate an upper light level for the validity of the equation. As long as only (physical) light scatter plays a role, one should not expect such an upper limit. In view, however, of the fact that at very high levels of the adaptation luminance the visual system seems to behave quite differently (see Sec. 3.2.1.), the question might be relevant. Vos himself gives a qualitative assessment of some of the relevant aspects in his studies on the use of sun-glasses (Vos, 1977,1977a). However, quantitative data are missing. We will consider the Vos equation to be valid for all luminance values relevant for tunnel lighting.

One more remark. The equation represents the "mean" value of a great number of individual observations. Vos (1984) does not discuss the accuracy of the equation, but it seems justified - in view of the experimental data given by Vos - that the spread is considerable; a factor of three both "up" and "down" seems to be quite feasible. That would include the age dependency as well. We will use furtheron the nominal value ( $a=10$ ) as an average. It should be noted that Vos (op. cit.) gives a more complicated formula that fits the experimental data even better. As the spread in the results are quite large, it seems to be accurate enough to use the simple form of the equation.

### 3.2.3. Straylight in the atmosphere $L_{a t}$

Here, the studies of Padmos are essential (Padmos, 1984; Padmos \& Alferdinck, 1983). These studies have been made especially for the tunnel lighting problems; they were made in contract with the Ministery of Transport (Verkeer en Waterstaat) of the Netherlands, in conjunction with studies related to the straylight in windscreens (see Sec. 3.2.4.). The major finding is that the atmospheric straylight may contribute considerably to the total straylight. Based on a number of theoretical considerations and a large amount of experimental data Padmos \& Alferdinck (1983) concluded to the following relationship:
$L_{a t(d)}=\frac{3.8}{V_{m}} L_{o(150)}$
where $L_{a t(d)}$ is the atmospheric straylight ( $c d / m^{2}$ ) at a distance $d$ (m) from the tunnel entrance; $\mathrm{V}_{\mathrm{m}}$ is the meteorological visibility (m) and $L_{o(150)}$ the average luminance measured within a cone with an apex of $2 \times 10^{\circ}$ around the line of sight (straight ahead) at a location 150 m in front of the tunnel.
$L_{\text {o }}$ is a quantity that is often used in tunnel lighting considerations; see e.g. CIE (1984). However, Schröter (1985) pointed out that this quantity can not be applied when the sun is near the line of sight.

Padmos (op. cit.) proposes to use only one value of $\mathrm{V}_{\mathrm{m}}$. His own data suggest, however, a simple relationship
$\log \mathrm{p}=\log \mathrm{V}_{\mathrm{m}}-2.3$
where p is the cumulative probability to have visibility equal or larger than $V_{m}$ ( p in \%; $\mathrm{V}_{\mathrm{m}}$ in $\mathrm{m} ; 700<\mathrm{V}_{\mathrm{m}}<10,000$ ). Again here a large spread must be taken into account. Padmos takes $\mathrm{p}=15 \%$, which equals 2500 m . One could also taken $p=10 \%$ or $p=5 \%$; resulting in $V_{m}>1700 \mathrm{~m}$ or $\mathrm{V}_{\mathrm{m}}>$ 1000 m . This change in the arbitrarily chosen value of p results in a change of a factor 2.5 in $\mathrm{L}_{\mathrm{at}}$.

Padmos (op. cit.) also gives a relationship between the ocular straylight and $L_{0}$ :
$L_{e}=a^{\prime} L_{o}$
where $\mathrm{a}^{\prime}=0.074$ for young adults and $\mathrm{a}^{\prime}=0.142$ for elderly observers. The spread is again considerable (the values scatter over a range of over a factor two both ways). It offers, however, an approximation of the relative importance of ocular and atmospheric straylight: they prove to be of the same order of magnitude.

### 3.2.4. Straylight in the vehicle windscreen $L_{w}$

Again here the studies of Padmos are essential; they as well are made under contract of the Dutch Ministry of Transport (Padmos, 1984; Padmos \& Alferdinck, 1983a). As one might expect, the contribution of the scatter from the windscreen is very complicated and shows a very large variation. Broadly speaking, there are four distinct components:

- scatter due to water droplets (haze, rain)
- scatter due to dirt (both inside and outside)
- scatter due to damage to the windscreen (scratches)
- scatter due the reflection of the vehicle interior in the glass. In all cases there is large distinction between the scatter of direct sunlight as compared to diffuse light; and finally the influence of diffuse light depends on the "angular distance" from the line of sight. All these factors (with the exception of the most severe, the water droplets) are considered very carefully by Padmos (op. cit.). The final results are "nominal" values for the straylight components of diffuse light and the central part of the field of view due to scatter in the windscreen (damage and dirt) $\mathrm{L}_{\mathrm{w}, 1}$ and the components from other sources $L_{w, 2}$.

It is shown that $L_{w, 1}$ depends upon the distance, and $L_{w, 2}$ not. Padmos (op. cit.) gives the following nominal relationships:

$$
\begin{aligned}
& \mathrm{L}_{\mathrm{w}, 1}(150)=0.07 \mathrm{~L}_{\mathrm{o}(150)} \\
& \mathrm{L}_{\mathrm{w}, 2}=0.05 \mathrm{~L}_{\mathrm{o}(150)}
\end{aligned}
$$

where $L_{w, 1(150)}$ is assessed for the "standard" distance of 150 m .

Combined this yields for distance $d$ (m):

$$
\begin{equation*}
L_{w}(d)=(0.093+0.00018 d) L_{o(150)^{\prime}} . \tag{4}
\end{equation*}
$$

Again it is difficult to estimate the accuracy of the relationship. It seems justified, however, to consider the nominal relationship (4) as a maximum practical value, because in most cases it is quite possible for the car driver to avoid values excessively higher by simply cleanning his windscreen (This remark does not diminish the responsibility of road authorities to clean the roads from rain, mud and salt, and the responsibility of car designers to avoid absurdly flat windscreens!).

### 3.3. The field factor f

The field factor $f$ expresses the relation between the laboratory and the "real world". The only way to determine $f$ is to assess $C^{\prime}$ in real tunnels and compare the results with the corresponding laboratory threshold value $C^{\prime \prime}$. This should be done for several different situations and several values of $L_{o v}$. Several attemps have been made to perform such experments. The results are not convincing as the experiments were, for practical and financial reasons, too limited in scope. It is suggested to set up more complete experiments. It should be pointed out, however, that the basic formula as introduced in Sec. 2.1 can be applied to a number of different questions, even if the field factor is not fully known.

The field factor actually includes a number of different aspects:
$f_{1}$ representing the condition of the eye (adaptation etc.);
$f_{2}$ representing the driving task (attention, vigilance);
$f_{3}$ representing the vision task (unexpected obstacles);
$\mathrm{f}_{4}$ representing the object (shape, size etc.);
$f_{5}$ representing the surround (tunnel entrance shape etc.).

Usually, one assumes that the field factor f is to be found as a multiplication of the differend aspects of it:
$\mathrm{f}=\mathrm{f}_{1} \times \mathrm{f}_{2} \times \mathrm{f}_{3} \times \mathrm{f}_{4} \times \mathrm{f}_{5}$
It should be stressed, that this mulitiplicatory assumption has not been proved in detail.

In view of what was indicated earlier, some further assumption may be made regarding $f$ and its constituents.

- $\mathrm{f}_{1}=1$, as the characteristics of the individual eye and the influence of the adaptation have been taken into account in other factors already. - $f_{4}=1$ as according the experiments of Schreuder (1964) the influence of the dimension of the objects are not large, and as the nominal value of the dimensions ( 7 minutes of arc, corresponding to 20 cm at 100 m ) is in the middle of the area of interesting small obstacles.
- $f_{5}=1$ as the influence of the tunnel surrounds are taken into account in other factors.
This implies that only $f_{2}$ and $f_{3}$ have to be determined. $f_{2}$ is difficult to assess as experimentation immediately will influence the level of arousal of drivers. It seems to be justified to assume $f_{2}$ to equal 1 , as the attention of drivers usually will be focussed on the tunnel when approaching. The eye-movement studies of Yoshikawa \& Narisada (1974) support this view; they found that the fixation of the observer's eyes was on the tunnel entrance long before the driver did reach the critical stopping point.
Finally, $\mathrm{f}_{3}$ must be assessed. For this, as a first approximation the measurement of Schreuder (1964) may be used. It should be pointed out that in this way the experiments are used rather differently than originally planned!

The experiments of Schreuder yielded the relationship between $L_{A}$ and $L_{2}$ with the intrinsic contrast C as a parameter. Taking into account the fact that $L_{\text {adef }}=0$ for intermediate values of $L_{A}$, and that in the experimental set-up $\mathrm{L}_{\mathrm{at}}=\mathrm{L}_{\mathrm{w}}=0$, it follows that $\mathrm{L}_{\mathrm{A}}=\mathrm{L}_{2}+\mathrm{L}_{\mathrm{e}}$. Using the Vosformula (Sec. 3.2.2.), $\mathrm{L}_{\mathrm{e}}$ can be calculated for the situation as used in the experimental set-up. $L_{e}=0.07 \mathrm{~L}_{1}$ where $\mathrm{L}_{1}$ is the luminance of the (uniform) surrounding field of view. For $L_{1}=1000 \mathrm{~cd} / \mathrm{m}^{2}$ this leads to $\mathrm{L}_{\mathrm{e}}$ $=70 \mathrm{~cd} / \mathrm{m}^{2}$. As already indicated:
$C^{\prime}=\frac{L_{2}}{L_{2}+L_{e}} C$ and $C^{\prime}=f C^{\prime \prime}$, because now $L_{e}=L_{d}$
This yields $\mathrm{f}=\frac{\mathrm{L}_{2}}{\mathrm{~L}_{2}+\mathrm{L}_{\mathrm{e}}} \cdot \frac{\mathrm{C}}{\mathrm{C}^{\prime \prime}}$

Schreuder (1964, p. 74) gives the relationships between $L_{1}, L_{2}, C$ and $p$ (the probability of detection):
for $p=0.50: \log L_{2}=-1.04+0.50 L_{1}{ }^{1 / 5}+39.1 C^{-5 / 4}$
for $p=0.75: \log L_{2}=-0.97+0.51 L_{1}^{1 / 5}+39.1 \mathrm{C}^{-5 / 4}$

For $L_{1}=1000 \mathrm{~cd} / \mathrm{m}^{2}$ and $\mathrm{C}=10 \%$ (chosen for the calculation) this results in $L_{2}=43.7 \mathrm{~cd} / \mathrm{m}^{2}$ for $\mathrm{p}=0.5$; and in $L_{2}=53.7 \mathrm{~cd} / \mathrm{m}^{2}$ for $\mathrm{p}=0.75$. This yields for f :
$f_{0.1 ; 0.5}=2.9$
$\mathrm{f}_{0.1 ; 0.75}=3.27$
where $f_{0.1 ; 0.75}$ stands for the field factor $f_{3}$ for $C=0.1$ and the probability of detection of 0.75 . The difference between the f-values for $p=$ 0.5 and $p=0.75$ suggest part the spread in these results. $f_{3} C \prime$ becomes then 0.0386 and 0.0435 respectively for $\mathrm{p}=0.5$ and 0.75 , and for $\mathrm{C}=$ 0.1.

Table 1 gives the relevant values for other values of $C$.

It should be stressed that this assessment of the field factor f by assuming that only $f_{3}$ differs from one, is an approximation only. Further experiments are needed in order to assess $f$ more precisely. However, for purposes of comparison between different design aspects this approximation can be applied. When, for example, the relative merits of "counterbeam" lighting are to be quantified, the field factor $f$ presents itself in both sides of the equation and can therefore be eliminated. For the predetermination of the precise value of the luminance in the tunnel entrance, the field factor must be known quantitatively.

### 3.4. The value of $\mathrm{L}_{\text {。 }}$

For the design of tunnel lighting installations it is essential to know the luminance level to be expected on the open road outside the tunnel. It is, however, difficult to assess this value, particularly because it is not always clear in which way the outside luminance influences the required value of $L_{2}$.
According to the ideas that were behind the experiments of Schreuder, where the adaptation was considered as an essentialy slow process, the outside luminance equals the adaptation level near the tunnel entrance. A considerable amount of "history" should be included in the assessment; at the other hand, as the adaptation was a time average with a long
averaging time basis, it was considered to be accurate enough to take the average horizontal illuminance $\mathrm{E}_{\mathrm{h}}$ and the average reflection. For the highest practical value with $\mathrm{E}_{\mathrm{h}}=100,000$ lux and $\rho=0,25$ this leads to a luminance (called $\mathrm{L}_{1}$ ) of about $8000 \mathrm{~cd} / \mathrm{m}^{2}$. This value was the base of all ensuing considerations. In the CIE-recommendations (CIE, 1973) a suggestion - and not more than that! - was given to arrive at a somewhat more accurate approximation of $L_{1}$, particularly for mountain tunnels.
$L_{1}=\frac{L_{0(150)}+2 L_{0(100)}+3 L_{0(50)}}{}$
where $L_{0}$ is the geometric average of the luminance within the area of a cone with an apex of $10^{\circ}$ (an "opening" of $2 \times 10^{\circ}=20^{\circ}$ ) and a line of symmetry coinciding with the line of sight. $L_{o(150)}$ is the value of $L_{o}$ at a distance of 150 m in front of the tunnel. $\mathrm{L}_{0(100)}$ and $\mathrm{L}_{0(50)}$ the $\mathrm{L}_{\mathrm{o}}$ values for 100 m and 50 m . Practical experience, however, did show that this approximation was not very helpful, as primo it did not approximate $\mathrm{L}_{1}$, and secundo it was not particularly relevant for tunnels.
Work of Narisada and his collaborators did show that $L_{o}$ can be used all the same, be it in a different setting. The "equivalent luminance of the standard field $\mathrm{L}_{1}^{\prime}$ " was introduced, which is defined as "a hypothetical luminance ... for which the perception .... is just equivalent to that under given non-uniform luminance field conditions". So, $\mathrm{L}_{1}^{\prime}$ can be understood as a quantification of the state of adaptation. It should be mentioned that the size of the standard field in not clearly defined; sometimes the $\mathrm{L}_{1}$-field as used in the experiments of Schreuder (1964) is used (being a square subtending some $2 \times 10^{\circ}$ ), and sometimes the full halfsphere. As a result of glare from the extreme periphery there is a difference; it is some $10-20 \%$. It was concluded that " $\mathrm{L}_{\mathrm{o}}$ when multiplied by 1.5 represents $L_{1}$ (Schreuder type) in the access zone of a tunnel with sufficient accuracy for practical applications".
The above quotations are from CIE (1984), a study that is mainly based on the studies of Narisada and his collaborators. That report certains a very comprehensive bibliography.

From these results it can be concluded that $L_{o(150)}$ can be used as a base for the design of tunnel lighting installation.
As indicated earlier, Schröter (1985) has indicated that $L_{\text {o }}$ does not represent the adaptation luminance well enough in case of a low position of the sun. In this case, and in many others, it is desirable to have a more
accurate assessment of the adaptation luminance. In the Netherlands, a detailed computer programme has been developed that enables the precise assessment of the adaptation luminance in all positions in front of tunnels also in the design stage. The programme is based on the "full" glare formula as given by Vos (1984).

### 3.5. Example

The expression for $L_{\text {o }}$ completes the assessment of all the separate factors that are part of the "basic formula" (1) as indicated above. An example will be worked out here.
$\mathrm{L}_{2}=\frac{\mathrm{L}_{\mathrm{d}} \mathrm{f} \mathrm{C}^{\prime \prime}}{\mathrm{C}-\mathrm{C}^{\mathrm{f}} \mathrm{C}^{\prime \prime}}$

We have found $\mathrm{C}^{\prime \prime}=0.0177$ and $\mathrm{f}=3.27$; $\mathrm{fC}{ }^{\prime \prime}=0.0579 . \mathrm{L}_{\mathrm{d}}$ was subdivided $L_{d}=L_{a d e f}+L_{e}+L_{a t}+L_{w}$
For intermediate values $\mathrm{L}_{\mathrm{adef}} \simeq 0$.
Further, we have found
$L_{e}=a^{\prime} L_{0}\left(a^{\prime}=0.074\right.$ for young and $a^{\prime}=0,142$ for old observers $)$
$L_{a t}=\frac{3.8}{\bar{V}_{m}} \mathrm{~d}_{\mathrm{d}} \mathrm{L}_{\mathrm{o}}(150)$
$L_{w(d)}=(0.093+0.00018 d) L_{o(150)}$
$L_{0}=\frac{1}{1} .5 L_{1}^{\prime}$

When we take $C=0.2$ (visibility requirement), $d=150 \mathrm{~m}$ and $\mathrm{V}_{\mathrm{m}}=2500 \mathrm{~m}$ (85\%) the result is $L_{2}=0.1038 \mathrm{~L}_{1}^{\prime}$.
This is only an example of the assessement. In view of the many values that an arbitrarily chosen and in view of the large spread in some of the values used here, the result is not accurate at all. And furthermore, it should be pointed out that in many practical cases the quantities used in the formula do not cover the experience; this is particularly the case for $L_{0}$ and $L_{1}^{\prime}$.

### 3.6. The spread in the basic formula

The basic formula can be written as follows
$L_{2}=\frac{\left(p_{\text {adef }}+a^{\prime}+\frac{3.8 \mathrm{~d}}{\bar{V}_{m}}+0.093+0.00018 \mathrm{~d}\right)}{1.5\left(\mathrm{C}^{-}-\bar{f} \bar{C}^{\bar{n}}\right)}$
in which $p_{a d e f}=L_{a d e f} / L_{1}^{\prime}$. We will discuss the influence of variations of the individual parameter terms as indicated above.
A. Assume $p_{a d e f}=0.2$ in stead of 0 .

The result is that $L_{2}=0.152 \mathrm{~L}_{1}^{\prime}$ in stead of $\mathrm{L}_{2}=0.1038 \mathrm{~L}_{1}^{\prime}$.
B. Assume the observers are aged : $a^{\prime}=0.142$ in stead of 0.074 .

The result is $\mathrm{L}_{2}=0.121 \mathrm{~L}_{1}^{\prime}$
C. Assume $\mathrm{V}_{\mathrm{m}}$ is $10,000 \mathrm{~m}$ or 1000 m in stead of 2500 m . The result is $\mathrm{L}_{2}=0.061 \mathrm{~L}_{1}^{\prime}$ or $0.185 \mathrm{~L}_{1}^{\prime}$ respectively.
D. Assume $f=2.9$ in stead of 3.27. The result is $L_{2}=0.089 L_{1}^{\prime}$.
E. Assume $\mathrm{L}_{\mathrm{o}}=\frac{1}{1 . \overline{3}} \mathrm{~L}_{1}^{\prime}$ in stead of $\frac{1}{1.5} \mathrm{~L}_{1}^{\prime}$.

The result is $\mathrm{L}_{2}=0.120 \mathrm{~L}_{1}^{\prime}$.
F. Assume we select a contrast $C$ of 0.3 or 0.5 in stead of 0.2 .

The result is $\mathrm{L}_{2}=0.064 \mathrm{~L}_{1}^{\prime}$ or $0.036 \mathrm{~L}_{1}^{\prime}$.
G. Assume we select a different distance d: we take $50,75,100$ and 200 m in stead of 150 m . The result is $\mathrm{L}_{2}=0.061 \mathrm{~L}_{1}^{\prime} ; 0.072 \mathrm{~L}_{1}^{\prime} ; 0.081 \mathrm{~L}_{1}^{\prime}$; and $0.128 \mathrm{~L}_{1}^{\prime}$ respectively.
H. We will not consider another degree of light scratter in the windscreen; if one would do so, the influence on $L_{2}$ might be even larger.

As the basic formula is a rather complicated one, it is not allowed to just add these different discrepancies. For an assessment of the influence on $L_{2} / L_{1}^{\prime}$ of the combined effect of several of these parameters, a more complete "sensivity analysis" is required. We will not do this, as the primary aim of this exercise is to indicate the considerable spread in the outcome, in the value of $L_{2}$ to be selected, as a result of a moderate change in the assumed or postulated values of different parameters in the formula. And furthermore, this exercise may suggest some order of magnitude of the resulting spread in the outcome. The results of this exercise are summarized in Table 1.
The conclusion of all this is, that it does not seem to be useful to be very precise in the calculation or the measurement of the different parameters. Furthermore, it seems that the rule-of-thumb as used in the CIErecommendations ( $L_{2} / L_{1}=0,1$ ) falls well within the area that is covered by the more elaborate assessment as given here (CIE, 1973).

## 4. APPLICATION OF THE BASIC FORMULA

We will discuss a few specific design element of tunnel lighting systems in view of the basic formula; qualitatively and sometimes quantitatively it can be indicated what is the influence on the lighting design.

### 4.1. Counterbeam lighting

When the light from the tunnel lighting luminaires is directed in a direction opposite to the direction of driving of the traffic, we may speak of counterbeam systems. This systems has two distinct advantages: firstly the luminance yield of the road surface in the tunnel (expressed in $c d / m^{2}$ per lux) is higher, and secondly the contrasts of obstacles on the road in relation to the road surface is higher, in both cases when compared to the more traditional symmetric lighting (Blaser \& Dudli, 1982; PIARC, 1979, 1983). Practical experience showed that a "pure" counterbeam system is not satisfactory; the optical guidance is poor, and the glare is disturbing. In practice, the counterbeam is more an "asymmetric" lighting.
The advantage of the higher luminance yield is counteracted to a certain extent by the fact that the total light output of the special counterbeam luminaires - which have to incorporate more precise optical control - is usually considerably lower than that of conventional luminaires. No general data can be given, but a gain of some $30 \%$ in luminance seems reasonable.
'The other advantage is real. The observed (as well as the intrinsic) contrast is higher because the lighting (the illuminance) on the frontal surfaces turned towards the approaching driver is considerably lower than in a traditional (symmetric) lighting installation. Details are given in the proceedings of a conference that had been held in Innsbruck for the occasion of the opening of the Arlberg-tunnel in Austria (Anon, 1978). In terms of the basic formula this means that $C$ is larger. In stead of the usual value of 0.2 we may select (or postulate!) a higher value. How much higher depends on the degree of asymmetry of the lighting installation. We indicated in Sec. 3.6. that for $C=0.3$ and 0.5 the relative profit as regards the reduction of the required value of $L_{2}$ is about $40 \%$ and $65 \%$ respectively. When additionally an extra gain of $30 \%$ may be found as a result of the improved luminance yield, $L_{2}$ might be only $40 \%$ or $25 \%$
respectively of the corresponding $L_{2}$-values in symmetrical installations. These values correspond quite good with values measured in practice, and with a number of driving experiments in a real tunnel (Blaser \& Dudli, 1982).

It should be pointed out, however, that this profit is only valid for obstacles on the road with vertical planes turned towards the driver. We have briefly suggested in the Introduction that on the base of modern investigation it is likely that the visual aspects of the driving task will have to be described in rather different terms. It remains therefore to be seen in how far this profit as regards the admissible reduction of $\mathrm{L}_{2}$ really is an advantage.

### 4.2. Daylight screens

The high values of the luminance needed in the entrance zone of tunnels can be realized in two ways: one may install artificial light (lamps) or one may apply subdued daylight, that is daylight that is reduced by means of screens or louvres. Those screens are characterized by the fact that in a first approximation the luminance of the road surface underneath them ( $L_{2}$ ) is proportional to the illuminance at the top of the screens. It should be pointed out, however, that this proportionally is nearly completely lost when the screens are constructed from high and narrow elements, particularly if they are made of material that easily corrodes. Practice indicates that such screens show a transmission that depends very heavily on the degree of cloudiness of the sky and on the position (altitude) of the sun. Furthermore, the transmission is usually far too low to be satisfactorily applicable. Details of this are given by Schreuder (1981), Swart (1979), Van den Bijllaardt (1975, 1977). More recent investigations did show that a satisfactory solution can be found by applying screens that are not constructed of high, narrow elements (Tan et al., 1983). These screens are not "sun-tight", meaning that in some circumstances direct sunlight may reach the road surface underneath the screen. In experiments that will be briefly discussed furtheron (Sec. 4.3) it was shown that this direct sunlight causes less disturbance than was previously supposed. It should be noted that under certain circumstances the $\mathrm{L}_{\mathrm{w}}$ could increase to unacceptable values. Obviously, screens that are not suntight do show a transmission that is not constant. Practice showed, however, that for most situations the discrepancy was not very large, so that here we use as an approximation a constant transmission.

The basic formula can be rewritten in this case (with $p, p^{\prime}$ and $p$ " as factors of proportionality)
$L_{2}=\frac{L_{d} f C^{\prime \prime}}{C-f C^{\prime \prime}}=\frac{p f C^{\prime \prime}}{C-f C^{\prime \prime}} L_{o}=\frac{p^{\prime} f C^{\prime \prime}}{C-f C^{\prime \prime}} L_{1}^{\prime}=\frac{p^{\prime \prime} f C^{\prime \prime}}{C-f C^{\prime \prime}} E_{h}$

For a wide range of value of $L_{o}$ (or of $E_{h}$ ) all parameters are constant, so that $L_{2}=k E_{h}$ with $k$ is a constant. Only for very high or very low values of $E_{h}, k$ is not constant any longer: for very high values one may not disregard $L_{a d e f}$ and for low values $C^{\prime \prime}$ does increase. This means that screens may be not adequate in very bright weather and in the twilight.

### 4.3. Retroreflecting devices

In many cases the tunnel entrance lighting is supported by retroreflecting devices; in some cases they even substitute the lighting (PIARC, 1979).

For retroreflecting devices, the contrast $C$ can be written as
$\mathrm{C}=\frac{\mathrm{L}_{3}-\mathrm{L}_{2}}{-\bar{L}_{2}}$
The basic formula becomes:
$L_{2}=\frac{p^{\prime \prime} f C^{\prime \prime}}{\frac{L_{3}-L_{2}}{L_{2}}--f C^{\prime \prime}}$
$L_{3}-L_{2}\left(1+f C^{\prime \prime}\right)=p^{\prime \prime} f C^{\prime \prime} E_{h}$
In a very dark tunnel entrance $L_{2} \simeq 0$.
$\mathrm{p}^{\prime \prime}$ can be found as follows:
$\mathrm{p}^{\prime}=\frac{1}{1.5} \mathrm{p} ; \mathrm{p}^{\prime \prime}=\frac{\pi}{\rho} \mathrm{p} ; \mathrm{p}^{\prime \prime}=8.4 \mathrm{p}($ for $\rho=0.25)$
This leads to $L_{3}=0.158 \mathrm{E}_{\mathrm{h}}$.

For a retroreflecting device $L_{3}=R E_{p}$. For normal good sheet materials we may take $R=200$ ( $\mathrm{cd} / \mathrm{m}^{2}$ per lux).
So the visibility of the retroreflecting device is guaranteed when
$\mathrm{E}_{\mathrm{p}} \geq \underline{0}-\frac{158}{\mathrm{R}} \underline{E_{h}}=0.00079 \mathrm{E}_{\mathrm{h}}$

Schreuder (1964, Figure 21) indicates that $E_{p} / E_{h}=0.00079$ corresponds to a distance of about 60 m , implying that retroreflectors may be useful up to this distance even in the absence of vehicle headlights. It follows that retroreflectors may be useful even in well-lit tunnels.

### 4.4. The tunnel facade

Practical experience has shown that applying dark colours at the tunnel facade and the other surfaces around, result in a great improvement in the visibility. In fact, this was the major finding on which the "third generation" of tunnel entrance lighting was based (Schreuder, 1980).
Why this is a fact may be demonstrated as well from the basic formula, as the value $L_{o}$ is determined to a considerable extent by the luminance of these surfaces. As the geometry plays a predominant role in the assessment of $L_{o}$ it is not possible to indicate how large the influence is in general terms. It has to be assessed for each tunnel, for each observation distance and for each lighting and weather condition separately. Furthermore, a change in the luminance of the various surfaces will influence the separate components of $L_{d}$ in different ways. The indication as given in the basic formula when all the components of $L_{d}$ depend in the same way on $L_{o}$ is, an indicated above, only an approximation.

### 4.5. Driving speed

As such, the driving speed has no direct influence on the lighting parameters of the tunnel installation. However, the distance from which the relevant objects must be seen increases sharply with the driving speed. If one assumes that the object is such that the approaching driver must be able to come to a stop before he hits the object, the relevant distance $d$ is the "safe stopping distance $d_{s}$ ". For a constant retardation $q$ this is
$d_{s}=v_{0} \tau+\frac{v_{o}{ }^{2}}{2 q}$
where $v_{0}$ is the speed at the start of the stopping manoeuvre and $\tau$ is the combined "reaction time". When $\tau$ is expressed in sec, $v_{o}$ in $m / s e c$ and $q$ in $\mathrm{m} / \mathrm{sec}^{2}, \mathrm{~d}_{\mathrm{s}}$ follows in m .
Now, there is difference in opinion as to the relevant values of $\tau$ and of q. For a very alert driver, a car in good condition, and emergency stopping manoeuvre and a dry horizontal road one may assume $\tau=1$ and $q=5$. For less alert drivers and wet road and/or more leisurely stopping, one may find $\tau=3$ and $q=3$. In Table 2 the resulting values of $d_{s}$ are given for a number of relevant values of $\tau, q$ and $v_{0}$, showing a very wide range of values of $d_{s}$.

The consequences of a variation of the selected value of $d_{5}$ are very important for the lighting design, particularly as regards the length of the threshold zone. As the adaptation to the lower luminance of the tunnel interior will usually begin not sooner than at some tens of meters in front of the tunnel, the value of $d_{s}$ determines to a large extent the length of the threshold zone. This length $l_{t h}$ may be found as
$l_{t h}=d_{s}-d_{a}$
where $\mathrm{d}_{\mathrm{a}}$ is the distance from the adaptation point (Schreuder, 1964) or the fixation point (Narisada \& Yoshikawa, 1974) to the tunnel portal. Thus, for speeds that are customary for motor tunnels $l_{t h}$ is fairly large; for motorway tunnels it may be quite large indeed. If, however, the driving speed is low, and if $d_{a}$ is large - e.g. in mountain tunnels with little traffic - it is possible to have $d_{s}<d_{a}$ : this implies that a threshold zone is not needed at all.

The required value of $L_{2}$ depends on the speed as well. In Table 1 it is shown that for $d=50 \mathrm{~m}$ (corresponding with low speed traffic) $\mathrm{L}_{2} / \mathrm{L}_{1}^{\prime}$ may be as low as 0.046 ; for $\mathrm{d}=200 \mathrm{~m}$ it must be about double this value. From these consideration it is clear that the driving speed has a very pronounced influence on the tunnel lighting design. It should be noted that this relates to the influence of the actual driving speed; it is well-known that local speed limits are not very well obeyed, so that a speed limit is usually not an effective means to reduce the requirements on the lighting requirements.

### 4.6. Variations in daylight

We discussed earlier several aspects of the consequences of variations in the daylight. First, at very high levels of daylight the adaptation deficiency cannot be disregarded any more; the term $L_{\text {adef }}$ differs from zero. This is especially important for tunnels in extremely open countries and for tunnels where the combination of sun and snow is a common experience. For the Dutch situation it is rather an exception; therefore in tunnels in the Netherlands this effect is usually disregarded. A second daytime aspect is the fact that at low levels of ambient daylight (e.g. twilight) the value of $\mathrm{C} \mathrm{\prime} \mathrm{\prime}$ increases. This is obviously of importance for all tunnels; it means that in twilight additional light must be installed under
daylight screens. A third aspect related with daylight is the colour of the tunnel facade. All these aspects have been dealt with in earlier sections. In other aspects the variations in daylight do not influence the relative value of $L_{2}$; according to the basis formula, $L_{2}$ is proportional to $L_{0}$ and to $L_{1}^{\prime}$. It is precisely this fact that is used when applying daylight screens. This proportionality requires, for obvious reasons, a change in the tunnel entrance lighting according to the variations in the daylight. This is a practical point of great importance.

Tunnels that are equiped with artifical light require just as all tunnels often a high level of luminance at the entrance. This means that usually a large number of lamps is required; the application of a small number of very powerful lamps (e.g. SON 1000 W ) hardly results in a visually acceptable installation. This large number of lamps permits a fairly simple adaption of the light level to variations in the daylight level by simply switching the lamps. Even with SON and SOX lamps that sometimes require a fairly long starting or re-starting time, switching can be applied as the daylight usually changes only slowly. In some cases a refinement can be found in dimming the lamps. With modern ballasts this can be done easily and efficiently with TL and SON lamps.

The main problem is, however, to find the appropriate daytime level. Usually one takes $L_{\text {。 }}$ for this. This is easily measured by means of an adapted Lux-meter: a standard measuring cell with a screen that restricts the field of view. In fact the Lux-meter is used as a luminance meter in this fashion. The meter must be placed in such a way that $L_{o}$ is assessed, that is to say in such a way that the cone is $2 \times 10^{\circ}$ and that the axis of the cone is parallel to the road axis, taking into account any slope in it. Padmos (1984) proved experimentally a fact that was encountered in practice: the horizontal illuminance near the tunnel does not give any useful information at all and cannot be used under any condition (See also Schröter, 1977, 1985). At the other hand, $L_{0}$ seems to work pretty well under more normal conditions. A more refined method by applying a converted television camera is described by Van den Bijllaardt (1977). See also Van Bommel \& De Boer (1980), Chapter 17.

When, however, the conditions are not completely "normal" also the use of $L_{0}$ can result in erroneous results. This is more in particular the case when the sun is at a low elevation, and is nearly in the line of the
tunnel axis. If the sun is visible near the tunnel portal the influence is obvious. The way $L_{\circ}$ is assessed as an arithmical mean of luminances within the cone does not count the direct sun glare in a sufficient way. As Schröter (1985) found from theoretical considerations and from practical experience, the adaptation should be assessed more precisely. Schröter applied the Stiles-Holladay formula for this. As this formula is not applicable for angles smaller than some $1.5^{\circ}$ of axis the results may be not accurate enough. Application of the Vos-formula might give considerable improvement. Schröter proposed to develop a special apparatus for this; this may be done fairly simply and effectively by means of an adapted luminance meter. In fact, he proved that a prototype according these lines did perform satisfactorily (Schröter, 1977). It is also indicated that applying $L_{0}$ under such conditions may result in an error of large proportions. Schröter (1985) gives a rather extreme example: with a small dark inner field and a very bright, large outer field $L_{0}$ would be nearly $8000 \mathrm{~cd} / \mathrm{m}^{2}$ whereas the value according to Stiles-Holladay was "only" some $1100 \mathrm{~cd} / \mathrm{m}^{2}$. Other examples can be given where $\mathrm{L}_{\mathrm{o}}$ would result in a value much too low. If this value is used, as is usual, to regulate the luminance in the tunnel entrance, it is quite possible that the $L_{2}$ values can be way off, resulting in either a very poor visual situation or a wasteful equipment. Further study is required to find the optimal way to assess in practice the value of the daylight.

The lighting in the tunnel entrance should follow the variations in the daylight. As indicated already, it does not seem to be necessary to allow for very rapid variations. Another point is that it does not seem necessary to follow the variations very precisely. We have indicated earlier that the variations in the $L_{2}$ values as following from the basic formula are quite considerable as a result of variations that are inherent to the arbitrarily chosen parameters. It is not easy to indicate on theoretical grounds how large the discrepancy may be between the actual value in the tunnel entrance and the value of $L_{2}$ as follows from the basic formula. Practical experience suggests, however, that a factor of two both ways is hardly noticeable and that a factor of three is quite acceptable. Now, the entrance lighting is usually executed as a number of consecutive steps. It seems therefore acceptable if the consecutive steps are about a factor of three apart. In an extreme case where a value of $L_{2}$ of 1000 $\mathrm{cd} / \mathrm{m}^{2}$ is sometimes needed as a maximum and where the lower value is 10 $\mathrm{cd} / \mathrm{m}^{2}$, this would require five steps, viz. $1000-300-100-30$ and 10
$\mathrm{cd} / \mathrm{m}^{2}$. In most cases a smaller number of steps is sufficient (Schreuder, 1964). The steps can be switched on and off according to a command signal from the measuring apparatus as described above. In several tunnels such systems are installed; they perform a satisfactorily (Van den Bijllaardt, 1977a; Schröter, 1977).

When considering steps in the luminance in the tunnel entrance one should not forget the rest of the entrance zone. It is not acceptable to have at the end of the threshold zone of say some $500 \mathrm{~cd} / \mathrm{m}^{2} \mathrm{a}$ "jump" down to the say $5 \mathrm{~cd} / \mathrm{m}^{2}$ of the tunnel interior. Schreuder (1964) did give suggestions in which way the luminance in the "transition zone" of the tunnel may be reduced without causing serious problems in the visual perception. As a rule of thumb, a factor of ten in luminance may be accepted in a period of two to three seconds (see also CIE, 1988). When considering the different luminance levels of the consecutive switching steps in the threshold zone this "adaptation" effect should not be disregarded, because in doing so a "black hole" effect may easily result at the end of the threshold zone. As was found in the experiments in the Benelux-tunnel in the Netherland regarding daylight screens it was found that this effect may cause real trouble when not satisfactorily dealt with (see Sec. 4.3). Furthermore it should be pointed out that at low values of adaptation these adaptation effects are systematically slower; this implies that at the lower switching steps the requirements for the transition zone become relatively speaking more severe. Only relatively speaking; as the relevant luminance values are quite low, it is not difficult to fulfill the requirements in practice.

## 5. EXPERIMENTS ON TUNNEL LIGHTING ASPECTS

### 5.1. Introduction

During the last decennia a large number of experiments has been made as regards tunnel lighting. The foregoing is based to a large extent on such investigations which have been indicated explicitely only in a small number of cases. A comprehensive review of these investigations is given in Schreuder (1981), but even there many investigations were not included. In this chapter we will deal with a number of recent investigations that are directly related to the system of tunnel lighting design that is used in the Netherlands. Many of these investigations were executed by the Locks and Weirs Division of Rijkswaterstaat (the Dutch Ministry of Transport so to say). In most cases they are not published separately. The survey given here can not render in full the important contribution of this Division. Further we will quote from other important studies of other departments of Rijkswaterstaat, of the Nijmegen University and of SWOV. Finally some preliminary data from the CIE TC 4.05 on tunnel lighting will be quoted, data coming from a draft Technical Report (CIE, 1988).

### 5.2. The assessment of the veiling luminance

The veiling luminance as a result of the scatter in the eye is a very important component of the visual disturbance a driver may experience when approaching a tunnel. As indicated earlier (Sec. 3.2.2) the studies of Vos provide the basis to assess this effect. In order to calculate the veiling luminance also in practical situations, mr. J. Jansen of Rijkswaterstaat designed a computer programme. This programme consists of two parts. The first part, mainly a standard designing programme, enables to construct a perspective view from a road scene - e.g. a tunnel entrance on the basis of the actual drawings of the tunnel. In this way a perspective view of the tunnel entrance from any point of observation may be constructed, also when the tunnel is in the design stage only. The second part is the actual calculation of the veiling luminance. This part of the programme is based on the Vos-formula (see Sec. 3.2.2), and uses the fact that, as it deals with "physical" straylight, the different components of the veiling luminance are directly cumulative: the Vos-formula may be summated or integrated.

We will not deal here with the details of the programme, which proved to be quite complicated. The programme is used as follows: first a perspective view of the tunnel from the selected position of observation is calculated from the first part of the programme and projected on the monitor screen. Then the corners of the area from which the contribution to the veiling luminance is requested - e.g. the road surface in front of the tunnel - are traced by means of a $X-Y$ crosswire scanner. Then the luminance value of that part of the field of view is fed in. This value may follow from direct measurements in reality or it may be calculated or estimated in case of a tunnel in the design stage only. The programme then assesses the contribution of that part of the field of view to the total veiling luminance, with the luminances weighted according to the Vos-formula. This process is repeated for all relevant parts of the field of view; the sum total of all these parts gives the desired value of the veiling luminance. Two remarks should be added: first, the programme may encompass polyhaedrons but not curves, and second, as the Vos formula just as the Stiles-Holladay formula approaches infinity at $\theta=0^{\circ}$, the precise centre of the field of view should be excluded from the calculation. The programme does take these aspects into account.

The programme works quite well. In Figure 3 an example is given where the veiling luminance is calculated for the Kil-tunnel (near Dordrecht in the Netherlands). The calculated values are based on luminance measurements in the real tunnel given in Figure 4. The method seem to yield very similar results will direct measurements of the veiling luminance. It should be pointed out, however, that this is not to be considered as a validation of the programme; the measurement of the veiling luminance was made using the Prichard luminance meter and the Fry glare lens attachment. This method of assessment of the disability glare is an approximation only (Padmos \& Alferdinck, 1983; Hartmann et al., 1986).
Furthermore, the Fry lens follows a different rule as does the Vos-formula that is used for the veiling luminance computer programme. Keeping this in mind, the agreement between the two ways to assess the veiling luminance is very satisfactory, increasing the confidence one might have in the different components: the Vos-formula, the computer programme and the actual measurements. At present, the programme is adapted to make it more "user-friendly".

The computer programme is used to calculate the value of the field fac-
tor $f$ (see Sec. 3.3). The value of $L_{e}=0.0056 \mathrm{~L}_{1}^{\prime}$. Because the lower values of the angles are difficult to set with the crosswires, we used 0.007 in Sec. 3.3, allowing for a certain "safety margin".

### 5.3. Daylight screens; the Benelux-tunnel experiments

The Benelux-tunnel, opened for traffic in 1967 is part of the extremely important ringroad around Rotterdam in the Netherlands (Schreuder, 1973; Stiksma (ed.), 1987). It is a North-South tunnel underneath the Maas river which carries most of the sea-going vessels that port in Rotterdam. The tunnel is some 800 meters long. It consists of two two-lane tubes with an additional truck climbing lane near the exits. The tunnel has slight curves both horizontally and vertically. It carries as an average some 60,000 vehicles per day. At both entrances and both exits aluminium daylight screens over a length of about 130 m have been constructed. In the original design, these screens were "suntight": under no circumstance direct sunlight could reach the road surface on or the tunnel walls under the screens. As a result of the very severe corrosion of the untreated aluminium, the overall transmission of the screen was reduced very markedly; furthermore the overall transmission was beginning to depend quite considerably on the weather situation and the position of the sun.

Between 1979 and 1984 a series of experiments was executed in the entrance zone of this tunnel with two distinct aims: first to improve the entrance of the Benelux-tunnel itself, and second to find a more general solution for the design and construction of daylight screens to be applied in other tunnels in the Netherlands - both existing tunnels that required overhaul and new tunnels to be built in the near future. The experiments consisted of a series of different constructions of the daylight screens to be built full-scale at the West entrance of the tunnel - the tube for North-South traffic. Each of the alternatives was left for quite some time to gain experience in different times of the day and different seasons. Generally speaking all experiments consisted of crosswise beams over the road, of different shape, different colour and different interdistance. All of them did represent screens that were NOT suntight: in all cases the direct sunlight could sometimes reach the road or the walls under the screen. The first seven alternatives consisted essentially of cross beams of 1.22 m high and 0.20 m wide. They were set at different interdistances and in part covered with other types of
screens or supplemented by smaller screens or beams. Some of these alternatives proved to be reasonable, but none of them was really satisfactory. So, as the final solution another type of beams was used; they were much smaller, having a Z-shaped cross-section with a height of 0.20 m and horizontal flaps at the top and the bottom of 0.065 m . They were painted black, and put perpendicular to the tunnel axis, that is in an East-West position. The entrance zone was subdivided in four sections each 30 m in length. The center-to-center distance of the beams decreased in each following section, being $0.6 ; 0.5$; 0.4 and 0.3 m respectively (see Figure 5; Tan et al., 1983).

In each case photometric measurements were made regarding the luminance in the approach zone and the luminance and horizontal illuminance in the entrance zone. Furthermore the veiling luminance was measured from driving cars at different positions in the tunnel taking into account the reflections and light scatter in the vehicle windscreens. And finally in each case quite extensive subjective appraisals were made, partly by expert and partly by the driving public at large. Some of the results are given in Figure 6 (Van den Brink, 1987), where the relative values of $\mathrm{L}_{\mathrm{o}}$ (according the usual definition) are given, normalised for $\mathrm{L}_{\text {o }}$ at 150 m in front of the tunnel. It is clear that alternative no. 8 gives the best result: a smooth gradual decrease throughout the full approach and entrance zones. This alternative was selected as the final solution for the Benelux-tunnel; for the other tunnels to be overhauled or to be constructed a solution will be chosen that is very similar, be it that some adjustments to the specific situation of these tunnels must be allowed for.

The fact that the screens are not suntight proved under some conditions to offer rather severe disturbance. More in particular it was shown that the light scattered in the vehicle windscreen and the additional veil that resulted from the reflection of the vehicle interior in the windscreen could result in severe disturbance of the visibility into the tunnel. It was found that these problems could not be solved as long as screens were used that were not suntight. However, it was found that the disturbance resulting from this light scatter and light veil could be reduced by taking care that the luminance within the threshold zone was as high as possible - higher than the values usually quoted for adequate visibility. It should be pointed out that those values usually do not take the influence of the vehicle windscreen into account.

As was mentioned earlier, it was found in these experiments that it is really important to ensure that the luminance at the end of the threshold zone is reduced gradually and over a sufficient length towards the low luminance prevailing in the tunnel interior. If this aspect is neglected, a severe "black hole" effect may result at the end of the threshold zone. Finally, it was found that the center-to-center distance of the beams is important in view of disturbance caused by flicker. Contrary to what was assumed earlier, also when experienced only briefly, flicker may be quite disturbing. It was found that for the driving speeds that are usually found in the Benelux-tunnel (some 70 to $110 \mathrm{~km} / \mathrm{h}$ ) the distance should be about half a meter. This effect was relevant for the selection of the interdistances that were finally adopted: ranging from 0.6 to 0.3 m .

A more complete report of the results is given by Van de Brink (1987), see also Tan et al. (1983).

### 5.4. The shape of the entrance; the Schiphol-tunnel experiments

The Schiphol-tunnel is one of the major road tunnels in the Netherlands. It was opened for traffic in 1966 (see Schreuder, 1973; Stiksma (ed.), 1987). The tunnel is under the main runway of Schiphol, the Amsterdam International Airport. The road is the main freeway between Amsterdam to the North and The Hague and Rotterdam to the South, forming the most important motorway connection in the Netherlands. The countryside is completely flat, and the tunnel is hardly under the surface: when approaching it the tunnel looks rather like a construction on the surface - somewhat like a large barn one has to enter. This proves to present the major problem at the tunnel. The tunnel itself consist of two tubes each containing three traffic lanes and hard shoulders at both sides.

Again here the entrance zone consisted of a screen of aluminium grids that as a result of severe corrosion showed an overall transmission of between 2 and $5 \%$ as compared to the design value of $12 \%$ and the new value of over $20 \%$ ! (see Swart, 1979). As pointed out by Schreuder (1981) it seems to be a very poor idea to use untreated aluminium for daylight screens for motor tunnels, particularly if they are located in regions with a corrosive atmosphere (sea, chemical industry). As the entrance zone consists of a structure on the ground and only over the entrance (not over the exit) it presents itself, as indicated earlier as a "barn".

The subjective pressure on the drivers who had to enter the barn-like entrance of the tunnel at high speeds was considerable, particularly as the "barn door" usually seemed to be pitch-black.

In view of the complaints received from the driving public it was felt that the tunnel entrance should be overhauled. This idea was supported by the fact that the tunnel presents a severe bottle-neck in the motorway network around Amsterdam, and that more recently a number of severe accidents happened near the tunnel. Finally, also the actual lighting installation did not satisfy any longer, being nearly 20 years old. So the tunnel was to receive a complete "face lift". The first step in this was an investigation made by the Psychology Department of the Nijmegen University. The results of this study are presented in a report by Leeuwenberg \& Boselie (1984).

It is interesting to see in which way a purely psychological approach leads to a somewhat different result. The study is essentially qualitative and deals primarily with visual illusions based on the perspective view of drivers. The approach is not unlikely to that of the theoretical treatises regarding the aesthetics of drawing and painting: really a very refreshing and original approach! The results are also rather original: the main recommendations were to discard or at least to reduce the length of the daylight screens so that the "barn door" effect was reduced as a result of the visible sidewalls. The aim was to ensure that the Schipholtunnel would look like other more "normal" tunnels. One may expect that drivers will be acquainted with other tunnels so that the Schiphol-tunnel will not present an unexpected sight. Furthermore the perspective view of the road leading into the tunnel will be more clearly defined (see Figure 7). It was suggested that the part of the reinforced entrance lighting that was lost by reducing the length of the screens should be compensated for by increasing the light level in the closed section of the tunnel - a suggestion that unfortunately is not followed by the road authorities.

This study is interesting not only because it suggested a considerable improvement for the Schiphol-tunnel: it also seems to point towards a system in which the elusive notion of "visual guidance" may be operationalized. This approach combines notions of perspective viewing with visual illusions and with pattern recognition and expectation of future situations.

The recommendations of the Nijmegen report are followed (apart from the reinforcement of the transition zone lighting!). The results are satisfactory. As a further improvement the daylight screens are replaced by beams similar to those as found from the experiments in the Benelux-tunnel (see Sec. 5.3). The tunnel is described by Stiksma (ed.) (1987). And finally the lighting in the tunnel interior will be adapted to modern traffic situations particularly to the fact that trucks are higher than in the past and that traffic cannot be interrupted for the maintenance of the lighting installation.

### 5.5. The cut-off of vehicle windscreens

In the discussion on the adaptation point an important factor is the question as to from which distance from the tunnel entrance the sky usually extremely bright - ceases to be visible from the position of the driver of the cars that approach the tunnel. This is determined by the vertical visual cut-off of the vehicle windscreen. In the past, usually a value of $8^{\circ}$ was taken as representing the maximum angle between the line connecting the eye and the upper rim of the windscreen, and the horizontal (Schreuder, 1964). When considering glare in street lighting, a value of $10^{\circ}$ was considered as sufficient to describe discomfort glare and $19^{\circ}$ as sufficient to describe disability glare. Recent measurements have indicated that all these values are not relevant at all for the practical situation. From samples of in total nearly 900 (passenger)cars on urban and rural roads in a number of countries in Western Europe it was found that the cut-off angle shows in practice a very wide range. The logarithm of the angle is nearly perfectly normally distributed with an average at $24.5^{\circ}$ and values of $14^{\circ}$ and $44^{\circ}$ representing the 2.5 and 97.5 percentiles (see Figure 8). The measurements are described by Schreuder (1985). The conclusion is that the actual cut-off is much larger that than previously assumed, resulting in the need to shift the adaptation point to a location much closer to the tunnel. Another consequence is that the area of integration for the Vos formula in the assessment of the ocular straylight reaches much higher as well. That influence is, however, not very great as the contribution of areas far from the line of sight decreases with the square of the angle: in this region the Vos formula approaches closely the Stiles-Holladay formula.

### 5.6. Classification for tunnels

In theory one may assess the lighting requirements for tunnels on the basis of the basic formula, taking into account all the relevant aspects of that particular tunnel. In practice, however, there is a considerable need for a more simple approach, particularly for a first rough design of the installation. In this respect, classification schemes for tunnels are often quite useful.

The Permanent International Association of Road Congresses PIARC made in its document on tunnel lighting a proposal for the classification of tunnel entrances, mainly aimed at a distinction as regards the requirements for the entrance lighting. This classification is rather crude; it distinguishes only eight types of tunnel entrances. The way to make the relevant distinction is to select from eight pictures the one that looks most closely like the tunnel under consideration. As a first approximation this system has its merits, but for the actual design of lighting installations it is not accurate enough (see Figure 9) (PIARC, 1979). Tan (1978) proposed a different classification not primarily based on the surroundings but rather on the position of the tunnel in relation to the sun (to the compass direction) and on the "degree of difficulty of the traffic conditions". The classification is given in Table 3 A en B . This classification has a number of advantages in comparison to the PIARC system. There is, however, until now no experience, particularly with the way to assess the "degree of difficulty". See also Tan et al. (1983).

The CIE TC 4.08 on tunnel lighting is considering another classification. The outline is given in Figure 10 (CIE, 1988). Obviously it is to early to judge this system; it seems to give adequate distinction as regards driving speed; at the other hand it seems that the distinction in only three types of surrounding (flat open country; partly open and mountain/-built-up area) is not sufficient to include the more common types of tunnel surroundings, and definitely not some special cases, and finally, the traffic composition and traffic situation (including traffic density) are not indicated explicitely. Further consideration is clearly still required.

A fourth proposal of tunnel classification relates specially to short tunnels and is based on a research programme of the Locks and Weirs

Division of Rijkswaterstaat. The first and major problem in short tunnels is to consider which tunnels are really "short" and in which way these may be subdivided according to their visual needs. It is well-known that the actual length of the tunnel along its longitudinal axis does not give adequate information. The classification described here suggests to use the way one may look through the tunnel. The experiments were carried out by the Locks and Weirs Division of Rijkswaterstaat. They consisted of subjective appraisals - on the basis of diapositive slides taken at 50 m distance - by some 70 observers of 26 different short tunnels. The observers had to indicate whether they felt they could pass through the tunnel without reducing speed and also without the danger of not seeing objects like pedestrians in the tunnel.
It was found that the degree one could look through the tunnel (the "throughlook $\mathrm{K} "$; see Figure 11) is really a measure for the appraisal. Furthermore, there seem to be at least three "clusters" of tunnels, designating very poor and very good tunnels (where nearly everyone either stops or in contrast continues) and a third cluster where the opinions are divided. This is demonstrated in Figure 12 where the percentage of people that proceed without reducing speed (\% yes) is plotted against K . In Figure 12 also the average and the standard deviations per cluster are indicated; it is clear that Cluster 1 and 2 do not differ significantly; however, Cluster 3 is significantly different from the other clusters. The system is described in detail in Schreuder \& Fournier (1985).

It is not certain whether this classification can be used for drafting recommendations for the lighting of short tunnels; for this, further research is required. It seems, however, to be useful for such further study, where tunnels of the first cluster may be used to study the lighting requirements for difficult tunnels, the second cluster to decide which tunnels do require (daytime) lighting and tunnels from the third cluster to determine what is the best equipment of tunnels that do not require a daytime lighting.

## 6. CONCLUSIONS, RECOMMENDATIONS

### 6.1. Conclusions

1. Assuming that the visibility in tunnel entrances can be expressed in the possibility to detect small diffuse reflecting objects on the road surface the requirements for tunnel entrance lighting can be described with one formula (the basic formula).
2. The basic formula expresses the tunnel entrance luminance level $L_{2}$ as a function of the disturbing luminance $L_{d}$, the threshold contrast $C^{\prime \prime}$ and the contrast $C$ that is assumed for the object, involving a "fieldfactor" $f$ that relates $C^{\prime}$ to $C^{\prime \prime}$ ( $C^{\prime}$ being the visible contrast).
3. The basic formula runs:

$$
\mathrm{L}_{2}=\frac{\mathrm{L}_{\mathrm{d}} \mathrm{fC}^{\prime \prime}}{\mathrm{C}-\mathrm{fC}}
$$

4. The disturbing luminance consists of four elements:

- the adaptation deficiency $L_{a d e f}$
- the scatter in the ocular media $L_{e}$
- the scatter in the atmosphere $L_{a t}$
- the scatter in the vehicle windscreen $L_{w}$

5. For low-land tunnels under average circumstances $L_{a d e f}$ may be disregarded.
6. For $L_{e}, L_{a t}$ and $L_{w}$ numerical value are known.
7. C" follows from laboratory measurements.
8. C is selected on the basis of practical experience.
9. Finally, the field factor consists of several elements. Most of these elements can be accounted for; only the difference in the conditions of observation between the laboratory and the real world requires further study.
10. Concluding it seems possible to assess the required level of luminance in the tunnel entrance under all practical low-land situations when two assumptions are made:

- first, the visual aspects of the driving task of car drivers can be adequately described with the detection of small diffuse reflecting objects on the road surface in the tunnel;
- second, the field factor as introduced here describes adequately the difference between the conditions of observation between the laboratory and the real world.


### 6.2. Recommendations

1. It is recommended to base the design methods for tunnel entrance lighting on the basic formula introduced here, taking into account the numerical values and the variations therein as found in different research.
2. It is recommended to study the visual aspects of the driving task; more in particular the visually critical objects that are essential for the performance of the visual task. As it is not to be expected that the visually critical elements in tunnels will essentially be different from those on the open road, it is suggested to combine the tunnel circumstances with the ongoing research regarding road lighting.
3. It is recommended to study the "field factor" in reality by comparing in driving tests in actual tunnels the threshold of detection with the laboratory tests.

It is suggested to use two vehicles following each the while driving through tunnels; the leading vehicle carrying a visual test object and the following vehicle carrying the observer as driver (and the recording equipment). It is essential to measure the luminance and the luminance distribution in the field of view simultaneously. It is not necessary to do these measurements under many varying conditions. In theory one value only would seem to suffice as f is introduced as a constant multiplying factor. As the constancy of $f$ is not established beyond doubt it is suggested to do the measurements at two or three different values of the surround luminance. It should be noted that the equipment needed for such measurements can be used afterwards to make practical assessments of the lighting quality in existing tunnels.

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Figure 1. Calculated thresholds for targets of different size with uniform background luminance assuming positive contrast and 100 per cent probability of seeing. After Adrian \& Eberbach (1979), Figure 3.

Figure 2. Influence of variations in the starting level $L_{b}$ of the luminance on the adaptation $t$ for different values of $L_{b} / L_{e} . L_{e}=$ end value of luminance. After Schreuder (1964), Figure 46.

Figure 3. Computer generated view of the Kil tunnel, the Netherlands, distance 100 m .

Figure 4. Luminance measurements and calculated veiling luminance contributions of the Kil tunnel, the Netherlands, distance 100 m . Measured at $\mathrm{E}_{\mathrm{h}}=$ 55.000 lux. Total veiling luminance (without No. 2) $164 \mathrm{~cd} / \mathrm{m}^{2}$. Measurements after Anon (1984), Figure 3.

After 5. Final sun screen design; distance, shape and dimension of screen elements. After Tan et al. (1983), Figure 6.

Figure 6. Relation between relative value of $L_{0}$ and distance, for-alternative 1 (sun), $5+6$ (sun) and 8 (cloudy). After Van den Brink (1987), Figure 10.

Figure 7. A proposal for the Schiphol tunnel entrance. After Leeuwenberg \& Boselie (1984), Figure 23.

Figure 8. The visual cutt-off angle $\alpha$ of vehicle windscreen. After Schreuder (1985), Figure 1.

Figure 9. Luminance values to be considered. After PIARC (1979), Figure 3.

Figure 10. Line sketches of actual tunnel entrances. After CIE (1988), Figures 5.1-5.8).

Figure 11. The degree one can look through a tunnel (the "throughlook K"). After Schreuder \& Fournier (1985), Figure 1.

Figure 12. The relation between the subjective appraisal (\% yes) of short tunnels and the throughlook K. After Schreuder \& Fournier (1985), Figure 2.


Figure 1. Calculated thresholds for targets of different size with uniform background luminance assuming positive contrast and 100 per cent probability of seeing. After Adrian \& Eberbach (1979), Figure 3.

$\therefore — \because L_{b} / L_{e}=10$
$\therefore-L_{b} L_{b}^{e}=1000$

Figure 2. Influence of variations in the starting level $L_{b}$ of the luminance on the adaptation $t$ for different values of $L_{b} / L_{e} \cdot L_{e}=$ end value of luminance. After Schreuder (1964), Figure 46.


Figure 3. Computer generated view of the Kil tunnel, the Netherlands, distance 100 m .


| Nr. | Luminance <br> $\left(\mathrm{cd} / \mathrm{m}^{2}\right)$ | $\mathrm{L}_{\mathrm{s}}$ <br> $\left(\mathrm{cd} / \mathrm{m}^{2}\right)$ | Nr. | Luminance <br> $\left(\mathrm{cd} / \mathrm{m}^{2}\right)$ | $\mathrm{L}_{\mathrm{s}}$ <br> $\left(\mathrm{cd} / \mathrm{m}^{2}\right)$ | Nr. | Luminance <br> $\left(\mathrm{cd} / \mathrm{m}^{2}\right)$ | $\left.\mathrm{L}_{\mathrm{s}}{ }^{2} \mathrm{~cd} / \mathrm{m}^{2}\right)$ |
| :--- | :---: | ---: | ---: | :---: | ---: | ---: | ---: | ---: |
| 1 | 3040 | 68.2 | 9 | 3995 | - | 17 | 113 | 0.2 |
| 2 | 216 | 44.3 | 10 | 4230 | 1.9 | 18 | 1175 | 0.7 |
| 3 | 649 | 4.3 | 11 | 884 | - | 19 | 378 | 0.4 |
| 4 | 7332 | 59.3 | 12 | 790 | - | 20 | 926 | 0.2 |
| 5 | 757 | 1.7 | 13 | 691 | - | 21 | 1240 | - |
| 6 | 3103 | 1.2 | 14 | 526 | - | 22 | 1010 | - |
| 7 | 3670 | 9.8 | 15 | 2068 | 2.5 | 23 | 2540 | - |
| 8 | 2440 | 2.9 | 16 | 566 | 0.8 |  |  | - |

Figure 4. Luminance measurements and calculated veiling luminance contributions of the Kil tunnel, the Netherlands, distance 100 m . Measured at $\mathrm{E}_{\mathrm{h}}=$ 55.000 lux. Total veiling luminance (without No. 2) $164 \mathrm{~cd} / \mathrm{m}^{2}$. Measurements after Anon (1984), Figure 3.


After 5. Final sun screen design; distance, shape and dimension of screen elements. After Tan et al. (1983), Figure 6.


Figure 6. Relation between relative value of $L_{\text {o }}$ and distance, for alternative 1 (sun), $5+6$ (sun) and 8 (cloudy). After Van den Brink (1987), Figure 10.


Figure 7. A proposal for the Schiphol tunnel entrance. After Leeuwenberg \& Boselie (1984), Figure 23.


Figure 8. The visual cutt-off angle $\alpha$ of vehicle windscreen. After Schreuder (1985), Figure 1.



Portal in open country with little background
$4000-3000 \mathrm{~cd} / \mathrm{m}^{2}$


Poctal with montain batheroum $1000-2000 \mathrm{ed} \mathrm{m}^{2}$

Figure 9. Luminance values to be considered. After PIARC (1979), Figure 3.


Stopping distance 160 m Sky $35 \%$



Stopping distance 100 m Sky $27 \%$


Stopping distance 160 m Sky $14 \%$


Stopping distance 100 m Sky $18 \%$


Stopping distance 100 m sky $4 \%$

Figure 10. Line sketches of actual tunnel entrances. After CIE (1988), Figures 5.1-5.8).


$$
\mathrm{K}=\frac{\mathrm{EFGH}}{\mathrm{ABCD}} \times 10
$$

Figure 11. The degree one can look through a tunnel (the "throughlook K"). After Schreuder \& Fournier (1985), Figure 1.


Figure 12. The relation between the subjective appraisal (\% yes) of short tunnels and the throughlook K. After Schreuder \& Fournier (1985), Figure 2.

## TABLES 1-3

Table 1. Variation in $L_{2} / L_{1}^{\prime}$

Table 2. Stopping distance $d_{s}(m)$ for different values of the speed $v_{0}$ ( $\mathrm{m} / \mathrm{sec}$ ), overall reaction time $\tau(\mathrm{sec})$ and retardation $q\left(\mathrm{~m} / \mathrm{sec}^{2}\right)$.

Table 3A. Classification of tunnels according to entrance lighting. After Tan et al. (1983), Table 2.

Table 3B. Recommended values for the illuminance in the threshold zone of tunnels. After Tan et al. (1983), Table 1.

| Source | Value |  | Resulting value | Relative |
| :--- | :--- | :--- | :--- | :--- |
| nominal | altered | of $L_{2} / L_{1}^{\prime}$ | difference |  |

Table 1. Variation in $L_{2} / L_{1}^{\prime}$

| $\begin{aligned} & \mathrm{q} \\ & \mathrm{~m} / \mathrm{s}^{2} \end{aligned}$ | $\mathrm{v}_{0}=10 \mathrm{~m} / \mathrm{s} \quad(36 \mathrm{~km} / \mathrm{h})$ |  |  |  |  | $\mathrm{v}_{\text {。 }}=15 \mathrm{~m} / \mathrm{s}$ |  |  | ( $54 \mathrm{~km} / \mathrm{h}$ ) |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\tau=1$ | 2 | 3 | 6 | 10 | 1 | 2 | 3 | 6 | 10 |
| 1 | 60 | 70 | 80 | 110 | 150 | 127 | 142 | 157 | 202 | 262 |
| 1,5 | 43 | 53 | 63 | 93 | 133 | 90 | 105 | 120 | 165 | 225 |
| 2 | 35 | 45 | 55 | 85 | 125 | 71 | 86 | 101 | 146 | 206 |
| 3 | 26 | 36 | 46 | 76 | 116 | 52 | 67 | 82 | 127 | 187 |
| 4 | 22,5 | 32,5 | 42,5 | 72,5 | 112,5 | 43 | 58 | 73 | 118 | 178 |
| 5 | 20 | 30 | 40 | 70 | 110 | 37 | 52 | 67 | 112 | 172 |
| 6 | 18 | 28 | 38 | 68 | 108 | 34 | 49 | 64 | 109 | 169 |
| 8 | 16 | 26 | 36 | 66 | 106 | 29 | 44 | 59 | 104 | 164 |
| q | $\mathrm{v}_{\mathrm{o}}=20 \mathrm{~m} / \mathrm{s} \quad(72 \mathrm{~km} / \mathrm{h})$ |  |  |  |  | $\mathrm{v}_{\mathrm{o}}=30 \mathrm{~m} / \mathrm{s}$ |  |  | ( $108 \mathrm{~km} / \mathrm{h}$ ) |  |
|  | $\tau=1$ | 2 | 3 | 6 | 10 | 1 | 2 | 3 | 6 | 10 |
| 1 | 220 | 240 | 260 | 320 | 400 | 480 | 510 | 540 | 630 | 750 |
| 1,5 | 153 | 173 | 193 | 253 | 333 | 330 | 360 | 390 | 480 | 600 |
| 2 | 120 | 140 | 160 | 220 | 300 | 255 | 285 | 315 | 405 | 525 |
| 3 | 87 | 107 | 127 | 187 | 267 | 180 | 210 | 240 | 330 | 450 |
| 4 | 70 | 90 | 110 | 170 | 250 | 142 | 172 | 202 | 292 | 412 |
| 5 | 60 | 80 | 100 | 160 | 240 | 120 | 150 | 180 | 270 | 390 |
| 6 | 53 | 73 | 93 | 153 | 233 | 105 | 135 | 165 | 255 | 375 |
| 8 | 45 | 65 | 85 | 145 | 225 | 86 | 116 | 146 | 236 | 256 |

Table 2. Stopping distance $\mathrm{d}_{\mathrm{s}}(\mathrm{m})$ for different values of the speed $\mathrm{v}_{\mathrm{o}}$ $(\mathrm{m} / \mathrm{sec})$, overall reaction time $\tau(\mathrm{sec})$ and retardation $\mathrm{q}\left(\mathrm{m} / \mathrm{sec}^{2}\right)$.

${ }^{x}$ ) A : short tunnels with vertical curvatures
B : long under passes
C : (very) long tunnels

Table 3A. Classification of tunnels according to entrance lighting. After Tan et al. (1983), Table 2.

| Class | Illuminance (maximum values) <br> artificial light <br> a | b | (lux) <br> daylight <br> a | screens <br> b |
| :---: | :---: | :---: | :---: | :---: |
| I | 6000 | 10,000 | 10,000 | 30,000 |
| II | 3000 | 5,000 | 3,000 | 10,000 |

Table 3B. Recommended values for the illuminance in the threshold zone of tunnels. After Tan et al. (1983), Table 1.

