THE LIGHTING OF VEHICULAR TRAFFIC TUNNELS

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1964

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CENTREX PUBLISHING COMPANY — EINDHOVEN

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VEHICULAR TRAFFIC TUNNELS

This book was written as a thesis for a doctor's degree at the
Technical University, Eindhoven

This book contains viii + 118 pages, 57 illustrations and 8 pages with photographs

U.D.C. Nr. 628.791.6 : 624.19

Printed in The Netherlands

PREFACE

As long as there have been railways, there have been tunnels. But the need for lighting tunnels was not felt until one began making tunnels for road traffic. The engine-driver of a train only needs to pay attention to the signals, but the road user on the other hand needs light to steer by. At night he can see with his headlamps just as well in a tunnel as on an unlighted road; but if he enters a tunnel in the day-time, the headlamps are no help. Used as he is to the daylight, he will be as blind as a bat for the first five or ten seconds, and in order to bridge this highly dangerous visual gap, extremely strong lighting, whose intensity must approach that of daylight, is needed particularly at the entrance of tunnels.

This problem was not fully realized when the first road tunnels under rivers (in New York, London, Liverpool, Hamburg) were built; and the luminous efficiency of the lamps available at that time was such that even if the problem had been realized, it would not have been possible to provide adequate lighting without the expenditure of vast sums of money.

Hardly had the sodium lamp appeared on the market when it was made use of in the Schelde tunnel near Antwerp. This was only a humble beginning. More and more road tunnels are now being built under rivers, and even through mountains to replace the roads over the high passes which are often impassable in the winter.

The Commission for Public Lighting of the Netherlands Foundation on Illumination has occupied itself intensively with tunnel lighting since 1960. They have received much help here from the Locks and Dams Section of the Netherlands National Water Board, who designed the Velsen tunnel, and the Illumination Engineering Laboratories of the Philips Factories in Eindhoven, where a series of theoretical and practical studies of various factors involved in tunnel lighting have been carried out under the leadership of J.B. de Boer. In 1963 the above-mentioned Commission published their "Recommendations on Tunnel Lighting", which deals not only with long tunnels but also with the short ones which are playing an increasingly important role in urban traffic.

In this book the author, who has been closely involved in the investigations carried out in the Philips Laboratories, discusses the problems of tunnel lighting in much greater detail than was possible in the Recommendations of 33 pages, with 20 pages of examples.

I regard Dr. Schreuder's book as an important step towards perfect tunnel lighting, which will contribute to increased road safety.

Prof. Dr.-Ing. N. A. Halbertsma

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CHAPTER 1

INTRODUCTION

The transport of passengers and goods has played such an important role, particularly during the last decades, that not only one cannot ignore it any longer, but even it constitutes the deciding factor in many aspects of daily life. This applies especially to motorised traffic because it is only due to this that real mass transportation has become possible.

The demands made on the means of transport both on the vehicles and in still greater measure on the roads and highways are very high. The demands on the road system are determined by three criteria, *capacity, speed* and *safety*. These three criteria are closely interdependent and depend moreover to a great extent on *driving comfort*. The word "comfort" in this connection must certainly not be thought as a provision signifying luxury; we mean the need to construct the road with all the facilities needed in such a way that it can be driven over with a minimum of physical and psychological strain on the part of the road user. The facilities comprise such diverse things as beaconing, lighting, guidance, layout of crossings and so on. The importance of driving comfort led to the investigations which have been carried out in various places into discomfort glare in street lighting, the visibility of traffic signals and so forth.

In an ever increasing number of cases one can only cope with the growing stream of traffic by building traffic tunnels instead of using the less efficient conventional methods of improving the road network. It can be added here that throughout this study *every artificial covering of a road* will be called a "tunnel", irrespective of the length and the nature of the covering. The aim of using tunnels is to serve traffic in as efficient a manner as possible. Tunnels are completely utilitarian constructions. All means must be used to make the usefulness of the tunnel as great as possible, even sometimes against arguments of an architectural or aesthetic nature. A tunnel which is built to prevent traffic obstructions must naturally not be a hindrance to traffic itself; the driving comfort, as well as the capacity, driving speed and safety must be at least equal to those on the adjacent roads.

To drive a motor vehicle one needs a great deal of information about the environment. This information is almost all of a visual nature. This means that a stretch of road and especially a tunnel only fulfils the purpose when the necessary information is actually provided. Therefore the lighting plays a decisive part.

The lighting of traffic tunnels, particularly during daytime, gives rise to a number of problems which cannot be solved by simple methods. The reason for this is the impossibility, both technically and economically to light a tunnel interior by rational methods as brightly as an open road in sunlight. One has to reckon with a great difference in the average luminance between the tunnel and the open road. Therefore problems must be expected particularly at the entrance and exit.

In passing the entrance or exit the visual system does not maintain a steady state. Since tunnel lighting deviates from the circumstances usually found in lighting techniques, as regards the importance of transition conditions, a large part of this study will be devoted to these transition conditions. The lighting of the tunnel interior must however also satisfy certain requirements concerning, for example, the luminance level or the inconvenience caused by flickering originating from the light sources.

A division of tunnels into *short* and *long* is, apart from the actual length, often also important in connection with the location of the tunnel. We frequently come across short tunnels within towns, for example under railway yards or busy squares, and long tunnels under rivers, canals or mountains. Of greater importance is, however, that with a short tunnel the exit is already visible from a point before the entrance. This implies different demands on the lighting compared with long tunnels.

In discussing the lighting of long tunnels considerable attention is paid to the entrance. Special stress is laid on the use of subdued daylight. For the terminology used in this discussion reference should be made to Fig. 1.

It is not only the daytime lighting which has to satisfy high requirements; the lighting which functions at night must also be designed with care. In fact, during part of the year the evening rush hour falls in complete darkness. The demands made on the lighting at night, however, are quite different from those in daytime.

We must finally point out the need to allow the possibility of introducing alterations in the lighting installation.

Even when a tunnel is viewed merely as an utilitarian construction, the lighting includes aspects of a *physiological, psychological, technical, economic* and *aesthetic* nature. These aspects are considered in Chapter 2

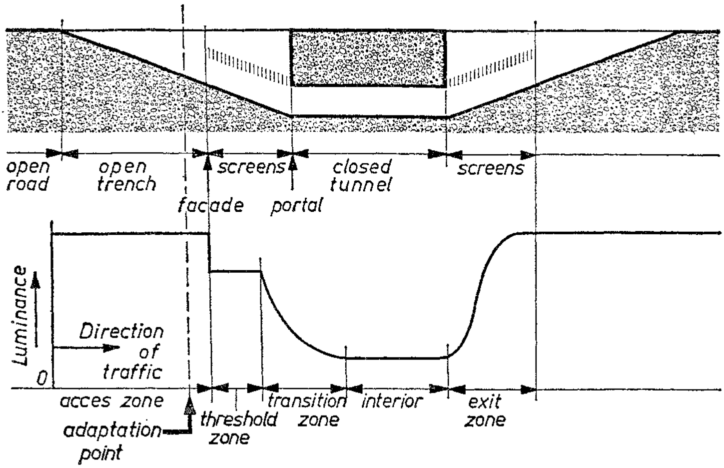

Fig. 1. Terminology.

of this study – some in detail, others summarily. Extensive investigations have been carried out for the physiological aspects. For the sake of clarity these experiments are described together in Chapter 5. The material collected in Chapters 2 and 5 served as a basis for drafting the "Recommendations on Tunnel Lighting" issued by the Netherlands Foundation on Illumination (1963) *).

The Chapters 3 and 4 of this study in which the lighting of long and short tunnels respectively is discussed, form at the same time a supplement to and a summary of these recommendations.

*) References see: Bibliography, Chapter 7.

CHAPTER 2

ASPECTS OF TUNNEL LIGHTING

2.1. **Physiological aspects of tunnel lighting**

2.1.1. INTRODUCTION

The information which is necessary for the adequate driving of a motor vehicle is gathered mainly by visual means. Consequently the amount of information obtained depends very much on the lighting conditions. On the other hand, when this dependence is known it is possible, starting from hypotheses concerning the necessary amount of information, to stipulate the requirements on the lighting. When discussing entrance lighting of tunnels we shall restrict ourselves in the first place to hypotheses about the visibility of obstacles. Obstacles must be visible at such a distance that the necessary manoeuvres can be executed in a reasonable and effective manner. The question whether a certain obstacle under certain circumstances is visible or not depends to a great extent on the sensitivity of the eye of the observer. The sensitivity can be adjusted with respect to the circumstances; the processes relevant to this adjustment will be discussed briefly.

In general the sensitivity of the human eye is determined by the retinal illumination, which is related to the distribution of the luminance in the field of vision. Imperfect image formation and scattering of light cause a light distribution over the retina which does not exactly correspond to the luminance distribution of the field of vision. The influence of the diameter of the pupil will be dealt with separately.

In stationary conditions the sensitivity of a certain part of the retina is determined in the first place by the local illumination on that part, but it will also be influenced by the illumination of other parts of the retina. The nature of this influence is uncertain. Presumably both effects of neural origin and effects of entoptical stray light play a part. In this study the word *induction* is used for the total effect of the influence of the various neighbouring parts of the retina on the sensitivity of the part under consideration. The adjustment of the sensitivity of a part of the retina to a change of the local illumination is called *adaptation*. The resulting sensitivity of the part of the retina under consideration is termed *the state* *of adaptation* of that part. One particular state of adaptation of a part of the retina can occur as the result of different luminance distributions in the field of vision. Such luminance distributions are regarded as *equivalent*. That state of adaptation may also occur as the result of a field of vision with a uniform luminance. This luminance is termed the (*equivalent*) *adaptation level* of the particular distribution of luminance over the field of vision. If the luminance of the field of vision or of part of it changes, each part of the retina reaches in course of time a new state of adaptation. The time necessary for the adjustment is called *adaptation time* and the time-dependent effect itself the (*visual*) *adaptation*.

In the lighting of tunnel entrances two problems in particular are closely connected with the nature of the adaptation process of the human eye.

The first is that with a given state of adaptation and consequently with a given adaptation level, only objects with a luminance not far below that adaptation level can be perceived. This *induction* effect is likely to arise when a tunnel entrance has a substantially lower luminance than the open road. As a result of the induction from the part of the retina on which the open road is projected onto that on which the tunnel entrance is projected, the entrance will look like a black area (a "black hole"), irrespective of its actual luminance. In such a black hole no details can be discerned.

The second property of the eye which presents a problem is the complexity of the *adaptation* to changes in the local illumination on the part of the retina under consideration. Quick changes in the illumination are not always followed immediately by adaptation, as a result of which both the ease of vision and the visual performance decrease. In extreme cases this decrease can be so strong and so sudden that for a time no observation can be made at all.

The distinction between the phenomena of induction and of adaptation, as defined above, is made because both phenomena do not necessarily occur together. Under circumstances the local illumination on the part of the retina under consideration may remain constant together with its state of adaptation, while at the same time by changes in the surrounding illumination induction effects arise. The contrary result occurs when a change in the local illumination provokes adaptation, while the induction effects remain constant. In the latter case, however, the change in the local illumination is not immediately followed by the adaptation. One must expect the induction effects to precede the adaptation. Keeping this in mind, in practice always a fixed point can be indicated on the road towards the tunnel, where the visual performance of an approaching driver starts to be influenced by adaptation. When the driver is at that point on the road, which is called *adaptation point*, the presence of the image of the dark tunnel entrance on his point of fixation begins to influence the state of adaptation of that central part of the retina. The position of the adaptation point will be discussed in Section 3.2. As a rule it lies at a fairly short distance from the tunnel entrance. This means that the motorist approaching the tunnel must be able to gather information concerning the first part of the tunnel even before he has reached the adaptation point. Observation under these conditions is obstructed solely by induction, because adaptation only begins to play a part when the motorist has passed the adaptation point.

Apart from the adaptation, also the *pupil reflex*, i.e. the change in the diameter of the pupil with a change in the luminance of the field of vision, has an influence on the adjustment of the sensitivity of the eye. For this reason the pupil reflex is sometimes described as an adaptation effect. According to our definition it is better to say that the pupil reflex widens the range of the adaptation by stopping down the light entering the eye. Because the variations in the diameter of the pupil are only small, we will neglect the influence of the so-called pupil adaptation.

The discussion of the induction and adaptation phenomena forms the most important part of this study as these two groups of phenomena constitute the greatest problems in the lighting of tunnels. Moreover, a considerable amount of experimental work has been carried out in both. In view of the clarity of the presentation the discussions of the phenomena and of the experiments are not presented consecutively. A survey of the phenomena and a short synopsis of the experimental results are given in Chapter 2, while the experiments themselves are discussed in detail in Chapter 5. The practical conclusions of these dissertations together and in conjunction with the other considerations discussed in Chapter 2, are dealt with in Chapters 3 and 4 and especially in Section 3.2.

2.1.2. INDUCTION

We assume that the visual adaptation of a road user driving across the open road does not change to an appreciable extent. This assumption is justified on the one hand by the fact that during the day the lighting outside is usually rather diffuse, and on the other hand by the fact that the image of the outside world constantly moves across the retina. The eye is adapted to a mean value of luminance, the mean equivalent adaptation level (see Section 2.1.1). Further on we shall call this level the *outer luminance* L_1.

Under this assumption the induction phenomena are fairly simple to describe. With each value of L_1 we must look for that value of luminance (now called L_2) which must be present at the beginning of the tunnel in order to be able to see the obstacles which may spell danger to traffic. Representative of the smallest and most unobstrusive obstacle that one should still be able to see we have chosen a *critical object* of 20 $\times$ 20 cm^2 with a luminance L_3. This critical object must be visible with a probability of observation of 75 % at a distance of 100 metres when the contrast C between the object and its background (given by $C = (L_2 - L_3)/L_2$), equals 20 %. This choice guarantees a reasonable visibility of practically all dangerous traffic obstacles without being too strict.

In order to establish which values for L_2 must be chosen in dependence on L_1 we made a number of experiments according to the following scheme. An observer sits in front of a screen of luminance L_1 over its entire surface. For 0.1 sec a shutter can be opened in this screen (see Fig. 2). This shutter reveals a small field with luminance L_2 and an object with luminance L_3. The contrast between the object and its immediate background is again indicated with $C = (L_2 - L_3)/L_2$. The observer must state whether he has spotted the object. If he does see it, this means that the difference between luminances L_2 and L_3 is above threshold. With a fixed value of L_1 and of C this procedure is repeated for a number of values of L_2. From the results we are able to deduce the value of L_2 at which the object is visible with a probability of 75 %. This procedure is repeated with other values of L_1 and C. More exact details of the experiments are described in Section 5.1.

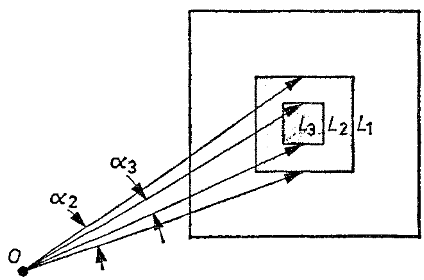

Fig. 2. Outline of the experimental set-up for tests on induction $\alpha_2 = 1°$ $\alpha_3 = 7'$.

To specify the necessary luminance level in the first part of the tunnel we require primarily that part of the experiments which refers to the visibility of the critical object mentioned above. The results are shown in

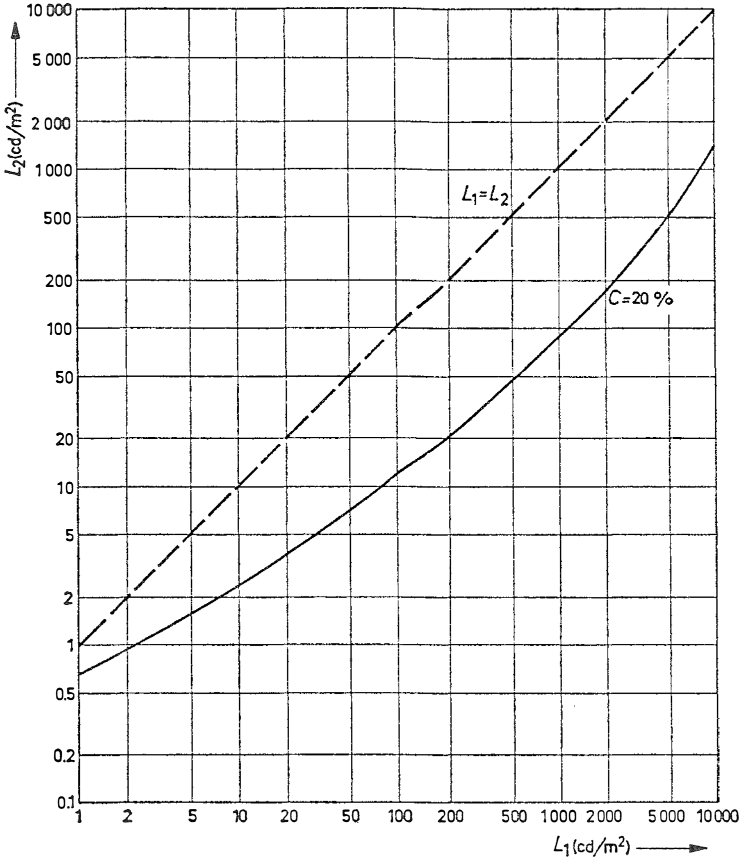

Fig. 3. Relationship between L_1 and L_2 for an object of 7′ with a contrast of 20 % to be visible in 75 % of cases when it is displayed for 0.1 sec ($L_3 < L_2 < L_1$).

Fig. 3. In it we find the relation between the outer luminance L_1 and the minimum luminance which must be present at the beginning of the tunnel (L_2) in order to be able to see an object of 20 $\times$ 20 cm² which shows a contrast of 20 % in respect to its background in 75 % of cases at a distance of 100 m, whenever that object is displayed for 0.1 sec. Fig. 3 applies to $L_3 < L_2 < L_1$.

The time during which the object is displayed and the dimensions of the object have only little influence on the minimum value of L_2. This is also the case with another choice of percentage of probability in which the object is visible. The influence of a change in the choice of contrast is substantially greater, but still small with respect to the influence of a change in L_1. This means that there is considerable freedom of choice in the critical object.

Since the experimental set-up is of a very diagrammatic form we must look for further confirmation of the results. For this purpose measurements are made on a scale model which is constructed in such a way that the composition and the alteration of the field of vision correspond exactly to that of a motorist who is approaching a tunnel (see Section 5.4). The dynamic character of the observation comes fully into play here. This is achieved by letting the observer ride along the model while he looks at the road through a periscope. In this model objects are displayed for 0.1 sec. Here, too, the observer must state whether the object is seen or not. Good conformity is found between the two tests. We can assume that Fig. 3 may also be used for actual tunnels.

For the practical application of the data we must find out what range of values of L_1 is relevant. The upper limit of that range is of special importance in so far as high values of L_2 are necessary for high values of L_1. From registrations of the horizontal illumination it appears that in the open field the value of 100 000 lux is surpassed fairly regularly (see also Section 5.5).

On a perfect white diffuser this illumination of 100 000 lux should give a luminance of $100\,000/\pi$ or about 32 000 cd/m^2. The surfaces which appear on or near the open road (such as road surfaces, grass verges, house fronts etc.) seldom have a reflection factor of more than 0.25, so that 8 000 cd/m^2 can be considered as the highest value of L_1 which is of practical interest. This value agrees well with the directly measured luminances given in Section 5.5. When, however, surfaces appear at a tunnel entrance with a reflection factor higher than 0.25 the luminance values we get will also be proportionally higher. Sometimes materials with high reflection factors have been purposely chosen for the decoration of the tunnel facade. This and other aesthetic aspects are discussed in Section 2.2.

From Fig. 3 we see that for $L_1 = 8\,000$ cd/m^2 and a contrast value $C = 20\ \%$ the luminance in the beginning of the tunnel L_2 should be at least 1 000 cd/m^2. Here we may add, that the latter value corresponds with the luminance of a dark grey surface with a reflection of about 3 % when seen under the illumination of 100 000 lux we mentioned before. Black velvet has a reflection of about 1 %; under these circumstances its luminance will be about 300 cd/m^2, a luminance far higher than we will find actually at the entrance of many existing tunnels. These entrances are therefore correctly described as a black hole.

If we again study Fig. 3 we notice that over a substantial range of L_1 values below 8 000 cd/m² the ratio between the minimum value of L_2 and the value of L_1 is approximately constant. This means that in a lighting system in which L_2 depends directly on L_1 a fixed ratio between L_2 and L_1 can be sufficient, a ratio which must amount to a little more than 0.1. This consideration is of great importance when no artificial lighting is used for the first part of the tunnel, but a construction which subdues the daylight. If the effective light transmission of such a gridlike construction amounts to more than approximately 0.12, the lighting at the beginning of the tunnel will satisfy the requirements demanded for practically all daylight conditions. Only during dusk supplementary

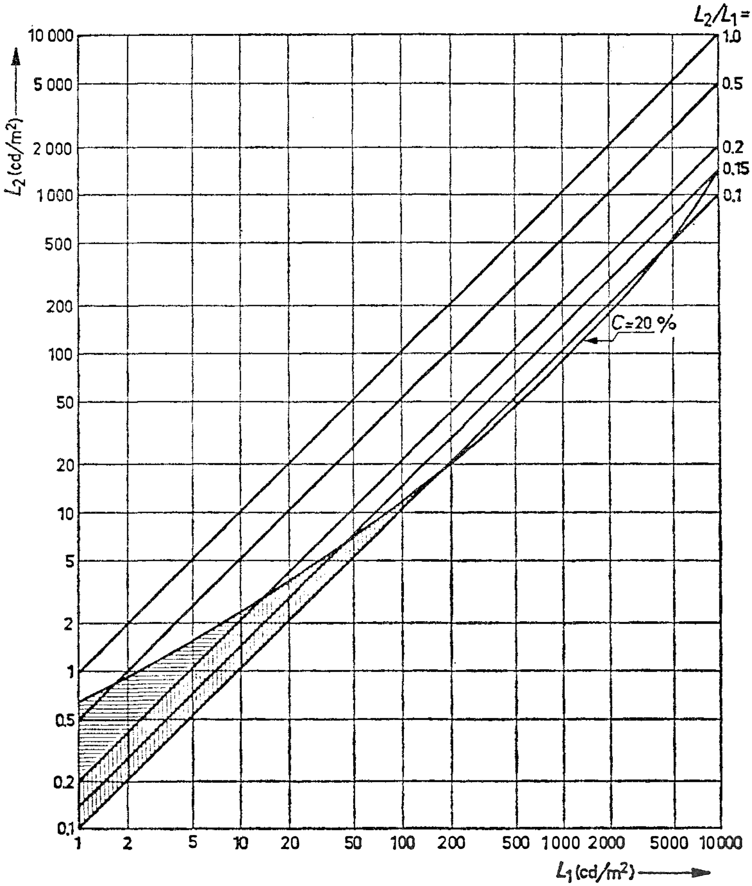

Fig. 4. With low L_1 and constant L_2/L_1 supplementary lighting is necessary.

lighting is necessary, which must be all the more powerful and should be switched on all the sooner, the lower the light transmission of the screens. Fig. 4 illustrates this for some cases. In the double log scale used the lines of constant transmission or constant ratio between L_2/L_1 are straight lines under 45°. The shaded areas between the straight and curved lines (taken from Fig. 3) indicate the contribution which has to be made by the supplementary lighting so as to make the critical objects visible even at low L_1 values.

Similarly, when the beginning of a tunnel is lit by artificial light, the necessary values of L_2 can be read from Fig. 3. The lighting installations must be so designed that the luminance in the tunnel entrance can be raised far enough to match the highest possible value of outer luminance. This means that with $L_1 = 8\,000$ cd/m^2 the minimum value of L_2 will amount to 1 000 cd/m^2. If the outer luminance is lower, part of the lamps can simply be extinguished or dimmed. We shall return later to the technical and economic aspects and the design of the entrance lighting (Sections 2.4 and 3.2), but right now we should like to point to the great problems which have to be solved if the entrance lighting is done by artificial lighting only.

Finally, we must indicate at which part of the tunnel the luminance L_2 has to be effective. The area with luminance L_2 has to serve as background for possible obstacles. In this respect the walls and the road surface of the tunnel deserve special attention: in narrow tunnels the walls prevail, in wide tunnels the road surface.

The area with luminance L_2 must be long enough to form a background to an object which is at a distance of 100 m (the distance we assumed for the critical object). For this background function some 20 m is needed. This means that the length must be about 120 m in total. The beginning of the area must not be placed at the beginning of the tunnel, but at the adaptation point, because when the motorist passes the adaptation point, the adaptation comes into play (according to the definition). Since the adaptation point frequently lies some tens of metres before the tunnel entrance it is generally sufficient if the area of constant luminance L_2 in the tunnel (the *threshold zone*) is 50 to 80 m long (see further Section 3.2).

2.1.3. ADAPTATION

The adaptation of the retina does not immediately follow the changes in the luminance or in the luminance distribution of the field of vision; the adaptation lags behind. One can compare, however, the state of adaptation of any part of the retina at any moment with the state of adaptation which occurs as the result of a hypothetical field of vision with uniform luminance that is visible for a long time. The two conditions are equivalent if the resulting states of adaptation are equal. The course of the adaptation can be expressed by the succession of luminance values of equivalent fields. The retardation of the adaptation is expressed by the fact that the luminance value of the hypothetical field of vision is not equal to the luminance of that part of the field of vision which is projected on the part of the retina under consideration. The difference between these two luminances is a measure of the retardation of the adaptation and is called the *adaptation defect* (to be expressed in values of luminance). There is, however, no way of evaluating the state of adaptation during alterations, so that the concept "adaptation defect" can be employed only in qualitative considerations. More especially we can consider the entrance lighting of tunnels as a means of keeping the adaptation defect within reasonable limits.

The adaptation from one luminance level to another is a complex phenomenon, even when both luminance levels lie within the range of photopic vision. In the first place we must make a distinction between light adaptation and dark adaptation, i.e. between the changes in sensitivity which occur as a result of an increase and of a decrease in the luminous intensity respectively. We shall be mainly concerned with dark adaptation, which plays an important role when a driver enters a tunnel in daytime.

The change of the sensitivity following a reduction in the luminance of the field of vision is the result of three effects. These are adaptation, a change in induction and a change in pupil size. The three effects are not independent of each other, but we have discussed them separately.

We have defined adaptation as a change in the sensitivity of a part of the retina as a result of a change in the retinal illumination on that part. When defined in this way, the adaptation corresponds to what is sometimes known as *local adaptation*. When the retinal illumination is reduced, the local adaptation expresses itself in the existence and subsequent disappearance of the *negative after-images*. The time necessary for the complete disappearance of the after-images depends strongly on the circumstances and on the previous "history of the eye". In some cases several minutes may elapse before the final state of adaptation is reached (see Schouten, 1937). The object we have taken as critical (Section 2.1.1), when observed under stationary conditions, is substantially above the threshold for visibility. Consequently, when observation is made with decreasing luminance, the adaptation time may be considerably shorter than the time necessary to reach the final state of adaptation. With other words, it is sufficient to restrict ourselves to *partial adaptation.* When partial adaptation is considered, it is usually the ease rather than the possibility of perception which is limited as a result of the presence of after-images.

A change in the luminance of the field of vision results in a change in the induction. This change in induction constitutes a very important element in the adjustment of the sensitivity of the visual system; it seems logical therefore to describe the changes in sensitivity resulting from a change of the rate of induction as an adaptation effect. Because the change in the sensitivity is not restricted to the parts of the retina where the illumination changes, the term *general adaptation* seems to be appropriate. Being an induction effect of origin, the nature of the process is, as indicated before, not completely understood. Because entoptic stray light plays a role, one may expect the time involved to be very short. In fact, under the conditions related to tunnel lighting, the "general adaptation" can be regarded as being instantaneous.

We have already indicated that the pupillary reflex can be neglected due to its small range of operation.

Although the change of the sensitivity of the visual system is governed by all three effects mentioned above, it is the (local) adaptation which is the most important for the lighting of entrances of tunnels, because the after-images normally extend over the larger part of the field of vision, and because the disappearance of the after-images takes a fairly long time. Although the after-images mostly do not hamper the observation of obstacles very severely, it may be difficult to get a clear view of the road and the traffic situation. In particular, one can not always be certain that the road is really free if no obstacles are seen, since the after-images usually produce a spotted or striped impression. Their appearance should be avoided in view of their influence on driving comfort, which occasionally can be severe.

Practically all properties of the eye show a dependence on the state of adaptation and could therefore be used in principle to determine the adaptation. As indicated in Section 5.2 none of them can be used in the circumstances met at tunnel entrances since they either do not depend on the local adaptation or do not react sufficiently sensitively to adaptation changes or are not suitable for investigations with quickly changing effects.

For this reason the subjective appraisal of the change in brightness is chosen for the experiments. The observer is placed in front of a large screen of uniform luminance. The luminance of the screen can be adjusted continuously by the observer himself. A small object is fixed upon the screen. The observer is told to reduce the luminance of the screen as quickly as possible without producing disturbing after-images and not that quick that the object becomes invisible. This luminance is recorded. In this way a course of luminance is determined that keeps the adaptation defect small. We are dealing with partial adaptation only. (The experiments are described in detail in Section 5.2). The most important result is given by the drawn line in Fig. 5 in which the time intervals are converted into length intervals for a speed of 72 km/h.

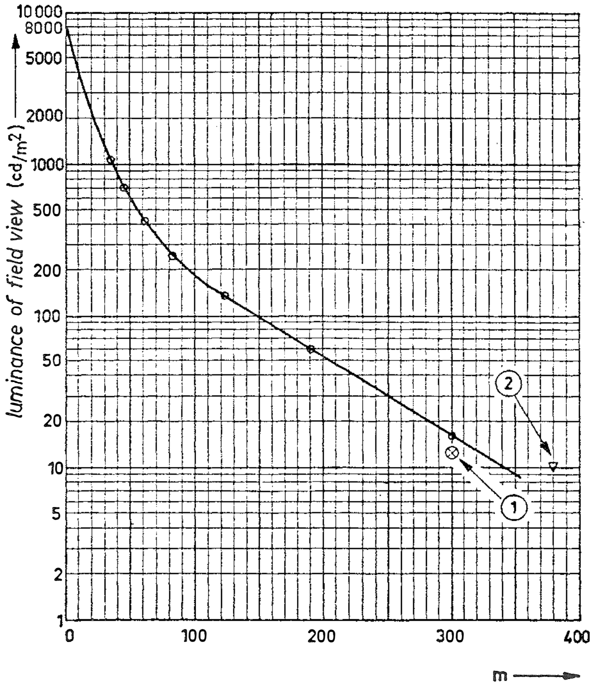

Fig. 5. Relationship between luminance of field of vision L and distance in tunnel 1 necessary for satisfactory adaptation. Speed 72 km/h (20 m/sec) 1 and 2: results of additional experiments (see text).

For confirmation of this we used the appraisal of sudden luminance changes. The time is recorded which is necessary – after a sudden transition in the luminance of the field of vision – to make the after-images fade to a degree at which they no longer cause any trouble. This is in fact a direct measurement of the adaptation time lag. The results are inserted in Fig. 5, point 1. A further confirmation is found by simulating a number of tunnel entrances on the scale model already mentioned. Every set-up corresponds to a fixed time available to cover the transition from the open road to the tunnel interior. The different transitions are shown in a sequence unknown to the observer. The observer must state whether each transition is acceptable or not, when taking into account the influence of after-images only. The results of this test are also given in Fig. 5, point 2. (The test itself is described in Section 5.4.)

Although the criterion used in these experiments is subjective, the results agree well with one another. This means that Fig. 5 can be used for stipulating the conditions required for the lighting of tunnel entrances.

In conclusion we can state that it is necessary to ensure adequate means for visual adaptation as well as the conditions required to prevent a black hole effect at the entrance of tunnels. These conditions can be learned from Fig. 3, while the measures necessary to prevent adaptation problems are indicated in principle in Fig. 5. These two groups of data together form the basis of the conditions required for the entrance lighting of tunnels. The formulation of these requirements is given in Section 3.2.

2.1.4. FLICKER EFFECTS

Flicker effects are those phenomena which are the result of periodic luminance changes in the field of vision. The impression made by these periodic changes is in the first place dependent on the repetition frequency. With low frequencies (lower than approx. 1 c/s) each turn is perceived as such. If the frequency is higher than a certain value the periodic character of the lighting cannot be distinguished any longer. This frequency is called *flicker-fusion frequency* and as a rule amounts to 50–80 c/s. Flicker frequencies which lie close below the fusion frequency can be a great nuisance (Collins, Hopkinson, 1957). Another kind of trouble can occur as the result of flicker frequencies in the intermediate range. With the speeds and the distance of fittings from each other usual in tunnels, flickering often occurs in that particular range.

Most experiments on this subject were made with a scale model of a tunnel. The movement of the observer is simulated by sliding an endless belt of alternately transparent and opaque sections along an elongated light source. The transparent sections represent fittings which are mounted in a long row. The repetition frequency is adjustable by means of continuous regulation of the belt velocity. Though only the belt is in motion the observer has the impression that he himself is driving through the tunnel with variable speed. The observer can state at which frequencies flicker trouble occurs.

By using other belts, fittings with different light distribution can be simulated (see also Section 5.3).

The results lead us to three important conclusions. The *first* is that the impediment in question has a maximum at a frequency between 5 and 10 c/s and as a rule is negligible at frequencies below 2.5 c/s and above 13 c/s. The *second* is that little impediment is encountered if the dark sections cover only a small part of the total length of the belt. The *third* indicates that the hindrance is never severe if the transition between light and dark sections is gradual.

The *first conclusion* indicates which distances between light sources should be avoided with different driving speeds.

The *second conclusion* is of great importance when *continuous line lighting* is used. By this we understand lighting in which the fittings are connected with each other lengthwise along the tunnel. Small sections of the line will always remain dark, such as end plates of fittings and lampholders. The distance between those dark sections is, however, unimportant. This means that trouble due to flickering will never occur in a tunnel which is illuminated with continuous lines, irrespective of the length of the individual lamps or fittings.

The *third conclusion* indicates that this type of line lighting allows for instance every other lamp to be extinguished at night without greatly increasing the flicker nuisance, provided that at least sudden transitions in the candle power distribution of the fittings are avoided. However, it is advisable to reduce the luminance in the tunnel during the night by allowing all the lamps to burn but dimming them by reducing the luminous flux (see Section 2.3.2).

When the fittings are not mounted in a continuous or more or less continuous row the flickering can be very disturbing, in particular when sudden transitions in the candle power occur e.g. through crosswise placing of the fittings. This disturbing effect cannot be avoided entirely. With a repetition frequency lower than 2.5 c/s however, the disturbance is only slight. This means that the distance of the light sources from each other must be at least 10 m if we assume a speed of 90 km/h (25 m/sec) as normal. Because tunnels are usually only low, this requirement makes it difficult to realise satisfactory uniformity in the luminance pattern on walls and road surface. In order to allow the repetition frequency to be higher than 13 c/s the interdistances between the fittings must be made so small that the result closely approaches continuous line lighting.

2.1.5. THE LUMINANCE LEVEL IN THE TUNNEL INTERIOR

In long tunnels the entrance zone is usually followed by a section in which the lighting seen in length is unchanged. This part is called the *interior* (Fig. 1). The lighting of the interior is generally looked upon as a provision completely on its own. This way of looking at it may be handy in practice, but is not entirely correct. The demands made on the design of daytime lighting in the interior depend to a great extent on the quality, the type and above all the length of the entrance lighting. The entrance lighting must always allow the road user to adapt himself to the luminance in the tunnel. If opportunity for complete adaptation exists, the codes for night time street lighting can be employed, because these recommendations always presuppose complete adaptation. For open roads a value of 1.5 to 2 cd/m^2 is often recommended for the average road surface luminance. Because of the special character of a tunnel, the small space, the pressure of traffic and the great danger of jams,

TABLE 1

ILLUMINATION IN SEVERAL TUNNELS

Year	Place	Illumination level (lux)	Reference
1933	Antwerp	ca 15	Gaymard (1958)
1934	Mersey	6	Smith, Waldram (1957)
1938	Engelberg	60	*)
1941	St. Cloud	15	*)
1941	Rotterdam River Meuse	ca 30	*)
ca 1950	Antwerp Scheldt	50	*)
1952	St. Cloud	30	Cohu (1960)
1952	Lyon Croix Rousse	30	Smith, Waldram (1957)
1955	London Airport	22	id.
ca 1955	London Blackwell	20	id.
1956	Le Havre	30	id.
1957	Stuttgart	40	Jainski (1959)
1957	Velsen	105	*)
1957	Lammerbückel	60	Jainski (1959)
1958	Brussels	500	Cohu (1960)
1958	Berlin	250	Spriewald, Niederführ (1959)
1958	Rendsburg	180	Jainski (1961)
1959	Vancouver	110	Lassen-Nielsen (1961)
1959	Orly	120	Busson (1960)
1962	Rotterdam River Meuse	70	*)

*) Not published reports. Rounded off values.

a higher average luminance is required, for instance, 3–4 cd/m². These are the values which are relevant for tunnel lighting at night.

It is, however, out of the question to have the transition zone constructed in such a way that complete adaptation to the low level in the tunnel can also be achieved in daytime. This is not an absolute necessity: we have seen that sufficient means for perceiving traffic obstacles can be obtained with partial adaptation. This means that higher demands are made on the lighting of the interior during daytime than at night. How high these demands are, again depends on the design of the entrance and is further determined by economic factors. It is therefore difficult to quote general data.

A starting point is found by the practice of many years standing in tunnel construction and lighting. The illumination installed in a number of tunnels is given in Table 1 and Fig. 6. From this we see that illumina-

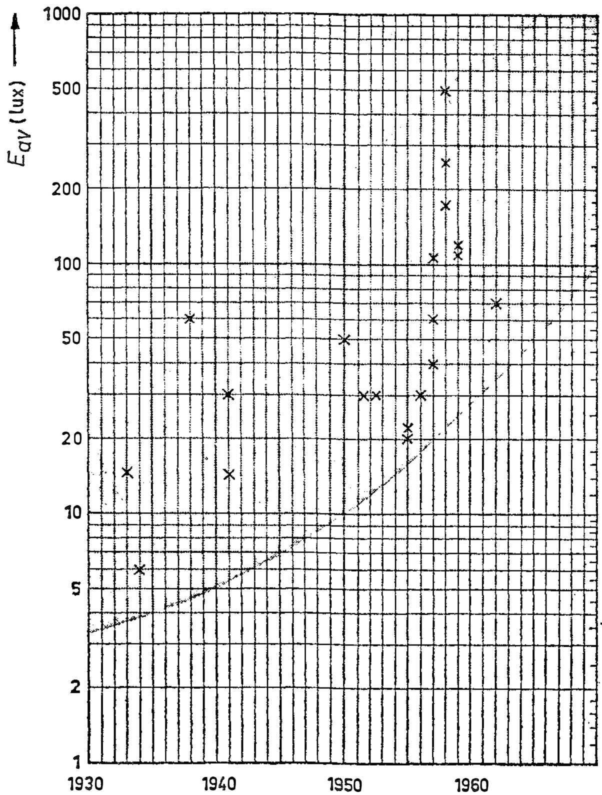

Fig. 6. Increase of the average illumination in tunnels between 1930 and 1960.

tions of 100–200 lux have been used fairly frequently in recent years. There has been a definite increase in the level in the course of the years. This increase is also evident from those cases where new lighting is installed in an old tunnel.

As a rule an illumination of 100 to 200 lux corresponds to an average luminance of about 10–20 cd/m². On account of this we may suppose that a value of 10 cd/m² must be regarded as a minimum for the interior of a tunnel, provided that in all other respects the tunnel is well lit and that the entrance lighting meets the requirements. This value agrees well with the result of an enquiry among road users. The outcome of it was that a luminance of 6 cd/m² was considered to be on the low side (see Section 5.6).

2.1.6. EXITS

During *daytime* the exit of a tunnel appears as a brilliant "white hole" to a motorist who has driven for several minutes in the tunnel. All obstacles will stand out as a silhouette against the exit and are thus clearly visible. This effect can be still further enhanced by providing the walls and the road surface at the exit with a covering of a high, almost mirror-like reflection (see Fig. 7a and 7b). A clear tunnel exit without other traffic thus presents no problems in the visibility of obstacles.

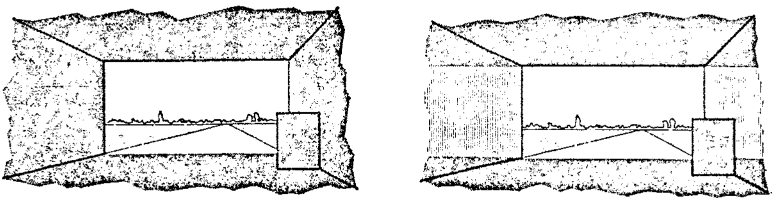

Fig. 7. Effects of specular reflection of the walls at the tunnel exit.

An entirely different situation is encountered when the exit is not free. It may happen that part of the exit is screened, for example by a lorry. The vehicle itself screening the exit is clearly visible, but not the traffic following it. A motor scooter riding behind the lorry can be a dangerous obstacle to traffic, when it is not visible (see Fig. 8). The part of the exit remaining clear is now acting as a glare source. This glare can only be compensated by greatly increasing the lighting in the vicinity of the exit. The extent of this increase is difficult to quote in general terms since the glare depends on many variable factors. We shall, however, give two extreme cases between which those found in practice always lie.

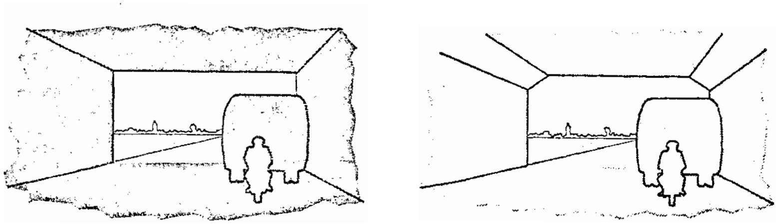

Fig. 8. Effect of additional lighting at the tunnel exit.

The *first extreme* is that the clear part of the exit does not influence the adaptation at all. This implies the absence of induction and glare effects. The eye of the observer is adapted to the luminance of the tunnel interior. When this is adequately lighted, the lighting needs not to be increased; the tunnel part near the exit may be considered as an ordinary piece of the interior of the tunnel.

The *second extreme* is that the eye of the observer is fully adapted to a luminance equal to that of the unobstructed part of the exit, i.e. to the luminance of the open road outside the tunnel. The visibility of obstacles can be determined with the aid of Section 2.1.2 and Fig. 3. L_1 is again the adaptation level and now corresponds with the luminance of the area behind the exit, C is the contrast between the obstacle (the scooter) and its background, while L_2 is again the luminance of the background (the lorry). It follows from this that under these circumstances the luminance at the exit must be equal to that at the threshold zone at the entrance.

The situations as we find them in practice lie between these two extremes, because the clear part of the exit will have at least some influence, though the observer will usually not be fully adapted to the while hole. The state of adaptation will therefore be somewhere in between. This is illustrated by some experiments. These were made in the apparatus used for investigating the induction effects. The luminance $L_1 = 8\,000$ cd/m^2 is set up only on a small screen nearest to the shutter opening. The luminance on the rest of the screen is 10 cd/m^2 and represents the tunnel interior. The results indicate that under these circumstances the influence of the exit is relatively small: the circumstances approach more the first than the second extreme (see also Section 5.1).

There are, however, often reasons why the exit has to be made identical with the entrance (for example, in tunnels for two-way traffic) so that, if the conditions with respect to induction for the entrance have been fulfilled, this opening will certainly be satisfactory as exit.

Next to the induction and the glare, the adaptation also must be considered with the lighting of exits. Both changes in induction as well as the pupil reflexes require only little time in transitions from dark to bright. Just as with transitions from light to dark, the (local) adaptation lags behind. This can give rise to considerable nuisance. This nuisance however usually can be reduced in a simple fashion, such as by planting trees near the tunnel exit.

Difficulties at a tunnel exit can also occur *at night* when the road outside the tunnel has a lower luminance than the tunnel itself. In that case the tunnel *exit* appears as a black hole. The lighting has to satisfy requirements similar to those which apply to the entrance in daytime. These requirements can again be deduced from Fig. 3. But now we must call the luminance of the tunnel L_1 and the luminance of the road outside L_2.

We learn from Fig. 3 that for low values of L_1 conditions become more critical: L_2 should not be less than about 30 % of L_1. These conditions are not met if the tunnel lighting remains burning at full strength during the night and if we choose a level of 2 cd/m^2 for the outgoing road in accordance with the normal codes for street lighting. The lighting in the tunnel must be reduced. This can be achieved either by switching out part of the lamps or by dimming them. The latter is to be preferred both for reasons of lighting techniques and for aesthetic considerations, in spite of a small economic disadvantage.

2.2. Psychological and aesthetic aspects

DISTRIBUTION OF THE ATTENTION

An experienced driver in normal circumstances only needs to give a small portion of his conscious attention to get along in traffic. Driving a car is almost entirely automatic, even as regards complicated actions such as starting up and changing gear (see, for example, Steffen (1962), von Hebenstreit (1961) and Forbes et al. (1958)). If, however, unexpected or unusual problems occur, normally only a conscious decision can lead to the correct actions under the circumstances. This needs conscious attention which may not be available at that moment.

In view of the foregoing, a road, and also a tunnel, can only be regarded as safe when three conditions are satisfied. The first is that no sudden changes in the pattern of behaviour are required, so that no interruptions in the logical sequence of events occur. An interruption is avoided if the driver has enough time to direct his attention to the situation which is about to change. An important aid in this is, especially in tunnels, the optical guidance which will be discussed later. The second condition is that the attention of the road user is not distracted but remains directed on the traffic. In tunnels the noise in particular can be very distracting so that the favourable results of a good lighting installation can again partly be spoiled. The third condition is that the unavoidable monotony in tunnels does not slacken the general alertness.

These three conditions can be summarised in the following rule: *The surroundings must be so designed that the driver is induced to use the appropriate measure of conscious attention at the right moment and in the right place.*

OPTICAL GUIDANCE

Optical guidance means the use of visible aids to indicate the course of the road. In daytime, on the open road, the boundaries of the road surface, the marking of the verge and also the road markings deserve particular attention. Examples of guidance and misguidance are given by Nap (1961) and Lorentz (1961). At the entrance and in the interior of a tunnel, however, primarily the light sources have to be considered. Yet only rarely the importance of optical guidance is quoted (for example, by Geenens (1947)), although good results can be achieved precisely by improving the entrance of existing tunnels with simple means. The course of the road can be made visible even though the rest of the tunnel entrance is impenetrably black (see Plate 1). We need not fear the occurrence of glare with the luminance level customary in tunnels.

INFLUENCE OF NOISE

The nuisance which is experienced in a tunnel as a result of an acoustical surround different from that on the open road is partly the result of the rise of the noise level and partly of the change in the reverberation times. The influence of high noise levels on work performances is, among others described by Broadbent (1958), Grimaldi (1958) and Grognot and Perdriel (1961). Two of the conclusions resulting from these works are:

a. those tasks in particular for which quick reactions are necessary at unexpected moments are hampered by noise;
b. in particular, noise with a strength of 90 dB or more is of great influence.

In tunnels substantially higher values may yet occur. Van Os (1958, see also "recommendations" 1963) has measured in the tunnel at Rotter-

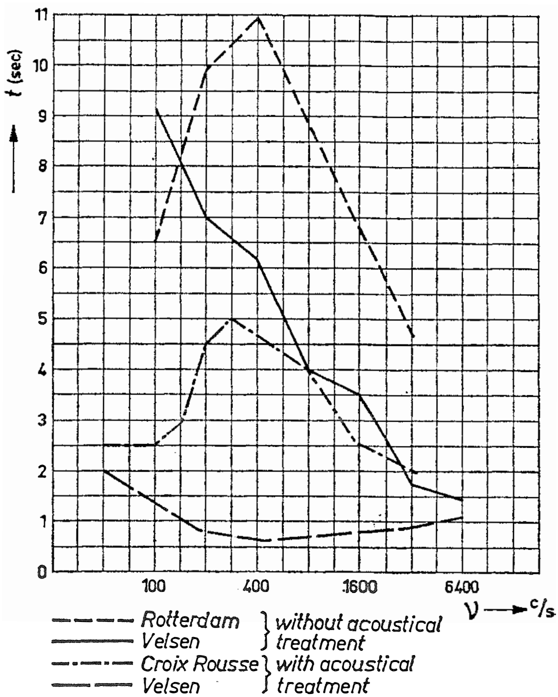

Fig. 9. Effect of acoustic treatment on the reverberation times. t = reverberation time; ν = frequency.

--- Rotterdam } without acoustical treatment; —— Velsen

.–.–.– Croix Rousse } with acoustical treatment; — — Velsen

(After: Comité des Tunnels Routiers, 1959)

dam an average level of 95 dB with peaks of 110 dB. In Velsen, after application of a sound absorbent layer on the ceiling, an average level of 80 dB with peaks of 95 dB was measured. The favourable effects of acoustic treatment is evident from the fact that in the enquiry described in Section 5.7 not a single comment is made about noise.

Another cause of distracting the attention in tunnels is often found in the long reverberation times. This means that the direction and distance of a noise cannot easily be determined. Also in this case, a sound absorbent layer on the ceiling makes a great improvement, as can be seen in Fig. 9. In the tunnels at Velsen (with an acoustic covering) and Lyon the reverberation time is considerably less than in the tunnels at Rotterdam and Velsen without such cover.

AESTHETIC ASPECTS

A tunnel is an utilitarian construction. The aesthetic wants always have to remain subordinated to the requirements to fulfil its aims as well as possible. It is wrong, for instance, to cover the facade of the tunnel with light coloured ornamental concrete as happened in the tunnel at Velsen. In sunshine the facade has a very high luminance. Consequently the tunnel entrance appears like a black hole in spite of the high luminance in there *). On the facade of the tunnel at Rendsburg a mosaic ornament is put up which, in addition to that, distracts the attention from the road (see Plates 2 and 3). Sometimes, however, a tunnel serves as a "status symbol" of a town or country. There is nothing against expressing that symbolism in the exterior of the construction as long as the decorations do not interfere with the proper function of the tunnel.

2.3. Technical aspects

2.3.1. AIR POLLUTION

At the entrance as well as in the interior of tunnels very thick clouds of exhaust gases and dust may present considerable problems during heavy traffic. In two respects such clouds of exhaust gas differ from natural fog. In the first place the light absorption of those fumes is considerable. Secondly, the size of the particles is mostly small with respect to the wavelength of the light. Magill et al. (1956) quote for this a value of around 0.1 μ. When natural fog is so dense that traffic is hindered the size of the droplets is mostly of the same order of magnitude as the wavelength of the light (see Kurnick et al., 1960). This means that in thick fog the scattering of the light is not dependent on the wavelength. In clouds of exhaust fumes, however, short-wave light is more strongly dispersed than long-wave light. This can be observed very easily. Fog is colourless (white or grey) but the colour of the clouds of exhaust fumes depends on the direction under which they are observed. The sun seen through a cloud has a brownish-red colour since the short-wave light is much more scattered. If the cloud is lit sideways it looks blue since then the short-wave light dominates. For application in tunnels, therefore, light sources which do not radiate short-wave light, like sodium lamps, deserve preference (see also Section 2.3.3).

Thick clouds of exhaust fumes often occur near deep-lying tunnels in which the exit of one tunnel tube lies close to the entrance of the other. This applies particularly when there is no open grid construction for screening of daylight through which the fumes can escape. Whenever these clouds are lit by the sun, the luminance can become very high.

*) Quite recently part of the facade has been given a dark finish.

At the northern entrance of the Maas tunnel in Rotterdam we have measured in some instances luminances up to 2 000 cd/m². At moments when there was little traffic in the tunnel the luminance was still between 100 and 300 cd/m². Clouds with such high luminance reduce the possibilities of perception at the tunnel entrance because of a veiling effect.

For the discussion of these impediments to observation we shall refer back to Section 2.1.2 where we introduced L_1 as outer luminance, L_3 as luminance of the obstacle to be observed and L_2 as the luminance of the immediate background of that obstacle, i.e. the road surface or the wall in the threshold zone of the tunnel. Here we introduce:

$$C_i = \frac{L_2 - L_3}{L_2}$$

known as *intrinsic contrast*. The luminances L_2 and L_3 are those of the objects themselves.

A veil with luminance L_v between the objects and the observer reduces the luminance of the obstacle to: $L_3' = (L_3 + L_v)$ and that of the tunnel to: $L_2' = (L_2 + L_v)$. The contrast as seen by the observer (indicated by the *reduced contrast* C') becomes less, namely:

$$C' = \frac{L_2' - L_3'}{L_2'} = \frac{(L_2 + L_v) - (L_3 + L_v)}{L_2 + L_v} = \frac{L_2 - L_3}{L_2 + L_v}$$

Consequently:

$$C' = C_i \frac{L_2}{L_2 + L_v}$$

Because of the presence of the veil, however, the brightness of the tunnel entrance is increased, for instead of L_2 we must now take L_2'. The contrast for the same L_1 value which can still just be seen with L_2' is smaller than with L_2, as can be seen from Fig. 3. Thus the reduction in contrast is at least partly compensated by the reduction of the threshold. This is demonstrated in Fig. 10. For $L_1 = 8\,000$ cd/m² the relation between the just visible contrast and the luminance in the tunnel is indicated for an observation probability of 75 % and an object size of 20 × 20 cm². The figure contains results of the measurements described in Section 5.1. The drawn curve indicates the relation between C_i and L_2. The same curve refers to the relation between C' and L_2' when threshold conditions are considered. For every combination of C' and L_2' the relevant C_i and L_2 values can be calculated when L_v is known. This has been done for $L_v = 100$ cd/m²; the points thus found are plotted in Fig. 10 and are connected by the dashed curve.

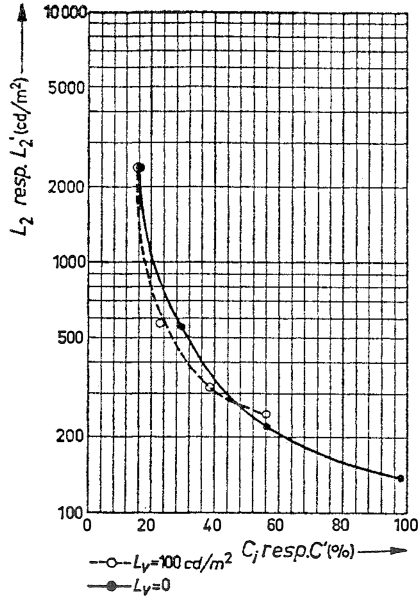

Fig. 10. Influence of smoke clouds on the visibility at tunnel entrances. (L_1 = 8 000 cd/m²).

The two curves practically coincide; this means that the visibility is not seriously hampered through exhaust clouds with a luminance of 100 cd/m². A similar reasoning can hold for higher values of L_v. The results, however, are of little practical value, because when the clouds are very heavy the absorption of light predominates the scattering. Only when such clouds cannot develop, can good visibility be ensured.

There is no rain or wind in the interior of the tunnel to remove the dust and soot, thus leaving a deposit which greatly reduces the reflection to provide high reflection from the walls. This should be maintained by of the walls. Because the quality of the lighting in the tunnel is to a large extent determined by the luminance of the walls, it is absolutely necessary using the right wall covering and through regular and thorough cleaning. Data for this are given by Comité des Tunnels Routiers (1959) and Wentink (1957). As a rule strong cleaning agents (such as trichlorethylene) and brushes are used so that the wall covering must be proof against corrosion and wear. Mostly glazed tiles or wall paint on a plastic base are used.

The fittings also must comply with strict requirements (see Section 2.3.3). The materials for sound absorbent layers usually cannot be cleaned and therefore they will soon turn black. For this reason only the ceiling can be considered for acoustic treatment.

2.3.2. ELECTRICAL INSTALLATION

We will not deal with the electrical installations of tunnels in general. For this, for example, see Comité des Tunnels Routiers (1959) and van Riemsdijk and Alpherts (1946). However, some points which concern the lighting very directly have to be discussed. These are: the provisions for emergency supply, the influence of temperature on the output of lamps and dimming devices.

Emergency supply

If ever the lighting in a tunnel suddenly fails the consequences are incalculable. At least part of the lighting always must remain burning. Therefore an emergency supply is necessary which comes into action automatically and instantly. Accumulators or a fly-wheel generator, for example, are suitable for this. If the breakdown lasts longer than some ten seconds or, maybe, some minutes whenever accumulators are used, then a diesel aggregate must be ready to take over the lighting as well as the ventilation. In order to cope with failures in which the main voltage does not break down entirely the electrical installation must be duplicated. Finally, each fitting and each group of fittings must be equipped with the necessary fuses for small failures. The lamps must be connected (in cyclic order) to the three phases of the network.

Temperature dependence

The fluorescent tubes frequently used in the lighting of tunnels have two disadvantages. The specific luminous flux as well as the minimum ignition

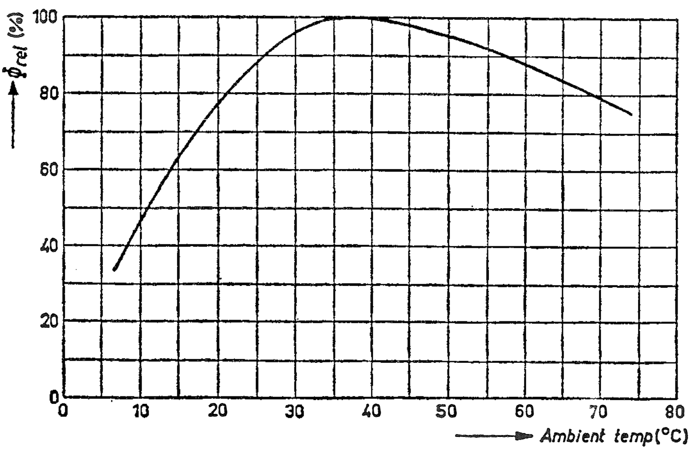

Fig. 11. Temperature dependence of the specific luminous flux ϕ_{rel} of a fluorescent lamp. (After: De Boer, 1961).

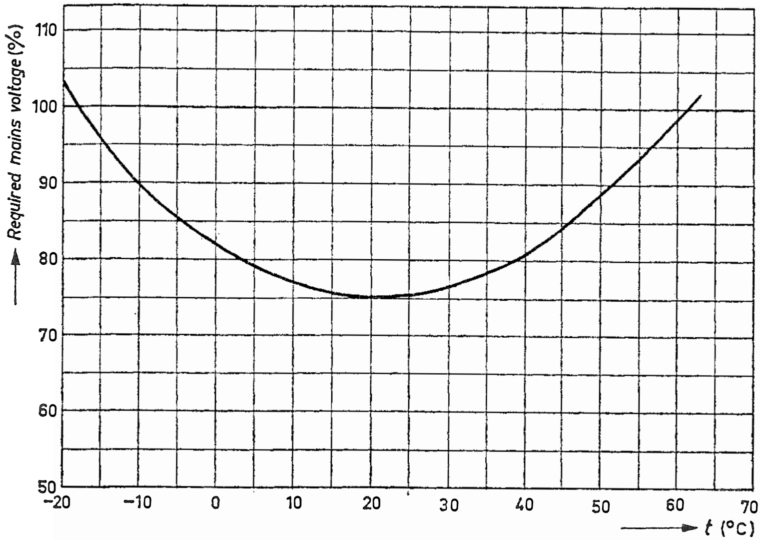

Fig. 12. Temperature dependence of the actual mains voltage on which a fluorescent lamp can ignite. Valid for a 40 watt lamp type "TL" M rapid start. (After: Philips Catalogue 10.094).

voltage strongly depend on the ambient temperature of the lamp. Both are related to the similarly temperature-dependent vapour pressure of the mercury in the tube. The measure of dependence rests on the type of lamp and the type of ballast (see Elenbaas (1959)). Fig. 11 and 12 demonstrate the effects for a fluorescent lamp of the type "TL" M 40 W*).

Apart from the design of the ventilation system this temperature dependence must certainly be taken into account in the design of fittings. On the one hand this means that in tunnels, just as in street lighting, the fittings for fluorescent tubes must be enclosed, and on the other hand that fittings for two or more lamps must be of fairly large volume. Other gas-discharge lamps and incandescent lamps hardly show any temperature dependence.

Dimming installations

Even in closed fittings the luminous flux of fluorescent lamps, and thus the luminance level in the tunnel, remains strongly dependent on the air temperature in the tunnel. If two out of three lamps are switched off, the resulting luminance level will as a rule not be exactly one third of the level for which the total installation is designed. This temperature

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*) Pre-heat hot cathode instant start fluorescent lamp.

dependence of the luminance level can be avoided by using a continuously adjustable dimming device which is controlled by a photocell. Thyratron tubes are generally used in the dimming installation (see Geenens and Reid (1950) and Spriewald and Niederführ (1959)). New possibilities are offered by controlled silicon rectifiers (thyristers) which are already being used for interior lighting (von Zastrow (1962)). The controlled rectifiers have a very high efficiency and a very long life. They require no maintenance so that the difference in costs between dimming and extinguishing is negligible. The other advantages of dimming compared with switching out for night time lighting have already been mentioned before and refer chiefly to flicker effects (Section 2.1.5).

2.3.3. LIGHT SOURCES – FITTINGS

In tunnel lighting the most important demands made on the light sources are: a high specific luminous flux, long life and easy means of integrating them in a fitting. The lamp types suitable for this are:

a. Sodium lamps (with integral vacuum glass, indicated by SOI).
b. High pressure mercury lamps with fluorescent bulb (HPL).
c. Fluorescent tubes ("TL").

In some installations incandescent lamps are still used while in the near future high pressure mercury lamps with colour correction in the discharge are to be employed. Sodium and mercury lamps are of small dimensions, but produce a high luminous flux, while fluorescent tubes are long and give a small luminous flux per unit of length. For entrance lighting and in short tunnels where high luminance levels must be reached sodium and mercury lamps are therefore recommended while for the interior of tunnels fluorescent tubes are preferred. Mercury lamps and fluorescent tubes can be combined conveniently in entrance zones. Sodium lamps are advantageous from the point of view of visibility (see Schreuder (1962)).

Table 2 gives a comparison between the different light sources. In order to make a comparison possible we assume that in all cases the fittings are installed in continuous lines.

Fittings are usually mounted lengthwise in tunnels whether in uninterrupted lines or not. The most suitable location depends on the shape and dimension of the tunnel cross section. Some frequent cases are sketched in Fig. 13 together with the rough outline of the most favourable light distribution. Fittings against or close to the wall (Fig. 13a and 13b) give better lighting of the walls and facilitate maintenance of the fittings. In very wide or high tunnels the fittings must be mounted against the

TABLE 2

COMPARISON OF LAMPS FOR TUNNEL LIGHTING

Lamp	High pressure mercury with fluorescent bulb		Fluorescent		Sodium	
Type	HPL 125 W	HPL 1000 W	"TL" M 40 W/33 RS	"TL" M 120 W/33 RS	SOI 85 W	SOI 200 W
Watts per unit (ballast incl.)	136	1 043	55	148	105	232
Length per unit (metre) (luminaire)	0.30	0.70	1.30	1.65	0.55	0.90
Luminous flux per unit (lumen) (100 h)	5 400	52 000	2 850	7 300	8 000	22 000
Flux per metre (one line) (lumen)	18 000	74 000	2 200	4 400	14 500	24 500
Average illumination (lux) (E) [1]	1 350	5 500	160	330	1 060	1 800
Average luminance (cd/m^2) (L) [2]	150	600	17.5	35	120	200
Watts per metre (two lines)	910	3 000	85	185	380	515
Luminance per (watt per metre) ($cd \cdot watt^{-1} \cdot m^{-1}$)	0.17	0.20	0.21	0.19	0.32	0.39

[1]) Tunnel width 9 metres. Utilisation coefficient of luminaire 0.33. Two lines.

[2]) Average reflection factor $r = 0.3$. Influence inter-reflections according to Smith and Waldram (1957).

$$L = \frac{E}{\pi} \cdot \frac{r}{1 - 0 \cdot 45r}.$$

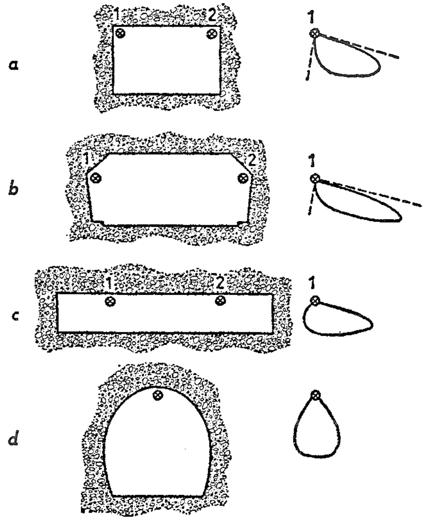


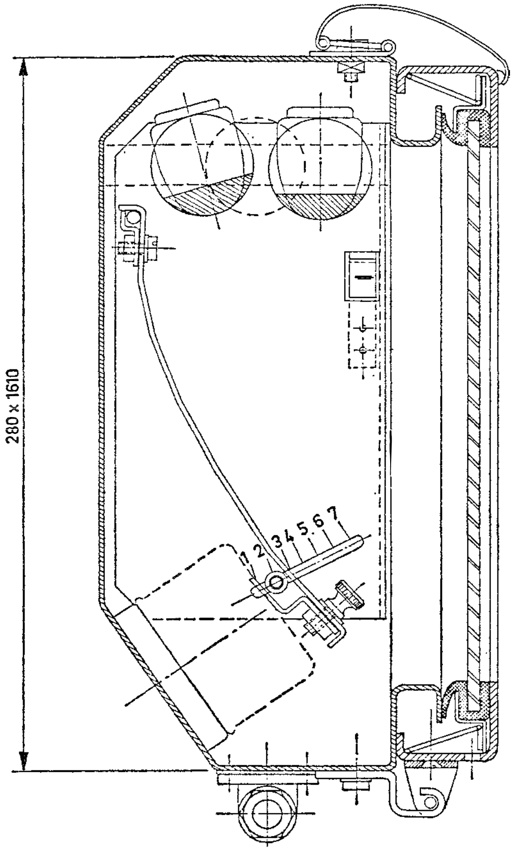
Fig. 13. Position of fittings in tunnels of different crosssection with the corresponding light distributions desired.

ceiling (Fig. 13c and 13d). A good optical guidance can be achieved in this way.

The desired light distribution is obtained by means of an optical system. In the case of Fig. 13a and 13b rather high demands are made on the light control, in particular when it is desired to keep the ceiling dark. An example of such a fitting is given in Fig. 14. The mirror and the lamp in the fitting are adjustable so that the direction in which the maximum candle power is directed can be adjusted – without altering the light distribution – according to the dimensions of the tunnel where the fitting is to be installed. The mirror can be lifted in order to reach the ballast and the fuse. With the aid of an adjusting device the fitting can be arranged in straight rows. Fig. 15 gives the polar light distribution of the fitting provided with a reflector fluorescent lamp of the type "TL" MF 65 W. A two-lamp version is also possible.

A fitting for tunnel lighting must comply with the following conditions concerning the mechanical construction. First, the risk of damage both by traffic and by cleaning must be made as small as possible by a flat and robust design. Secondly, the fitting must be completely watertight and be proof against cleaning agents and exhaust gases. Thirdly, the fitting and the lamps must be easily accessible and easy to maintain. The fitting which in shown in Fig. 14 satisfies all these conditions.

There is no point in fixing lengthwise fittings with louvres. The aim of these louvres is to reduce the brightness of the fitting in directions more



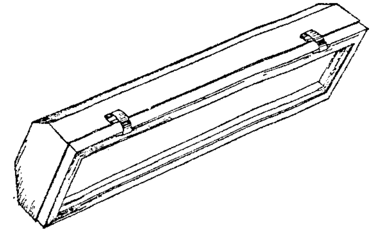


Fig. 14. Example of construction of a fitting for tunnel lighting.

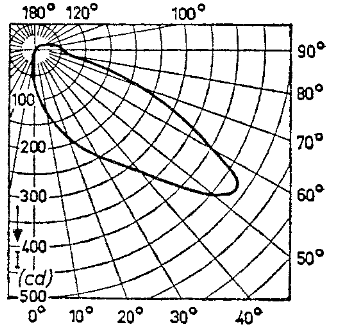


Fig. 15. Polar candle power distribution of the fitting shown in Fig. 14.

or less parallel with the road surface. In fact, however, a fairly high brightness in these directions is no drawback, because optical guidance is made easier by lines of light that are clearly visible. The louvres reduce the effective light output of the fittings substantially, in particular as they soil quickly and are difficult to clean. In several tunnels where louvres of this kind were intially installed they have been withdrawn.

2.3.4. USE OF DAYLIGHT IN TUNNELS

Considering the daytime lighting of tunnels, in three ways natural daylight can be exploited:

a. The use of subdued daylight at the entrance zone of long tunnels (daylight screening).
b. The application of light slits in the roof of short tunnels.
c. The use of the light that falls into the tunnel through the exit.

a. *Daylight screening*

Constructions to screen the daylight must absolutely satisfy the condition that under no circumstances whatever direct sunlight strikes the road surface below the screen. If this does happen, the regular patterns of shadows present a very disturbing effect. In Plate 4 a situation of that kind is simulated. The direct sunlight can be diffused, for example, through glass building units, or be screened by slats. The first method is not very satisfactory as the transmission of this kind of screen – especially in view of the amount of soiling – is too small to reach the high luminance values necessary at the beginning of the tunnel. Some examples of application are the tunnel Jenner at Le Havre, the tunnel at the Porte de Clignacourt in Paris and the tunnel Ferney at Geneva (see also Table 12).

Swierstra (1951, 1952) has shown a method of determining the shape of the openings in a grid which transmit no direct sunlight at any position of the sun. An outline can be defined within which all openings must lie. The outline has the form (h cot ε) of which h is the height of the grid and ε the maximum height of the sun for different directions. The form in which this outline is used for the design of the tunnel at Velsen is given in Fig. 16 (Wentink (1962)). Some values for ε and for (cot ε) are given in the figure for 52° N. lat. The figure is only valid for grids in which the slats are vertical. Every shape which lies within this outline is "sunproof" and can be employed, but as a rule the shape of a parallelogram is chosen.

The amount of light which falls directly through an opening defined in

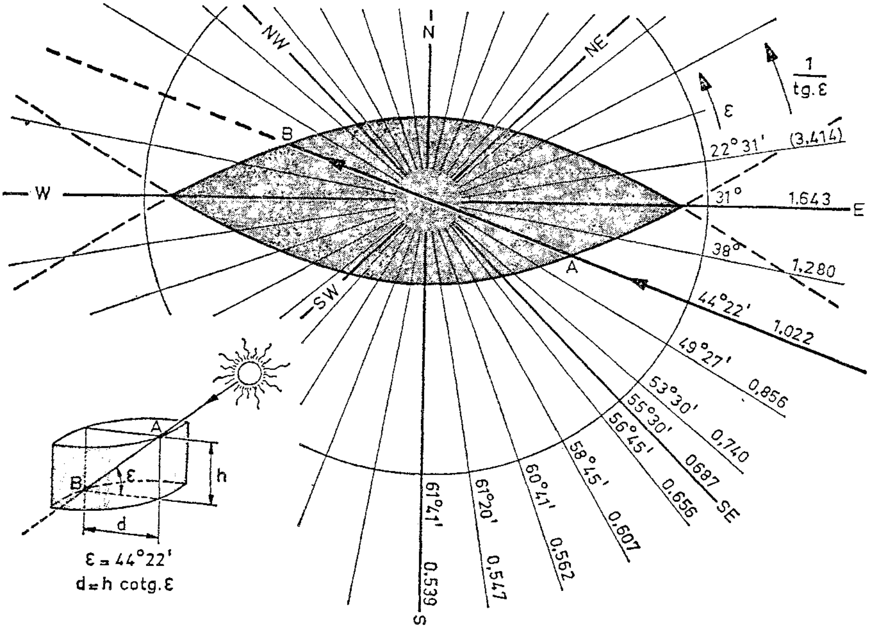


Fig. 16. Diagram of solar altitudes. ε = maximum elevation of the sun; d = width of grid opening for height h = 1; (cotg. ε). Diagram is valid for June 21th at 52° Latitude North.

this manner is fairly small. In order to make grid constructions with a high effective transmission the slats must have a high – but not specular – reflection. This means that soiling again is very important.

To illustrate the influence of reflection, Fig. 17 shows the results of some measurements on grid elements of the same shape, but different height and in two designs, i.e. painted glossy white and dull black. The difference in transmission appears to be very considerable. Transmissions of 10–13 % can well be realised provided that the surfaces of the grid elements have a bright colour and do not accumulate dirt too easily. The values of 10–13 % are necessary in order to obtain the ratio mentioned in Section 2.1.2 between the luminances outside and inside the tunnel.

Two remarks must be made concerning the realisation of the grids.

The first is that the grid elements must not be too small because they easily can get covered with snow. Neither must they be too large since the whole construction becomes heavy and costly. As a rule the grids are made 0.5 to 1 m high and are constructed of aluminium or concrete. Another problem is offered by the snow that falls through the openings on to the road below the grid. If the grid is well constructed the sun cannot reach the road. Consequently, the snow will not thaw, causing a slippery road surface. This may cause great trouble particularly in mountainous regions. Closed screens are also unsuitable because the snow stays on top of the screen and obstructs the light.

The second remark is related to grid constructions that lie very deeply below ground level. As demonstrated in Fig. 18 the area of the grid being in shadow can differ, although the sun height and therefore the illumination on the open field is the same. This causes a difference in the illumination under the grid. The ratio between the luminance outside and that under the screen is thus no longer constant.

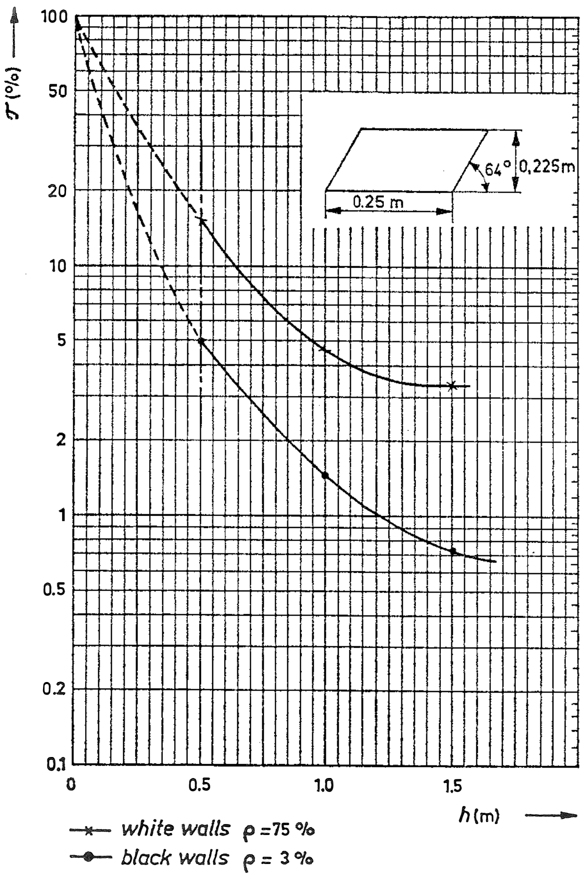


Fig. 17. Relationship between transmission τ and height h of grids.

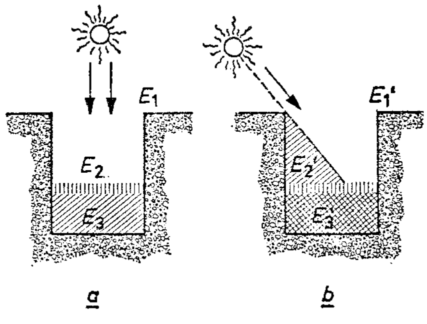


Fig. 18. Influence of the depth of daylight screens.
$E_1 = E'_1$; $E_2 = 2E'_2$; $E_3 = 2E'_3$.

Daylight screens of many designs have been frequently employed, especially in recent years. Some examples are given in Table 12.

b. *Daylight slits*

Sometimes daylight slits can be used in tunnels of medium length (Section 4.3). With the aid of the formula quoted by Higbie (1934, Chapter V, Section 33) an estimate can be made of the effect of slits of this type if we assume that the slit is very long and that it can be considered as a diffuse light source. The formula runs:

$$E = \frac{\pi B}{2} (\sin \gamma_2 - \sin \gamma_1),$$

in which E is the illumination at a point P, B the luminance of the slit

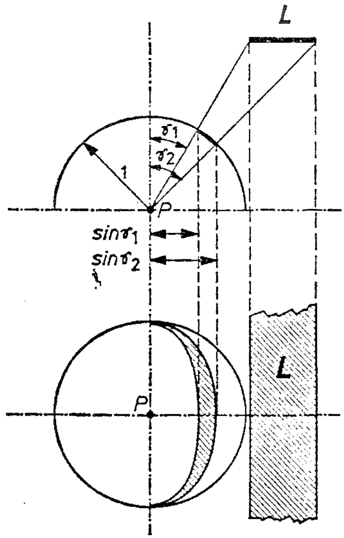


Fig. 19. Determining the transmission of daylight slits. (After: Higbie, 1934, pp. 158–159). L = luminous plane.

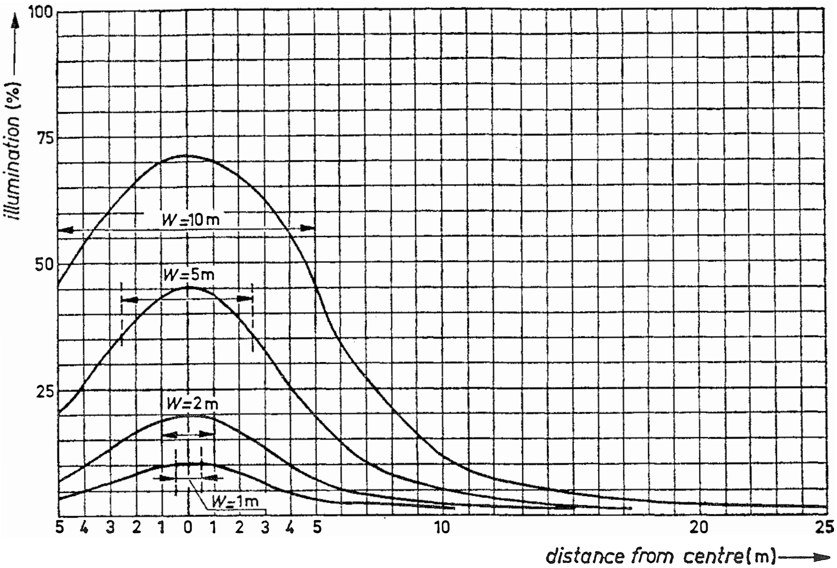


Fig. 20. Transmission of daylight slits. w = width of slit. Illumination outside 100 % ($w = \infty$).

and γ_1 and γ_2 are the angles at which the edges of the slit are seen (see Fig. 19). With the help of this formula the illumination at different points in the tunnel can be calculated. Some results are reproduced in Fig. 20. Even a slit 1 m wide already contributes considerably to the illumination in the tunnel. The same conclusion can be drawn from measurements of Lossagk (1955). The calculations are valid for a diffuse sky. If sunlight falls through the slit the contribution to the illumination is even greater and the slit becomes consequently still more effective. In fact, the tunnel of medium length is than divided that way into two very short tunnels.

c. *Daylight penetration into the tunnel*

Daylight enters a tunnel at the entrance as well as at the exit. Fig. 21 reproduces the course along the tunnel of the horizontal and the vertical illumination near a tunnel end. Fig. 21 is constructed from measurements and from calculated data. It shows that the contribution to the illumination of the penetrating daylight can be neglected after a few metres. Both the horizontal and the vertical illumination are generally about equal at either end but not so the resulting luminances. Since the light which penetrates through the exit into the tunnel strikes the road surface and the walls at grazing angles and is directed against the line of observation a high

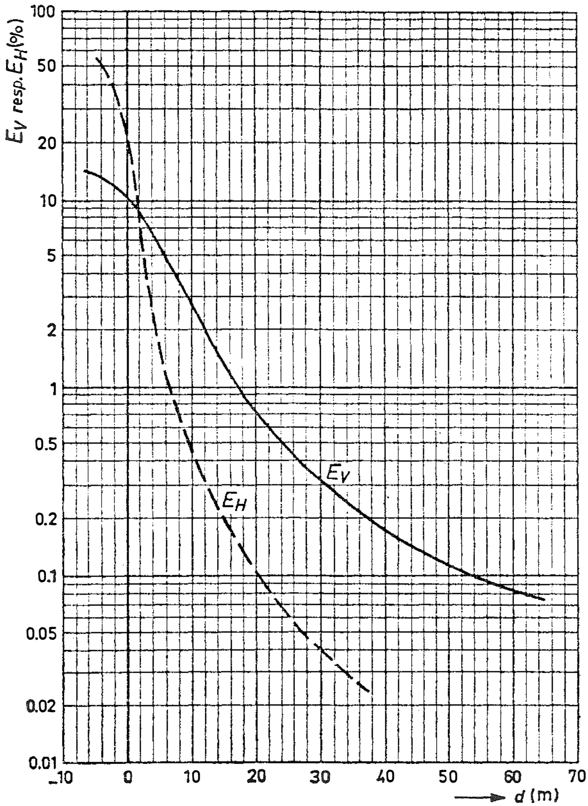


Fig. 21. Penetration of daylight. Horizontal and vertical illumination in % with horizontal illumination outside = 100 %. *d* = distance to tunnel entrance. The graphs are constructed partly from calculated, partly from measured values.

luminance can result with a low illumination. This is of great importance for short tunnels and the exit of long tunnels (Sections 2.1.6 and 4.2).

2.4. Economic aspects of tunnel lighting

2.4.1. THE COSTS OF TUNNELS AND TUNNEL LIGHTING

Time and place of a tunnel project evidently have a great influence on all economic considerations involved. Some general considerations can however be given. If not otherwise stated the figures quoted apply to the Netherlands in 1963 *).

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*) 10 dutch guilders (*ƒ* 10.—) equal about £ 1.

TABLE 3

BUILDING COSTS FOR SEVERAL TUNNELS

Tunnel	Year	Length (m)	Costs	Estimated equivalent (1963) (millions)	Reference
Holland tunnel, New York	1927	2 800 (2 x)	$ 48 000 000.—	*f* 500	Werkman (1959)
Maas tunnel, Rotterdam	1941	1 072	*f* 18 000 000.—	*f* 55	Werkman (1959)
Velsen	1957	768	*f* 60 000 000.—	*f* 60	Werkman (1959)
Dias Island tunnel, Vancouver	1959	658	$ 21 000 000.—	*f* 70	Lassen-Nielsen (1961)
Sidney	1962	400	£ 3 500 000.—	*f* 35	"Cahill Expressway" (1962)
Clyde tunnel	1963	685 (2 x)	£ 10 500 000.—	*f* 110	Colvin, Rigg (1962)
Coen tunnel, near Amsterdam	± 1966	587	*f* 54 000 000.—	*f* 54	Eggink (1963)
IJ tunnel, Amsterdam	± 1967	1 039	*f* 120 000 000.—	*f* 120	Snijder (1963)
Thames tunnel, Dartfort	1963	1 570	£ 10 100 000.—	*f* 100	"Tunnel onder de Theems" (1957)
Mont Blanc	1964	11 600	F. 200 000 000.—	*f* 150	Wharton (1963)
Court-Roumont, Switzerland	?	4 400	Sw.Fr. 35 000 000.—	*f* 30	Minnig (1961)
Lion Rock tunnel, Hong Kong	1963	1 420	$ 15 000 000.—	*f* 55	"Lion Rock Tunnel" (1963)

For short subways and viaducts the constructional costs quoted usually lie between *f* 400.— and *f* 800.— per square metre of road enclosure (Hoefakker (1962)). The same calculation cannot be made for long tunnels since the costs depend too much on the particular circumstances. Nevertheless, to give an impression of the order of magnitude the constructional costs of several tunnels are quoted in Table 3 as well as the years in which these tunnels were built or are to be built.

Even less can be said with certainty about the running costs. Some data are given by the Comité des Tunnels Routiers (1959). For illustration we quote the amounts given in that study on the tunnel at Velsen (see Table 4). It is interesting to note that the share of the lighting is only about 17 % of the total running costs.

TABLE 4

RUNNING COSTS FOR 1958, TUNNEL VELSEN

Personnel for exploitation	*f* 40 900.—	
Police	*f* 120 000.—	
Other personnel	*f* 10 000.—	
		f 170 900.—
Power costs lighting and signalisation	*f* 53 700.—	
Power costs ventilation	*f* 3 000.—	
Power costs (other)	*f* 15 300.—	
Costs of vehicles for maintenance and police	*f* 47 150.—	
		f 119 150.—
Maintenance of lighting	*f* 5 000.—	
Maintenance of ventilation	*f* 6 000.—	
Maintenance (other)	*f* 50 650.—	
		f 61 650.—
	Total	*f* 351 700.—

of which the costs of lighting for 1958 were *f* 53 700.— + *f* 5 000.— = *f* 58 700.— or about 17 %.

In order to get an idea of the costs of installing and operating the lighting in a tunnel we have made a comparison between some installations which fall within the practical possibilities. A survey of the calculations is given in Table 5. The data concerning the illumination and luminance are based on measurements of test installations made in the tunnel at Velsen. Two systems with fluorescent tubes are compared (one with fittings with light control and one without), one system with high pressure

TABLE 5 COMPARISON OF LIGHTING INSTALLATIONS

Number	1	2	3	4	5
Lamp	Fluorescent tube	Reflector type fluorescent tube	High pressure mercury lamp with fluorescent bulb	Sodium lamp with attached vacuum shield	
Type, power	"TL" M 40 W/33 RS	"TL" MF 40 W/33 RS	HPL 250 W	SOI 85 W	SOI 200 W
Luminaire	no control	mirror type	recessed mirror type	refractor type	refractor type
Position	on the wall (continuous line)	on the wall (continuous line)	in the wall (discontinuous)	in the roof (discontinuous)	in the roof (discontinuous)
Distance (c. to c.) (m)	1.30	1.30	4.0	9.0	9.0
Luminous flux (lm) (100 h)	2 850	2 520	11 500	8 000	22 000
Watts (ballast included)	55	55	267	105	232
Efficiency luminaire [1]	0.27	0.40	0.30	0.45	0.45
Average illumination (lux) [5]	145	237	250	115	320
Average luminance (cd/m²) [5]	6.7	11	11.5	9.0	25
Number per km (two rows)	1 540	1 540	500	222	222
kW per km	84.5	84.5	133	23.3	51.5
Price lamps, replacement costs incl.	f 9.25	f 9.75	f 40.—	f 37.50	f 70.—
Price luminaire, ballast incl.	f 160.—	f 240.—	f 300.—	f 250.—	f 300.—
Installation costs [2]	f 246 000.—	f 370 000.—	f 150 000.—	f 55 500.—	f 66 500.—
Amortisation (10 years) 4 % [4]	f 30 000.—	f 45 500.—	f 18 500.—	f 6 800.—	f 8 200.—
Power consumption [3][4]	f 73 500.—	f 73 500.—	f 116 000.—	f 20 300.—	f 45 000.—
Life (h)	7 500	7 500	6 000	5 000	5 000
Replacement costs	f 16 500.—	f 17 500.—	f 29 000.—	f 14 500.—	f 27 000.—
Total running costs [6]	f 120 000.—	f 136 500.—	f 163 500.—	f 41 600.—	f 80 200.—
Costs "per lux" [4][6]	f 825.—	f 575.—	f 650.—	f 360.—	f 255.—
Costs "per cd/m²" [4][6]	f 17 900.—	f 12 400.—	f 14 200.—	f 4 600.—	f 3 200.—

[1] Fraction of lamp luminous flux on a road width of 7 metres.
[2] Cable costs, mounting costs etc. not included, because they can be considered as equal for all installations.
[3] 8 700 burning hours per year, f [illegible].10 per kW/h.
[4] Per year per km.
[5] Based on actual measurements on trial installations.
[6] Amortisation, power, replacement.

mercury lamps in recessed fittings in the walls and two with sodium lamps in refractor fittings which are mounted transversely into the ceiling. The data apply to a tunnel section 1 kilometre long, 9 m wide and 4.5 m high.

Most striking is the advantage of light control for the lighting with fluorescent tubes and the high luminance yield of the transverse sodium fittings. The installation costs given in Table 5 do not refer to the entire lighting installation, but only to the part that is influenced by the choice of the type of installation. The total installation costs of the lighting are therefore considerably higher. A sum of *f* 2 000 000.— is quoted for the tunnel at Velsen (Wentink (1962)) amounting to about 3 % of the total building costs of the tunnel (see also Jainski (1961)).

The costs of the entrance lighting are greatly influenced by the type and location of the tunnel. A comparison is made between the costs of entrance lighting done completely with artificial light and the costs of a system of daylight screening, assuming that small aluminium grids are used and that the grid construction has no other function. The costs of the grid construction belong therefore entirely to the lighting. The calculations are given in Table 6. For artificial lighting we assume the application of the most advantageous design given in Table 5, i.e. with transverse 200 W sodium lamps (Column 5). Account is taken of the extra cables and transformers. The maximum level required is 1 000 cd/m^2; a great deal of the time, however, some of the lamps can be switched out.

A lighting installation must also be placed under the grid for the periods of twilight and night. The lighting chosen is equal to that in Column 2 of Table 5. The price of the grid of *f* 200.— per sq.m is based on the costs of the tunnel at Paris-Orly. The two systems are compared in Table 7. The costs apply for a section of 100 m long. It is obvious that the grid construction is substantially cheaper than the installation with artificial light.

The costs of a grid do not appreciably depend on the transmission, i.e. on the luminance level to be achieved; the costs of the artificial lighting, however, are almost proportional to the desired luminance level. So there is a level where artificial light and grids are equal in costs. If we assume that with artificial light the costs are quite in proportion to the maximum luminance level required (i.c. 1 000 cd/m^2) and with grids independent of it, we can deduce that at a level of about 660 cd/m^2 the installation costs, at a level of 110 cd/m^2 the running costs, and at a level of 260 cd/m^2 the total annual costs are the same for the two systems (Table 7).

With the assumptions used in this example the most economic entrance

TABLE 6

COSTS OF ENTRANCE LIGHTING

Artificial light

Up to 1 000 cd/m², 890 luminaires per 100 metre, 206 kW.

Installation analogous to n° 5 of Table 5 (luminaire and ballast + cable *f* 350.—) . . . . total	*f* 310 000.—	
Cables, switches, regulations, transformers	*f* 50 000.—	
Installations costs	*f* 360 000.—	
Amortisation (10 years, 4 %)		*f* 44 000.—
Power costs 870 h at 100 % intensity		
870 h at 30 % intensity		
1350 h at 10 % intensity		
1350 h at 3 % intensity		
4320 h at 1 % intensity		
8760 h at 15.5 % (av.)		*f* 27 500.—
Replacement for average burning time of 15.5 %		*f* 16 500.—
Total running costs		*f* 88 000.—

Daylight screening

A night time installation is necessary, for instance like Table 5, n° 2.

Installation per 100 metres	*f* 37 000.—
Amortisation (10 years, 4 %)	*f* 4 500.—
Power (burning time 55 %)	*f* 4 000.—
Replacement (burning time 55 %)	*f* 1 000.—
Running costs	*f* 9 500.—

Screens (aluminium louvres)

Estimated price per m²	*f* 200.—
Surface (length 100, width 10 m)	1 000 m²
Installation costs	*f* 200 000.—
Amortisation (30 years, 4 %)	*f* 12 000.—

TABLE 7

RELATIVE COSTS OF ENTRANCE LIGHTING

	Artificial light	Louvres
Total installation	*f* 360 000.—	*f* 237 000.—
Relative	100 %	66 %
Total amortisation	*f* 44 000.—	*f* 16 500.—
Power costs	*f* 27 500.—	*f* 4 000.—
Lamps	*f* 16 500.—	*f* 1 000.—
Total exploitation costs	*f* 44 000.—	*f* 5 000.—
Relative	100 %	11 %
Total running costs	*f* 88 000.—	*f* 21 500.—
Relative	100 %	26 %

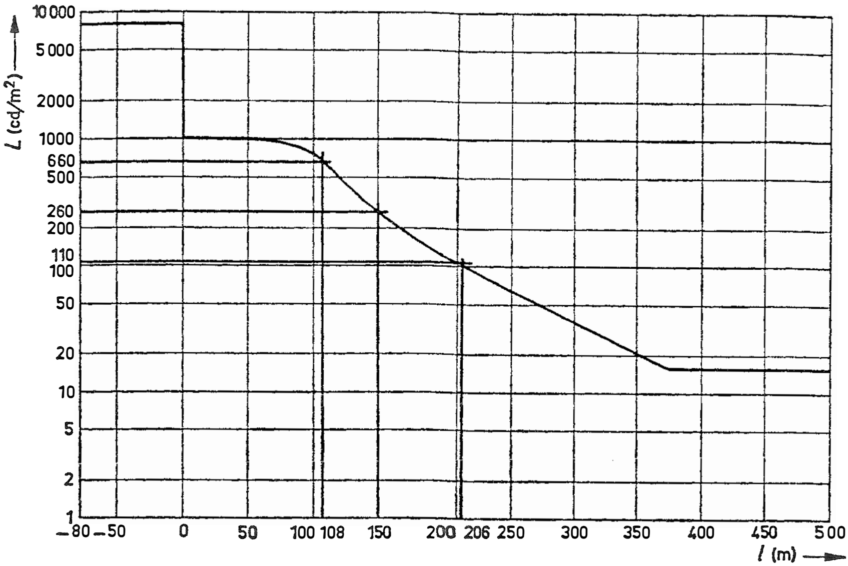


Fig. 22. Entrance lighting executed partly with subdued daylight and partly with artificial light.

lighting consists therefore partly of grids and partly of artificial light. This is illustrated in Fig. 22. This figure indicates the course of the luminance as desired at the beginning of a tunnel. The construction of this figure is discussed in Section 3.4. The points of intersection with the horizontal lines at 660, 260 and 110 cd/m² respectively indicate the points where, according to the assumption made before, the change from grids to artificial lighting should be made to achieve the minimum of installation costs, annual costs and running costs respectively.

2.4.2. THE ECONOMICS OF TUNNELS AND TUNNEL LIGHTING

The construction of tunnels only can be justified if the community saves more by it than the costs amount to. In this case it is not relevant that the costs consist of actual outlay while the savings are, in fact, outlay which has not been made.

An important saving is made by shortening the travelling time. For the simplicity of the demonstration we assume that the amount saved per time unit is independent of the time saved. This implies that all time saved can be utilised in full for other purposes. Table 8 gives some estimates

TABLE 8
COSTS OF TIME LOST

Author	Place	Costs per person per hour	*f*	Reference
Podestà	Rome	718 lire	4.15	Coquand (1961)
Claes	Brussels	50 frs.B.	3.60	id.
—	USA	3 to 5 F.	2.55 to 3.65	id.
Barry and Rick	Gr. Britain	£ -/10/7	5.50	after Dawson (1961)
"Channel tunnel"	USA	£ -/ 9/0	4.50	id.
West	USA	£ -/20/1	10.40	id.
Lawton	USA	£ -/ 9/9	5.05	id.
Chaffey	Scotland	£ -/10/8	5.50	id.
—	France	£ -/7/6 to -/10/6	3.90 to 5.45	id.
		Costs per car per hour		
Feuchtinger	Germany	DM 6	5.40	Feuchtinger (1956)
Björkman	Sweden	Sw.kr. 5	3.00	Björkman (1961)

made by various authors of the costs of the time loss. From this we assumed a saving of *f* 6.— per car per hour, assuming an average seating of 1.5 persons per vehicle. The savings made by less wear and lower petrol consumption are ignored. When the costs are known, we can determine how much time should be saved to make a tunnel pay. Some calculations have been made taking again the tunnel at Velsen as an example (see Table 9).

TABLE 9
REMUNERABILITY OF TUNNELS

	Tunnel	Lighting installations only	Ferry service (8 boats)
Building costs	*f* 60 000 000.—	*f* 2 000 000.—	*f* 9 000 000.—
Amortisation	*f* 3 500 000.—	*f* 246 000.—	*f* 1 400 000.—
Exploitation	*f* 350 000 —	*f* 59 000.—	*f* 2 600 000.—
Running costs	*f* 3 850 000.—	*f* 305 000.—	*f* 4 000 000.—
Number of cars	7 000 000	7 000 000	3 000 000
Costs per car	*f* 0.55	*f* 0.043	*f* 1.33
Necessary time saving (min) . (Assumption: *f* 6.— per car per hour)	5.5	0.43 (25.8 sec)	13.3

It follows from this table that a time saving of about six minutes is sufficient to make the building of such a tunnel an economic proposition. In reality the saving achieved will be a multiple of those six minutes. We can conclude from this that as a rule tunnels are highly remunerative.

For comparision Table 9 includes the costs for the car ferries across the IJ in Amsterdam taken from the annual report of the Municipal Transport Corporation (Wijt (1960)). It follows from the comparison that both the running costs and other annual costs of a ferry service are considerably higher than those of a tunnel. This means that even apart from the great time saving a tunnel is much cheaper than a ferry service.

In principle it is possible to deal in a similar way with the economics of tunnel lighting. The relevant calculations are included in Table 9. They lead to a minimum time saving of about 26 seconds to make the tunnel lighting remunerative. If no lighting should be installed, these 26 seconds should be accepted as time loss, allowing a decrease in average speed. This result, however, is of little practical value.

Besides, it is questionable whether a reduction in lighting would really lead to a speed reduction. The contrary has been measured by Gonseth (1960) at the Holland Tunnel in New York. In the winter the switching out of the entire entrance lighting had no influence on the driving speed. A similar effect is found in our measurements at Velsen. During the day the average driving speed in the tunnel was higher than at night, although the traffic situation as well as the lighting situation are considerably better at night than during the day. The speed on the level section of the open road was, however, almost precisely the same. Some results of the measurements are given in Table 10.

TABLE 10

MEASUREMENTS OF DRIVING SPEED (VELSEN APRIL 18 AND 19, 1962)

	Number of cars	Open road	Tunnel interior	Difference
Day time	104	81.5	91.4	9.9 (significant)
Night time	100	81.6	85.5	3.9 (significant)
Difference		0.1 (not significant)	5.9 (significant)	

Average driving speeds in km/h. Significance at 95 % level.

From this we may expect a poor lighting installation to have an unfavourable effect on road safety. On account of the small number of tunnels the statistics are not sufficiently reliable to serve as a base for study, but in fact the data quoted in Table 11 suggest a strong dependence of the safety on the lighting level. This tendency is quite marked for the last three tunnels which had about the same traffic. The number of breakdowns, however, shows no relation to the lighting level, but appears to be directly proportional to the traffic – as would be expected – suggesting a comparable traffic situation in these three tunnels.

TABLE 11

ILLUMINATION AND ACCIDENTS

Tunnel	Year	Traffic (millions)	*E* (lux)	Accidents	Break-down	Reference
Rotterdam	1957	19	30	560	1300	Comité des Tunnels Routiers (1959)
Lyon	1957	6.4	30	104	277	id.
Antwerp	1957	5.2	50	36	396	id.
Velsen	1961	7	105	5	398	Wentink (1962)

From this chapter on economic aspects three important conclusions may be drawn:

a. Tunnels are highly remunerative when time savings are expressed in cash.
b. A good lighting installation requires only a small fraction of the total costs of the tunnel both as regards the initial installation costs and the running costs.
c. An increase in the lighting level is likely to lead to a marked decrease in the number of accidents.

CHAPTER 3

THE LIGHTING OF LONG TUNNELS

3.1. Introduction – Difference between long and short tunnels

The various aspects of tunnel lighting discussed in Chapter 2 form the basis for the design of lighting installations for tunnels. At the same time the material has served as the foundation for the publication "Recommendations for Tunnel Lighting" issued by the Netherlands Foundation on Illumination (1963). These Recommendations are directed to the practical construction of the installation. The Chapters 3 and 4 of this study form on the one side a supplement to the Recommendations and at the same time a summary also. In this framework it is impossible to avoid all repetition, which also applies to the material discussed in Chapter 2.

In the consideration of the lighting the tunnels are divided into two groups, namely long and short tunnels. A tunnel is called *short* when in the absence of traffic the exit and the surrounding beyond it are clearly visible from a point some distance in front of the tunnel. All other tunnels are called *long*.

The question as to whether a certain tunnel must be classified as long or short naturally depends in the first place on its length, but the situation, the presence of bends or dips, and the form and dimensions of the cross profile are also of great influence. It is quite possible that the same tunnel should be regarded from one side as long, but from the other side as short. An example of this is given in Plate 5.

Because this classification into long and short tunnels has a far-reaching influence on the demands on the lighting installation, the two classes are dealt with separately in Chapters 3 and 4 respectively.

3.2. Position of the adaptation point – Length and lighting of the threshold and transition zones

THE ADAPTATION POINT

The *adaptation point* is defined as the point on the road where the adaptation of the eye of a road user approaching the tunnel begins to be

Plate 1. *Optical guidance at a tunnel entrance.*

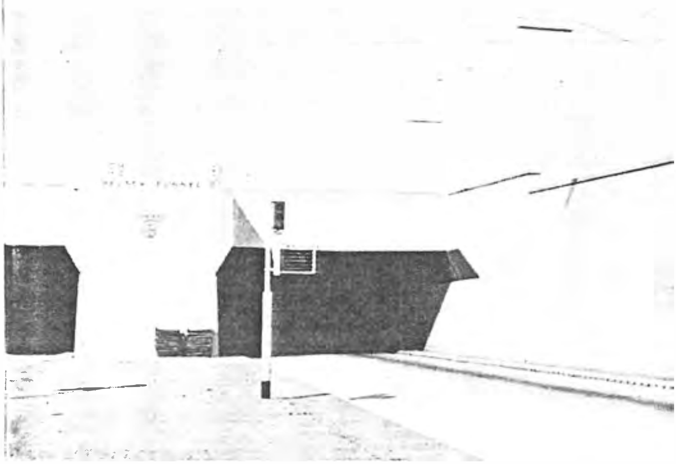
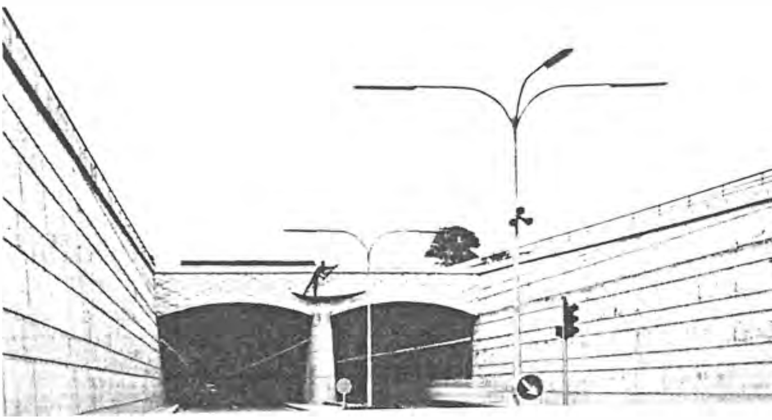


Plate 2. *Facade of the tunnel at Velsen.*

Plate 3. *Facade of the tunnel at Rendsburg.*



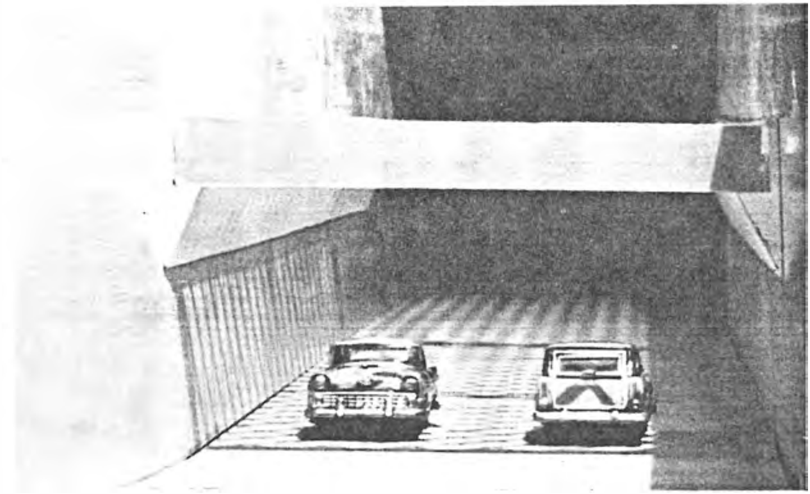
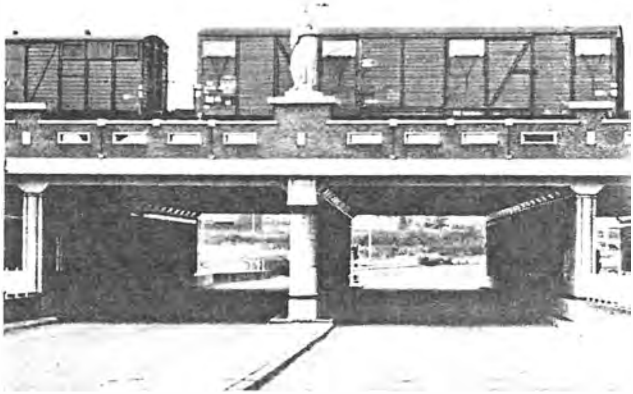


Plate 4. *Patches of sunlight below a grid which is not "sunproof".*



a

Plate 5. *Example of a tunnel regarded as short from one side (a) and long from the other (b).*

b

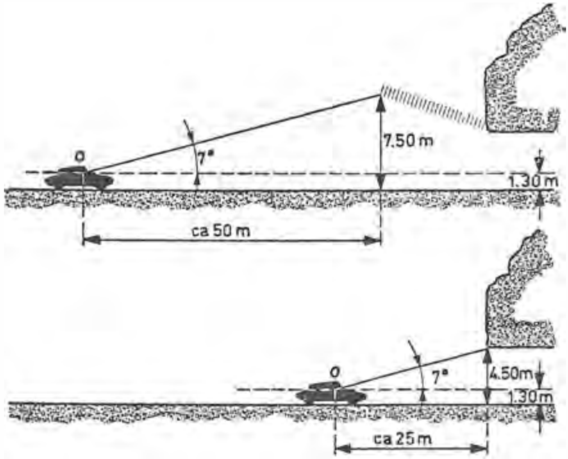


Fig. 23. Location of adaptation point depends on the height of the tunnel entrance.

influenced by the presence of the dark tunnel entrance (Section 2.1.1). The distance from the adaptation point to the tunnel entrance is chiefly determined by the construction and dimensions of the access zone and the tunnel facade. When the facade is carried out in a bright colour and consequently has high luminance, the adaptation begins only to be affected when the last part of the facade has disappeared behind the upper rim of the windscreen. We have taken 7° as the average value for the shielding angle of windscreens (see Fosberry (1958, 1959)). When the lower border of the facade is at normal height the adaptation point lies about 25 m before the tunnel entrance. If this height is raised, for example to 7.5 m, the adaptation point can lie at a distance of about 50 m (see Fig. 23). This raising of the facade is a very effective expedient, particularly for tunnels in mountain sides and for tunnels in which daylight screens of small height are installed. Further aids are dark finish of the facade and other neighbouring surfaces, which has already been mentioned more than once. By these means the adaptation can already be influenced before the last part of the facade has vanished from the field of vision. With a well designed construction the distance of the adaptation point from the tunnel entrance can amount to 50–60 m.

LENGTH OF THRESHOLD ZONE

The minimum length of the *threshold zone* (see Fig. 1) is dependent upon the distance V at which the critical object has to be visible. To this should be added a stretch of about 20 m which serves as background for obstacles.

For tunnels without speed restrictions V must be assumed at 100 m (Section 2.1). For tunnels in which a speed limit of 50 km/h applies V can be set at 60 m. These values are considerably greater than the minimum braking distance. With a retardation of 7 m/sec^2, this distance is about 50 m for 100 km/h and about 12 m for 50 km/h. The margin between the minimum braking distance and V, which is necessary above all in view of traffic coming from behind, is chosen extra large for town tunnels with speed restrictions. The length of the threshold zone must therefore amount to (V + 20) metres reduced by the distance between the adaptation point and the tunnel entrance. In most cases 50 to 80 m will be sufficient.

LENGTH OF TRANSITION ZONE

When the car driver has passed the adaptation point his eyes begin to adapt themselves to the dark area of the tunnel entrance. When the luminance decreases according to the curve given in Fig. 5, inconvenience caused by after images is prevented. These luminances must exist at points at a distance V in front of the observer. Since the adaptation prevails, the areas with high luminance close to the observer have only little effect, because they are reproduced on other parts of the retina. The conditions for adequate visibility are satisfied when a transition zone with a luminance course according to Fig. 5 is linked to the threshold zone.

This will be illustrated in Fig. 24. In this illustration the drawn line represents the course of the luminance and the dash line the course of the adaptation. When the adaptation is indicated with the luminance of equivalent fields of vision, a measure to be expressed in luminance values can be used – although theoretically – for the adaptation (see Section

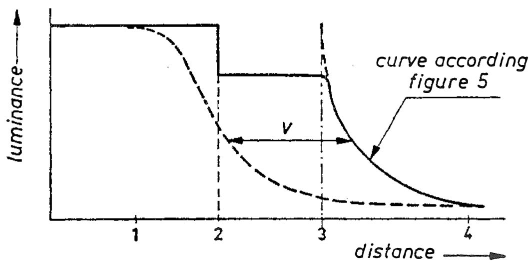


Fig. 24. Course of the luminance in the entrance zone in diagram form.
1 = adaptation point;
2 = tunnel entrance; beginning of threshold zone;
3 = end of threshold zone;
4 = beginning of interior.

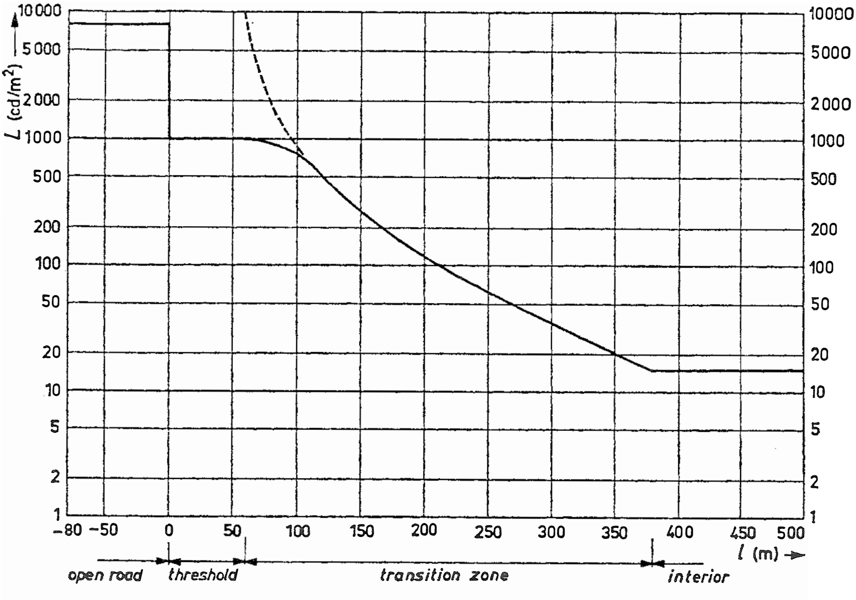


Fig. 25. The recommended luminance course. Speed 75 km/h.

2.1.3). In Fig. 24, point 1 represents the adaptation point. The threshold zone with a length rather less than *V* runs from point 2 to 3 and the transition zone, with a luminance course according to Fig. 5, from point 3 to 4. The interior begins at point 4. At the adaptation point the adaptation begins to change, first slowly but more quickly when the road user gets nearer to the tunnel entrance (point 2). The range of observation now lies behind the threshold zone. The luminance decreases according to the curve of Fig. 5. The adaptation thus also follows this curve, which just satisfies the condition for absence of inconvenience due to after images, until the interior of the tunnel is reached.

According to Fig. 5 the transition zone must be about 300 m long for a driving speed of 75 km/h and for a luminance in the interior of 15 cd/m². The threshold zone linked to this means that the whole entrance zone must be 350–400 m long. The recommended luminance course is reproduced schematically in Fig. 25. Another choice of driving speed results in another length of the transition zone. At 50 km/h the transition zone must be about 200 m long, and the whole entrance zone is thus about 250 m. If one has to reckon with very fast drivers the entrance zone has to be longer.

THE LIGHTING OF THE ENTRANCE ZONE

The three methods to be considered for lighting the entrance zone, viz. artificial light, open grids and closed screens have already come under discussion more than once, as well as the economic attraction of a combination (Section 2.4.1). Table 12 gives a summary of some of the advantages and disadvantages of the systems, together with several examples.

TABLE 12

COMPARISON OF SYSTEMS FOR ENTRANCE LIGHTING

	Artificial light only	Open louvres	Closed diffusing screens
Extra room needed for construction	none	much	much
Extra ventilation	none	none	much
Avoiding a "black hole" effect for high values of L_1	impossible	good	hardly possible
Same for low values of L_1	very good	only with additional lighting	only with additional lighting
Adaptation to daylight variations	only with complicated installations	automatically	automatically
Hindrance of snow	none	much	much
Examples	Rotterdam (Vreugdenhill, 1952)	Velsen (Wentink, 1957; Zijl, 1958)	Geneva (Ernens, 1960)
	Brooklyn-Battery (Geenens, Reid, 1950; Swetland et al., 1957)	Orly (Busson, 1960)	Le Havre (Huet, 1956)
		Rendsburg (Jainski, 1961)	

3.3. **Recommendations**

Many points which are important for the lighting of long tunnels have come to the fore in the previous chapters. In this chapter a systematic survey will be given which is simultaneously a summary of Chapters 2, 3, 4, 6 and 7 of the already mentioned "Recommendations for Tunnel Lighting" (Netherlands Foundation on Illumination, 1963).

a. THE ENTRANCE

1. The access zone must be kept as dark as possible. The surfaces which

fall within the field of vision must have a low reflection factor and must be unobtrusive in other aspects also. As far as possible the sky should be screened by trees or buildings.

2. The luminance in the threshold zone must be at least 1/10 and preferably 1/8 of the luminance of the access zone.
3. The opening of the tunnel entrance must be as high as possible.
4. The lighting installation in the threshold zone must already be visible from outside the tunnel.
5. The length of the threshold zone must be at least 50 m and for preference 100 m.
6. The luminance in the transition zone must decrease according to Fig. 5. The zero point of this diagram must be at the end of the threshold zone.
7. As a rule the entrance lighting preferably is carried out partly with subdued daylight, partly with artificial light. By this means the chance is smaller that clouds of dust or exhaust gases will occur in front of the tunnel.

b. THE INTERIOR

8. The luminance in the interior in daytime must be at least 10 cd/m^2, preferably 15 to 20 cd/m^2.
9. The lighting preferably should be carried out with uninterrupted rows of long light sources arranged lengthwise.
10. The luminous intensity of the fittings must be distributed by means of optical control in such a way that a uniform distribution of luminance is achieved on walls and road surface.
11. In interrupted lines of fittings, distances of 1–10 m preferably should be avoided.
12. The fittings must be dust- and water-tight, and be proof against corrosive cleaning agents. They must be easy to maintain and must not project inside the profile of free space.
13. The walls must be covered with a material that has a high but not specular reflection, has a smooth surface and is proof against rigorous cleaning.
14. The ceiling must be covered with a sound absorbent material.
15. The road surface must be as light as possible.
16. Optical guidance must be achieved by making the light sources clearly visible and by using clear beaconing for the carriage ways and kerblines.
17. Dust and exhaust gases must be quickly removed by good ventilation.

18. The electrical installation must be well protected, among other things by providing for an emergency supply.

c. THE EXIT

19. The exit must be constructed as much like the entrance as possible.
20. The walls and the road surface at the exit must have a high specular reflection.

d. NIGHT LIGHTING

21. The lighting at night must satisfy the same conditions as by day. This applies particularly to the avoidance of flicker effects. The installation of a continuously adjustable dimming device deserves commendation.
22. A luminance transition greater than 3 to 1 at the tunnel exit must be avoided. The connected roads must be well lit.

3.4. **Examples**

As an illustration, the lighting of a set of four tunnels is very briefly described. The choice of the tunnels has no bearing on the quality of the

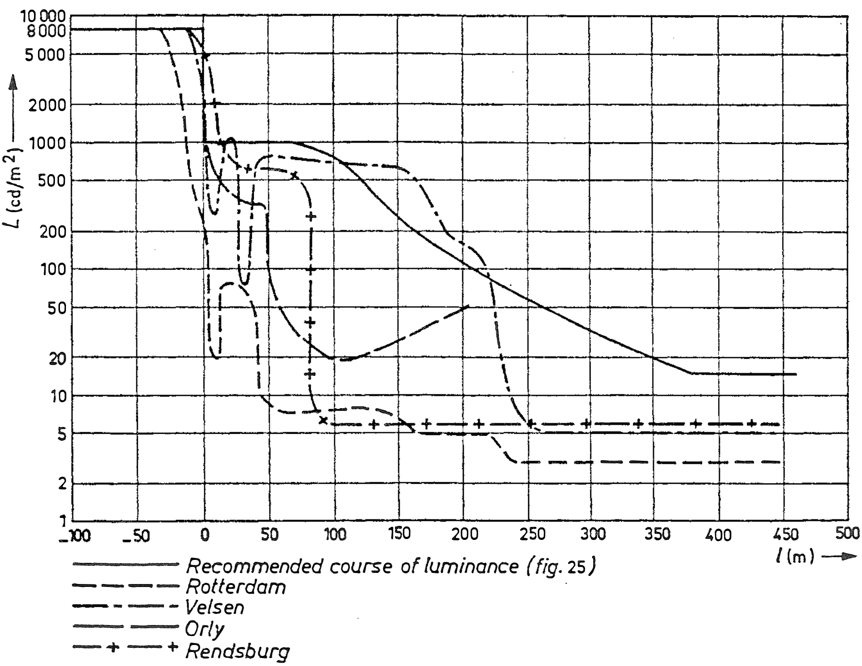


Fig. 26. Results of measurements.

TABLE 13

EXAMPLES OF LONG TUNNELS

Number	1	2	3	4
Location	Rotterdam	Velsen	Paris	Rendsburg
Crossing	River Meuse	Canal to Amsterdam	Aerodrome Orly	Canal of Kiel
Number of tubes (main tunnel)	2	2	1	2
Width (wall to wall) (m)	7.50	9.50	24 (total 40)	7.50
Length (closed tunnel) (m)	1 072	768	300	640
Length (total) (m)	1 072	1 111	400	800
Opened for traffic	1941 (re-lighted 1962)	1957	1960	1961
Speed restriction (km/h)	50	none	none	80
Interior lighting	sodium	fluorescent	sodium	fluorescent
Spacing luminaires (m)	6	4.50	variable	continuous line
Luminaires	recessed; walls	recessed; roof	walls	walls
Luminance interior (cd/m²)	2.5 [1])	5.5 [1])	20–25 [1])	6 [2])
Flicker frequency at 50 km/h (c/s)	3	4	variable mostly $>$ 8	no flicker
Tunnel walls	enamel tiles	concrete, paint	one side columns other side concrete	concrete slabs
Threshold zone	artificial light	concrete gratings	aluminium louvres	concrete louvres
Luminance in threshold (cd/m² or fraction of L_1)	about 33 cd/m²	15 % [1])	5 % [1])	8 % [2])
Length of daylight screening (m)	none	South 200, North 143	50	80
Length of transition (m)	30	240–180 resp.	125	80

[1]) Own measurements. [2]) Calculated.

lighting and only serves to explain a number of points which have come to the fore in the previous chapters. For this purpose a few general data concerning these tunnels are brought together in Table 13. The tunnels, apart from that at Rendsburg, are described in the "Recommendations", Chapter 8. A photo of each tunnel is also added (Plates 2, 3, 6, 7). In Fig. 26 the course of the road surface luminance is recorded. The values are based in part on our own measurements and in part calculated on the basis of other data. To make a comparison possible all values are reduced under the assumption that on the open road the luminance $L_1 =$ 8 000 cd/m^2 and the horizontal illumination equals 100 000 lux. For this reason the values quoted should only be regarded as an indication. Fig. 26 also includes the recommended luminance course according to Fig. 25.

CHAPTER 4

THE LIGHTING OF SHORT TUNNELS

4.1. The length of unlit tunnels

In Section 3.1 we defined a tunnel as "short" when in the absence of traffic the exit and its surroundings are clearly visible from a point at some distance before the tunnel. The tunnel appears in the field of vision as a *dark frame* (see Fig. 27). During the entire drive through the tunnel the central part of the field of vision is taken up by an area with high luminance, so that adaptation to the lower level of the tunnel hardly occurs. This implies that the visibility of objects in the dark frame of the tunnel is only limited through the effects of induction because the outside luminance remains the adaptation level.

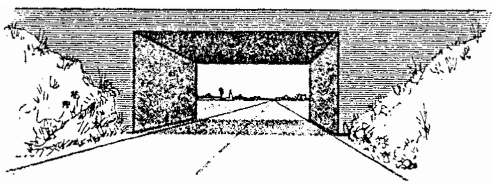


Fig. 27. A short tunnel appears as a "dark frame".

All other problems which are important in long tunnels such as the influence of flickering and noise can be neglected because of the insignificant length of short tunnels.

Obstacles in the tunnel can be seen either if they protrude against the bright environment of the exit or if they are sufficiently illuminated. If the width of the dark area of the road occupies a smaller angle than the smallest object that must still be visible, this object can always be seen (see Fig. 28). It will be seen from Fig. 29 that with a minimum object height of 20 cm and an observation distance of 100 m the dark strip on the road surface should not occupy more than about 20 m. Taking the daylight from the exit and the entrance into account the tunnel can often be up to about 50 m long without lighting being necessary during the day. In longer tunnels the exit takes up too small a part of the field

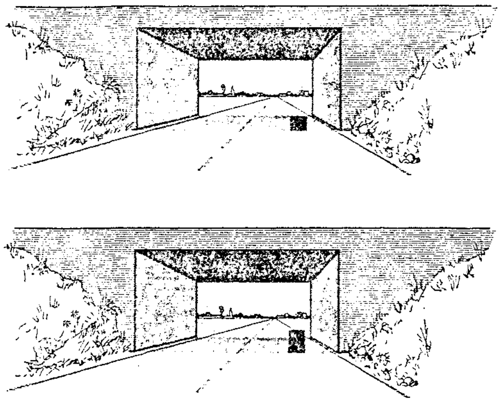


Fig. 28. A small obstacle is invisible but a large obstacle stands out against the background behind the tunnel.

of vision to serve as an effective background. If the tunnel is not straight, or if the density of traffic is normally very great, the silhouette effect is less marked, so that tunnels of a shorter length already should be lighted. The situation is analogous to that at the exit of a long tunnel (see Section 2.1.6). Here too, a high luminance is obtained by making use of a wall covering with a high specular reflection.

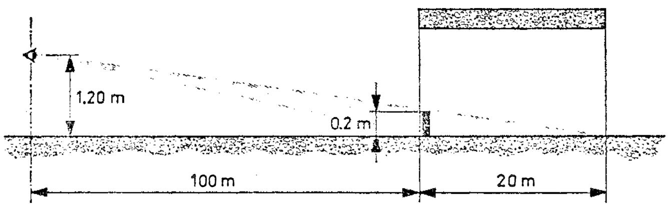


Fig. 29. Width of a dark strip in an unlit tunnel.

4.2. **Requirements for the lighting of short tunnels**

The requirements set for the lighting of short tunnels which are too long to go without lighting are, as mentioned, solely decided through effects of induction. The values stated in Section 2.1.2 and which can be read in Fig. 3, can also be used for short tunnels. This means that when high demands are made on the quality of the lighting the tunnel must have a luminance of about 800 cd/m^2 and preferably of about 1 000 cd/m^2 over its entire length. Only when this condition is satisfied can we be certain that satisfactory visibility is guaranteed under all circumstances. Depending on the installation and the condition of maintenance of the tunnel, illumination values of around 5 000 to 10 000 lux are needed to reach this luminance. In most cases these values are regarded as an economic impossibility. A substantially lower level is installed so that for a considerable part of the time the visibility is inadequate. But even a still more restricted lighting installation is not entirely valueless since through reflections of the lamps in car bodies for example, at least something of the objects in the tunnel can be seen.

In some cases it is possible to reach the high luminances required by placing elongated fittings vertically against the wall. The fittings themselves form the background for objects in the tunnel. Fluorescent lamps are the most suitable for this. We must not expect to realise a very refined lighting installation in this way. The practical and the economic advantages are, however, considerable. An example of this type of installation is given in Section 4.4 (see also Cohu (1960)).

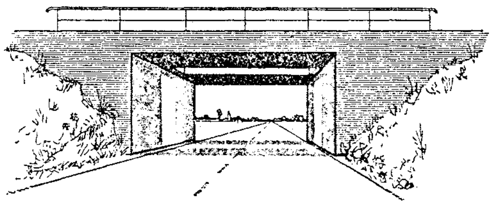


Fig. 30. Application of a bright cross strip.

If a tunnel is just too long to remain unlit it is often sufficient and economically attractive to illuminate only a midway stretch of the tunnel which results in a bright cross strip in the tunnel (see Fig. 30). An obstacle in the tunnel now can be seen if it protrudes as a dark silhouette either against this cross strip or against the exit. For this the cross strip must be of adequate length and must have sufficiently high luminance. Owing to the perspective of the picture of the road, ten metres is about the minimum length. The luminance must again be very high for satisfactory visibility. Since obstacles present in the cross strip itself must also be visible a luminance of 800 to 1 000 cd/m^2 is again recommended. The experimental lighting described in Section 4.4 appears to have not the desired effect as far as this is concerned, although over a length of 20 m in the tunnel the luminance was 150 cd/m^2.

The high luminance value required can be achieved in a simple manner by leaving a large opening in the roof of the tunnel. The tunnel is actually divided into two smaller tunnels. For this purpose the opening should preferably be about ten metres long. A much smaller gap, however, already makes a considerable contribution to the lighting of the tunnel as can be seen from Fig. 20 (see also Lossagk (1955)).

4.3. Summary – Recommendations

A number of aspects of the lighting of short tunnels is summed up in this Section 4.3. It forms at the same time a summary of Chapter 5 of the "Recommendations on Tunnel Lighting".

1. A classification and a survey of the recommended lighting are given in Table 14, taken from Chapter 5 of the "Recommendations".
2. The walls and road surface must have a specular reflection as high as possible, especially in tunnels without lighting. The tunnel must be as wide as possible for the penetration of daylight to have the maximum effect.
3. The use of a daylight slot is recommended for lighting a cross strip in the tunnel.
4. The bright cross strip must occupy at least 10 m of the tunnel length, prefrerably more.
5. Lighting can sometimes be carried out with elongated vertical fittings placed against the wall. They will serve as a background for obstacles.
6. In general it is sufficient in the lighting of short tunnels to consider only the problems resulting from induction phenomena.

TABLE 14

RECOMMENDED LIGHTING FOR SHORT TUNNELS

(After "Recommendations on Tunnel Lighting" (1963))

	Favourable (no bends, no dense traffic, only motorised traffic)		Unfavourable (bends and/or dense traffic and/or mixed traffic)	
No lighting	Class 1a	0 to 50 m	Class 1b	0 to 25 m
Cross strip lit (to about 800 cd/m^2)	Class 2a	50 to 80 m	Class 2b	25 to 40 m
Total length lit (to about 800 cd/m^2)	Class 3a	80 to 100 m	Class 3b	40 to 100 m
Lighting according to recommendations for long tunnels	Class 4, more than 100 m			

4.4. Examples

A brief description of some tunnels is given as illustration. More details about these tunnels are given in the "Recommendations on Tunnel Lighting". Some data are introduced in Table 15. The first tunnel (Table 15, no. 1) is very short so that no lighting is necessary. The second tunnel has to be considered as short from one side and long from the other. The third could be regarded as short if a road crossing did not lie directly after the tunnel. Traffic on the crossing street cannot properly see the traffic in the tunnel coming from the right. Experimental lighting with vertical tubular lamps is employed in this tunnel. The fourth tunnel is fairly straight but too long to stay unlit. In this tunnel experimental lighting is installed to introduce a bright cross strip. The experiment has proved negative in so far as it has been found that even 150 cd/m^2 is still not sufficient in this case. Some figures and a sketch of the traffic situation in these tunnels are added (Fig. 31–34 and Plate 5 and 8–10).

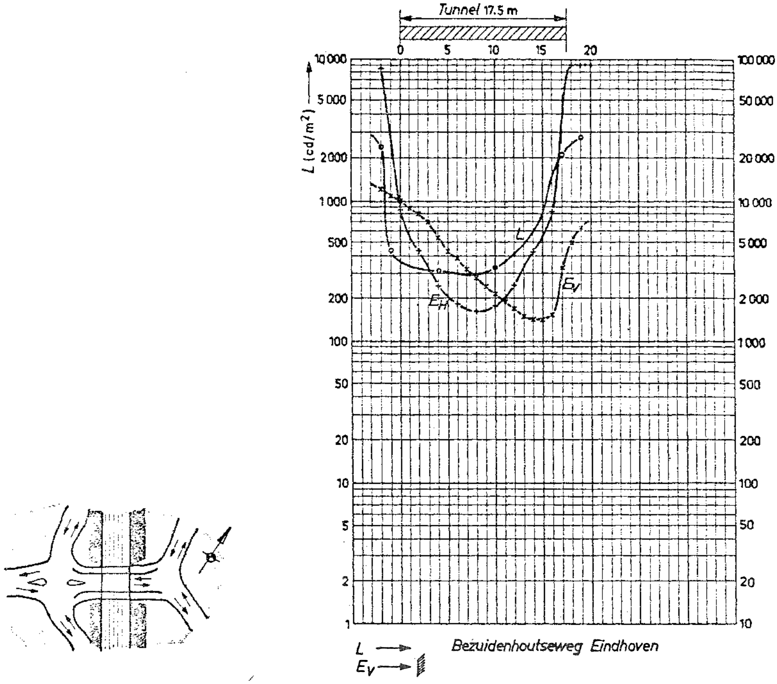


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Fig. 31. *a*. diagram of traffic situation; *b*. measuring results.

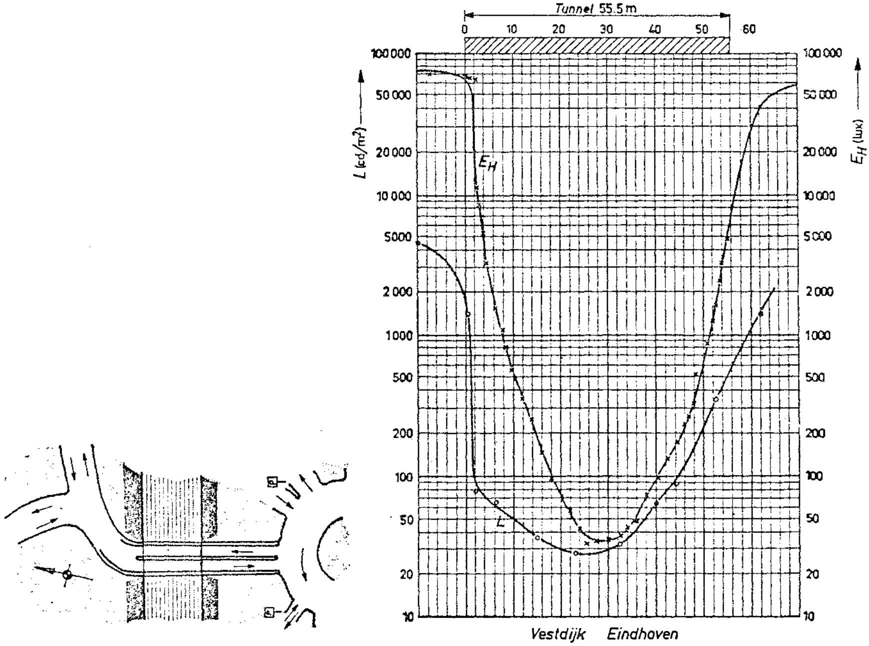

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Fig. 32. *a*. diagram of traffic situation; *b*. measuring results.

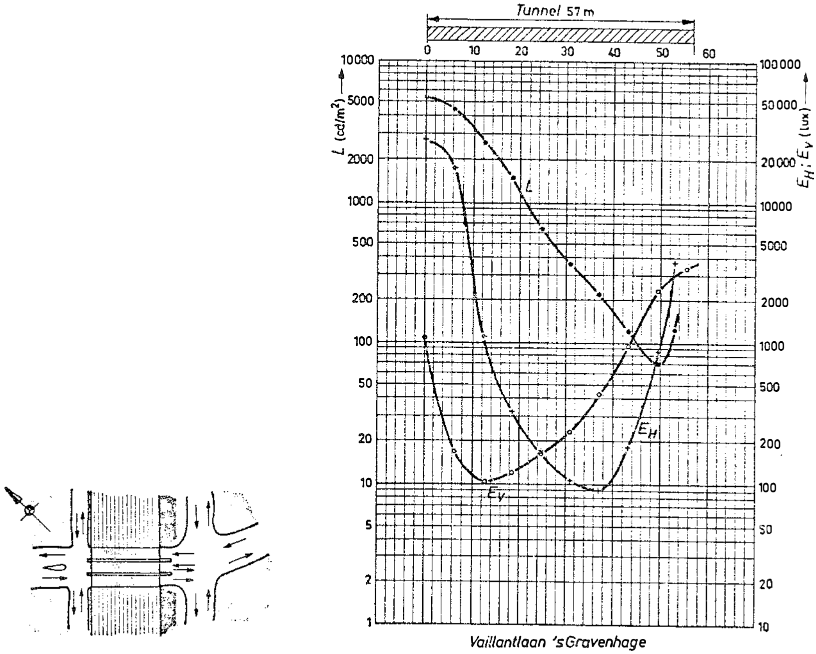

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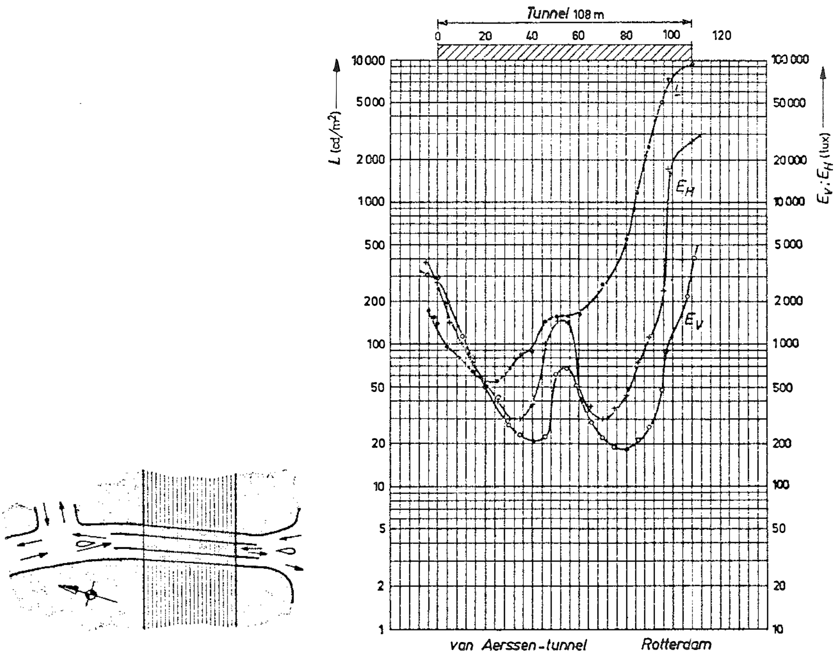
Fig. 33. *a*. diagram of traffic situation; *b*. measuring results.



a b
Fig. 34. *a*. diagram of traffic situation; *b*. measuring results.

TABLE 15

EXAMPLES OF SHORT TUNNELS

Number	1	2	3	4
Location	Eindhoven	Eindhoven	's-Gravenhage	Rotterdam
Name	Bezuidenhoutseweg	Vestdijk	Vaillantlaan	Van Aerssen tunnel
Length (m)	18	55	57	100
Number of tubes	3	4	3	3
Width of main tube(s) (m)	7	7	8	9.5
Traffic one/two way	two	one	two	two
Traffic	miscellaneous no pedestrians no bicycles	miscellaneous no pedestrians no bicycles	motorised only	motorised only
Daytime lighting	none	none	2 × 7 fittings, 2 × fluorescent 40 W each	2 lines fluorescent reinforced with HPL 250 W over first 20 m
Experimental lighting	—	—	2 × 15 vertical rows, each row 2 luminaires high	crossline of light with 8 lamps HPL 1000 W in tunnel roof

Plate 6. *Tunnel at Rotterdam.*

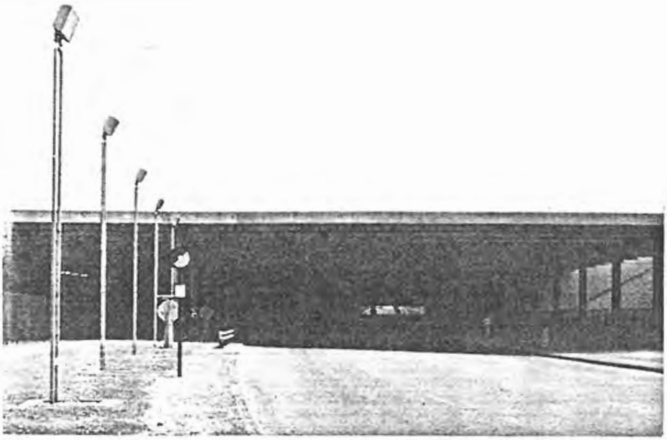


Plate 7. *Tunnel at Orly.*

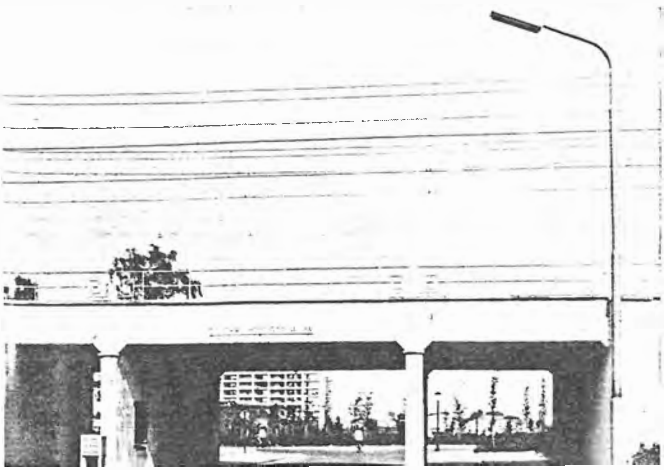


Plate 8. *Tunnel Bezuidenhoutseweg, Eindhoven.*

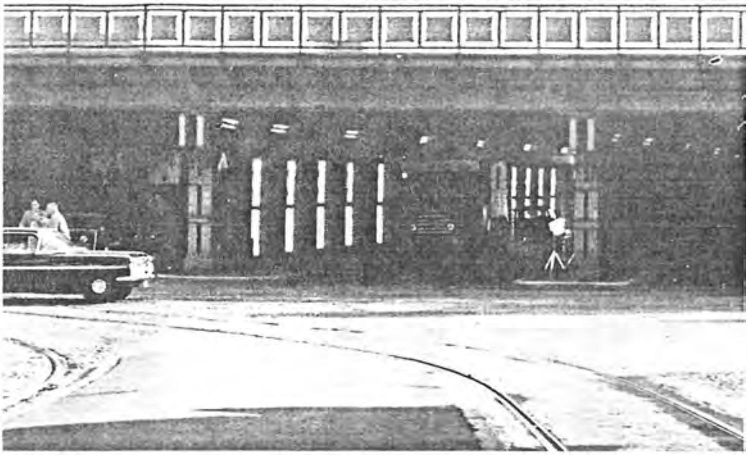


Plate 9. *Tunnel Vaillantlaan, 's-Gravenhage.*

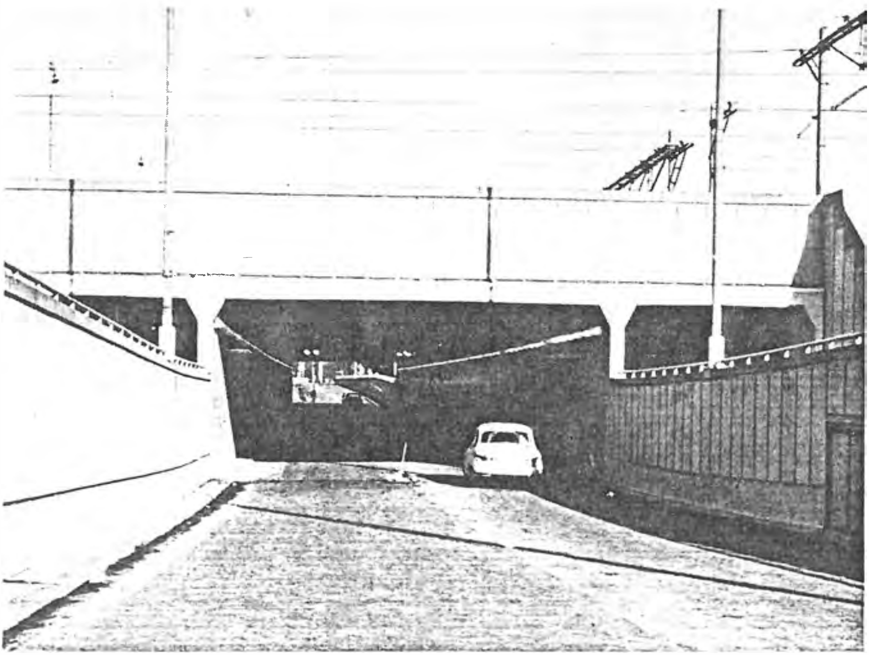


Plate 10. *Van Aersen tunnel, Rotterdam.*

CHAPTER 5

EXPERIMENTS AND MEASUREMENTS

5.1. Experiments concerning induction phenomena

a. THE PROBLEM

The occurrence of induction means that a tunnel entrance often appears as a dark hole in front of a motorist approaching the tunnel. In the discussion on this phenomenon in Section 2.1.2, it is shown that the greatest inconvenience occurs before the road user has reached the adaptation point, when the state of adaptation of his eyes is not yet altered. The experiments concerning these phenomena have therefore to be executed in such a way that the state of adaptation of the observer is constant. With this constant state of adaptation we have to ascertain how the visibility of an object depends on the contrast between object and background if both the luminance of the object L_3 and the luminance of its direct background L_2 differ from the adaptation level L_1.

b. CHOICE OF THE LIMITS OF THE PARAMETERS TO BE VARIED

Road safety demands that obstacles which constitute a danger are seen and recognised soon enough to carry out the manoeuvre required because of the presence of the obstacle without endangering the drivers' own vehicle, the obstacle or the rest of the traffic. The manoeuvre in question can, for example, be stopping in front of a large obstacle or changing direction to avoid a small obstacle. These demands are assumed to be met when on an average an object of 20×20 cm² is seen in 75 % of cases at a distance of 100 m, if in addition the contrast between the object and its immediate background amounts to 20 %. This object is called the *critical object* (Section 2.1.2).

In the nature of things this forms a compromise: it is frequently necessary to see and recognise objects or parts of objects of smaller dimension or with less contrast. It must often also be possible to see objects at a still greater distance, though most obstacles are larger and in part at least show greater contrast. It is therefore necessary to investigate not only the critical object but oher objects as well.

In the experiments to be described in this section the contrast is varied between 7.5 % and 97 % and, to find out whether negative contrasts give similar results, between – 12 % and – 560 % *).

For the size of the object we have taken the equivalent of 20, 40 and 80 cm at 100 m. This agrees with values for α_3 of 7′, 14′ and 28′ (Fig. 2).

For the luminance L_1 (the adaptation level) all values are taken which are of importance for tunnel lighting. These run from 1 cd/m² up to and including 10 000 cd/m². A discussion on this maximum value is given in Section 5.4.

It is a prerequisite for the tests that the state of adaptation is not altered when presenting an object. The shutter used must therefore be opened for as short a time as possible. Values below 0.1 sec cannot be used because the visual system reacts unequally to stimuli which last respectively shorter or longer than 0.1 sec. For this see, for example, Schober (1958), Bouman (1952, 1953). With long observation times the eye is adapted to a field in which the object itself and its background remain visible so that in fact a different phenomenon is investigated. See Schumacher (1942) and Berek (1943). We may see from the measurements of Kern (1952) that, if $L_2 > L_1$, a time of 0.5 sec is too long to allow us to speak of an unaltered adaptation status. We carried out most of the experiments for $t = 0.1$ sec and also made some measurements with 0.2 and 0.3 sec.

If the state of adaptation does not change during the opening of the shutter, the measurements must be independent of the dimension of the size of the shutter opening. For this size we used the values of $\alpha_2 = 1°$ and $\alpha_2 = 3°$.

For a number of practical reasons we used two systems of measurements, one for the bulk of the experiments in which α_2 and t were constant (*construction 1*) and another system for some additional experiments in which α_2 and t were variable (*construction 2*). These constructions will be discussed separately.

*) According to the definition $C = \frac{L_2 - L_3}{L_2}$ the contrast can lie between + 1 and – ∞.

c. MEASURING ARRANGEMENT (CONSTRUCTION 1)

A constant state of adaptation is maintained by continuously displaying to the observer a screen with a luminance L_1 over the whole surface. From the point of observation the screen is seen at an angle of about $2 \times 10°$. Up to about $2 \times 5°$ outside the centre the luminance is uniform, within the measuring accuracy. An opening closed by a shutter is made in the centre of this screen. The opening subtends an angle α_2 (see Fig. 35). The shutter is only opened for a short time t; in this way a surface with luminance L_2 is displayed and at the same time an object is seen at an angle α_3 with luminance L_3. The luminance L_1 is continuously adjustable between 100 and 10 000 cd/m² by changing the voltage of the light sources S_1.

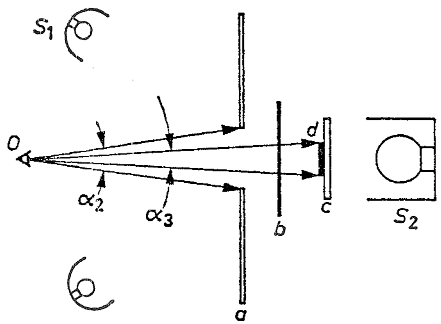


Fig. 35. Diagram of the experimental set-up for tests on induction.

a = screen		*d* = object	
b = shutter		S_1, S_2 = lamps	
c = glass slide		*O* = observer	

Internally mirrored 220 V/150 W incandescent lamps were used for this purpose. A neutral filter is placed in front of the observer for values of L_1 between 1 and 100 cd/m².

In construction 1 the shutter consists of a big disc, driven by a synchronous motor, which rotates in 6 sec. A small gap in the disc shows the opening for the fixed time $t = 0.1$ sec. The angle α_2 also has a fixed value, in fact, 1°.

The simultaneous display of a background with luminance L_2 and an object with luminance L_3 is obtained by placing in front of lamp S_2 a glass plate which is provided in part with a vacuum-evaporated neutral filter. A 220 V/300 W magnifying lamp with an opal bulb is used for S_2. The luminance of the part of the bulb used (4×4 cm^2) is uniform within 2 %. Transmission and luminance of the different parts of the glass plate are therefore proportional. A square is put on the glass plate. The square is either provided with a neutral filter (thus $L_3 < L_2$) or it is left open ($L_3 > L_2$). Since the transmissions and thus the luminance ratios between L_2 and L_3 are fixed once and for all, and with them the contrasts between L_2 and L_3, it is more convenient to use the variables L_1, L_2 and C instead of the variables L_1, L_2 and L_3. $C = (L_2 - L_3)/L_2$ is a measure for the contrast between L_2 and L_3. The two groups of variables are equivalent.

The method used here for obtaining the differences between L_2 and L_3 has the following advantages.

The first is that by the use of vacuum-evaporated neutral filters every edge or facet is avoided between the object and the background.

Secondly, the contrast need not be adjusted for every measurement, so that no errors of adjustment can occur. This is important because in every series of experiments the same contrast is shown several times in succession with different values of L_2.

Thirdly, the results expressed by a contrast and a background luminance connect more directly with road traffic in practice than if they were expressed in luminance alone. Naturally we need a different filter for each contrast value.

The luminance L_2 can be adjusted between 100 and 10 000 cd/m^2 by regulating the voltage of the lamp S_2. For lower values of L_2 filters of 10 % and 1 % transmission respectively can be used. Since the value of L_2 has to be changed many times in each series of experiments we used 24 fixed steps of L_2 logarithmically divided over the two decades. This was done to save time and to avoid errors of adjustment. To achieve this one of 24 different resistances can be switched into the grid circuit of a thyratron dimming installation. Plate 11 represents the set-up while Plate 12 gives an impression of the field of vision with the shutter open.

The tentative measurements concerning the influence of dazzling caused by the tunnel exit (the "white hole", Section 2.1.6) are also carried out with this construction. For this the screen is lit to 10 cd/m^2 (representing the tunnel interior) while next to the opening in the screen a surface as big as the opening (4×4 cm²) is shown with a luminance of 8 000 cd/m². This small bright surface (part of a fluorescent lamp) represents the tunnel exit.

d. MEASURING PROCEDURE (CONSTRUCTION 1)

After a few minutes of adaptation to a certain luminance L_1, an object with contrast C is shown several times. L_2 is changed in a random sequence unknown to the observer. A number of successive values of L_2 are shown, situated round the observation threshold which is estimated on the basis of a short test directly preceding the actual experiment. Each of these L_2 values, usually 5 to 8 in number, is shown five times in all. After each presentation of the object, the observer has to state whether he is certain he has seen the object or not. The observer is warned by an acoustic signal a second before each presentation. The time between two presentations is 6 sec.

No. 311

Measurements on induction

Name v.d.S	*Datum* 22-11-1961
Age 58	L_1 300
Filter for L_2 1%	C 96.8 %
75% *value of* L_2 8.7	50 % *value of* L_2 7.0

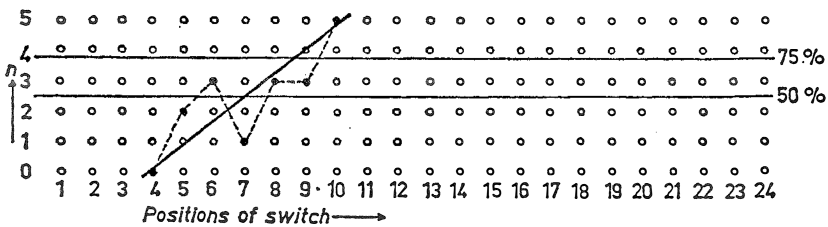


Fig. 36a. Example of recorded measuring data.

Such a group of 25–40 observations for one value of L_1 and one value of C is plotted in a diagram as shown in Fig. 36a. The abscissa gives the consecutive steps for L_2 and is therefore a scale for log L_2. The ordinate states the number of positive reactions with the relative L_2 values and can be considered as giving the observation probability. The straight line that gives the best fit to the points on the diagram is drawn. This fitting is done by visual inspection.

As is shown further on, this method is sufficiently accurate. The straight line cuts the lines of 50 % and 75 % observation probability at certain points. The L_2 values belonging to these points can be found by interpolation. These values are used for the further calculations.

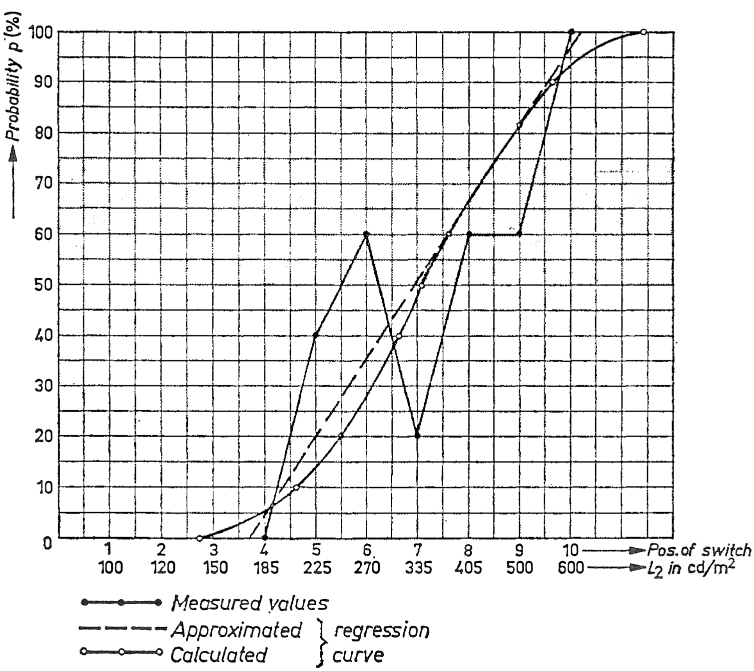


Fig. 36b. Comparison between approximated and calculated regression curves.

The straight line is, in fact, an approximation of a regression curve. To find out whether the approximation is not too inaccurate, the regression curves were calculated from a sample of 20 diagrams and compared with the approximated lines. There appeared to be a small systematic difference, our approximated lines having rather too great a slope. The difference, however, is disregarded because the successive L_2 values lie very close to each other, and because the approximated lines are not used to make an estimation concerning very high or very low probabilities. As illustration, Fig. 36b, which contains the same measurement results as Fig. 36a, gives the approximated line as well as the calculated regression curve in the form of the relation between the observation probability p and L_2. Actually the difference between the curves is only slight.

The experiments belong to the type known as *constant stimuli*. By this we understand an experimental procedure in which the observer is presented with the quantity to be investigated (in this case L_2) in a number of fixed values and in an unknown sequence. Some reaction is expected from the observer at each presentation. Since the observer does not know what value is presented to him, he cannot influence the results. This is an advantage over the method in which the observer himself adjusts the quantity under investigation by continuous regulation (the method of the average error). A drawback is that, in general, a greater number of experiments is needed.

The reaction which the observer must give consists of a choice of two possibilities: "positive reactions" in which he states he is certain he has seen the object, and "negative reactions" in all other cases. This type is called *phenomenal report* (see Blackwell (1952, b) and Guilford (1954)).

In our experiments we always present an object. This is known to the observer. Moreover, he knows precisely where and when the object will appear and what it looks like. Time for search and recognising is thus not required. It is not necessary to make any correction for reactions that do not depend on observation but on guesswork, because there is nothing to guess.

e. RESULTS

The experiments made with construction 1 can be divided into four groups which will be discussed separately.

Group 1

Group 1 comprises the observations which are the most important for the "black hole" problem *). With ten male observers of whom five are

*) The experiments of group 1 are the basis for part of the already mentioned "Recommendations on Tunnel Lighting" (1963). Part of the results is described by De Boer (1963) and the author (Schreuder, 1963).

between 25 and 30 years of age (1–5) and five are between 50 and 60 years old (6–10) measurements are made for four values of L_1 and four values of C (see Tables 16 and 17). In some cases no proper approximation can be found for the regression curve. The estimated values of log L_2 for these cases are set in brackets in the tables.

Because of the great importance of the measurements of Group 1, the results have been made the subject of a detailed statistical analysis.

A summary of a variation analysis is given in Table 18. From this analysis it is found that the main effects (Persons (P), Contrasts (C) and Luminances L_1 (L)) and the interactions PC and PL are significant. A more detailed analysis proved that the significance of the PC and PL interactions is not likely to be the result of the age difference between the two groups of observers. It is important to note that the interaction CL has

TABLE 16

RESULTS OF EXPERIMENTS

Relationship between log L_1 and log L_2

		Observer										
		1	2	3	4	5	6	7	8	9	10	
Log L_1	C(%)	Values of log L_2										Mean
3.98	15	3.04	3.79	3.28	3.07	3.76	3.56	3.00	3.71	3.49	(3.27)	3.40
	26.8	2.50	2.94	2.77	2.47	2.70	2.68	2.71	2.72	2.75	2.51	2.68
	56.9	2.27	2.52	2.50	2.25	2.23	2.27	2.39	2.43	2.42	2.22	2.35
	96.8	2.07	2.53	2.21	2.06	2.05	2.10	2.28	2.21	2.22	2.09	2.18
3.48	15	2.45	2.19	2.54	2.72	3.21	3.10	2.72	3.40	2.79	(2.74)	2.79
	26.8	1.85	2.27	1.72	2.08	2.33	2.17	2.18	2.18	2.34	1.91	2.10
	56.9	1.70	1.66	1.67	1.54	1.74	1.77	1.79	1.91	1.98	1.75	1.75
	96.8	1.54	1.65	1.59	1.42	1.64	1.59	1.59	1.77	1.65	1.68	1.61
3.00	15	2.12	2.74	1.89	2.10	2.79	2.65	1.58	3.02	2.29	(2.50)	2.37
	26.8	1.61	1.76	1.59	1.29	1.60	1.75	1.52	1.56	1.69	1.66	1.60
	56.9	1.01	1.37	1.14	0.86	1.25	1.28	1.10	1.29	1.18	1.37	1.18
	96.8	0.93	1.20	1.04	0.83	1.21	1.02	1.09	1.15	1.06	1.24	1.08
2.48	15	1.29	2.01	1.66	1.66	2.44	1.22	1.74	(1.91)	2.21	(1.59)	1.77
	26.8	1.11	1.38	0.97	0.81	1.59	1.21	0.92	1.32	1.40	0.64	1.14
	56.9	0.58	0.81	0.72	0.42	0.90	0.83	0.86	0.90	0.84	0.82	0.78
	96.8	0.48	0.81	0.59	0.58	0.80	0.72	0.70	0.77	0.68	0.56	0.67

$p = 50\,\%$ $\alpha_2 = 1°$ $\alpha_3 = 7'$ $t = 0.1$ sec

TABLE 17

RESULTS OF EXPERIMENTS

Relationship between log L_1 and log L_2

		Observer										
		1	2	3	4	5	6	7	8	9	10	
Log L_1	C(%)	Values of log L_2										Mean
3.98	15	3.13	3.89	3.47	3.34	3.82	3.78	3.09	3.86	3.59	(3.52)	3.51
	26.8	2.64	3.05	2.91	2.61	2.81	2.79	2.80	2.84	2.98	2.82	2.85
	56.9	2.38	2.63	2.60	2.38	2.33	2.34	2.63	2.49	2.47	2.38	2.45
	96.8	2.18	2.61	2.38	2.14	2.18	2.23	2.39	2.28	2.22	2.29	2.31
3.48	15	2.52	2.39	2.69	2.82	3.30	3.27	2.83	3.49	2.85	(2.85)	2.91
	26.8	2.02	2.43	1.80	2.21	2.43	2.46	2.46	2.34	2.45	2.06	2.25
	56.9	1.70	1.81	1.77	1.60	1.82	1.92	1.86	2.01	2.09	1.83	1.85
	96.8	1.65	1.73	1.67	1.59	1.75	1.71	1.71	1.81	1.72	1.77	1.71
3.00	15	2.31	2.83	1.96	2.33	2.84	2.81	1.76	3.10	2.39	(2.60)	2.42
	26.8	1.76	1.86	1.77	1.45	1.75	1.83	1.61	1.76	1.81	1.79	1.75
	56.9	1.11	1.48	1.27	1.06	1.45	1.41	1.26	1.45	1.39	1.47	1.36
	96.8	1.10	1.32	1.13	0.99	1.33	1.13	1.15	1.24	1.17	1.32	1.21
2.48	15	1.40	2.17	1.84	1.81	2.49	1.38	1.82	(1.93)	1.43	(1.63)	1.91
	26.8	1.16	1.46	1.25	0.94	1.68	1.31	0.99	1.46	1.49	0.77	1.24
	56.9	0.67	0.92	0.80	0.56	1.08	0.89	0.89	0.99	1.03	0.94	0.71
	96.8	0.52	0.85	0.69	0.65	0.89	0.81	0.77	0.84	0.80	0.70	0.85

$p = 75\,\%$ $\alpha_2 = 1°$ $\alpha_3 = 7'$ $t = 0.1$ sec

TABLE 18

RESULTS OF ANALYSIS OF VARIANCE

Effects	Degrees of freedom n	Mean squares	Significance
P (persons)	9	0.327	+
C (contrast)	3	11.5	+
L (luminance L_1)	3	18.1	+
PC	26	0.067	(+)
PL	27	0.051	(+)
CL	9	0.015	—
Rest variance	77	0.025	

(75 % level)

no significance. This means that all curves $L_2 = f_1\ (C)$ for constant L_1, and also all curves $L_2 = f_2\ (L_1)$ for constant C are similar.

The results of Group 1 can be represented by a formula of the form:

$$\log L_2 = K_1 + K_2 L_1{}^a + K_3 C^b \qquad \text{(a)}$$

in which K_1, K_2, K_3, a and b are constants. The numerical value of these constants depends on the observer. Here, too, a product term of L_1 and C is missing. For the average among the 10 observers formula (a) can be written:

$$\text{for } p = 50\ \%: \log L_2 = 1.04 + 0.50\ L_1{}^{1/5} + 39.1\ C^{-5/4} \qquad \text{(b)}$$

$$\text{for } p = 75\ \%: \log L_2 = 0.97 + 0.51\ L_1{}^{1/5} + 39.1\ C^{-5/4} \qquad \text{(c)}$$

Formulae (b) and (c) are valid for $300 < L_1 < 10\,000$ (in cd/m²) and for $15 < C < 96.8$ (in %) and may only be used for calculating the values of $\log L_2$ within this range. The formulae give no indication of the physiological or physical connection between the variables and do not represent more than a numerical approximation of a number of measurements.

Consideration of the formulae teaches us that the influence of p on $\log L_2$ in particular is slight. Log L_2 is determined in the first place by L_1, hence the great importance already mentioned of avoiding very bright surfaces in the neighbourhood of tunnel entrances.

Group 2

Group 2 includes an extension of Group 1 for low L_1 values. The observations were made some considerable time after those of Group 1. Not all the original observers were available. The data are recorded in Table 19.

The average values of $\log L_2$ from Group 1 and Group 2 are given together in Table 20. These data are plotted in Fig. 37. Because the two groups are in good agreement we used one set of curves in Fig. 37. One will notice again that the curves for the different contrasts have the same shape. With this in mind we have constructed Fig. 3. From formula (b) the relation between L_1 and L_2 for $C = 20\ \%$ is calculated for $300 < L_1 < 10\ 000$ cd/m². This curve is extended as far as $L_1 = 1$ cd/m² by making use of the shape of the curve of $C = 26.8\ \%$ from Fig. 37.

As the expiriments described here differ greatly in their design from the methods published so far, there is only little opportunity of comparing the results with those of other investigations. Schumacher (1942) has made comparable tests with very long exposition times. He has found curves which show fairly good agreement in form with Fig. 37. Lythgoe

TABLE 19a

RESULTS OF EXPERIMENTS

Relationship between log L_1 and log L_2

Log L_1	C(%)	Observer 1	2	3	4	5	6	7	8	9	10	Mean
		Values of log L_2										
3.38	15	2.63	3.03	2.58	2.02	3.04	2.03	2.39	3.12	2.41	2.77	2.60
	26.8	1.97	2.01	1.73	1.77	2.17	1.84	1.68	1.82	1.94	1.82	1.88
	96.8	1.47	1.60	0.88	1.34	1.55	1.29	1.45	1.47	1.41	1.58	1.40
2.50	26.8	0.94	1.80	0.85	0.90	1.17	1.35	0.96	0.85	1.11	1.21	1.11
2.00	26.8	0.46	0.81	0.66	0.42	0.83	0.86	0.87	0.42	0.95	0.66	0.69
1.00	26.8	0.37	0.29	−0.14	0.12	−0.33	−0.75	0.07	0.38	—	−0.10	0.01
0.50	15	0.51	—	—	0.31	0.32	—	0.34	—	−0.21	−0.59	
	26.8	−0.03	−0.19	−0.23	−0.27	−0.14	−0.44	−0.13	0.22	0.16	−0.54	−0.16
	56.9	−0.51	−0.32	−0.53	−0.67	−0.54	−0.69	−0.53	−0.24	−0.31	−0.45	−0.48
	96.8	−0.63	−0.41	−0.64	−0.81	−0.57	−0.81	−0.55	−0.27	−0.45	−0.79	−0.59
0.00	26.8	−0.40	−0.50	−0.43	−0.42	−0.39	−0.74	−0.24	−0.47	−0.51	−0.75	−0.48

p = 50 % $\alpha_2 = 1°$ $\alpha_3 = 7'$ t = 0.1 sec

TABLE 19b

RESULTS OF EXPERIMENTS

Relationship between log L_1 and log L_2

Log L_1	C(%)	Observer 1	2	3	4	5	6	7	8	9	10	Mean
		Values of log L_2										
3.38	15	2.74	3.12	2.77	2.17	3.25	2.31	2.50	3.23	2.49	2.94	2.75
	26.8	2.05	2.12	1.94	1.93	2.31	2.07	1.76	2.05	2.03	1.92	2.02
	96.8	1.50	1.69	1.76	1.47	1.67	1.44	1.56	1.53	1.47	1.63	1.57
2.50	26.8	1.03	1.23	1.00	1.01	1.28	1.67	1.13	1.10	1.33	1.41	1.22
2.00	26.8	0.53	0.97	1.06	0.46	0.95	1.04	1.01	0.47	1.14	0.78	0.84
1.00	26.8	0.43	0.40	−0.01	0.25	−0.19	−0.49	0.31	0.55	—	−0.04	0.13
0.50	15	0.65	—	—	0.42	0.40	—	0.57	—	−0.04	−0.54	
	26.8	0.07	−0.02	−0.08	−0.21	−0.07	−0.34	0.01	0.32	0.29	−0.49	−0.05
	56.9	−0.43	−0.24	−0.42	−0.55	−0.45	−0.48	−0.44	−0.18	−0.19	−0.40	−0.38
	96.8	−0.59	−0.30	−0.65	−0.77	−0.41	−0.59	−0.48	−0.24	−0.40	−0.48	−0.49
0.00	26.8	−0.28	−0.45	−0.32	−0.31	−0.30	−0.64	−0.10	−0.39	−0.38	−0.63	−0.38

p = 75 % $\alpha_2 = 1°$ $\alpha_3 = 7'$ t = 0.1 sec

TABLE 20a

AVERAGE VALUES OF RESULTS OF EXPERIMENTS

Relationship between log L_1 and log L_2
(Group 1 and Group 2 from Tables 17 and 19)

Log L_1	$C(\%)$ 15	26.8	56.9	96.8
	Values of log L_2			
3.98	3.51	2.85	2.45	2.31
3.48	2.91	2.25	1.85	1.71
3.38	2.75	2.02		1.57
3.00	2.42	1.75	1.36	1.21
2.50		1.22		
2.48	1.91	1.24	0.85	0.71
2.00		0.84		
1.00		0.13		
0.50		–0.05	–0.38	–0.49
0.00		–0.38		

$p = 75\,\%$ $\alpha_2 = 1°$ $\alpha_3 = 7'$ $t = 0.1$ sec

TABLE 20b

AVERAGE VALUES OF RESULTS OF EXPERIMENTS

Relationship between L_1 and L_2, both in cd/m²
(from Table 20a)

L_1	$C(\%)$ 15	26.8	56.7	96.8
9 550	3 250	710	280	205
3 000	815	180	71	51
2 400	560	105		37
1 000	260	56	23	16
320		16.5		
300	81	17.5	7.1	5.1
100		6.9		
10		1.3		
3.2		0.89	0.42	0.31
1		0.42		

$p = 75\,\%$ $\alpha_2 = 1°$ $\alpha_3 = 7'$ $t = 0.1$ sec

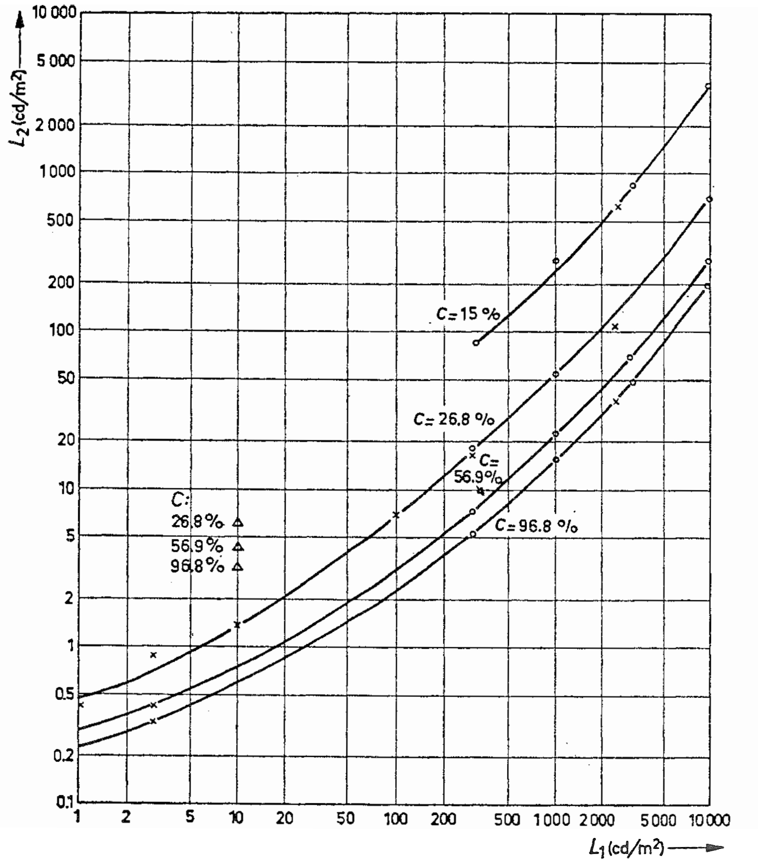


Fig. 37. Relationship between the outer luminance L_1 and the minimum luminance L_2 in the tunnel for different values of the contrast C. o Group 1; x Group 2; Δ Group 4.

(1932) describes measurements in which the visual acuity was measured under similar conditions. He also found curves which have the same shape as Fig. 37. Kern (1952) also obtained analogous results, although with exposition times that were longer than ours.

Group 3

According to the definition $C = (L_2 - L_3)/L_2$ we have used for the contrast, C is positive if $L_3 < L_2$ and negative if $L_3 > L_2$. Group 3 includes experiments to find out whether the visibility depends on the contrast being positive or negative. The experiments are carried out by

TABLE 21

RESULTS OF COMPARISON OF POSITIVE AND NEGATIVE CONTRASTS

Relationship between C and log L_2							
Log L_1	1.48	1.98	2.48	3.00	3.48	3.98	
L_1 (cd/m²)	30	95.5	300	1 000	3 000	9 550	
C(%)	Values of log L_2						Observer
96.8	0.11	0.43	0.85	1.32	1.73	2.61	1
	–0.16	0.19	0.52	1.10	1.74	2.18	2
56.9	0.21	0.54	0.93	1.47	1.81	2.63	1
	0.00	0.41	0.66	1.11	1.81	2.38	2
26.8	0.39	0.72	1.46	1.86	2.43	3.05	1
	0.26	0.46	1.16	1.76	2.03	2.64	2
15	0.85	1.41	2.11	2.83	3.35	3.89	1
	1.04	1.38	2.40	2.32	2.52	3.14	2
–11.6	1.44	1.90	2.04	2.15	2.77	3.74	1
	1.09	1.73	1.78	2.24	2.74	3.73	2
–17.3	1.23	1.67	1.92	2.26	2.62	3.21	1
	0.79	1.45	1.53	2.03	2.70	3.36	2
–50	0.52	0.90	1.17	1.63	1.98	2.64	1
	0.26	0.59	0.87	1.42	2.02	2.71	2
–144	0.13	0.36	0.53	1.10	1.44	2.26	1
	–0.32	0.12	0.45	0.87	1.51	2.20	2
–553	–0.65	–0.13	–0.02	0.52	0.95	1.69	1
	–0.99	–0.40	–0.12	0.37	0.81	1.68	2

$p = 75\ \%$ $\alpha_2 = 1°$ $\alpha_3 = 7'$ $t = 0.1$ sec

two observers for 9 values of C and 6 values of L_1. The results are recorded in Table 21. Since a variation analysis of the results has proved that there are no significant interactions between the variables, the average values for log L_2 for all values of L_1 can be used so that all the observations can be described with a single curve. In Fig. 38 the values of log L_2 for positive and negative contrasts are compared for $p = 75\ \%$. The difference between the two curves, although of statistical significance, is small for contrasts in the neighbourhood of 20 %. A comparable result was found by Blackwell (1946). Another much used definition for the

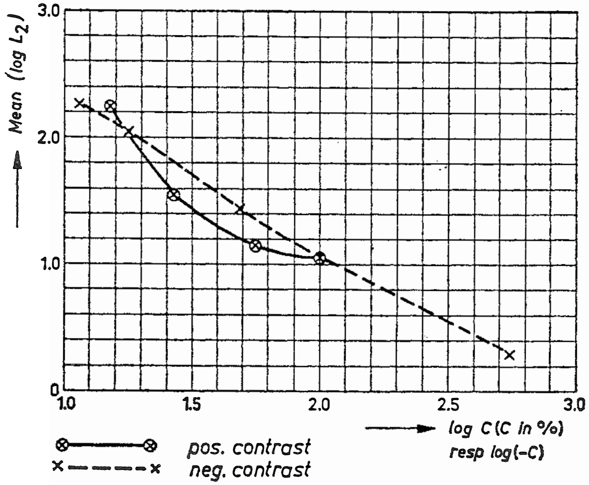


Fig. 38. Comparison of positive and negative contrasts $C = \dfrac{L_2 - L_3}{L_2}$

contrast is $k = L_3/L_2$. It may be seen from Fig. 39 that for small differences between L_3 and L_2 (thus $k \approx 1$) the curves for positive and negative contrast agree better than in Fig. 38, but for large differences of luminance the agreement is not so good. The use of $k = L_3/L_2$ as regards this is therefore not advisable above $C = (L_2 - L_3)/L_2$.

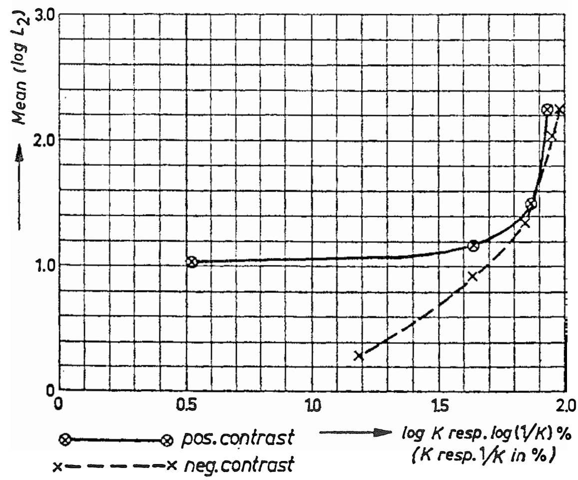


Fig. 39. Comparison of positive and negative contrasts $K = \dfrac{L_2}{L_3}$

Group 4

This group concerns a tentative investigation with conditions which can occur at a tunnel exit (the "white hole"). The results are given in Table 22 and are plotted in Fig. 37. The influence of the bright exit manifested itself by an increase in the minimum L_2 values. Under the circumstances of this experiment the exit area of 8 000 cd/m^2 in the screen with a luminance of 10 cd/m^2 was equivalent to a uniform screen of about 80 to 100 cd/m^2. The conclusion which can be drawn from this series of measurements has already been mentioned in Section 2.1.6.

TABLE 22

RESULTS OF THE "WHITE HOLE" EXPERIMENTS

Relationship between C and log L_2												
	Observer											
	1	2	3	4	5	6	7	8	9	10		
C(%)	Values of log L_2										Mean log L_2	Mean L_2 (cd/m^2)
26.8	0.67	1.20	0.94	0.57	0.69	0.34	0.78	1.50	1.14	0.55	0.84	6.9
56.9	0.53	0.92	0.77	0.26	0.51	0.44	0.55	0.76	0.82	0.63	0.62	4.2
96.8	0.49	0.72	0.63	0.09	0.41	0.50	0.54	0.59	0.49	0.59	0.51	3.2

$p = 75\,\%$ $\alpha_2 = 1°$ $\alpha_3 = 7'$ $t = 0.1$ sec

f. MEASURING ARRANGEMENT (CONSTRUCTION 2)

A part of the experiments has been made with a set-up that differed in some details from the set-up described above. The shutter mechanism allowed for changes both in the size of its opening α_2 and in the exposure time t. Instead of the continuously rotating wheel a slide is used.

This *construction 2* has been used employing a different experimental procedure. (In fact, the measurements with construction 2 preceded those of construction 1.) On indication of the observer the luminance L_2 was varied by the experimenter until the threshold of visibility was reached. Comparing the results of the two constructions, the criterion used here is about equal to an observation probability $p = 50\,\%$. Because of this difference in procedure the results of the constructions 1 and 2 were used separately.

The aim of the experiments with construction 2 (Group 5) was, to investigate the influence of variations in α_2, α_3 and t.

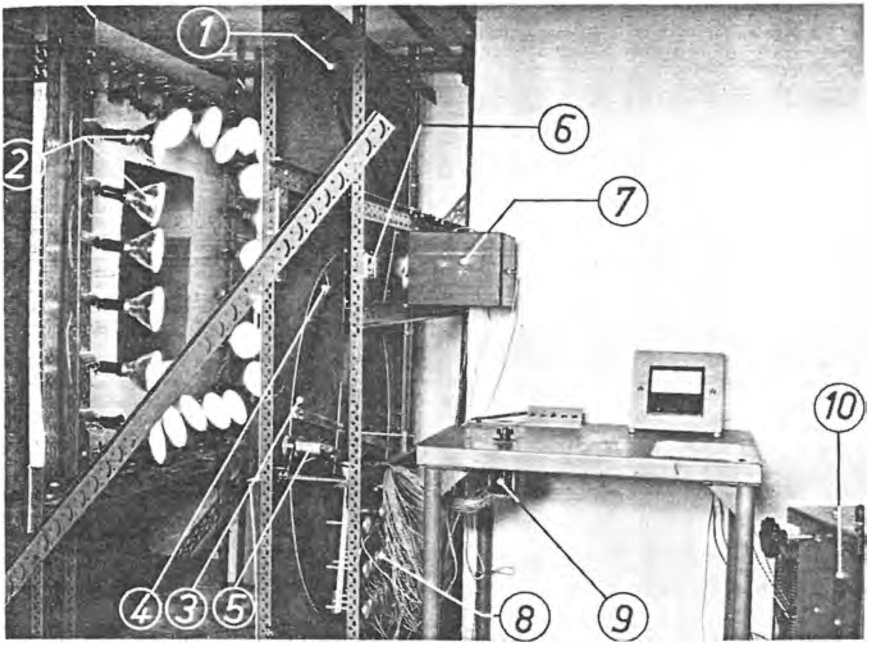


Plate 11. *Apparatus for measurements on induction.*

1. *screen (backside)*
2. *lamps* S_1
3. *disk shutter*
4. *shutter opening*
5. *synchronous motor*
6. *glass slide with object*
7. *housing for lamp* S_2
8. *potentiometers for setting of various* L_2 *values*
9. *24-position switch for selection of* L_2 *value*
10. *Variable transformer for regulation of* L_1

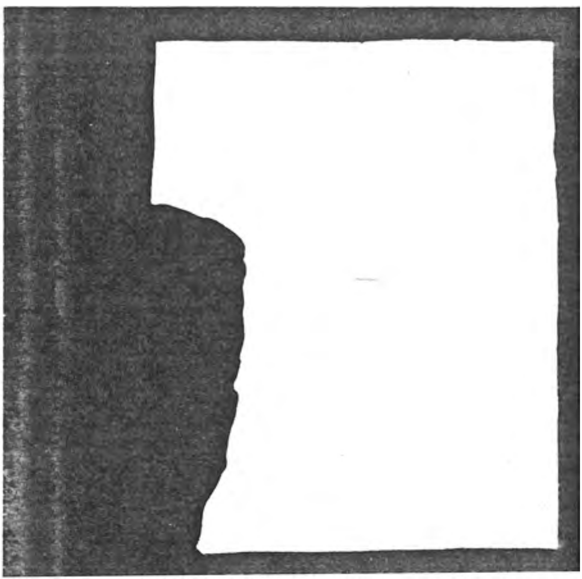


Plate 12. *Field of vision of the observer with open shutter.*

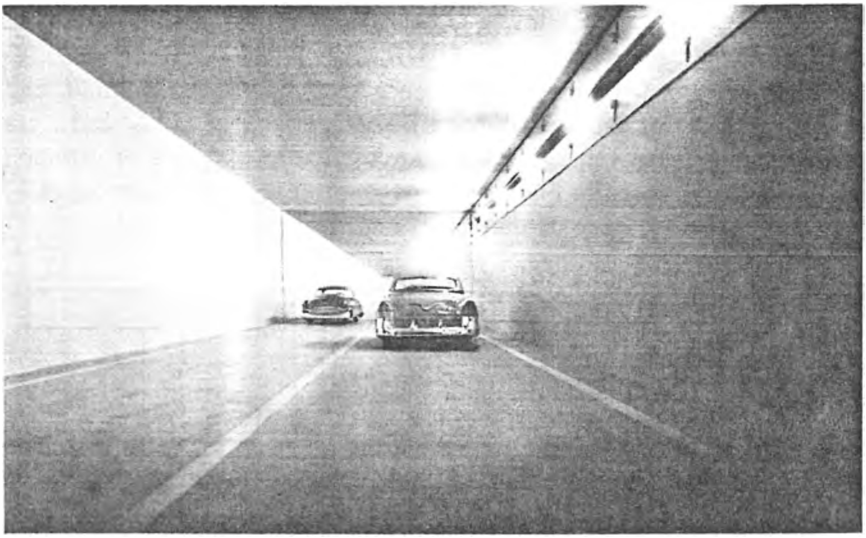


Plate 13. *Model set-up for tests on flicker phenomena.*

Plate 14. *Tunnel model. Observation place with periscope.*

g. RESULTS (GROUP 5)

Since the interactions with the luminance level L_1 were only small, and as only the relative changes resulting from variations of α_2, α_3 and t are important, the mean values of log L_2 are used. The influence of variation in α_3 and t is recorded in Fig. 40 and 41 respectively. The influence of α_2 falls within the accuracy of the observations.

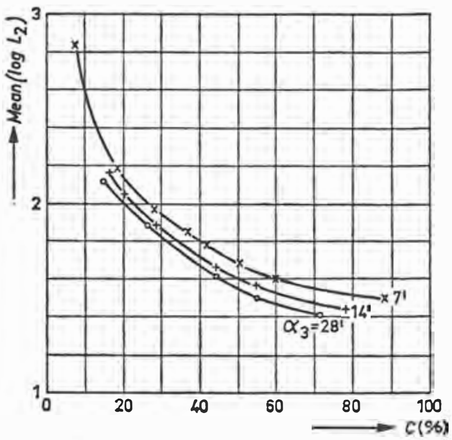


Fig. 40. Influence of variations of α_3 on the mean of log L_2.

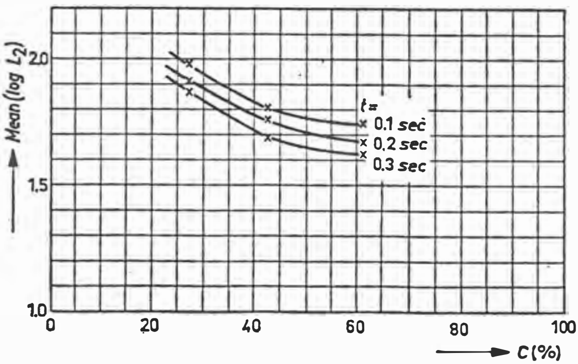


Fig. 41. Influence of variations of t on the mean of log L_2.

The dependence of α_3 can be compared with Blackwell's results, although those experiments were always carried out with a uniform background. For this purpose some interpolated values are given in Table 23 for the contrast difference found with equal average log L_2 and values of α_3 of 7′ and 28′. Expressed in relative measure the difference averages 21 %. Blackwell (1955, Fig. 3) records that for $t = 0.1$ sec and a surrounding luminance of 100 ft L, a change from 7′ to 28′ results in

TABLE 23

INTERPOLATED VALUES FROM FIGURE 40

Mean log L_2	C_1 ($\alpha_3 = 7'$)	C_2 ($\alpha_3 = 28'$)	ΔC	$\Delta C/C_1$
2.1	21.5	17	4.5	0.21
2.0	26	20.5	5.5	0.21
1.9	32.5	26	6.5	0.20
1.8	40	32	8	0.20
1.7	48.5	37.5	11	0.22
1.6	60	46	14	0.22
Mean				0.21

a contrast shift of about 60 %. The difference found is not equal but of the same order of magnitude.

Better agreement is found with Blackwell's results in the dependence of t. For $t = 0.1$ sec and $t = 0.3$ sec we found an average difference in log L_2 of about 0.15 (Fig. 41). The curves for object dimensions of 4′ and 16′ for 0.1 sec and 0.33 sec (Blackwell, 1952, a, Fig. 4 and 3) can at least for high luminance be made to coincide by a displacement of 0.15 in logarithms of the luminance.

h. CONCLUSIONS

The experiments and considerations described in this Section 5.1 result in one figure (Fig. 3) that can be used to appraise the visibility of objects. As regards the object which must still be visible in view of road safety (critical object) we have set out certain properties; these are the observation probability, the contrast, the dimensions and the observation distance of the object. From the foregoing it is clear that the luminance value L_2 in the tunnel entrance necessary for observation of the object depends in the first place on L_1 (the outside luminance) and on the contrast C between the object and its background. Compared to this, the observation probability, the observation time and the size of the objects appear to have only slight influence on the threshold value, as has the question whether the contrast is positive or negative. This means that any variation in the properties of the object has little influence on the recommended luminance in the tunnel entrance, so that all induction phenomena of importance for tunnel entrances can be compiled in a single curve (Fig. 3).

A separate investigation in which it is ascertained how far the results found with these stylised measuring methods can be used for tunnel lighting is described in Section 5.4.

5.2. **Experiments on adaptation**

a. THE PROBLEM

In Section 2.1.3 we described how the adaptation from one luminance level to another can be the immediate cause of problems in the transition lighting of tunnels. The change in the sensitivity of the visual system is caused by three effects: the disappearance of after-images, or (local) adaptation, changes in the induction, and changes in the size of the pupil. The first is the most important for tunnel lighting because of the fairly long adaptation time required. This means that only measuring methods in which the influence of local adaptation comes into play give practical results. The flicker-fusion frequency and the visual acuity depend on the state of adaptation but they provide no useful information on the course of local adaptation. The same applies to a somewhat lesser degree to the contrast sensitivity. For this reason we have used the subjective appraisal of luminance transitions, as is indicated already in Section 2.1.3.

The experiments fall into five groups, related to the admissible luminance jump, the admissible gradual luminance decrease, the adaptation time, the influence of the pre-adaptation time and the influence of variations in the pre-adaptation level. These five groups will be discussed successively.

b. THE ADMISSIBLE LUMINANCE JUMP (GROUP 1)

The *experimental set-up* consisted of a screen that subtended an angle of at least 10°, lit by reflector incandescent lamps. The highest luminance of the screen was 8 000 cd/m². The luminance could be regulated by dimming the lamps with a thyratron dimmer.

The *experimental procedure* involved the presentation of a number of sudden luminance transitions in which the ratio between initial and end luminances could have different values. They were displayed in a random sequence. Each transition was judged ten times by ten observers. Three values were used for the initial level L_b. The judging was carried out with a uniform field as well as with an object attached to the screen which subtended an angle of 7′ and which showed a contrast of about 7 % with its background.

The *results* are given in Fig. 42 in which the percentage of transitions is given which was found acceptable with regard to the presence of after-images.

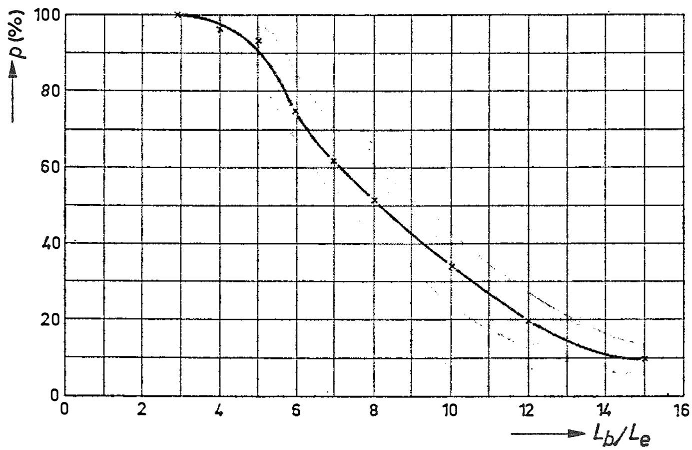


Fig. 42. Evaluating a sudden luminance transition. p = percentage of transitions found acceptable; L_b = beginning value; L_2 = end value of luminance.

The measurements led to the following *conclusion*: the presence of an object and the value of the beginning level proves to have no great influence. From Fig. 42 it may be seen that a sudden transition should not be greater than 6 : 1 if we aim at preventing trouble from after-images in more than 75 % of the observations.

c. THE ADMISSIBLE GRADUAL LUMINANCE DECREASE (GROUP 2)

The *experimental set-up* was the same as used for the experiments of Group 1, with this difference that the luminance of the screen could be regulated by the observer. The luminance was continuously recorded. The initial level was always 8 000 cd/m². To get better coordination in the experiments with practical tunnel lighting, the adjustment of the luminance is begun with a fixed sudden transition of 5 : 1 based on results of experiments in Group 1.

The *procedure* was as follows:

The observer was instructed to bring back the luminance as quickly as possible without the appearance of after-images and without an object of 7′ with a contrast of 7 % becoming invisible.

These observations were also carried out by ten observers, each observer making the test ten times.

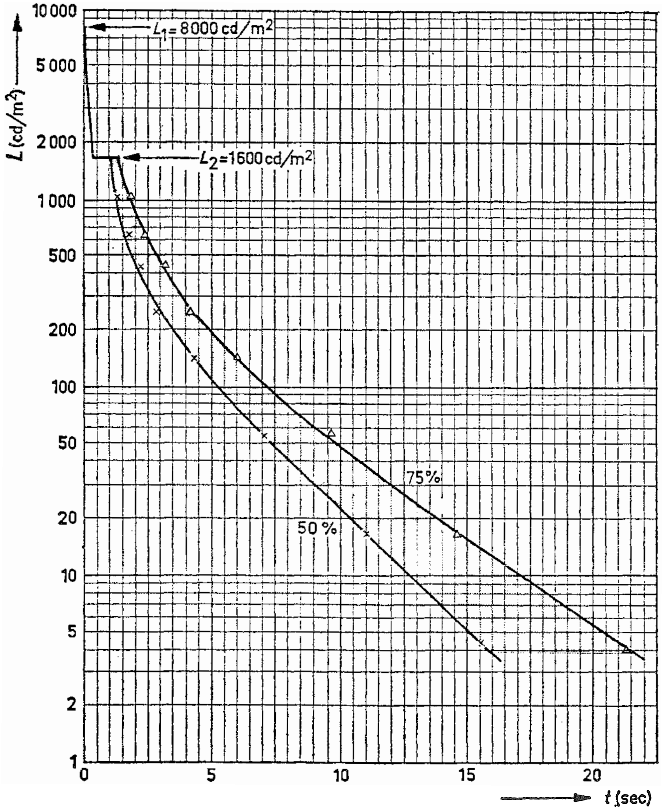


Fig. 43. Desired course of the luminance: results of adaptation tests. x = 50 % of observtaions; Δ = 75 % of observations.

The *results* together with the 50 and 75 percentages are given in Table 24. From Fig. 43, which reproduces the percentages given in Table 24, we notice that a sudden transition at the start of the test did not influence the further course of the adaptation; the measuring points can be connected very well with the zero point by a continuous curve without having to take the sudden transition into account. That sudden transition is consequently omitted in Fig. 5.

TABLE 24

MEASUREMENT OF COURSE OF ADAPTING LUMINANCE

Relationship between screen luminance and adaptation time

Luminance	Observer										Percentages	
(cd/m²)	1	2	3	4	5	6	7	8	9	10	50 %	75 %
1 060	1.69	1.75	0.76	0.84	2.48	1.40	1.45	0.79	0.30	0.52	1.25	1.70
685	1.88	2.07	1.31	1.42	3.86	1.94	2.37	1.04	0.43	1.26	1.70	2.20
445	2.14	2.33	1.83	2.26	5.13	2.55	3.14	1.30	0.54	1.70	2.20	3.05
250	2.53	2.99	2.42	3.53	6.40	3.36	4.83	1.72	0.85	2.53	2.80	4.05
137	3.71	4.03	3.65	6.05	9.21	5.21	6.05	2.35	1.70	4.39	4.15	6.10
58	5.45	6.41	5.23	9.39	12.14	7.88	8.77	3.08	2.85	7.22	6.75	9.45
16	9.13	12.10	8.75	14.72	17.07	11.11	15.26	4.26	4.90	14.07	11.00	14.90
4.5	16.80	19.61	14.10	19.32	23.23	16.43	23.50	7.93	7.34	19.60	15.45	21.10

Time (sec) to reach indicated luminance.

Luminance at beginning L_b = 8 000 cd/m².

Each value represents the average of 10 observations.

The measurements of Group 2 have very great significance for the lighting of tunnel entrances because the length of the transition zone and its luminance can be determined on the basis of these results. A further confirmation of these results seems therefore desirable. This is given in the Groups 3 and 4 which follow and in Section 5.4.

d. MEASUREMENTS OF ADAPTATION TIMES (GROUP 3)

The *experimental set-up* was in principle alike to that of Group 1, but of a different construction. This time only one value of the initial level or pre-adaptation level (L_b = 8 000 cd/m^2) was used and one value of the end level (L_e = 13 cd/m^2).

The *procedure* was different, however, from that of Group 1. After a pre-adaptation time of two minutes the luminance of the screen was suddenly decreased from 8 000 cd/m^2 to 13 cd/m^2. The observer had to state the moment at which in his opinion the after-images had decreased to a degree where they are no longer distinct. The pre-adaptation time of two minutes used with this group was chosen on the basis of the results of experiments of Group 4.

The *results* agree well with the results from Group 2 as is seen from Fig. 44 which shows the cumulative frequency distribution of the logarithms

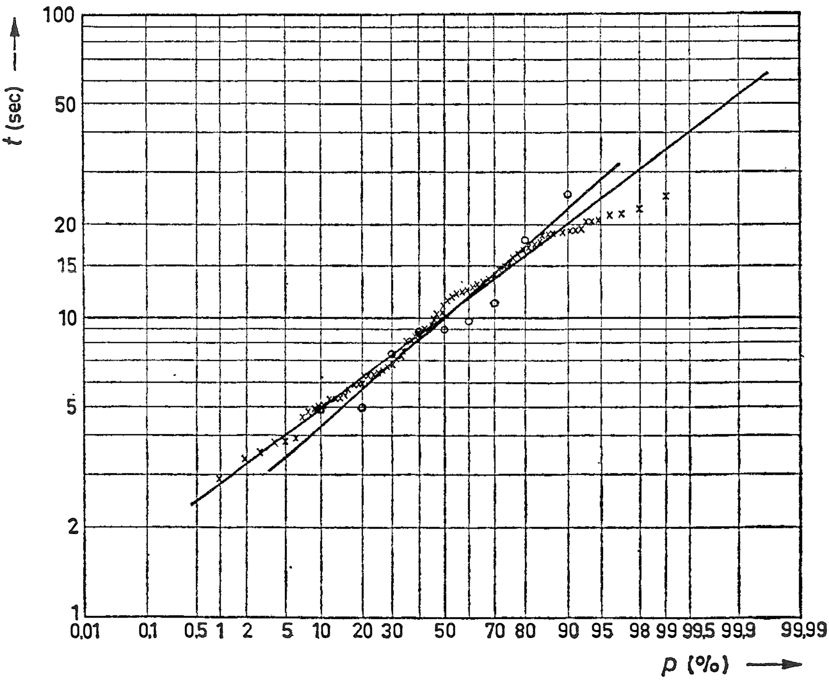


Fig. 44. Cumulative frequency distribution of the adaptation times. x = Group 2; o = Group 3.

of the time required for a transition from 8 000 cd/m² to 13 cd/m² found in Group 2 as well as in Group 3. Both groups appear to give normal distributions which show no significant difference, as can be proved by calculation.

It must be kept in mind that these experiments are related to *partial* adaptation. Complete adaptation will take considerably longer time (see Schouten (1937)).

e. THE INFLUENCE OF THE PRE-ADAPTATION TIME (GROUP 4)

The *experimental set-up* of the experiments of Group 3 has been used to investigate the influence of the pre-adaptation time. For these investigations a number of small grey squares seen at an angle of about 15′ and forming different contrasts with the background were attached to the

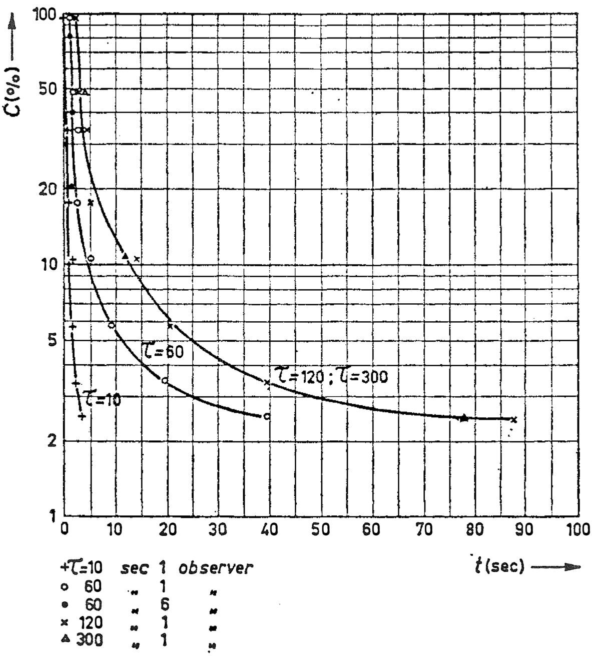


Fig. 45. Influence of variations of the pre-adaptation time τ on the adaptation time t.

screen. Only one level of the initial luminance L_b = 10 000 cd/m^2 and one level of the end luminance L_e = 20 cd/m^2 is used.

The *procedure* was different from that of the other groups, as the time was recorded that elapsed before the square of a certain contrast was visible again. No attention was paid to any discomfort arising from after-images. The experiments have been made by one observer; several points have been checked by six other observers under somewhat different conditions.

The *results* are given in Fig. 45. It is evident from these results that the pre-adaptation time is of great influence on the course of the adaptation. This means, in other words, that the light adaptation can take considerable time. It takes several minutes to reach a state of adaptation that is reasonably constant. Therefore we have used a pre-adaptation time of two minutes for our experiments.

f. THE INFLUENCE OF THE PRE-ADAPTATION LUMINANCE (GROUP 5)

The *experimental set-up* and the *procedure* were alike to those of the experiments of Group 3. For a number of values of the pre-adaptation luminance L_b and a number of ratios between this level and the end level L_e the adaptation times for one observer were measured as far as persistence of after-images was concerned.

The *results* are given in Fig. 46. In addition, Fig. 46 records the average adaptation time of this observer in the experiments of Group 3. The pre-adaptation luminance has a great influence on the adaptation time. There seems to be an optimum condition of L_b between 1 000 and 3 000 cd/m^2.

g. CONCLUSIONS

The experiments described above lead to the following conclusions:

1. The time required for adaptation from a high to a low level is not dependent on the luminance course during the transition. This follows from the agreement between the results of the experiments of Group 2 and 3.
2. For one level of the initial luminance one diagram can be given which indicates the desired course of the luminance at a tunnel entrance. A diagram of this sort is given in Fig. 5.
3. The pre-adaptation time seems to have a great influence on the

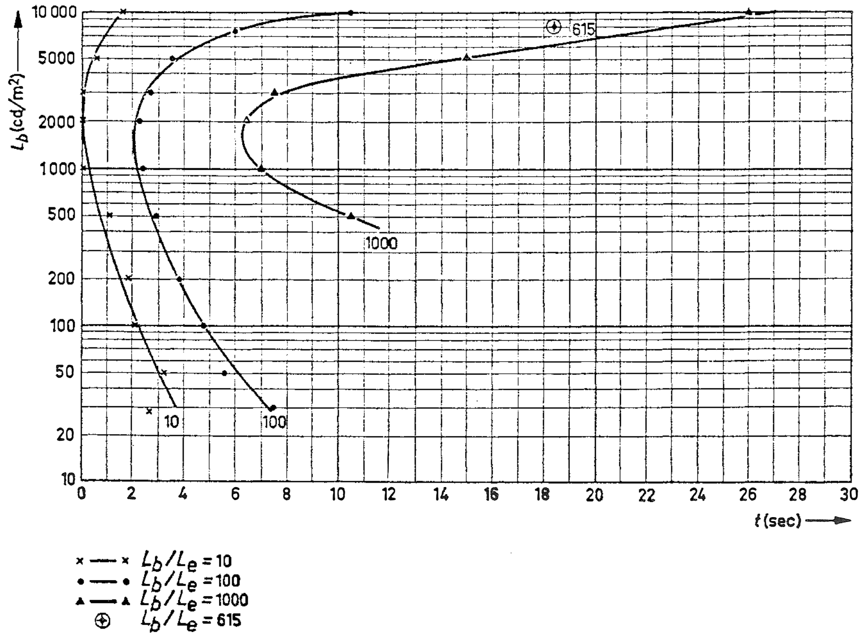


Fig. 46. Influence of variations in the starting level L_b of the luminance on the adaptation t for different values of L_b/L_e . L_e = end value of luminance.

adaptation time. This means that the time needed for adaptation from a low to a high level may not be disregarded. For this reason very great transitions in the luminance should be avoided near tunnel exits during daytime (see Section 2.1.6).

4. The pre-adaptation level appears to have a great influence. This enhances the importance of applying dark surfaces near the tunnel entrance.

5.3. **Experiments on flicker phenomena**

a. THE PROBLEM

The experiments aim at finding the range of repetition frequencies of luminances in the field of vision which have to be avoided in the lighting of tunnels. As already stated in Section 2.1.4 there is a range of frequencies well below the fusion-frequency within which considerable inconvenience can occur. The relevant frequencies in this problem are given by the number of light sources passed per second by a motorist in the tunnel, and therefore depend on the spacing of the light sources and the driving speed. Special attention should be paid to the lower limit of the range in question because this establishes the minimum distance at which fittings should be placed. The upper limit of the range of disturbance is so high, and the corresponding spacing is so small that we very closely approach a continuous line.

The phenomena to be investigated cause, to the extent to which they occur in tunnels, no clearly measurable fall in the visual performance. Experiments have to be carried out in the form of subjective judgments. The experiments have been performed in groups. Group 1 consists of the assessment of the frequency of maximum bindrance. Group 2 is set up specially to investigate the lower limit of the region of hindrance, and Group 3 consists of appraisals of actual installations.

As the experiments are related to periodic phenomena, it is convenient to use several notions that are normally restricted to the field of electric waves. These notions are indicated in Fig. 47.

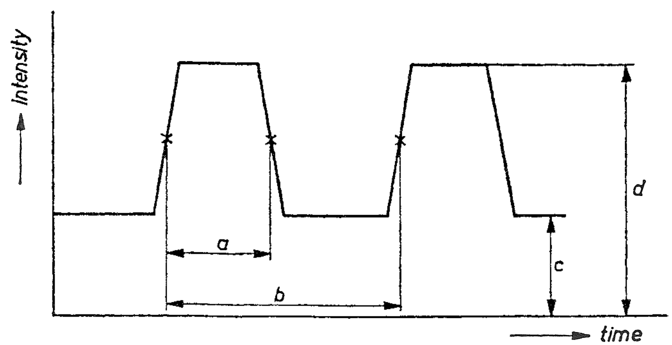


Fig. 47. Explanation of some terms used in the text: b = period; a/b = pulse-to-cycle fraction; d = maximum amplitude; d/c = modulation depth.

b. FREQUENCY RANGE OF MAXIMUM HINDRANCE (GROUP 1)

The *experimental set-up* consists of a 1 : 20 scale model 1.80 m long of a section of tunnel interior. The movement of the observer in the tunnel is simulated by allowing only the lighting fittings to move in the opposite direction. For this a slot is made in one of the side walls and this is illuminated from behind. An endless belt (a film strip) consisting of alternate transparent and opaque sections is moved along in front of this slot. The transparent parts form the light sources. The speed of the film strip and therefore the repetition frequency of the luminance changes can be continuously adjusted. An illustration of the field of vision is given in Plate 13. A few model cars are placed in the tunnel so that the influence of reflections on car bodies can be assessed. The experiments are carried out binocularly and with the natural pupil.

The apparatus was designed by R. Jantzen, Philips Hamburg. The measurements were partly made by Jantzen in Hamburg, partly by the author in Eindhoven.

The *Hamburg measurements* are made with increasing and then with decreasing frequency; the mean of these two is taken. The frequency adjustment is done by the observer himself. The experiments are done by five observers with several values of the light source luminance L_s, several values of the road surface luminance L_r and several values of the ratio κ of the transparent and opaque parts of the film (pulse-to-cycle fraction, Fig. 47). A summary of the results is given in Table 25a.

Part of this has been quoted by Jantzen (1960).

Under the circumstances in which these tests were carried out, the variations of L_s, L_r and κ do not appear to influence the frequencies in which the beginning, the end or the maximum of disturbance occurs. This suggests that the measure of disturbance is also unaffected by these variations.

The *Eindhoven measurements* were made with luminance values which lie closer to those customary in tunnels. The luminance of the light sources was $L_s = 0.9$ cd/cm^2, that of the road surface $L_r = 8$ cd/m^2. On instructions from the observer the experimenter successively regulated the frequency for the three criteria: lower limit of disturbance range (f_1), maximum disturbance (f_2), upper limit of disturbance range (f_3). The tests were made with 10 observers and always with a pulse-to-cycle fraction $\kappa = 0.25$. The results are given in Table 25b.

A *comparison* of the Hamburg and the Eindhoven results shows that the values of the Eindhoven measurements all lie somewhat lower than

TABLE 25a

MEASUREMENTS OF HINDRANCE DUE TO FLICKER EFFECTS

κ	L_s cd/cm²	L_r cd/m²	f_1 c/s	f_2 c/s	f_3 c/s
0.25	0.165	105	3.5	8.1	14.5
0.25	0.030	19	3.5	7.6	13.1
0.50	0.165	210	3.5	10.2	19.3
0.50	0.030	38	3.5	9.3	17.1
0.75	0.165	310	3.5	9.0	16.3
0.75	0.030	57	3.7	8.8	14.7
Mean of all observations			3.5	8.5	15.2
Estimated standard deviation			0.3	1.0	2.5

κ = pulse-to-cycle fraction
f_1 = lowest frequency of hindrance
f_2 = frequency of maximal hindrance
f_3 = highest value of hindrance
Estimated standard deviation for every cell is 20 %

TABLE 25b

MEASUREMENTS OF HINDRANCE DUE TO FLICKER EFFECTS

κ	L_s cd/cm²	L_r cd/m²	f_1 c/s	f_2 c/s	f_3 c/s
0.25	0.90	8	2.64	6.40	12.5
Standard deviation			0.34	1.8	5.5

the other but that the differences are not important. For the f_1 values, however, there is an indication that the unfavourable luminance distribution (higher light source luminance and lower road surface luminance) caused the lower limit of the range of disturbance to be brought down.

c. THE LOWER LIMIT OF THE FREQUENCY RANGE OF HINDRANCE (GROUP 2)

Another *experimental set-up* was used to find the lower limit of the range of hindrance in another way.

The observer had in front of him a uniformly lit screen with a luminance of about 3 cd/m². With the aid of an externally triggered stroboscope, very brief flashes were given on this screen (half-value time 10 μsec). The luminance of the screen during the flash was about 1–2 cd/cm². The repetition frequency of the flashes was regulated by the experimenter on instructions from the observer in such a way that the exact lower limit of the area of disturbance was found. A mean of 2.11 c/s was found for ten observers, in which the standard deviation was estimated at 1.1 c/s.

d. APPRAISAL OF FULL-SCALE INSTALLATIONS (GROUP 3)

Two sets of evaluations of flicker effects have been made in the tunnel at Velsen, from which it appears that the wave form and the pulse-to-cycle fraction of the periodic phenomena in the field of vision have a great influence on the degree of hindrance. The first evaluation is the enquiry discussed in detail in Section 5.6. The second evaluation was carried out in a test installation in the tunnel.

The *inquiry* leads to the conclusion that the normal lighting is regarded as disturbing. With the normal lighting installed in this tunnel the luminance inside a car increases very quickly when the car comes under a fitting recessed in the ceiling and decreases again with equal rapidity a short time later when the fitting is screened by the upper edge of the windscreen (see Zyl (1958)). The distance of the fittings is 4.5 m. The periodic phenomena can therefore be described with a great modulation depth, a pulse-shaped modulation and a small pulse-to-cycle fraction. The frequency lies, dependent on the speed, between 3 and 6 c/s.

The *test installation* was appraised by a dozen lighting experts. The test installation in question was a lighting system of a line of fluorescent lamps in fittings mounted at the upper side of the wall with a light distribution well suited to the tunnel. Every other lamp in this line was switched out so that the distance of the light sources, end to end, amounted to 1.20 m. A number of rides were made in this installation at various speeds between 50 and 120 km/h (flicker frequencies between about 5 and 12 c/s). The unanimous opinion was that the flickering gave no trouble. The reason for this appears to be that because of the lengthwise mounting of the fittings on the walls, there was a gradual increase and afterwards a gradual decrease in the luminance. Moreover, the fittings "overlap" considerably. The periodic phenomenon can therefore be described by a smooth course of the luminance with small modulation depth and a large pulse-to-cycle fraction.

e. DISCUSSION

It is evident from the tests that the lower limit of the disturbance range (which decides the minimum distance of the fittings) depends on the frequency, and also on the modulation depth and the pulse-to-cycle fraction. It is particularly clear that if the modulation depth is small and the pulse-to-cycle fraction is large, there is on the whole no disturbance. A survey of the results regarding the frequency relevant to the lower limit of the flicker disturbance range (f_1) is given in Table 26.

TABLE 26

MEASUREMENTS OF HINDRANCE DUE TO FLICKER EFFECTS

Summary of results

κ	L_s/L_r	M	f_1 (c/s)	Group
0.25–0.75	50–160	20	3.5	1
0.25	1 100	100	2.64	1
approx. 2×10^{-5}	10 000	10 000	2.11	2
approx. 0.1	1 000	5	disturbance at 3–6 c/s	3
0.5	1 000	1.2	no disturbance	3

κ = ratio in time between "Light" and "Dark" section of the period (pulse-to-cycle fraction)
L_s = luminance of light source
L_r = luminance of road surface
M = modulation depth
f_1 = frequency at lower limit of range of flicker

Although practically all the investigations reported in the literature have a bearing on flicker-fusion there is some agreement with the measurements described above.

Kelly (1961) and De Lange (1957) indicate that the visual system reaches its maximum sensitivity at a flicker frequency between 5 and 10 c/s when the adaptation luminance is about 2–20 cd/m^2. The measure of the sensitivity is the smallest modulation depth that can be discerned as a flicker.

The influence of the wave form is indicated by De Lange (1957) and Collins (1956). In general the sensitivity for pulse-shaped modulation of the source is higher than for the sinusoidal modulation.

The pulse-to-cycle fraction is treated by Crozier and Wolf (1941) and Bartley and Nelson (1961). The sensitivity decreases considerably when the pulse-to-cycle fraction increases, if we indicate a decrease in the fusion-frequency as a decrease in sensitivity to flicker.

f. CONCLUSIONS

1. A frequency of 2.5 c/s is a reasonable value to assume for the lower limit of the range of flicker disturbance.
2. The degree of hindrance and the frequency of the lower limit is greatly dependent on the wave form, the modulation depth and the pulse-to-cycle fraction.
3. Frequencies higher than 14 c/s as a rule provoke no hindrance. The maximum disturbance lies between 5 and 10 c/s.
4. For normal speeds centre-to-centre distance between approx. 0.75 m and 9 m must be avoided, except when the modulation depth is small.
5. Continuous line lighting is recommended.

5.4. Model studies

a. PURPOSE

In order to check a number of simplified investigations, especially concerning induction and adaptation effects, we used a scale model especially constructed to simulate tunnel entrances in daytime. The same sequence of events has to occur in the model in the same time as they would in an actual tunnel. The model must be dynamic.

We did use this model for the following investigations: the colour of light (Group 1), induction effects (Group 2), subjective appraisals of transition (Group 3) and registrations of contrast sensitivity (Group 4).

b. EXPERIMENTAL SET-UP

The observer's place is a movable seat, travelling below the road surface. By means of a set of mirrors (periscope) he can see the road as if he were driving a car through the tunnel (see Plate 14). Models of tunnels can be placed and quickly interchanged on the road surface. The total length of the model is 12 m. The area that can be used for experiments is about 10 m long and 1.20 m wide. For the simulation of the daylight we used 48 400 W high pressure mercury lamps, mirrored inside; at a height of 60 cm they gave a horizontal illumination of about 35 000 lux (see Plate 15). The field of vision is reproduced in Plate 16 *).

*) The model has already been described by Balder and Schreuder (1959). Several changes have been made since publication, though not of primary importance.

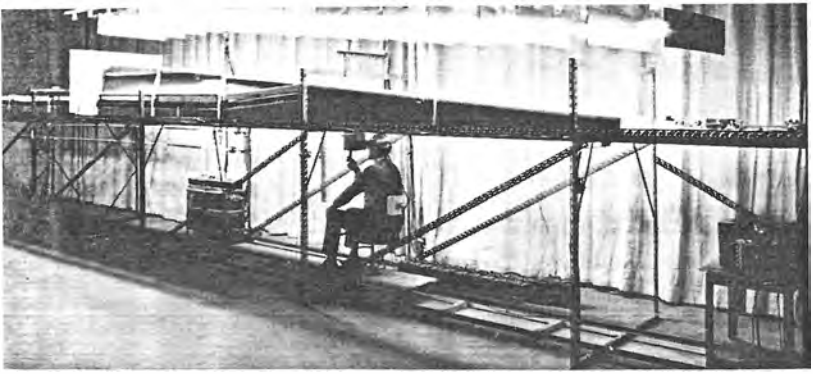


Plate 15. *Survey of tunnel model.*

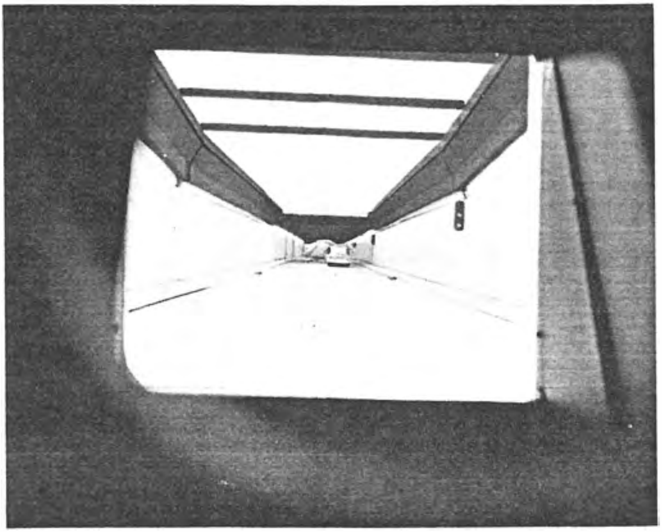
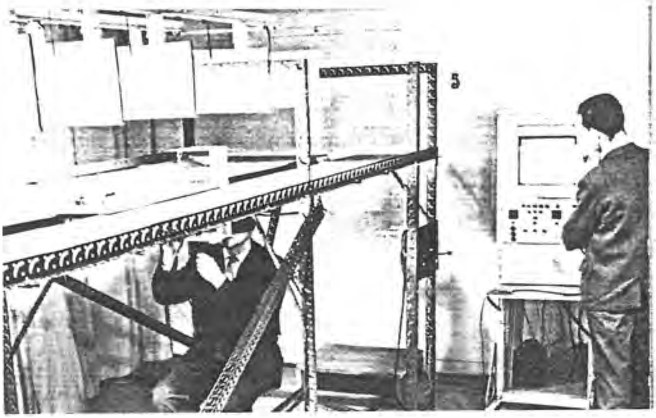


Plate 16. *Field of vision of the observer.*

Plate 17. *Survey of the arrangement used for contrast registrations (see text).*



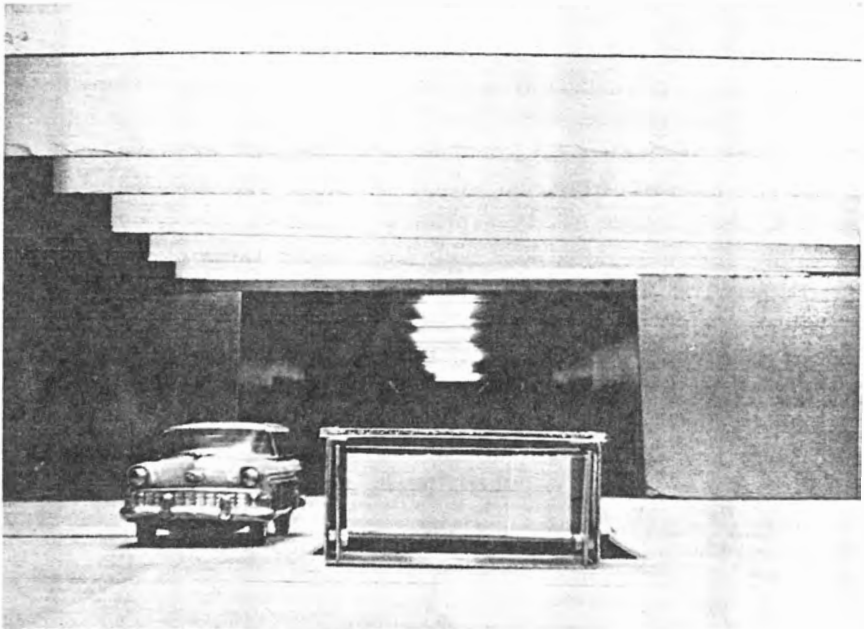


Plate 18a. *Field of vision with minimum contrast.*

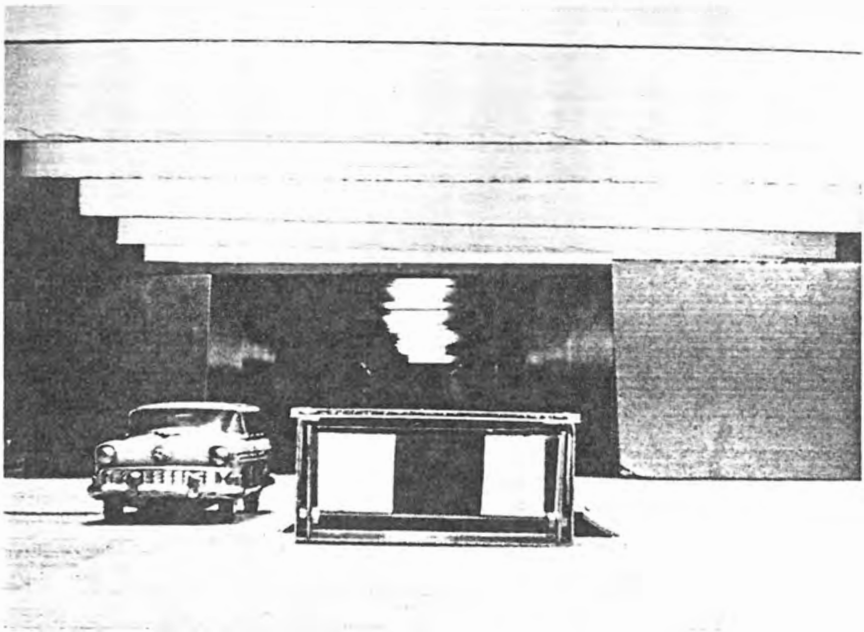


Plate 18b. *Field of vision with maximum contrast.*

A crosswise scale less than 1 : 20 cannot be used because the periscope has to pass through the tunnels. If this scale also has to be applied lengthwise, however, the space available would be too small to simulate long tunnel entrances. We used a negative lens to convert the lengthwise scale to a different measure from the crosswise scale. The perspective is exaggerated. The principle will be explained in the following calculation.

We assume that a negative lens with an absolute value of the focal length f is placed at a distance a in front of the observer. An object of height h at point v_1 in front of the lens will form a virtual image of height h' at a distance b_1 in front of the lens, if the rules of paraxial construction can be used (see Fig. 48). Under these assumptions we can state that:

$$\frac{1}{b_1} + \frac{1}{v_1} = \frac{1}{f}, \text{ therefore } b_1 = \frac{v_1 f}{v_1 - f} \qquad \text{(a)}$$

We shall assume further that this image is observed directly.

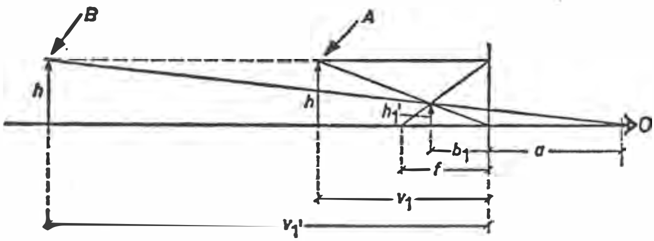


Fig. 48. Changing the scale in lengthwise direction by applying a negative lens (see text). A = real position of object; B = apparent position of object; O = observer.

The object appears to be at distance v_1' when the normal height is taken as known and if accommodation is disregarded. We can see from Fig. 48:

$$\frac{v_1' + a}{h} = \frac{b_1 + a}{h_1'};$$

$$\frac{v_1' + a}{b_1 + a} = \frac{h}{h_1'} = \frac{v_1}{b_1};$$

$$b_1 = \frac{a v_1}{v_1' - v_1 + a} \qquad \text{(b)}$$

(a) and (b) combined give

$$v_1' f = a v_1 - 2af + v_1 f \qquad \text{(c)}$$

For a second object also of height h but at point v_2, we find by the same reasoning:

$$v_2'f = av_2 - 2af + v_2f \tag{d}$$

Subtraction of (c) and (d) gives:

$$(v_1' - v_2') = (v_1 - v_2)\frac{a+f}{f}; \text{ or } \frac{v_1' - v_2'}{v_1 - v_2} = \frac{a+f}{f} \tag{e}$$

Formula (e) has the following meaning. Two objects separated by a distance $(v_1 - v_2)$ appear to be further apart when a negative lens is placed in the path of the light. The virtual increase in their separation depends on the distance between the eye and the lens and on the focal length of the lens. The cross diminution of the objects h_1/h and h_2/h is not relevant in this respect because the reasoning is only valid when we assume the virtual images to have the same size as the actual objects. In other words: the virtual images are projected at a point at such a distance that their apparent size is equal to the size of the original object. This optical illusion is only possible if the convergence of the two eyes is eliminated, i.e. in monocular vision.

So when we suppose the observation of a 1 : 20 scale model to be normal, the application of a lens causes a virtual lengthening of the model by the factor $\frac{f}{a+f}$. The lengthwise scale becomes 1 : $(20 \times \frac{a+f}{f})$. We took 0.55 m for a and 0.75 m for f so the lengthwise scale is 1 : 35.

c. EXPERIMENTS ON THE INFLUENCE OF THE COLOUR OF THE LIGHT (GROUP 1)

The *aim* of the experiments of Group 1 was to discover whether there is any difference between the transition from daylight to sodium light and that from daylight to fluorescent light.

The *procedure* involved the use of the visibility distance of Landolt rings. The visibility distance is defined as the distance between eye and object at the moment the position of the slit in the ring can be observed. The rings had an actual outside diameter of 5.5 mm and a reflection factor of 9 % and were placed in different parts of the tunnel. Two conditions were investigated, i.e. with and without daylight screening in front of the tunnel. The driving speed corresponded to 55 km/h. The observations were made by two observers. The Landolt rings were displayed at 14 places at least eight times each.

The *results* are given in Fig. 49, where for the two conditions the course of the luminance of the road surface and the course of the

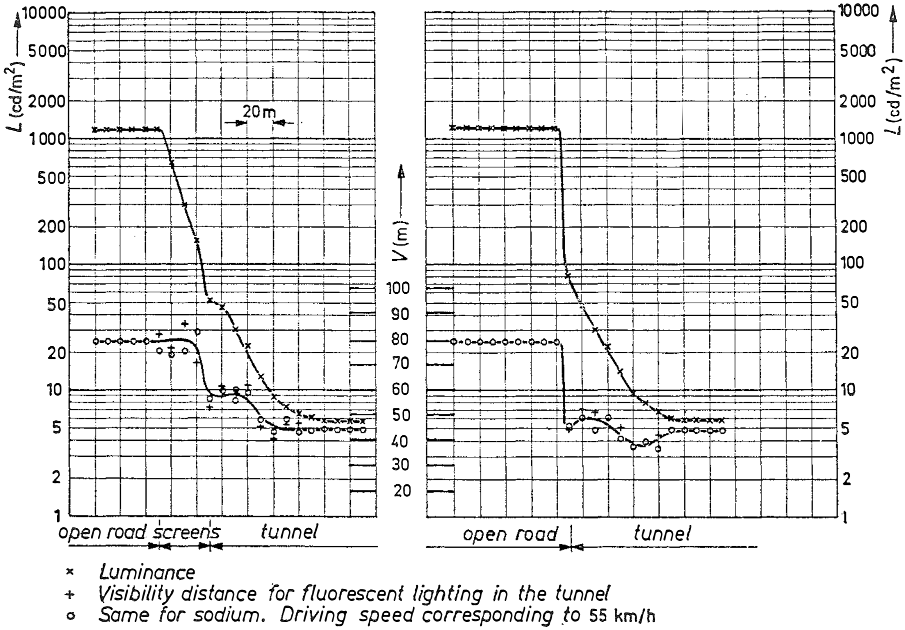


Fig. 49. Comparison of sodium and fluorescent lamps for tunnel entrances.

visibility distance are plotted. Fig. 49a indicates the visibility distance for both sodium and fluorescent lighting in the tunnel, when a daylight screening is used. Fig. 49b gives the corresponding results without a daylight screen. The visibility distances in the tunnel interior and on the open road were determined from all available measurements and were 44.8 m and 80.0 m respectively. The spread in the measurements is rather great. The estimated average standard deviation of the mean amounts to $\pm$ 2.5 m. An analysis of variance of the results proves that there is no significant difference between the two tested colours of the light. Although the position of the ring naturally has an important influence, the interaction between the colour and the position is not significant.

The *conclusion* of these measurements is that no important preference can be credited to either the use of sodium or fluorescent lighting when the visibility distance alone is considered. The presence of a daylight transition zone is proved to be highly significant, as was to be expected.

d. EXPERIMENTS CONCERNING INDUCTION EFFECTS (GROUP 2)

The *aim* of the experiments of Group 2 was to check the results of the experiments on induction described in Section 5.1.

The *set-up* was the model described before, in which we provided the periscope with objects which formed a certain contrast in relation to their immediate background. The objects were transparent neutral filters which were pushed up for 0.1 sec. As these were thin celluloid filters their visibility was governed by the contrast only and was not influenced by the edge. Furthermore, the objects were placed at an angle to prevent reflection in the surface. The apparent distance from the object to the observer is 100 m.

The *experimental procedure* was as follows. For one value of L_1 = 2 300 cd/m² and three values of L_2 we showed to ten observers objects representing five values of C. (L_1, L_2 and C have the same meaning as in Section 5.1.) The objects were displayed just at the beginning of

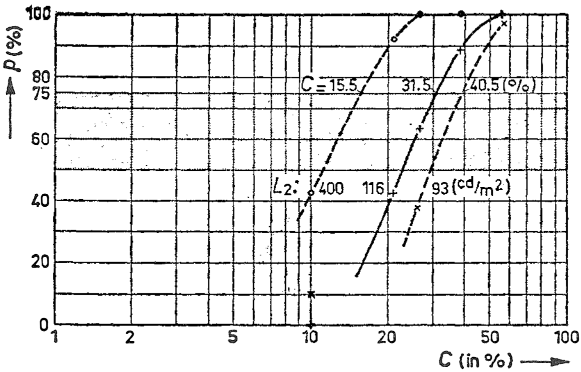


Fig. 50. Results of the model tests on induction. Estimation of regression curves.
L_1 = 2 300 cd/m²;
L_2 = 400 cd/m² → C_{75} = 15.5 %;
L_2 = 116 cd/m² → C_{75} = 31.5 %;
L_2 = 93 cd/m² → C_{75} = 40.5 %.

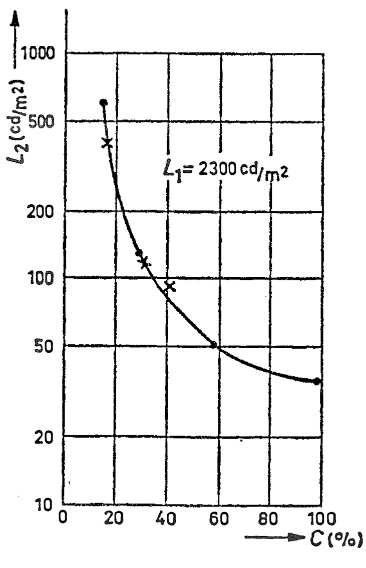


Fig. 51. Comparison of the model tests on induction with the tests from Section 5.1: —— from Section 5.1. x = model tests.

the entrance zone of the tunnel. The five objects were each shown five times. The number of times the object had been seen was again recorded.

Because the steps we used in the scale of values of L_2 were rather large, we did not estimate the regression curves for every observer, but used the regression curves for the average values. From these curves the 50 % and 75 % values can be estimated.

The *results* are given in Fig. 50. In Fig. 51 a comparison is made between the results of the experiments of Section 5.1 and those of Section 5.4. For this we have given the relation between L_2 and C for $L_1 = 2\,300$ cd/m², representing values interpolated from Fig. 37. The 75 % points from Fig. 50 are also plotted in Fig. 51. From this we can conclude that there is close agreement between the experiments of the Sections 5.1 and 5.4.

e. SUBJECTIVE APPRAISAL OF TRANSITIONS (GROUP 3)

The *aim* of the experiments of Group 3 was to check the tests on adaptation.

The *experimental set-up* consisted of seven different transition zones in the model, all with the same luminance at the beginning (L_b) and also at the end (L_e). The installations only differed in respect to their length (see Fig. 52). We used one driving speed. The differences in length are therefore equivalent to differences in time. The transitions could be very quickly interchanged merely by lighting or extinguishing a number of lamps. They were presented in random order unknown to the observer.

We used the following *procedure*: the observer had to indicate whether the transition was acceptable from the point of view of after-images. Each situation was only presented once every few days to prevent familiarity

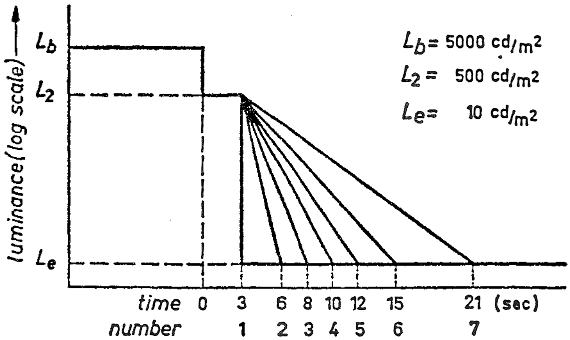


Fig. 52. Diagram of luminance courses in the adaptation tests with the model.

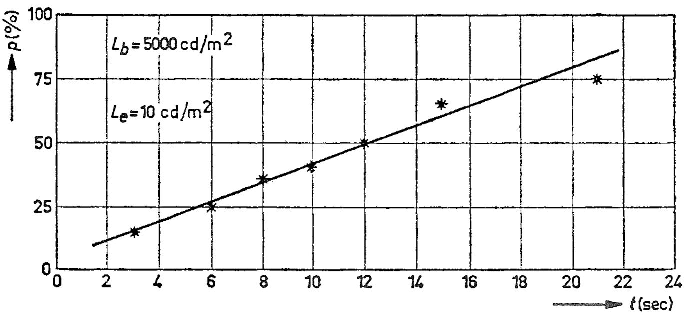


Fig. 53. Results of the adaptation tests with the model. p = the percentage in which the transition is judged to be favourable and t = the time necessary to complete the transition concerned.

with the different conditions. Pre-adaptation time was always two minutes.

The *results* are given in Fig. 53 for $L_b = 5\,000$ cd/m^2 and $L_e =$ 10 cd/m^2. Again the 75 % value can be indicated. This value is in good agreement with the other experiments and is plotted in Fig. 5.

f. RECORDING OF THE CONTRAST SENSITIVITY (GROUP 4)

The *aim* of these experiments was to observe the combined effect of induction and adaptation by means of the scale model. For this purpose we recorded the contrast sensitivity, under the assumption that the distinctness of a certain difference in luminance, or the distinctness of a contrast between two luminances, is a measure for the quality of the lighting. This means that the actual difference in luminance must increase to keep the difference in subjective brightness equal under lighting conditions that change for the worse. In fact, this is an estimation of the "adaptation defect" we have defined in Section 2.1.3.

The *experimental set-up* we used for the measurements is reproduced diagrammatically in Fig. 54. We placed two polarisation filters (c) on the farther end of the periscope in such a way that their respective transmission directions were perpendicular. Behind them was a mirror (b) and an opal glass (a). This arrangement ensures that the average luminance of the filters is always proportional to the illumination on the opal glass. This system was observed through the periscope ($d - e$) and an additional third polarisation filter (f). The filter f can be rotated along its normal axis; by turning it the transmission of the two filters c seems to change and with it the contrast between the two (see Fig. 55). The rotation of the filter f is transformed by a potentiometer h into a voltage difference

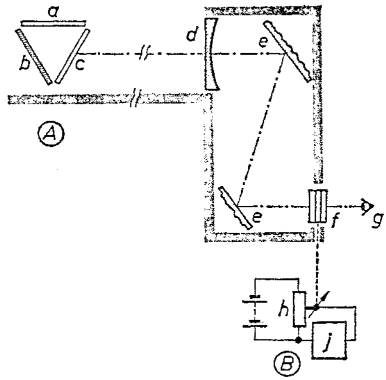


Fig. 54. Diagram of arrangement for continuously recording contrasts. a = opal glass; b = mirror; c = polarizing filters; d = negative lens; e = mirrors; f = polarizing filter; g = observer; h = potentiometer; j = registration device.

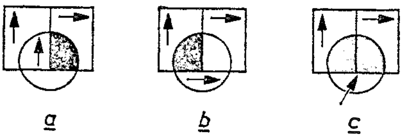


Fig. 55. Diagram of arrangement for continuous alteration of the contrast. The arrows indicate the directions of transmission of the polarizing filters.

which is registered by an automatic recorder j. The arrangement is shown in Plate 17. In Plate 18a and 18b the field of vision is shown at maximum and minimum contrast. To the right of the two polarisation filters, a neutral filter is placed on the periscope. This filter is used for the measurement of the illumination in the model.

The *measuring procedure* is as follows. The observer adjusts the contrast to a small but definitely perceptible value, while still outside the tunnel. He has the instruction to adjust the filter in such a way that throughout his journey from the open road outside down to the tunnel interior the contrast between the two polarisation filters c remains equally distinct.

In this way the seven installations mentioned in Group 3 were measured by one observer. The polarisation filter in the periscope, however, reduces the effective luminance of the field of vision. We now have $L_b = 2\ 000$ cd/m^2 and $L_e = 4$ cd/m^2.

Results are given in Fig. 56. The values of ΔC represent the difference in contrast between the starting level and the maximum value of the contrast found during the transition. The asymptote is found by taking the difference in the average of the end values of the contrast and the beginning values of the contrast. The averages are taken over all runs. The results are in reasonable agreement with other results of the same observer, the critical adaptation time being a little less than 20 sec. The

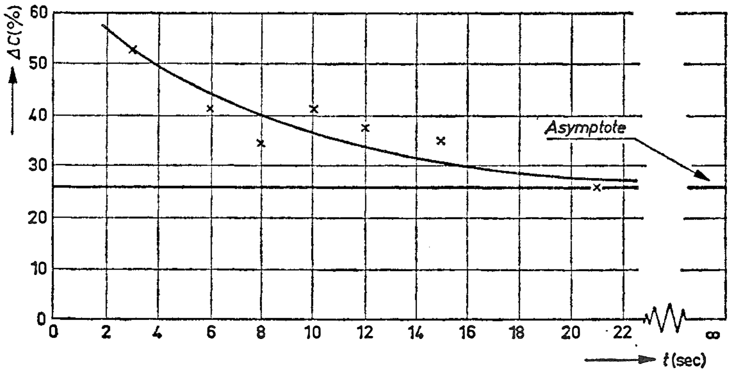


Fig. 56. Results of recording just visible contrasts. Relation between time t available for the transition and the required contrast increase ΔC.

values of the contrasts cannot be compared with those from other experiments as the contrasts used here are considerably above the threshold values.

g. CONCLUSIONS

The experiments described in this Section lead to the following conclusions.

1. With regard to the visibility of small objects the transitions from daylight to sodium light and from daylight to fluorescent light can be considered as equal.
2. The results of both the experiments on induction described in Section 5.1 and the experiments on adaptation described in Section 5.2 are valid for the circumstances occurring in a model of a tunnel. It is therefore highly probable that the results can also be applied for full scale installations.
3. When properly carried out, measurements of contrast sensitivity give the same results as a system of subjective evaluations.

5.5. **Values of luminance on the open road**

The difficulties caused in tunnel entrances by induction and adaptation depend to a great extent on the luminance outside the tunnel. On the basis of illumination records as well as luminance measurements, we have taken 8 000 cd/m^2 as the maximum value which is of practical importance.

The daylight records of Postma (1936) state that a horizontal illumination of 100 000 lux fairly frequently is exceeded. This may be seen from Fig. 57 which gives the cumulative frequency distributions of the horizontal illumination (derived from the Postma data) for the whole year as well as for the months of May, June, July and August. The values represent the mean of the recordings for 10 a.m., noon and 2 p.m. On the basis of this figure it can be estimated that 100 000 lux is exceeded in 18 % of cases in the summer and in 9 % during the whole year. This value is also given elsewhere as a practical maximum for daylight illumination, for example by Weber (1937), IES Handbook (1959).

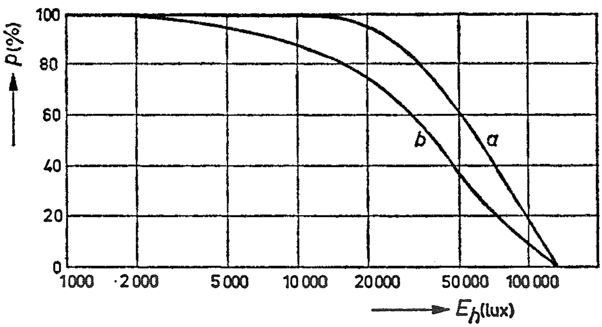


Fig. 57. Registered values of daylight illumination. (From: Postma, 1936). a = during summer months; b = whole year. Average of readings at 10, 12 and 14 h.

The following considerations were used to make an assumption of the luminance based on this illumination value. In the first place, daylight even with sunshine is predominantly diffuse, and in the second place, specular reflecting and very light surfaces near tunnel entrances can be avoided. This means that it is sufficient to use a single (diffuse) reflection factor. A greater reflection factor than 0.25 can mostly be avoided so that generally we do not need to reckon with luminances of more than 8 000 cd/m^2.

On the basis of our own measurements (see Table 27) which are published in part in the "Recommendations on Tunnel Lighting" (1963) and on the basis of other measurements such as those of Pagès (1959), Spencer (1954) and Jones and Condit (1941, 1948) it appears that, although this value is not always reached in practice, it is greatly exceeded in many cases.

TABLE 27

MEASURED VALUES OF LUMINANCES (in cd/m²)

Place / Tunnel	Eindhoven Bezuiden-houtseweg	Eindhoven Vestdijk	's-Gravenhage Vaillantlaan	Rotterdam Maastunnel	Velsen	Velsen	Paris Orly n° 2	Eindhoven Demer	Oirschot Flyover
Horizontal ill. (lux)	60 000	ca 40 000	60 000	77 000	ca 85 000	ca 85 000	ca 80 000	34 000	58 000
Time	15.00 h	15.30 h	11.00 h	13.00 h	13.00 h	13.30 h	13.00 h	11.00 h	10.15 h
Date	30-8-'62	30-8-'62	18-10-'62	22-2-'62	8-10-'62	8-10-'62	13-6-'62	3-3-'61	2-2-'62
Direction of observation	SE → NW	S → N	NW → SE	N → S	S → N	N → S	N → S	S → N	SE → NW
Air (horizon)	—	2 300	—	29 000	6 400	15 000	11 000	8 000	9 000
Tunnelfacade, light area	12 700	3 600	3 100	1 800	11 000	2 300	—	22 000	12 300
Tunnelfacade, dark area	—	650	2 600	410	—	850	—	11 000	—
Road surface in sun	2 400	1 400	4 700	2 200	7 300	7 600	2 900	2 800	7 600
Road surface in direction of reflection of the sun	—	4 500	32 000	12 300	14 500	18 000	10 000	—	12 300
Road surface in shade	460	—	2 000	1 400	—	2 400	—	—	—
Tunnel entrance	320	80	—	110	670	350	430	230	—
Grass or other dark area of surround	650		—	500	2 200	2 200	2 300	3 300	1 900 – 2 400

5.6. Enquiry among tunnel users

a. THE AIM

On May 29th 1961 under the supervision of the Market Development Department of Philips Nederland N.V. about 700 persons who had just passed through the tunnel at Velsen were questioned. The first aim of the enquiry was to discover whether flicker phenomena are regarded as annoying. The tunnel at Velsen was selected because the flicker phenomena are pronounced although the lighting as a whole is good. Apart from the flicker effects other interesting conclusions can also be drawn from this enquiry, especially concerning the lighting level in the tunnel and the transition from daylight to tunnel lighting at the tunnel entrance.

b. THE RESULTS OF THE ENQUIRY

The enquiry itself was built up in four stages to lead the observer to the flicker effects without influencing his opinions. We shall follow these four stages in the discussion.

The *first step* was a general question on the quality of the tunnel. Nearly all drivers were satisfied with it; only 2 % had comments to make. The flickering, the interior level and the transition were each regarded by about 1 % as not being completely satisfactory.

As the *second step* the drivers were asked for details which could be considered for improvement. Here the number of observers who gave a personal opinion was considerably greater; the percentage with objections concerning the flicker, the level and the transition were 9, 3 and 6 % respectively. All other objections together amounted to 12 % so that the lighting problem must be regarded as the most serious.

The *third step* involved questions about the lighting installation, the colour scheme and the road surface. It is interesting to note that in general the question about the lighting installation did not yield much in the way of fresh information, because there were not many more comments than in the second step. They were 10, 6 and 9 % for the flicker, the level and the transition respectively. The colour scheme and the road surface only got 9 %.

The *final step* was the question about the flicker effects. It was found that 40 % of the observers had noticed flicker phenomena, 6 % of whom had been disturbed, and 18 % annoyed by it, while 16 % had noticed it but had experienced no inconvenience. Among drivers who only infrequently used the tunnel about 25 % had noticed the flicker effects, compared with 50 % of drivers who passed through the tunnel nearly every day. We have listed the percentages mentioned in Table 28.

TABLE 28

PERCENTAGES OF DRIVERS WHO MADE COMMENTS ON

	Flicker	Interior level	Transition
Step 1	1	1	1
Step 2	9	3	6
Step 3	10	6	9
Step 4	40	not enquired	

c. DISCUSSION

From the answers on the enquiry it may be noted that as a rule road users do not consciously assimilate information. Only one or two per cent have an answer to a general question. When the questioning is more direct, however, it is found that a fair number of drivers have noticed the phenomena concerned.

A second fact to note is that the low level in the tunnel interior and the great transition between the open road and the entrance zone of the tunnel cause about as much annoyance as the flicker phenomena. Nearly 10 % of drivers mentioned these effects when asked about the lighting installation. We feel that this figure is too high for really good tunnel lighting.

d. CONCLUSION

In several instances the results of this enquiry confirm the results of other investigations.

The *first* is related to the level in the interior. At the time of the enquiry the luminance level of the tunnel interior was between 5 and 7 cd/m^2; we considered this as too low a value (Section 2.1.6).

The *second* refers to the black hole effect. The enquiry was held on a bright day; so at the beginning of the tunnel the jump in the luminance would in general be between 15 : 1 and 30 : 1, values that are too high according to the results given in Section 2.1.2.

And the *third* concerns flicker effects. The flicker frequency in the tunnel for 70 and 100 km/h is 4.3 and 6.3 c/s respectively; both are within the range of disturbance mentioned in Section 2.1.5, particularly when the wave form of the luminance is considered (Section 5.3).

Further, it is worth noting that only the three details discussed in this section are not in full accordance with the requirements considered in Chapters 3 and 4. In all other respects the lighting and the total installation of this tunnel are very good. Many of the other points which we have shown to be of extreme importance, such as optical guidance, sound absorption and ventilation are not mentioned by a single driver.

Resuming we may state that the results of this enquiry agree well with the results of the other experiments quoted in this study.

CHAPTER 6

SUMMARY

The thesis discusses the lighting of traffic tunnels, which has its own special place among the subjects of lighting techniques. This special place is due to the impossibility of lighting the tunnel interior as brightly as the sunlit open roads by a method that is acceptable both technically and economically. Consequently one always has to allow for a great difference in luminance on the open road and in the tunnel. This difference of luminance may entail visual problems, first because reliable perception is only possible if the luminance of both the object to be observed and the luminance of its direct background are not much lower than the average luminance of the field of vision, and secondly because the human visual system needs some time to adapt itself to changes (particularly if they are reductions) of visual-field luminance. This matter is dealt with in the first Chapter (the introduction) of the study.

The second Chapter deals with the general aspects of tunnel lighting, and first of all the physiological aspects. The influence of the two above-mentioned properties of the eye is discussed, indicated as induction and adaptation phenomena respectively. These two groups of phenomena account for most of the requirements to be met by the lighting of tunnel entrances. A number of other aspects of importance to the quality of the entire lighting installation are discussed, such as trouble due to flicker effects, glare at tunnel exits, and nighttime lighting. Some additional aspects of a general nature are discussed in the second Chapter, though in less detail than the physiological aspects. Psychological and aesthetic aspects mainly concern the measures that can supplement a favourable effect of the lighting (such as optical guidance) and the means to avoid disturbances of the favourable effect (e.g. disturbances due to noise). The technical aspects constitute some points in which tunnel lighting differs from normal lighting techniques, e.g. choice of light sources, design of fittings, use of natural daylight. Economic aspects concern the cost and the efficiency of tunnels. It is found that, as a rule, the usually very expensive tunnels are highly remunerative, when the time saved by the traffic is expressed in cash. It is shown also that even an extensive lighting system will constitute but a small portion of the total cost of a tunnel.

The third Chapter applies the results of the investigations described in the second Chapter to the lighting of long tunnels, entrance lighting again being given special emphasis. Especially the advantage of the application of subdued daylight is pointed out. A short description of several existing tunnels is addded as an illustration.

The fourth Chapter treats the lighting of short tunnels on the same basis. It is assessed how long an unlit tunnel might be. The advantage of the use of daylight slots in the tunnel ceiling is pointed out, a system which can often be readily applied to tunnels under railways. A few examples are added.

The fifth Chapter describes the details of the experimental investigations made, particularly those covering the physiological aspects. Here, too, induction and adaptation phenomena have received special attention. The influence of flicker effects also has been examined. Finally, a model project is described, with the aid of which a number of the results have been checked under conditions closely corresponding to actual traffic conditions.

The experiments described in the fifth Chapter and summarised in the second Chapter, form the basis of the "Recommendations on Tunnel Lighting" published by the Netherlands Foundation on Illumination (Nederlandse Stichting voor Verlichtingskunde). Summaries of these Recommendations have been appended to the third and fourth Chapters of this study, covering long and short tunnels respectively.

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ERRATA

(1) Page 72, Table 16.

"Mean" column shows for $\log L_1 = 3.00$:	Amend sequence to read:
1.08	2.37
1.18	1.60
1.60	1.18
2.37	1.08

(2) Page 73, Table 17.

Invert and transpose last two values in "Mean" column to read:

0.71
0.85

(3) Page 97, line 5 up.

Change b_1' to read: b_1