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TUNNEL ENTRANCE LIGHTING

A SURVEY OF FUNDAMENTALS FOR DETERMINING THE LUMINANCE IN THE THRESHOLD ZONE

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FORWORD

During its meeting in September, 1975, CIE Technical Committee TC-4.6, Road lighting, accepted a request to add a study of fundamentals of tunnel lighting to its working programme.

A subcommittee was appointed to draft a Technical Report which would serve as a background paper for international recommendations for tunnel lighting.

The subcommittee submitted its draft of the Technical Report to Technical Committee 4.6, which reviewed and edited the document.

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SUMMARY

The purpose of this report from the CIE Technical Committee TC 4.6 is to provide information on the lighting requirements for drivers approaching the entrance of a tunnel in daytime. The report is restricted to the first stretch of tunnels, called the threshold zone. The report firstly reviews the fundamental experiments on which the 1973 CIE Recommendations for Tunnel Lighting (as far as the threshold zone is concerned) are based. New investigations are described with which the original fundamental experiments may be applied more realistically. Results of driving experiments in a real tunnel under various lighting conditions are summarized. To complete the description of methods based on visibility two recently published methods that dispense with the original fundamental experiments are reported. Finally mention is made of an approach not directly based on visibility but on traffic flow. The report does not give a straightforward answer to all problems related to the lighting of threshold zones of tunnels, it gives the state of the art and as such it will form an important background for future tunnel lighting recommendations.

RÉSUMÉ

Le but de ce rapport du Comité Technique TC 4.6 de la CIE est de fournir des renseignements sur les besoins en éclairage des conducteurs approchant, de jour, l'entrée d'un tunnel. Le rapport est limité à la première zone des tunnels, appelée zone de seuil. Le rapport revient tout d'abord sur l'expérience fondamentales ayant servi de base aux recommandations CIE 1973 pour l'éclairage des tunnels (dans la mesure où la zone de seuil est concernée). De nouvelles investigations, avec lesquelles les expériences fondamentales originales peuvent être appliquées de façon plus réaliste, sont décrites. Des résultats d'expériences de conduite dans un tunnel réel sous des conditions photométriques variées sont résumés. Pour compléter la description des méthodes basées sur la visibilité, deux méthodes publiées récemment et n'utilisant pas les expériences fondamentales originales sont rapportées. Enfin, il est fait mention d'une approche non directement basée sur la visibilité mais sur le trafic. Le rapport n'apporte pas une réponse directe à tous les problèmes concernant l'éclairage des zones de seuil des tunnels, il donne l'état de l'art et ainsi il constituera une base importante pour les futures recommandations sur l'éclairage des tunnels.

ZUSAMMENFASSUNG

Dieser Bericht wurde im technischen Komitee CIE TC 4.6 ausgearbeitet. Er informiert über die Beleuchtungsanforderungen eines Kraftfahrers, der sich am Tage einer Tuneleinfahrt nähert. Der Bericht beschränkt sich auf den ersten Teil des Tunnels, die sogenannte Einsichtstrecke.

Dieser Bericht überprüft erstmalig die grundlegenden Untersuchungen, auf denen die CIE-Empfehlungen für Tunnelbeleuchtung (1973) basieren (im Bereich der Einsichtstrecke). Es werden neue Untersuchungen beschrieben, mit denen die früheren Basisuntersuchungen realistischer angewendet werden können.

Die Ergebnisse von Fahrversuchen in bestehenden Tunneln unter verschiedenen Beleuchtungsbedingungen sind zusammengefaßt. Um die Beschreibung der Methoden zu vervollständigen, die auf der Sichtbarkeit basieren, sind 2 kürzlich veröffentlichte Verfahren aufgenommen worden, die die früheren Originalarbeiten ersetzen könnten.

Schließlich wird ein ansatz erwähnt, der nicht direkt von der Sichtbarkeit, sondern vom Verkehrsfluß ausgeht. Der Bericht enthält keine einfachen Antworten auf alle Probleme, die bei der Beleuchtung der Einsichtstrecken von Tunneln auftreten, er schildert vielmehr den derzeitigen technischen Stand und bildet einen wichtigen Hintergrund für die zukünftigen Empfehlungen zur Tunnelbeleuchtung.

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SCOPE

This report is concerned only with the matters directly related to the fundamentals of the luminance to be provided in the threshold zone, the first part of the entrance zone, of traffic tunnels.

It does not cover other important matters concerning tunnel lighting, such as fundamentals of the lighting of other parts of tunnels, including the transition zone (the second part of the entrance zone), design procedures, calculation methods, lighting equipment, lighting control, maintenance which would be dealt with in recommendations and other specifications.

Taking into account the fact that the requirements for the lighting in the threshold zone vary according to many factors, not only visual conditions of drivers, but also weather conditions, road and traffic conditions, driving customs, construction and performance of cars, etc., this report does not intend to examine and/or analyse the matters with an accuracy beyond engineering necessity, even though it is of importance from a physiological and/or theoretical view point. The report will form a background to future Recommendations for Tunnel Lighting.

A number of specific terms and symbols has been introduced and used in the report and their definition will be found in the Appendix attached to the report. Other terminology is usually in accordance with the International Lighting Vocabulary (CIE 1970).

INTRODUCTION

In order to enable a driver approaching the entrance of a tunnel in daytime to perceive visual information in the relatively dark tunnel at a sufficient distance ahead to continue safe driving, an appropriate luminance has to be provided in the threshold zone of the tunnel.

The threshold zone is defined as the first stretch of the tunnel and it is that length of bright background which enables objects in the tunnel to be perceived by an approaching driver, at a distance equal to approximately the safe stopping distance from the tunnel facade. The safe stopping distance has a strong dependence on the speed of traffic (CIE 1980).

The 1973 CIE Recommendations for Tunnel Lighting are, as far as the lighting level required in the threshold zone is concerned, based mainly on model tunnel experiments carried out in the early sixties by Schreuder. These experiments, based on the detection probability of small objects, were done with a uniform luminance surrounding the tunnel entrance. In the present report the validity of these experiments is reconfirmed (Chapter 1). For practical tunnel-lighting design purposes, however, it is necessary to compare the actual non-uniform luminance distribution of tunnel surrounds with the uniform luminance as used in the model experiments. From practical experience it has become clear that the 1973 Recommendations do not give a satisfactory answer to the question of how to do this comparison. As a result too much weight is often given to the luminance of the road surface in front of a tunnel and sometimes leads to needlessly high values in the threshold zone.

Another point that has come up since the publication of the 1973 Recommendations is connected with the fact that the relatively dark tunnel entrance and its surrounds occupy an increasingly larger part of an approaching driver's field of view. As a consequence of this, the state of adaptation of the driver's eyes decreases. In the past it was assumed that the previous 'light history' of an approaching driver played a dominant role in determining the adaptation state of his eyes. In the 1973 Recommendations, therefore, the threshold zone luminance required is determined on the basis of the situations experienced by car-drivers at three distances in front of the tunnel entrance. In the present Report, taking into account neurophysiological studies, it is pointed out that a driver's light history is less important than had previously been thought. As a consequence it is proposed in the report that the luminance required in the beginning of the threshold zone, be determined on the basis of the situation experienced by a driver at the 'safe stopping distance' in front of the tunnel (Section 3.5). This distance is, of course, dependent upon the speed of approach.

In Chapter 3 of the report a method (Narisada et.al.) is described for determining a luminance value for non-uniform tunnel surrounds that is equivalent to the luminance of the uniform surrounds of Schreuder's model (this value is called "the equivalent luminance of the uniform field, $L'1$ "). Armed with this equivalence it is possible to use the results of Schreuder's original experiments to arrive at the threshold zone luminance required for actual tunnels. The equivalent value can be obtained from the equivalent veiling luminance, L_{seq} , resulting from the non-uniform tunnel surrounds, together with the luminance of the road surface in front of the tunnel. From measurements involving various existing tunnels it is concluded that the equivalent value can be approximated, with a sufficient degree of accuracy for practical purposes, from the straightforward average luminance value in a 20 degrees cone, centred on the direction of view (this value is called "the luminance in the access zone, L_0 ") multiplied with a factor of 1.5.

Adrian recently suggested a method that dispenses with the original experiments of Schreuder. With this method (reported on in Chapter 7) the threshold zone luminance required is obtained direct from a knowledge of the equivalent veiling luminance, L_{seq} , resulting from the non-uniform tunnel surrounds. For this purpose Adrian makes use of general laboratory research on contrast thresholds of the human eye.

Both Adrian's method and the method following from combining Narisada's and Schreuder's work, enable the determination of the threshold zone luminance once the visual task (in this case the detection of objects) is defined in terms of critical contrast, observation time and size of object. Chapter 2 discusses the visual task for a car-driver when approaching a tunnel. However, the deliberations of Chapter 2 do not lead to a firm general conclusion as regards the critical visual task. In fact it is pointed out that the critical visual task (and thus in turn the lighting level required) is also dependent upon the type of lighting system in use (Chapter 2.3). However, for identical critical contrasts and observation times and similar-sized objects, the lighting level required in the threshold zone as obtained using the Adrian method is different to that obtained by the Narisada-Schreuder method. Although some possible reasons for this discrepancy are indicated in the report, it is still the subject of discussion in TC-4.6. It is, important to emphasize, however, that both methods are based on a same parameter (the equivalent veiling luminance) to take the non-uniform tunnel surrounds into account. Very recently published work of Monie et.al. also makes use of this parameter. This work is based on an equivalence of visibility in the threshold zone and at the end of a hypothetical long tunnel where a driver is perfectly adapted (analogous to an open road during night). Since this work is not directly based on the detection possibility of a defined test object, a direct comparison with the results of the previously mentioned methods is not possible (Chapter 7).

Chapter 4 describes the results of driving experiments, based on detection of objects under different lighting conditions, in an actual tunnel (Bonomo). It appears that one has to take into account, as far as the detection of objects is concerned, not only the factors mentioned so far but also the effect of the atmospheric haze (and light scattering in car wind-screens). It also follows that at lower speeds, the lighting requirements are less stringent. The latter conclusion also follows from the above-mentioned study of Monie et.al.

The detection of small objects should not form the sole basis for tunnel lighting recommendations. For example drivers should also feel confident enough to approach and enter a tunnel without slowing down too much. The report gives information on this aspect by describing a study (Gallagher et al.) in which the deceleration behaviour of motorists approaching road tunnels was measured under different conditions of lighting (Chapter 6).

In conclusion, although the present report does not give a straightforward answer to all problems related to the lighting of the threshold zones of tunnels, it is felt that it will form an indispensable background for future tunnel lighting recommendations.

In this report, various different concepts of luminance and time are used. In order to avoid possible confusion, the symbols to be employed are summarised in an appendix to this report. It must be noted, however, that symbols in the appendix are valid only for this Technical Report.

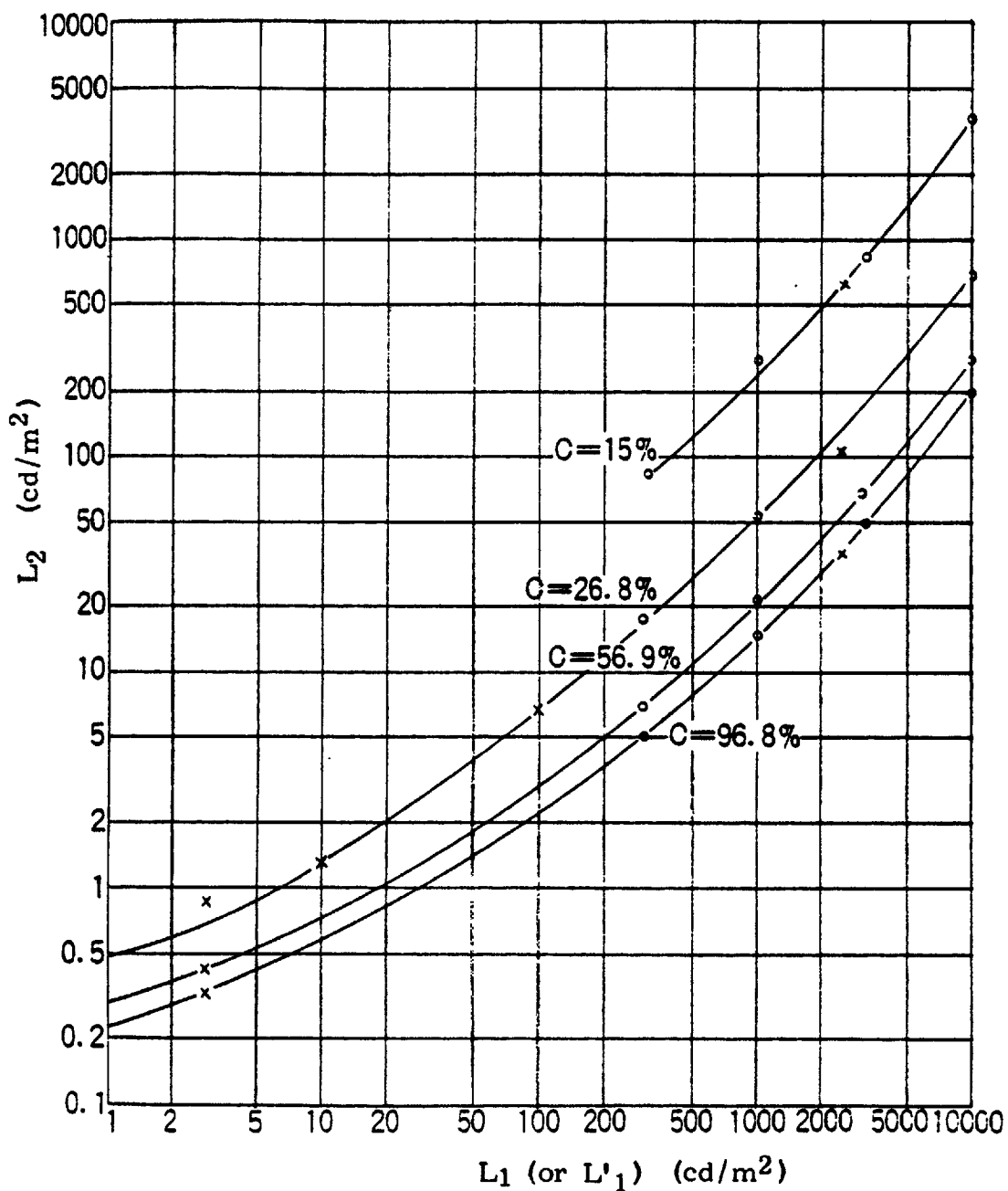


Figure 1. Relationship between the luminance of the standard field (L_1) and the luminance in the tunnel (L_2). The luminance contrast of the object (C) is taken as a parameter (Schreuder 1964).

Chapter 1: RELIABILITY OF THE FUNDAMENTAL EXPERIMENTS

1.1. Experiments and the results

In the experiments carried out by Schreuder (1964), on which the 1973 CIE Recommendations for Tunnel Lighting are based, an observer sat in front of a (uniform) field of luminance (L_1) described already in this paper. The observer's eyes were fully adapted to the luminance of the standard field before observations began.

In the centre of the standard field a square opening of 1 degree x 1 degree was provided with a mechanical shutter. When the shutter was closed, its luminance was also L_1 . After the pre-adaptation to the luminance L_1 , the shutter was opened for 0.1 second and revealed a small field (1 degree x 1 degree) of luminance L_2 together with an object, 7' x 7' in size, with a luminance contrast C against the small field of luminance L_2 .

The observer was asked to state whether he could perceive the object or not. The procedure was repeated for each value of C , and for a number of values of L_1 and L_2 . The results of the experiments thus obtained are shown in Figure 1, as relationships between the luminance of the standard field (L_1) and the luminance of the background (L_2) against which the object is just to be perceived.

In the figure, the luminance contrast (C) of the object : $C = 100 \times (L_2 - L_3)/L_2$ (%), is taken as a parameter (L_3 : the luminance of the object to be perceived).

It was found that, in order to enable the observer to perceive the object during its presentation, the luminance to be provided in the tunnel (L_2) as the background of the object must be higher than the value of $k \times L_1$, and that the value of k is roughly constant over a wide range of L_1 between 100 cd/m² and 5 000 cd/m².

The value of k varies according to the size of the object to be perceived, the duration of the object's presentation, the luminance contrast (C) of the object and the probability of perception (P). As a matter of fact, however, at lower and higher levels of L_1 , k is necessarily higher for a given luminance contrast (C). This suggests a physiological effect rather than experimental scattering. The subject will be further discussed in TC-4.6 in the future.

Narisada and Yoshimura (1974) have carried out similar investigations in their laboratory under similar visual conditions for a similar visual task of $C = 27.6$ (%). In Figure 2, their results are compared with those of Schreuder and it can be seen that both results agree with each other within the limits of experimental accuracy.

In addition, Schreuder (1971) compared his own data with the results of the experiments by Nakamichi and Narisada (1967) (See Section 3.2). As shown in Figure 3, Nakamichi et al.'s results give the relation between the background luminance (L_2), necessary to perceive the object, and the time (t_3) elapsed from the moment at which the observer started to fix

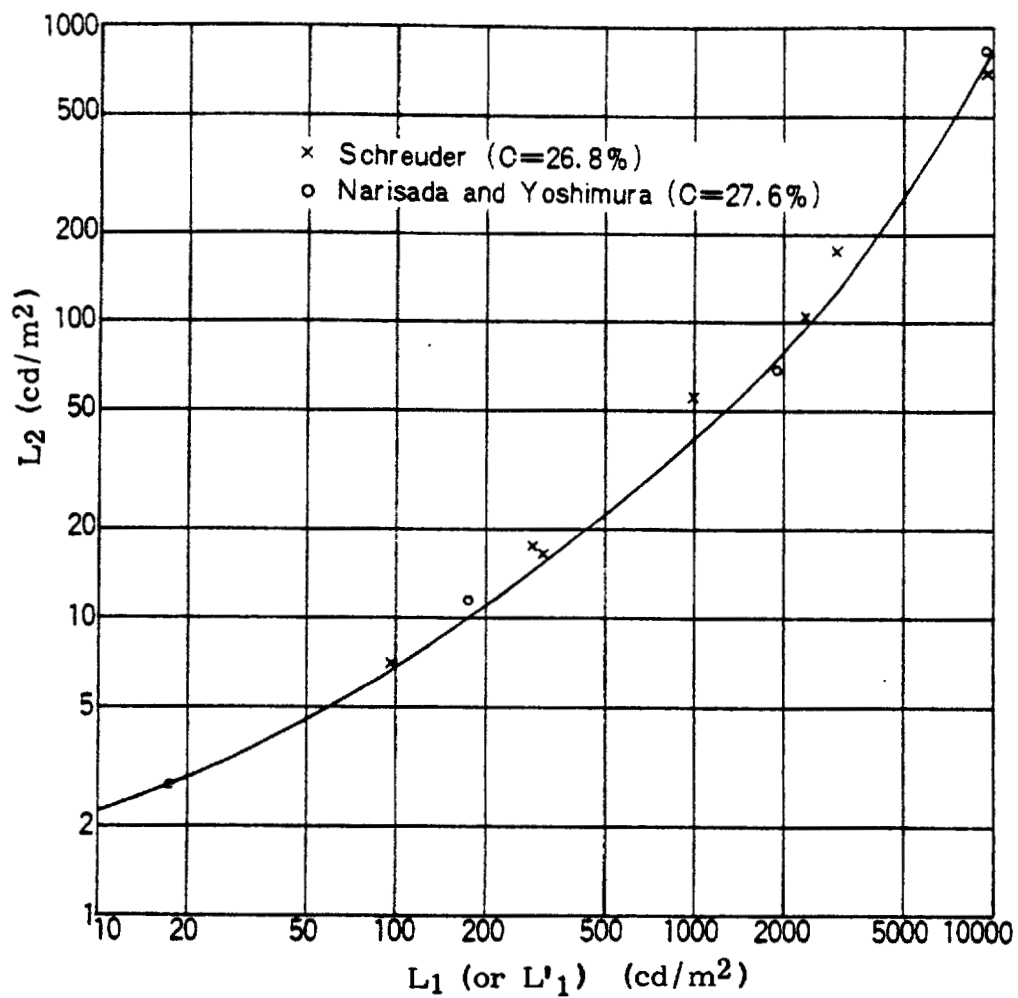


Figure 2. Comparison of data obtained by Schreuder with those by Narisada et al.

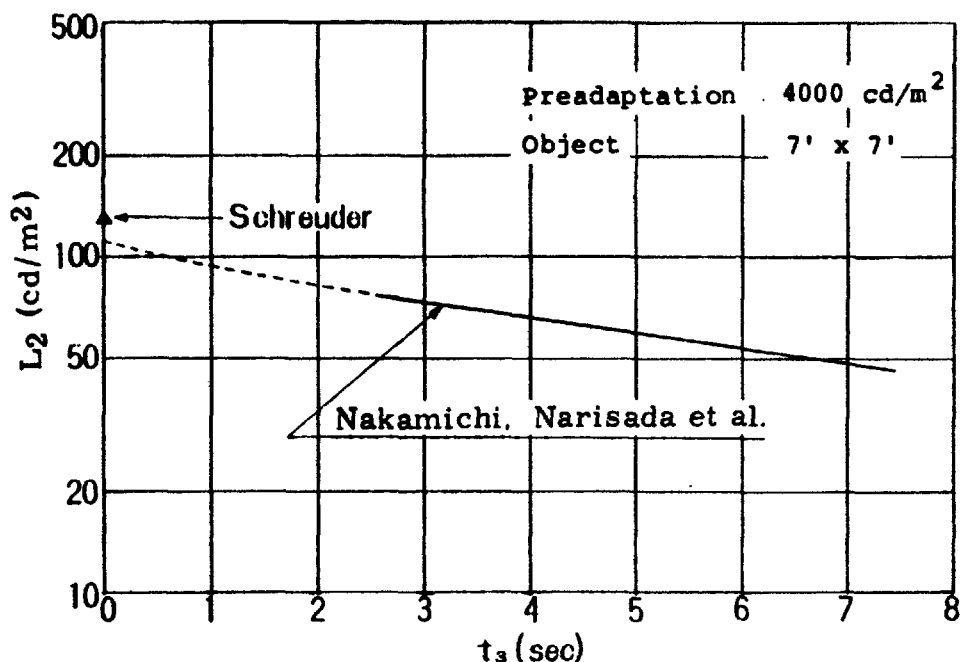


Figure 3. Comparison of the results by Nakamichi-Narisada-Yoshikawa and by Schreuder. The curve obtained by Nakamichi-Narisada-Yoshikawa is extrapolated to $t_3 = 0$ second. Schreuder's result under the similar visual conditions is given as a black triangle.

his visual attention on the tunnel mouth. In their experiments, the size of the tunnel mouth as it was seen at a distance of 150 metres from the portal was gradually increased as time elapsed, to simulate the driver's perspective during approach at constant speed of about 70 km/h.

Schreuder extrapolated Nakamichi et al's curve as in Figure 3 toward the direction of shorter time (t_3). By comparing his data obtained at $t_3 = 0$ sec. with the intersecting point of the extrapolated curve by Nakamichi et al at $t_3 = 0$ sec., Schreuder stated that his data for L_1 smaller than about 2000 cd/m² agree fairly well with the results of the experiments by Nakamichi and Narisada (1967).

Schreuder (1964) also showed good agreement between the results of the laboratory set-up and of a dynamic scale model.

Further, his results agree again for L_1 smaller than about 2000 cd/m² well with those by Mader and Fuchs (1966) who gave the following relationship:

$$L_2 = k L_1^{0.9} \quad \text{with } k = \text{constant.}$$

1.2. Possible influence of the size and the presentation time of the simulated tunnel mouth:

In the fundamental experiments, a simulated tunnel mouth, square in shape, (1 degree x 1 degree) was provided and it was presented for only 0.1 second (simultaneously with the presentation of the square object in the simulated tunnel) in the centre of a uniform screen.

Under actual traffic situations during approach, however, the tunnel mouth is seen not momentarily but throughout the approach in the driver's field of view and its apparent size increases gradually as he gets closer to it.

If one compares these situations with the manner with which the simulated tunnel mouth was presented to the observer in the experiments, a question may arise whether the visual conditions of the driver under actual traffic situations during approach were appropriately represented in the experiments. In this connection, taking the derivation procedure of the luminance in the threshold zone (to be described later in this report) into account, the function of the experiments must be understood correctly.

It must also be understood that, in relation to the derivation procedure the basic aim of the experiments is NOT necessarily to reproduce visual conditions under actual traffic situations during approach but to provide visual conditions for the observer's eyes under which their adaptation can be represented by the luminance of the uniform screen (at the centre of which the simulated tunnel mouth was presented) with an engineering accuracy. Answers for the above question will therefore be given later in this report in Section 3.5.

To achieve the aim, the experiments were to be conducted in such a manner that;

- as the background of the object to be perceived, a luminance (L_2) which was much lower than the luminance to which the observer's eyes were pre-adapted (= the luminance of the uniform 'standard screen', L_1) could be provided in the simulated tunnel mouth,
- the state of adaptation of the observer's eyes during observation was to be as stable as possible and was not influenced by the presentation of the much lower luminance and of the object in the simulated tunnel.

For this reason, the combination of a very small sized tunnel mouth and its momentary presentation was chosen in the experiments.

As a consequence, relationships between the luminance of the uniform screen (= standard field, L_1) and the luminance of the object background (= the luminance in the simulated tunnel mouth, L_2), as shown in Figure 1, were constructed, keeping the influence of the tunnel mouth at a negligible level.

1.3. Conclusions

Based on the comparisons above, it can be concluded that the experimental basis of the 1973 CIE recommendations is reliable as far as the experimental conditions applied are concerned, provided that the visual task to be performed by the approaching driver is realistically represented in the experiments. In the following, therefore, the appropriateness of the visual task represented in the fundamental experiments will be examined.

Chapter 2: APPROPRIATENESS OF THE VISUAL TASK OF THE DRIVER REPRESENTED IN THE FUNDAMENTAL EXPERIMENTS

In order to represent the most critical visual task which can possibly occur in actual driving, in the fundamental experiments by Schreuder (1964), a square object with an angular size of $7' \times 7'$ was used and presented to the observer in the simulated tunnel of size 1 degree $\times$ 1 degree for only 0.1 second.

The size of the object was taken to represent an obstacle of 0.2m $\times$ 0.2m located on the road surface 100 metres ahead. The size of 0.2m corresponds roughly to the least clearance between the road surface and the body structures of normal cars. This object is used to describe the visual task. However this object should not necessarily be identical to the critically dangerous obstacle for road traffic.

The duration of the object's presentation of 0.1 second was chosen so as to maintain a stable state of visual adaptation during the observations (as mentioned in 1.2). The size of the simulated tunnel was 1 degree $\times$ 1 degree, just because of the stable state of adaptation. The duration also was chosen to simulate the normal visual behaviour undertaken by the driver under actual dynamic driving conditions when he does not know where the obstacle(s) to be perceived will appear.

Finally, in order to derive the luminance value (L_2) recommended in the threshold zone in the 1973 CIE recommendations, a value for the luminance contrast (C) of 20% was chosen. (It must be noted that the aim was to select an object to represent the critical aspects of the visual task, and not necessarily the most dangerous obstacle on the road.)

Further, taking into consideration the general tendency of regression curves for observation results, that the luminance values necessary to perceive the object start to increase steeply for a small increase of probability of perception in the region where the probability exceeds about 80%, a probability of perception of 75% was chosen for determining data points from experimental results.

In this section, each of the parameters--the size of the object, the duration of the object presentation, the luminance contrast of the object and the probability of perception--will be discussed in some detail.

2.1. The size of the object:

a) Influence of the size of the object on the luminance to be recommended:

Using a similar experimental set up mentioned, Schreuder (1964) has investigated the influence of the apparent object size, employing a square object of luminance contrast (C) between about 10% and 90%, with an angular size between $7' \times 7'$ and $28' \times 28'$ under various conditions of luminance of the standard field (L_1).

The curve shown at the top of Figure 4 was constructed from his results for the object of $C=30\%$. (The absolute values indicated by the curve, however, cannot be applied for practical purposes, because the experiments did not necessarily represent visual conditions during driving.)

Based on the experimental results obtained by Blackwell (1946), for the conditions of $L_1=L_2$, Adrian (1969) derived a formula which gives the relationship between the luminance difference threshold (ΔL), the angular size of the object to be perceived (α), and the luminance of the object background ($L_2 = L_1$).

Using this formula, the relationship between the angular size of the object (α) and the minimum luminance of the background (L_2) which allows perception of the object was constructed and shown at the bottom of Figure 4 for an object with a luminance contrast of 30% as an example.

In Figure 4, the results obtained by Schreuder and those by Blackwell-Adrian appear not to agree with each other. As will be discussed later in this report, however, this is due, mainly, to the fact that entirely different experimental conditions were applied in the two investigations.

Using a dynamic tunnel lighting model described already by Narisada and Yoshikawa (1974), and by Narisada, Inoue and Bjorset (1977), Narisada conducted a series of experimental observations on the adaptation effect of the driver's eyes after entering the tunnel in daytime (reported by Tanabe, Hatayama et al., 1977).

In the experiments, the observer's eyes were pre-adapted to a constant luminance by focusing his visual attention onto a large uniform screen with a luminance of $4\ 000\text{ cd/m}^2$ located on the left-hand 'hard shoulder' of the access road in front of the observer at the starting point of the simulated driving.

After sufficient pre-adaptation, a tone signal was sent to the observer so as to turn his gaze from the uniform screen to the access road, as in actual driving, and then (by moving the road) the seated observer started to 'drive into' the simulated tunnel at an apparent speed of between 40 and 80 km/h.

In accordance with the prepared experimental procedure, in

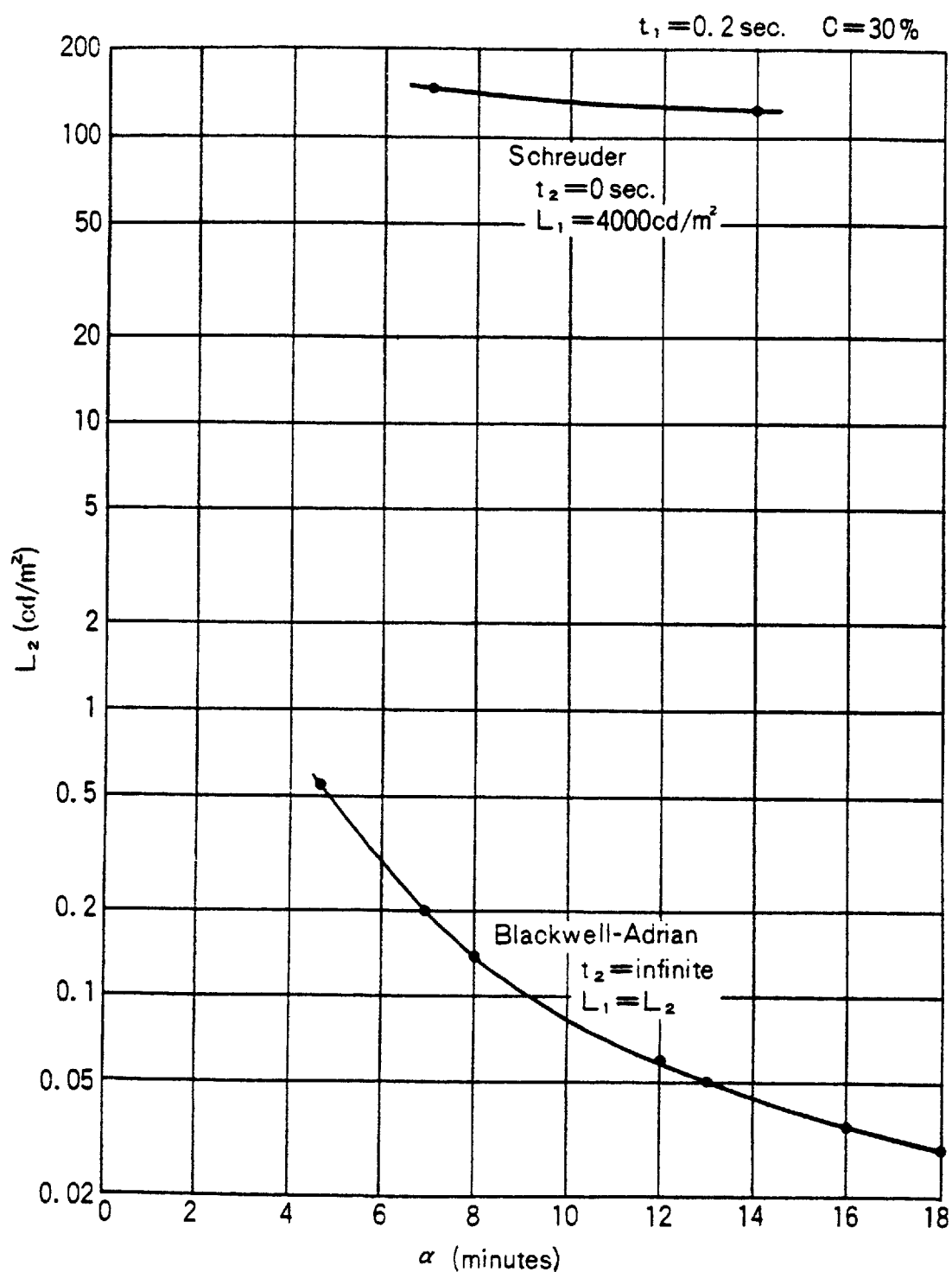


Figure 4. Comparison of data by Schreuder with those by Blackwell-Adrian.

the model tunnel, one of seven steps of the luminance between 0.11 and 10.0 cd/m² was provided in a random order, uniformly on the road surface over its full length.

The objects to be observed which were provided in the moving road were square in shape, having an angular size of 12.9, 6.9 and 4.7 minutes. The luminance contrast of the object was 30%. They were presented momentarily, for 0.2 second, at constant intervals of 3.0 seconds during the simulated driving from its beginning. The responses of the observer to the presentation of the objects were recorded on punch tape, automatically and successively, with reference to the moment when the objects were presented and observed.

Based on the results of the observations recorded, the probability of perception was calculated at every point with intervals of 3.0 seconds.

As a result, it was found that the probability increased gradually as the time elapsed from the moment when the observer entered the tunnel for each set of experimental conditions, composed of combinations of luminance in the tunnel, size of the object and driving speed; and that the probability was not influenced so much by the driving speed as by the luminance and the size of the object.

Finally, the time elapsed at which the probability reached a value of 90% was picked out for each luminance provided for each size of the object. Consequently, relationship between the luminance in the tunnel to ensure a probability of 90% and the time elapsed from the moment at which the observer entered the tunnel was drawn for each size of the object and shown in Figure 5 as three curves.

In the following, the data shown in Figure 5 will be compared with that of Schreuder and of Adrian-Blackwell.

It is self evident that it is not appropriate to compare such data for a short elapsed time (t_2) on a log-log scale as in Figure 5.

In Figure 6, the data is re-plotted on a semi-log scale. In the figure, the ends of the three curves and the data points by Schreuder (1964) taken from the curve at the top of Figure 4 can be connected by smooth curves as shown by dotted lines in the figure. This implies that the data obtained by Schreuder and by Narisada (reported by Tanabe et al.) have a similar tendency with a fair agreement.

From the results shown in Figure 5, the relationship between the angular size of the object and the necessary luminance in the tunnel (L_2) as shown in Figure 7 was constructed. The time elapsed (t_2) was the parameter.

In the figure, the results obtained by Schreuder and by Blackwell-Adrian, corrected for the same experimental conditions, are shown again for comparison.

(The absolute luminance values given in Figure 7 cannot be taken as a basis of the luminance value to be recommended for the interior zone of the tunnel, because the 'visual conditions' reproduced in the dynamic tunnel lighting model

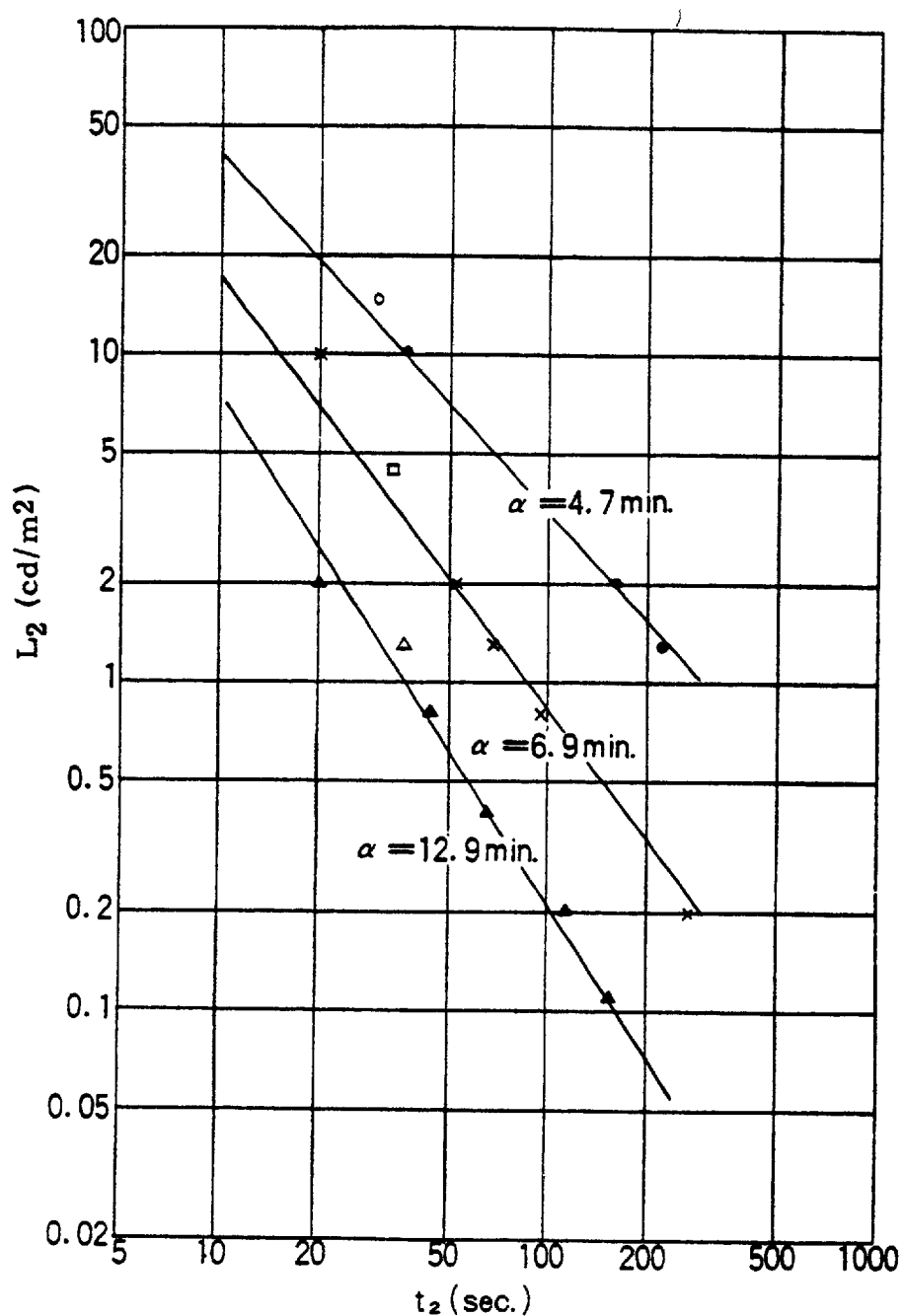


Figure 5. Relationship between the time elapsed from the moment when the observer 'entered' the tunnel (t_2) and the luminance in the tunnel (L_2) to perceive objects with various angular sizes (Preadaptation luminance = 4 000 cd/m^2).

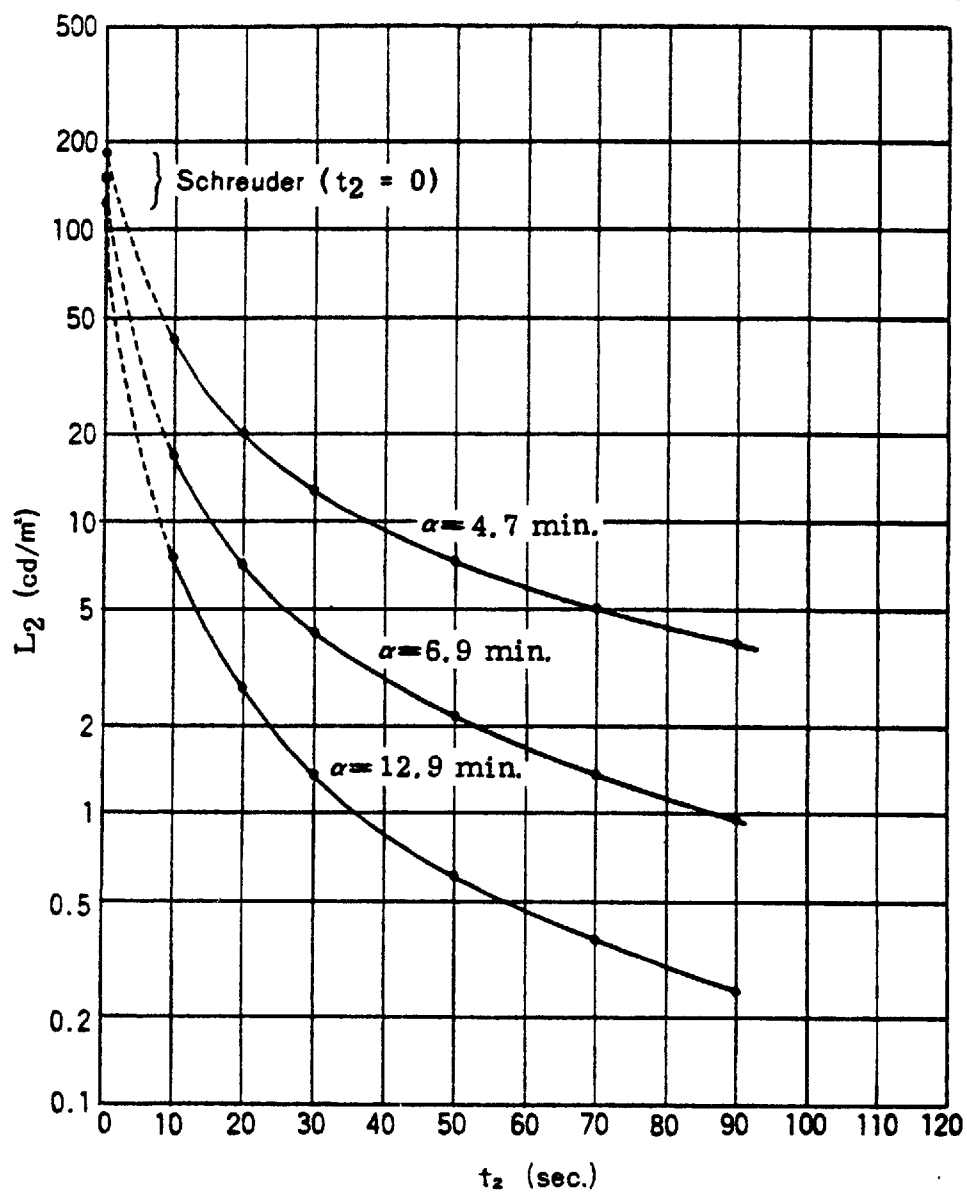


Figure 6. Re-plotting of the data shown in Figure 5.

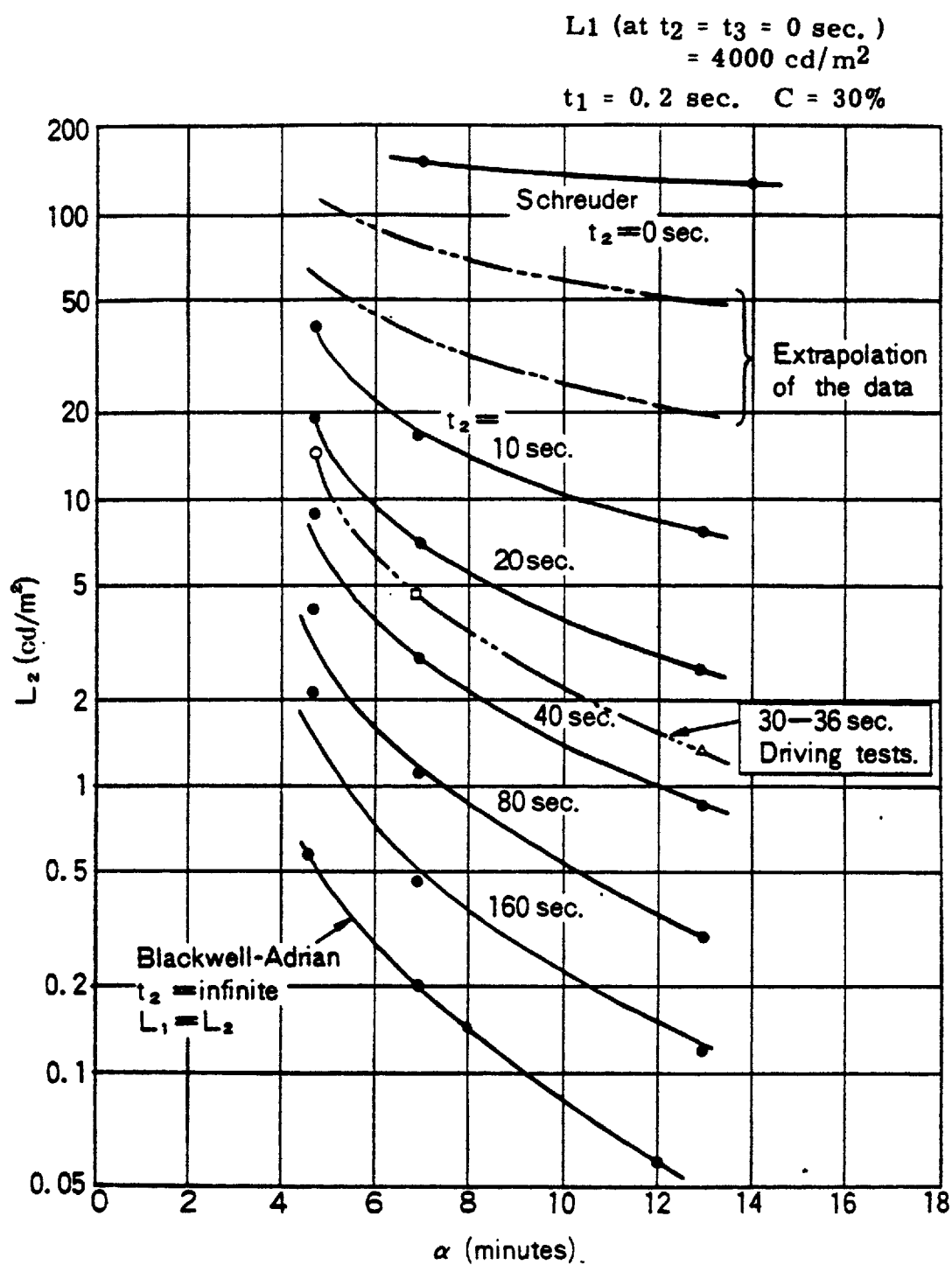


Figure 7. Comparison of data by Narisada-Tanabe et al., Schreuder and Blackwell-Adrian.