Practical Determination of Tunnel Entrance Lighting Needs

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The determination of the field factor that relates the visibility conditions in the laboratory to the visibility conditions for a car driver approaching the entrance of a long tunnel is discussed. Experimental results are given from research in the Netherlands. Suggestions are given for incorporation of these results in design methods for the lighting of tunnels.

During the day, the visual systems of car drivers and cyclists are adapted to the very bright daylight. When they enter a tunnel, their visual systems must adapt to the low luminance in the tunnel interior. The adaptation is usually disturbed by two factors: (a) the bright surroundings of the tunnel entrance restricts the adaptation, and (b) the adaptation to a relatively low luminance level may take considerable time.

The entrance at day is the major visual problem of tunnels for motor traffic. When the tunnel entrance (the threshold zone) is not adequately lit, the entrance is a "black hole," where no details can be seen (*1,2*). Usually the most crucial part of tunnel lighting recommendations is the entrance lighting during the day (*3–6*).

The black-hole effect results from several characteristics of the human visual system. First, it takes time—often a considerable amount—for the visual system to adapt from one level of brightness to another. Second, the perception in a dark part of the field of view is hindered when the dark area is surrounded by bright areas. These bright parts act as "glare sources," causing a light veil over the field of view. The effect of this veil can be expressed in terms of its luminance.

When considering the daytime entrance lighting, one must take into account one of the peculiarities of the visual system. When the visual system is adapted in a steady state to luminance values between 30 and 3000 cd/m^2, adaptation to another value in this range takes only a short time. Usually, it appears instantaneous. This may not always be the case, as was suggested also by Bourdy et al. (*7*,p.35;*8*). When, however, the steady-state adaptation level is higher than 3000 cd/m^2, it is well established that the adaptation may take considerable time; for high values (8000 cd/m^2 or more), it may take up to half a minute. This peculiarity leads to two distinct theoretical frameworks and to two distinct systems of tunnel lighting.

The first theoretical framework is the steady-state theory. The principle is that the steady state of the visual adaptation that builds up on the open road when approaching the tunnel is the determining factor for assessing visual problems at tunnels, as well as for solving them. This framework was developed in the 1960s by Schreuder and Narisada, more or less independent of each other; the discrepancies that appeared to exist proved to be no more than differences in the parameters. The steady-state theory was the basis for the original International Commission on Illumination (CIE) recommendations (*5*) and for many national codes in different countries.

The second theoretical framework is the stray-light theory. The basic idea is that near a tunnel entrance the visual system adapts immediately and that the only restriction in visual observation is the veil that extends over the field of view. The veil is thought to result from the light that is scattered in the visual system (eye lens and eye fluids). The idea was described in the late 1930s, and it was developed into a tunnel lighting system by Adrian. The revised CIE tunnel lighting document (*6*) is based on this principle, as are several national codes. The system is based on one of the different glare formulas currently in use. Adrian uses the Stiles-Holaday formula of the 1930s, and so do the French recommendations (*9*). Measurements are usually based on the almost equally old Fry formula, whereas the new recommendations of the Netherlands are based on the recent Vos formula (*4*). It should be stressed that as a source of stray light, the atmosphere and the car windshield often are more important than the ocular media. These aspects have been studied in considerable detail in France (*10,11*) and in the Netherlands (*12,13*).

The steady-state and stray-light theories are often considered to conflict; they are, however, conjoint and they will be described the following chapters.

STEADY-STATE THEORY

When the visual system of a car driver who approaches a tunnel is adapted in a steady-state mode to a very high level of luminance (L_1, e.g., 8000 cd/m^2 or more, corresponding to full summer sun on cement concrete or to sun on snow), for many seconds the adaptation is almost unchanged when the driver enters the tunnel. To ensure that the driver can look into the tunnel while still outside (to avoid the black-hole effect), the luminance in the threshold zone (L_2) must be high as well. Experiments made by Schreuder (*1*) and reconfirmed by Narisada (*14,15*) indicate that L_1/L_2 should be lower than 10 in high-speed tunnels and lower than 15 in other important tunnels. These values are taken as the basis for the original CIE recommendations (*5*).

There appears to be a conflict between the results of the experiments of Schreuder and Narisada. A precise analysis shows, however, that the differences in the results—and, even

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more so, the differences between the recommendations based on these experiments (the CIE and the Japanese recommendations)—are mainly differences in the selection of the parameters. As Schreuder has shown (*16*), the actual research results are almost identical when they are normalized for the time of observation, the preadaptation time, and the size and contrast of the object. A difference in the parameters relates to the conditions for which the research results are used. CIE focuses on tunnels in a flat, open country, where the adaptation to the dark entrance can begin at only a very short distance in front of the tunnel; the Japanese studies refer primarily to tunnels in mountainous areas, where the adaptation may begin at a much longer distance.

STRAY-LIGHT THEORY

The second theoretical framework is the stray-light theory. The influence of stray light on perception is a well-established fact. The first to point out the importance of stray light for tunnel lighting was Adrian (*17,18*). The lighting design system based on it is a.o. described in the new CIE guide (*6*).

When the luminance in the field of view of a driver approaching a tunnel is between about 30 and 3000 cd/m², the visual system adapts very rapidly—almost instantaneously—to other luminances within that range. When the driver is close enough to the tunnel portal so that he or she can fix the entrance opening (at a distance of 50 to 100 m), the visual system adapts to the luminance in the tunnel entrance: the threshold zone luminance (L_2). The value of L_2 should be selected in such a way that the appropriate observations can be made, taking into account the fact that the driver has a driving task to fulfill and that the time for observation of objects is limited.

L_2 can be assessed when the threshold of visibility is known and when the field factors that allow for the influence of driving and of the restricted observation time are known as well.

If one would install a lighting scheme with a value of L_2 assessed in this way, the visibility in the tunnel entrance would be unacceptably low. The most important factor has not yet been considered: the stray light that originates from the surroundings outside the tunnel. That light is scattered, and it forms a veil over the complete field of view. The veil increases all luminance values with the same amount (the equivalent veiling luminance, L_{seq}). All contrasts between objects and backgrounds decrease; consequently, objects are more difficult to see.

The veil consists of three important parts:

- The light scattered in the eye (the entopic stray light),
- The light scattered in the atmosphere, and
- The light scattered in the windshield of the vehicle.

All three parts are highly variable: the entopic stray light depends heavily on the angle between the source of the scattered light and the line of sight, the conditions of the eyes of the observer, and on the age of the observer. The atmospheric stray light depends heavily on the transmission of the atmosphere, on the meteorological visibility, and on the type of particles floating in the atmosphere (the aerosol). The windshield scatter depends heavily on the maintenance condition of the vehicle, on the windshield itself, and on the windshield wipers and washers—and of course on the driver's willingness to use them. In all three cases a variation of a factor of 10 can easily be found under circumstances that are otherwise perfectly normal.

In bright weather the luminous veil over the field of view poses the heaviest requirements on the lighting of tunnels. Such a veil reduces all contrasts in the field of view, including the objects that may be in the tunnel, "behind" the veil. The only way to ensure adequate visibility is to increase the threshold zone luminance (L_2) in the tunnel entrance. This counteracts the contrast reduction caused by the veil.

The veil and its causes, assessment, and composition are described in detail elsewhere (*19*). A brief summary follows.

Contrast is defined as

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

Here, C is the intrinsic contrast, and L_2 and L_3 are the luminances of the background and of the object to be perceived.

When a veil with a luminance L_d is present, all luminances are increased by L_d. The "visible" (proximal) contrast C' becomes

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

so

$$C' = \left(\frac{L_2}{L_2 + L_d}\right)C$$

Because $L_d > 0$, $C' < C$. In real traffic, an object can be seen only when C' is larger than the practical threshold of visibility. This practical threshold is larger than the "real" threshold (C''), such as is measured in the laboratory. The relationship is usually described by means of a field factor (f). The object is visible when $C' > fC''$. The minimal value of L_2 can be found as follows:

$$L_2 = \frac{L_d f C''}{C - fC''}$$

This formula will be called the basic formula. Obviously, L_2 can be established when the different values in this formula are known. Practice indicates that particularly the field factor (f) is important to know.

C is the intrinsic contrast of the objects that must be visible. C is chosen arbitrarily, usually 0.2 or 0.3. Such contrasts may represent such traffic obstacles as stones, boxes, and exhausts. Retroreflective devices and vehicle marker lights show much larger contrasts (apart from the negative sign).

Schreuder and Oud (*19*) show that the veiling luminance is composed from several parts:

$$L_d = L_{adef} + L_{eye} + L_{atm} + L_{glass}$$

where

L_{adef} = adaptation deficiency, that is, the degree to which the adaptation lags when the luminance in the field of view changes;
L_{eye} = ocular stray light;
L_{atm} = stray-light components of the atmosphere; and
L_{glass} = stray-light components of the vehicle windshield.

As indicated earlier, it is customary in flat countries to consider L_{adef} equal to 0. Details of the other components of L_d and their measurements are given in the literature (*12,13,20*).

The basic formula given for L_2 could not be used in practice because the field factor was not known accurately enough in the design stage of the tunnel. Some researchers used values that were based loosely on physiological studies that were irrelevant to tunnel lighting conditions. In fact, most recommendations are based on the selection of a number of standard or "nominal" conditions. The selection is somewhat arbitrary and reflects a policy decision as to what is the borderline between acceptable and unacceptable risk. Nevertheless, this procedure led to many outstanding tunnel lighting schemes.

FIELD FACTOR

At present, the field factor seems to be the major unknown factor in tunnel lighting design. Attempts by several researchers to assess the field factor either on the basis of physiological research (*21*) or on practical measurements (*10*) did not yield results that were accurate enough for design purposes. To fill this gap in the knowledge, special experiments were made in the Netherlands and in Japan, using a similar experimental setup.

When the formula for L_2 is reconsidered, it is clear that all of its elements can be either measured at a tunnel or assessed on the basis of the tunnel lighting design. Thus, the luminance in the threshold zone of the tunnel, the value needed for the tunnel lighting design, can be determined. The formula runs

$$L_2 = \frac{L_d f C''}{C - fC''}$$

As indicated, all items in the formula are known or can be found, apart from the field factor. The experiments described here are designed to find the field factor. For the determination of f, the basic formula is rewritten as

$$f = \frac{L_2 C}{C''(L_d + L_2)}$$

In the experiments to establish f, C represents the value of the intrinsic contrast of the object that can just be seen.

EXPERIMENTAL SETUP

Experiments were recently conducted in the Netherlands and in Japan. The Dutch experiments, which had the characteristics of a field test, will be described here. The experiments were done in 1989 in the tunnel in Dordrecht, a medium-sized town in the western part of the Netherlands. The experiments and the results are described by Schreuder (*22*), and a further analysis of the results is also given by Schreuder (*23*).

At the outset it was required that the observer be simultaneously the car driver. The measurements were made in normal traffic to ascertain that the driving task would be measured. The setup consisted of two cars that drove through the tunnel at a fixed speed and a fixed interdistance. In the front car was the object to be observed (a set of 0.25-m-high matte-gray numbers from 1 to 6 with decreasing contrast from 0.78 to 0.06); in the second car were the driver-observer and registration equipment. The numbers were visible continuously; every 1.5 sec the driver had to indicate the number with the lowest contrast that he or she could just perceive. All relevant data were recorded on one video recorder either directly or by radio link; data included the position and interdistance of both cars, their speeds, the daylight level, the lighting mode in the tunnel, the traffic intensity, the visibility, and the serial number of the test.

This setup differs in two respects from normal traffic. First, the observer is aware of taking part in an experiment, and second, the object is continuously visible. Studies on the attention and vigilance of drivers near tunnels—including eye-marker studies—do suggest, however, that in normal traffic, drivers near tunnels always focus their attention, and their gaze, at the tunnel (*14*). It is questionable whether this setup could be applied on normal open roads.

The experiments included a number of lighting measurements in and near the tunnel and the separate measurement under laboratory conditions of the contrast sensitivity threshold (C'') for all observers.

EXPERIMENTS

The field tests were made in the Drecht Tunnel in Dordrecht on July 4 and 5, 1989, between 6:00 a.m. and 8:00 p.m.—that is, from dawn to dusk. The weather was exceptionally bright and clear: the highest illumination in the open was more than 110,000 lux—almost a record; the meteorological visibility was well over 40 km most of the time. The Drecht Tunnel is a 2- by 4-lane tunnel 400 m long with pronounced horizontal and vertical curvatures. The lighting consists of several continuous rows of fluorescent tubes reinforced with high-pressure sodium lamps near the entrance. The lighting has been described by Foucart (*24*). It should be noted that since then the lighting has been renovated and the lighting levels have been reduced.

More than 150 experimental runs were made, each consisting of two passes through the tunnel. The total was 275 good measurements. The driving speed was 90 km/hr; the distance between the cars was between 60 and 80 m. During the measurements, the lighting levels outside and inside the tunnel were changed—the outside level as a result of the changes in natural daylight, the inside by selecting one of the available six lighting (switching) modes.

RESULTS

The results of the lighting measurements are given in Tables 1 and 2.

The veiling luminance (L_{seq}) is measured with a Pritchard luminance meter with a Fry glare-lens attachment. The average result was L_{seq} = 320 cd/m^2 (reduced by E = 100,000 lux). L_{seq} is also approximated with the standard equipment installed at the tunnel for the light control. Here, the average luminance is assessed in a measuring field of 7 by 14 degrees. This luminance is called L_p. L_p is measured continuously, and it is noted down in (arbitrary) scale units. It is therefore necessary to calibrate L_p in terms of L_{seq}. The measured known value of L_{seq} (320 cd/m^2) corresponds with 74 scale units of the control equipment. Using some "smoothing," the L_p-values given by the device could be calibrated in values of L_{seq} (Table 3).

TABLE 1 VALUES OF ILLUMINATION IN DRECHT TUNNEL (lx)

mode	distance 0-60m	60-100m	100-160m	160-400m
1	120	120	120	120
2	220	220	220	220
3	427	427	220	220
4	1288	1288	427	220
5	2303	1288	427	220
6	4427	2303	821	220

TABLE 2 LUMINANCE AND ILLUMINANCE VALUES IN THRESHOLD ZONE OF DRECHT TUNNEL

mode	left wall	right wall	road	average	E	E/L
1	5,5	5,5	5	5,3	120	22,6
2	13	10	12			
				12,3	220	17,9
3	14	14	11			
4	33	23	27	28	427	15,3
5	68	54	44			
				58	821	14,2
6	71	59	54			

Average of tubes for North- and South bound traffic. E: from Table I.

TABLE 3 CALIBRATION OF MEASURED L_p-VALUES IN TERMS OF L_{seq}-VALUES

light level outside		L_p (scale values) (interpolated)	L_{seq} (cd/m^2)
transition	0 >> 1	2,5	11,29
level 1		8,2	37,04
trans.	1 >> 2	15,0	67,76
level 2		21,6	97,57
trans.	2 >> 3	28,3	127,83
level 3		36,4	164,42
trans.	3 >> 4	45,3	204,62
level 4		59,3	267,86
trans.	4 >> 5	75,3	340,13
level 5		92,2	416,47
trans.	5 >> 6	113,4	512,23

The results of the measurements of the contrast in the tunnel are given in Table 4. Values are the average of all measurements for each value of the outside and the inside level. Not all combinations are represented: the lowest inside levels are missing at high outside levels. For reasons of road safety, these have been excluded from the measurements, because the measurements were made in normal traffic.

To determine f, the contrast as measured in the threshold must be established. The first two measuring points were excluded in view of the penetrating daylight. C is determined as the average for the points 3 to 9.

The threshold of the contrast sensitivity was assessed separately for all subjects that took part in the measurements, using a sinusoidal grid. In the first analysis the average value of C'' was used. In the final analysis each observer's own value of C'' was used.

In the tentative analysis (*22*), several shortcuts were taken. As a preliminary result, a value of f = 4,5 was given. A more precise analysis, in which the influence of a number of experimental and environmental factors was taken into account, did produce the value of f = 6.044, or—rounded off—f = 6.

The experiments in Japan produced a similar value for f. However, further work is needed to make a more accurate comparison between the data from Japan and those from the Netherlands. The preliminary results of the Japanese measurements are given by Yoshikawa (*25*).

CONCLUSIONS

It can be concluded from the experiments that the value of the field factor is f = 6.

This seems to be a reasonable representation of the experimental data. When applied to the Drecht Tunnel, the result is that the actual tunnel lighting scheme (where the luminance in the threshold zone is coupled automatically with the luminance on the open road) allows that a contrast close to 0,2 is usually visible. The results are not reconfirmed yet by studies of accidents or driving behavior; the latter is part of a plan for experiments.

The field factor is, as indicated earlier, an essential element for applying the stray-light theory to the design of tunnel entrance lighting installations. Further experiments are required, because it may be assumed that the field factor depends on the prevailing traffic conditions and on the design characteristics of the tunnel entrance.

In a proposal submitted to CIE, it is suggested to set up a more systematic international experiment (*26*). The main reasons for an international approach are the facts that in most countries the variations of climate and geography (morphology) are limited and that the tunnel lighting equipment follows national codes; in short, it is not possible to have enough experimental variability within one country to arrive at truly general results.

Furthermore, the results of the experiments in the Netherlands suggest that f, contrary to the assumption made at the outset of the study, is not a constant but depends to a certain degree on the outside luminance.

TABLE 4 RESULTS OF CONTRAST MEASUREMENTS

measuring point					1	2	3	4	5	6	7	8	9				
distance					4	8	12	16	20	24	28	32	36	40.. etc. meter			
	contrasts (in %)																
	..outside..				........entrance........									.transition			
light																	number
1-2	18	18	18	18	.	.	.	.	.	.	35	.	.	30	35	35	35	n=2
1-3	15	18	18	24	.	.	24	35	.	.	35	.	35	32	37	32	32	n=4
2-0	12	12	12	.	.	.	.	53	.	.	.	.	.	53	53	53	53	n=1
2-1	14	14	14	12	.	35	.	.	35	.	.	.	.	39	39	40	35	n=5
2-2	12	12	12	24	.	.	.	.	.	.	.	35	.	35	35	35	53	n=1
2-4	24	24	24	.	.	.	35	.	.	.	.	.	.	24	35	35	35	n=1
3-1	14	17	19	24	.	12	12	.	.	.	.	53	44	44	42	44	44	n=5
3-2	12	12	12	15	.	.	24	24	.	.	35	35	35	35	33	30	33	n=6
3-3	12	14	14	18	24	12	.	.	.	.	35	.	35	26	28	28	40	n=5
3-4	12	12	12	12	.	.	.	24	.	.	.	24	.	20	24	24	28	n=3
3-5	12	12	12	18	.	24	.	.	.	.	12	.	24	20	20	28	31	n=3
4-2	12	12	12	14	12	14	12	19	44	.	33	35	39	38	35	34	33	n=33
4-3	12	12	12	14	17	14	15	19	20	.	36	20	33	34	32	32	33	n=41
4-4	11	11	11	12	11	15	12	15	16	.	21	24	21	20	21	26	28	n=47
4-5	12	12	13	13	12	16	15	13	12	.	17	26	18	18	20	24	29	n=46
4-6	11	11	12	12	11	12	12	14	.	.	12	12	16	15	16	21	24	n=39
5-3	9	12	12	14	.	12	18	12	.	.	44	12	45	36	35	31	29	n=13
5-4	9	10	10	12	.	12	12	12	.	.	.	.	24	22	22	24	26	n=6
5-5	9	9	9	9	12	.	12	12	.	.	18	12	24	17	17	17	17	n=7
5-6	7	9	9	12	.	9	12	12	.	.	.	.	10	10	10	13	17	n=7

The average of the threshold contrasts for different lighting combinations (3-2 means level 3 outside, level 2 inside; values taken from Table I and II). Distances from the tunnel portal.

Also, the experimental equipment allows for a rapid assessment of the visibility in tunnel entrances. In this respect, the equipment can be used to test the performance of finished lighting installations. In the Netherlands the possibilities of setting up a commercial measuring and testing establishment are studied.

ACKNOWLEDGMENTS

The experiments described in this paper were made by SWOV in the summer of 1989 under a contract with the Netherlands Ministry of Transport, Division of Locks and Weirs. The experiments were prepared by Biesheuvel and Planken of the Technical College at Rotterdam and carried out by Stam & Van Vuren Consultants. The light measurements were made by Philips, Eindhoven and the contrast threshold measurements by the Eye Hospital of the University of Rotterdam. The authorities of the Drecht Tunnel in Dordrecht contributed in important ways to the experiments. The experiments are described in detail elsewhere (*22,23,27*).

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Publication of this paper sponsored by Committee on Visibility.