

# Visibility Under Transient Adaptation

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The Illuminating Engineering Society (IES) has adopted recommendations for the luminance transition in a tunnel that deviate greatly from the curves proposed by the International Commission on Illumination (CIE) and contained in the DIN (German Standards Institute) standard. IES has based its guidelines neither on practical considerations nor on scientific or experimental foundations. To clarify the discrepancy, the physiological processes of adaptation of the eye during a change in luminance have been modeled, and their impact on the required luminance in the transition necessary to ensure visibility has been derived. Using Fry's model for the kinetics of the eye's response and Adrian's  $\Delta L$  model, the course of the luminance transition has been calculated. The results are compared with the IES and CIE standards. A comparison of the resulting curve with the curve suggested by CIE reveals only small differences. In general, the comparison indicates that the experimentally determined CIE curve agrees with results derived from the fundamentals of dark adaptation. The IES suggestion, however, falls short. The eye requires about twice as long to adapt to the luminance transition as the IES proposal allows.

Recently, the Illuminating Engineering Society (IES) subcommittee on tunnel lighting released new guidelines on the lighting of tunnels and underpasses. These guidelines have been passed by various institutions and have become the basis for public practice.

The guidelines differ substantially in three points from the recommendations worked out by the International Commission on Illumination (CIE) (1), revealing a contradiction in basic concepts that cannot remain unresolved. One such concept relates to the transient adaptation taking place when a tunnel is entered in daytime and the subsequent adaptation to the decreasing luminance. The recommended length of the luminance transition zone is, according to the CIE guidelines, three times longer than the length suggested by IES. To reconcile this fundamental difference, scientific investigation of the transient adaptation and the underlying physiological processes appeared necessary. The aim of this study is to provide indisputable scientific evidence as the basis for critical discussion of the problem and to allow for a solution.

## BACKGROUND

The CIE recommendations are based on a modified curve worked out in 1962 by Schreuder and DeBoer (2). A similar curve is contained in the DIN (German Standards Institute) standards on tunnel lighting. The course of the luminance

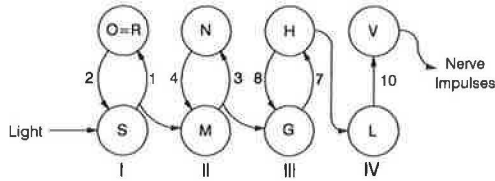
transition was found during tunnel simulation experiments with observers and is based on their 75 percent acceptance level of the luminance reductions after entering the tunnel. The results show that from high levels prevailing at the entrance of the tunnel, the eye needs approximately 12 sec to adapt to the interior luminance level of 10 cd/m<sup>2</sup>. For a speed of 80 km/hr (50 mph), the length of the transition zone must therefore be greater than two stopping distances (accepted safe stopping distance on dry pavement at 80 km/hr is 130 m). The IES guidelines, in contrast, recommend one stopping distance only. This recommendation resulted from assumptions and practical aspects and has neither experimental nor scientific foundation.

The length of the transition zone depends on the rapidity with which the eye can change its adaptation and has therefore been determined on the basis of visual physiology. Two mechanisms underlying the temporal course of adaptation are distinguished. One is the fast phase, called network or neuronal adaptation; the second is the slower phase, which is due to photochemical processes.

## KINETICS OF VISUAL ADAPTATION

In 1946, Jahn (3) attempted to describe the kinetics of dark adaptation mathematically using Wald's (4) visual cycle of rhodopsin. Fry (5) has further developed this model and implemented equations for the reaction kinetics of various intermediate products between the unbleached photopigment and the bleached stage in which we have vitamin A<sub>1</sub>-aldehyde and opsin involved in the process of adaptation. His interpretation of the substances  $s$ ,  $m$ , and  $h$  as indicated in Figure 1 fell short because the phosphoesterase of photopigments was not yet known, but the formulas for the reaction kinetics can generally be applied to describe the actual processes. Figure 1 is adopted from Fry's 1973 publication (5) and displays the mechanisms of excitation following the change in stimulus. The variables in Figure 1 are defined as

- $s$ —Concentration of visual pigment (rhodopsin in Jahn's model, but generally any photopigment).
- $O=R$ —Opsin and retinene that recombine to form the photopigment.
- $m$ —Visual white into which part of  $R$  is transformed. The  $m$  is a substance of a secondary process that is decomposed by the energy released by the primary process that is proportional to the retinal illumination in trolands ( $E$ ) and the concentration of  $s$  ( $E \cdot s$ ).
- $n$ —Decomposed substance  $m$ .



**FIGURE 1** Mechanisms subserving the retinal response to a flash of light.

•  $g$ —Substance in the tertiary mechanism that responds to the energy given off by the decomposition of  $m$ ; this energy is proportional to  $Esm$ .

•  $h$ —Substance to which  $g$  changes. For generating a response in the quarternary mechanism, it is the concentration of  $h$  that counts: it constitutes a catalyst for initiating the nerve impulses and therefore visual excitation.

The primary process  $I$  indicates the bleaching and regeneration of the photopigment. The rate of release of energy in the dissociating photopigment is directly proportional to  $k_1 \cdot E \cdot s$ , in which  $k_1$  is a constant. It may be assumed that the concentration of free opsin  $o = s - 1$ , where  $s$  is the photopigment concentration. So  $1 - s$  constitutes the reformation rate. The kinetics of the maintenance of photopigment can be described as follows:

$$\frac{ds}{dt} = k_2(1 - s) - k_1 E s \quad (1)$$

In a similar way, the equations for the following processes have been found to be

$$\frac{dm}{dt} = k_4(1 - m) - k_3 E s m \quad (2)$$

For the purpose of visibility consideration during the transitional adaptation, it is more appropriate to use  $h$  because its concentration is proportional to the frequency of the nerve impulses and therefore proportional to the brightness sensation.

The necessary luminance difference  $\Delta L$  of an object to be perceptible during the transition of adaptation is proportional to

$$\frac{dE}{dh} = \Phi_{\text{abs}} \quad \Phi_{\text{rel}} = \frac{dE/dh}{dE/dh_{t \rightarrow \infty}} \approx \frac{\Delta L}{\Delta L_o} \quad (3)$$

where  $\Delta L_o$  is the luminance difference threshold in steady-state condition at the end of the transition.

#### Time Course of Processes 1 to 4

The transient processes start and end at equilibrium values. For example, if the fovea is exposed to a steady stimulus, the concentrations of  $s$ ,  $m$ , and  $g$  reach those values. These concentrations can be calculated with Equation 1 in which  $ds/dt$  becomes equal to zero. Thus

$$\frac{ds}{dt} = 0 = k_2(1 - s) - k_1 E \cdot s$$

$$k_2 = (k_2 + k_1 E) \cdot s$$

$$\frac{1}{s} = 1 + \frac{k_1}{k_2} \cdot E$$

or

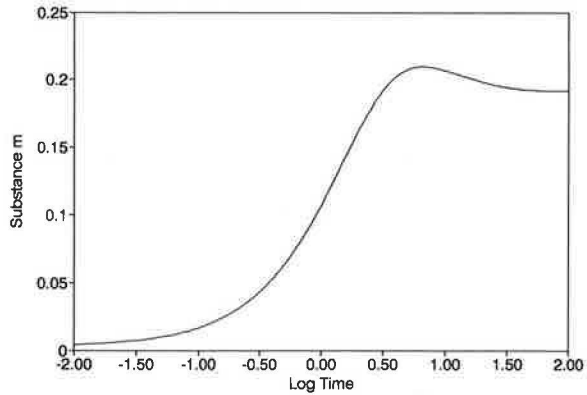
$$s = \frac{k_2}{k_2 + k_1 \cdot E} \quad (4)$$

The concentrations in steady-state conditions for  $m$  and  $h$  can be calculated in the same way.

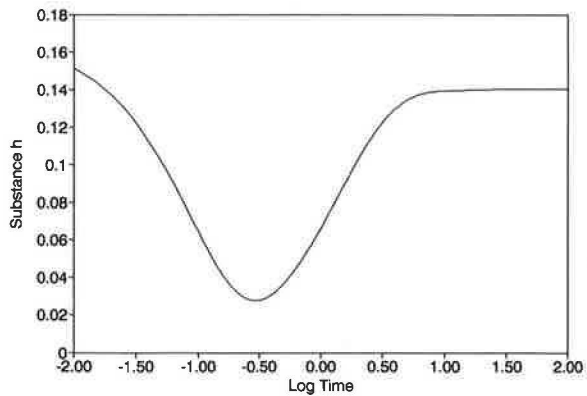
$$\frac{1}{m} = 1 + \frac{k_3}{k_4} s E \quad (5)$$

$$\frac{1}{h} = 1 + \frac{k_8}{k_7 \cdot s m E} \quad (6)$$

The graphs in Figures 2 and 3 show the time course of  $m$  and  $h$  after a sudden luminance reduction from 2000 to 8 cd/m<sup>2</sup>.



**FIGURE 2** Calculated time course of concentration  $m$  after luminance suddenly changes from 2000 to 8 cd/m<sup>2</sup>.



**FIGURE 3** Calculated time course of substance  $h$  after luminance suddenly changes from 2000 to 8 cd/m<sup>2</sup>.

The concentrations before and after the transition is completed would follow from Equations 5 and 6 and indicate the equilibril conditions. Calculation reveals that for high levels of  $E$ —for example,  $E > 10^4$  trolands—the product  $smE$  becomes constant and leads to a concentration of  $h = 0.652$ .

#### Calculation of Time Course of $s$ , $m$ , and $h$ Using Euler's Method

According to Euler's method, a numerical solution for differential equations can be calculated, providing that initial values for the variables involved are supplied. Using the steady-state equations given in Equations 4, 5, and 6, the starting values for  $s$ ,  $m$ , and  $h$  were obtained. These values were then used in Euler's difference equations.

$$s_{t+\Delta t} = s_t + \Delta t[k_2(1 - s_t) - k_1Es_t] \quad (7)$$

$$m_{t+\Delta t} = m_t + \Delta t[k_4(1 - m_t) - k_3Es_t m_t] \quad (8)$$

$$h_{t+\Delta t} = h_t + \Delta t[k_7Es_t m_t(1 - h_t) - k_8h_t] \quad (9)$$

where  $\Delta t$  is the time increment.

Once this model was set up in the computer spreadsheet, many trials were run to achieve results that fit the experimental data as found in the literature. Measurements of re-adaptation courses were made as early as 1936 by Lossagk (6) and more recently by Greule (7). Greule used more modern equipment that allowed precise control of the stimulus and presentation time.

In his investigation, Fry examined the required brightness difference threshold necessary for a response to take place, and he went on to study the effect of the stimulus duration on the threshold intensity required. Because  $h$  is the catalyst for the nerve impulse reaction, Fry proposed that  $dE/dh$  is proportional to the temporal threshold elevation over the steady state.

For clarity, Fry's deviation of  $dE/dh$ , as approximated by  $\Delta E/\Delta h$ , will be repeated here.

$$\frac{\Delta E}{\Delta h} = \frac{k_8}{k_7sm(1 - h_{on})^2} \quad (10)$$

The  $\Delta E/\Delta h$  is proportional to the luminance threshold value  $\Delta L$  necessary for perception. Basing its value on the  $\Delta L_o$  that is achieved in the equilibrium (steady state) at the end of the transition, we obtain the threshold multiplier  $\Phi$  that follows from

$$\Phi = \frac{\frac{dE}{dh}(t)}{\frac{dE}{dh}(t \rightarrow \infty)} \quad \text{from } L_{\text{high}} \text{ to } L_{\text{low}} \quad (11)$$

Using this formula for  $\Phi$ , we attempted to apply Fry's model, using Equation 10 for long flashes that would simulate sudden luminance changes to approximate the transition in a tunnel. Figure 4 depicts the course of the  $\Phi$  of the perception threshold that is necessary to keep the target visible during the

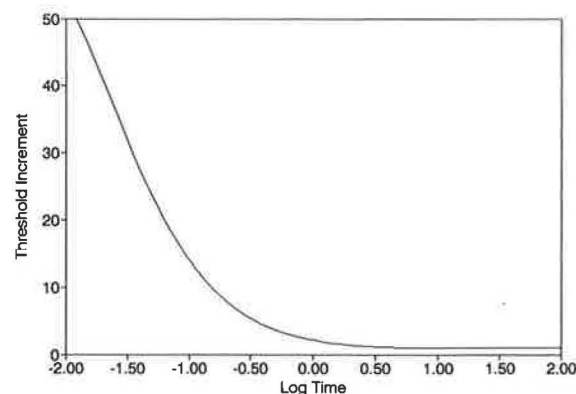


FIGURE 4 Calculated time course of threshold increment after luminance suddenly changes from 2000 to 8 cd/m<sup>2</sup>.

transition from 2000 to 8 cd/m<sup>2</sup>.  $\Phi$  indicates the multiple of the  $\Delta L$  threshold at the steady-state level of 8 cd/m<sup>2</sup>. As can be read from the curve, the steady-state threshold is reached approximately 3 sec ( $\log t = 0.5$ ) after the luminance drop.

Figure 5 shows the threshold increase  $\Phi$  for a sudden drop of the adaptation luminance from 2000 to 8 cd/m<sup>2</sup> as well as  $\Phi$  found for an increase from 8 to 2000 cd/m<sup>2</sup>. The solid lines are calculated according to the model using the constants found from Table 1. The data measured by Greule are also plotted; they are in good agreement with the calculated values. This seems to justify the use of the modified Fry's equations to describe the transient adaptation processes even though they were originally based on inappropriate assumptions.

The constants were found by the best match with the experimental data in Figure 5. It is interesting to note that only  $k_3$  and  $k_4$  had to be changed for up and down luminance jumps, because this appears to indicate different intermediate chemical processes as described before.

In Figure 6 early data by Lossagk are reproduced that were obtained with an apparatus that did not allow precise timing. Still, the data show reasonable agreement with the calculated curves.

#### Determination of Required Luminance Transition in a Tunnel

When entering a tunnel during daylight conditions, the eye must be able to adapt to the luminance inside the tunnel. The visual task is to detect objects at a much lower luminance level at any time during the entrance in order to ensure traffic safety. Therefore, it is extremely important that adequate lighting be provided, on the basis of the requirements of the course of dark adaptation. Luminance levels should also meet the subjective demands for safety that were found to parallel the lighting conditions (8).

#### Procedure

Whenever the adaptation luminance suddenly changed, from higher to lower levels or vice versa, the luminance difference

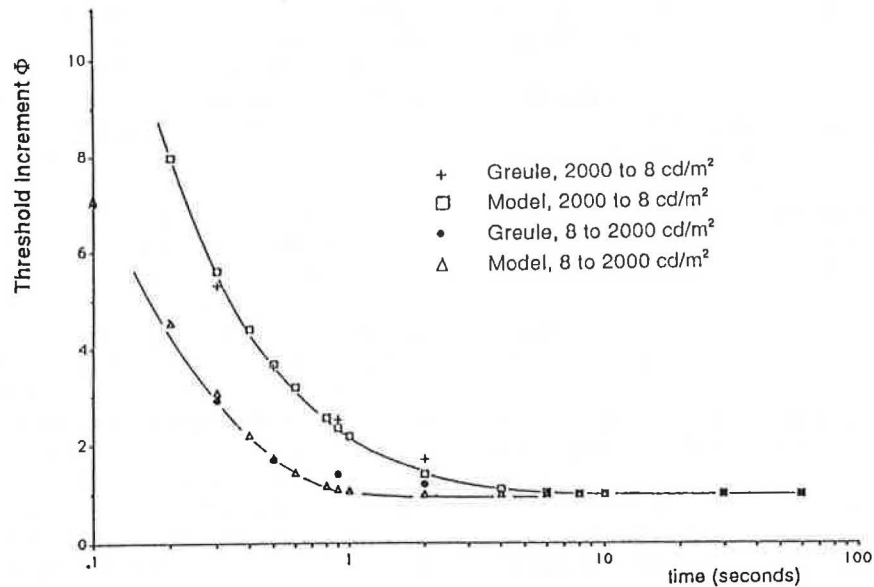


FIGURE 5 Calculated threshold increments  $\phi$  for luminance changes from 2000 to 8  $\text{cd/m}^2$  (upper curve) and from 8 to 2000  $\text{cd/m}^2$  (lower curve) compared with Greule's data (7).

TABLE 1 CONSTANTS FOR INCREASE IN STIMULUS (a) AND DECREASE IN STIMULUS (b)

Constant	Fry		Adrian/Fleming	
	a	b	a	b
$k_1$	$2 \cdot 10^{-7}$	$2 \cdot 10^{-7}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-6}$
$k_2$	1/130	1/130	1/13	1/13
$k_3$	$2.56 \cdot 10^{-5}$	$2.56 \cdot 10^{-5}$	$7.0032 \cdot 10^{-3}$	$7.0032 \cdot 10^{-4}$
$k_4$	0.00481	0.00481	0.1415	0.1415
$k_7$	0.1	0.1	0.1	0.1
$k_8$	10	10	10	10

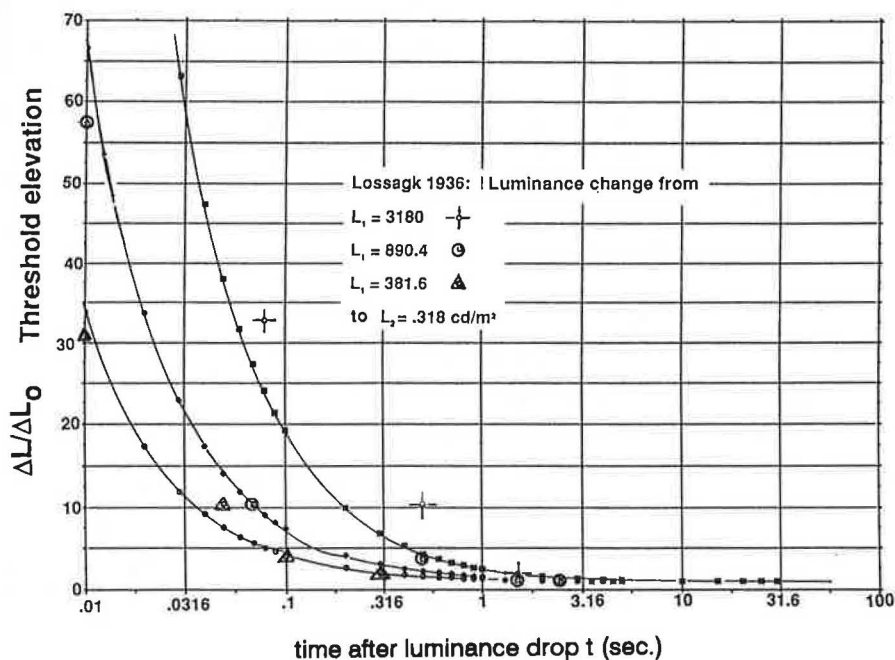


FIGURE 6 Lossagk's data compared with calculation.

threshold  $\Delta L$  increased until it reached—after a transitional period—its steady-state value  $\Delta L_o$  determined by the final  $L$ -level.

With  $\Phi$  known as a function of time after entering the tunnel, following from the model,  $\Delta L$  can be calculated.

Adrian (9) developed a method to calculate the  $\Delta L$  threshold for various adaptation luminances, targets, and exposure times. On the basis of his method, the required background luminance for a critical target size and practical observation time can be calculated for every  $\Delta L$ . As the necessary  $\Delta L$  is known from Equation 3 as a function of time in the transition, that can be transformed into the corresponding background luminance  $L_B = f(t)$ . This procedure was applied to all the graphs in Figures 7–10.

The actual required luminance levels  $L_B$ , following from the  $\Delta L$  in the transition, were computed and are shown in Figures 7–10.

The first calculation was carried out assuming that an observer is adapted to 500 cd/m<sup>2</sup> and enters a tunnel that produces (without any transition) a sharp drop to the inside luminance level of 3 cd/m<sup>2</sup>. The assumption of 500 cd/m<sup>2</sup> follows from practical considerations. Adrian (8) suggested a method to obtain the actual adaptation luminance ( $L_A$ ) when approaching a tunnel. According to this method,  $L_A$  is composed of the average luminance in the foveal field (~2 degrees) on which the stray light, created by the bright tunnel environment, is superimposed.

$$L_A = L_{2^\circ} + L_{\text{seq}} \quad (12)$$

where  $L_{2^\circ}$  equals luminance in the central 2-degree field and  $L_{\text{seq}}$  equals equivalent veiling luminance.

Practical measurements on tunnel sites revealed that a luminance in the entrance zone of 200 cd/m<sup>2</sup> prevails in reasonably lit tunnels. In bright daylight at about 47 to 52 degrees northern latitude, equivalent veiling luminance values between 150 to 450 cd/m<sup>2</sup> generally occur. With this in mind, an average of  $L_{\text{seq}} = 300$  cd/m<sup>2</sup> was chosen that resulted in  $L_A = 500$  cd/m<sup>2</sup>, as in the example.

For the  $L_B = f(\Delta L)$  calculations, a target size of 10 min arc and an observation time of 0.2 sec were used throughout. A target of that size is used internationally to express the visual task of drivers. It is the critical size that must be seen if a collision is to be avoided. It relates to an object 22 cm in square located ~85 m in front of the car. This is close to the safe stopping distance on an even and dry road for a speed of ~65 km/hr (40 mph). Studies on eye movements and fixation times have revealed that drivers devote in daytime an average 0.2 sec looking at locations in front of the car (10), which is the rationale for adopting that observation time.

Figure 7 shows the minimal luminance as a function of time after the abrupt drop assumed to take place at  $t = 0$  to the interior level of 3 cd/m<sup>2</sup>. The luminance course recommended by the CIE and that according to the DIN standard are also depicted for comparison. The CIE curve is supposed to start from 100 percent level of the entrance luminance, which again had to be assumed to be 200 cd/m<sup>2</sup>. The DIN curve, which was somehow derived from that of CIE, shows in the beginning a lesser slope than that recommended by CIE but drops slightly faster after  $t \sim 12$  sec. The calculated function shows a steeper slope in the initial phase of the transition, but levels off to approach the CIE curve after  $t \sim 16$  sec.

The steeper slope of the calculated  $L$ -function suggests that the luminance in the initial phase of the transition could be

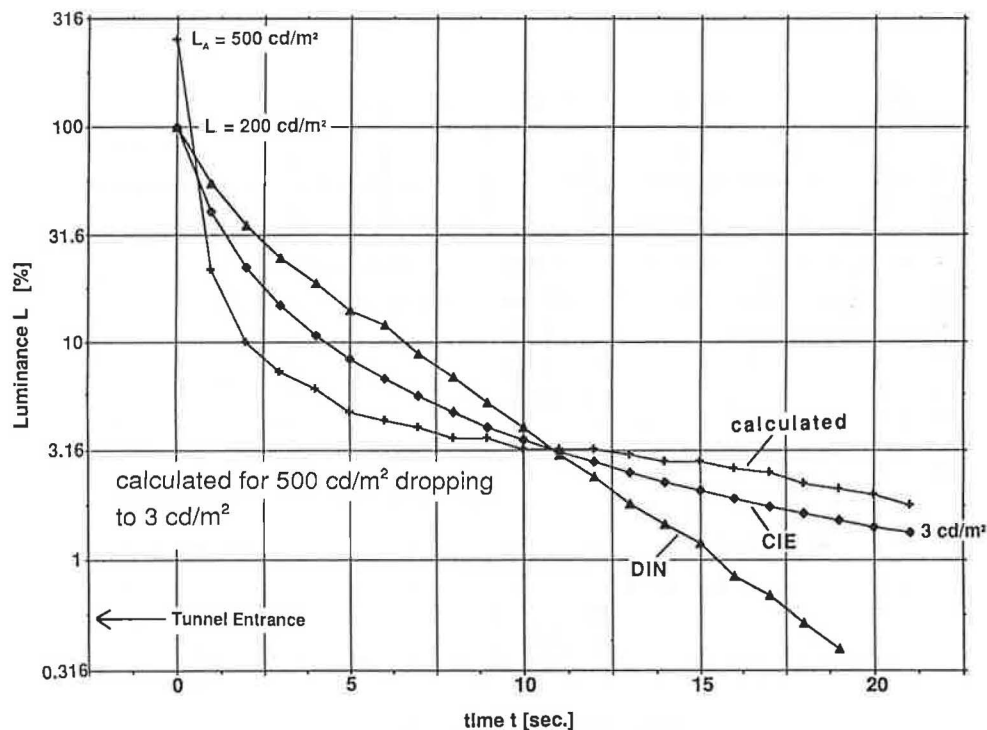


FIGURE 7 Comparison between CIE, DIN, and calculated transitions in one step.

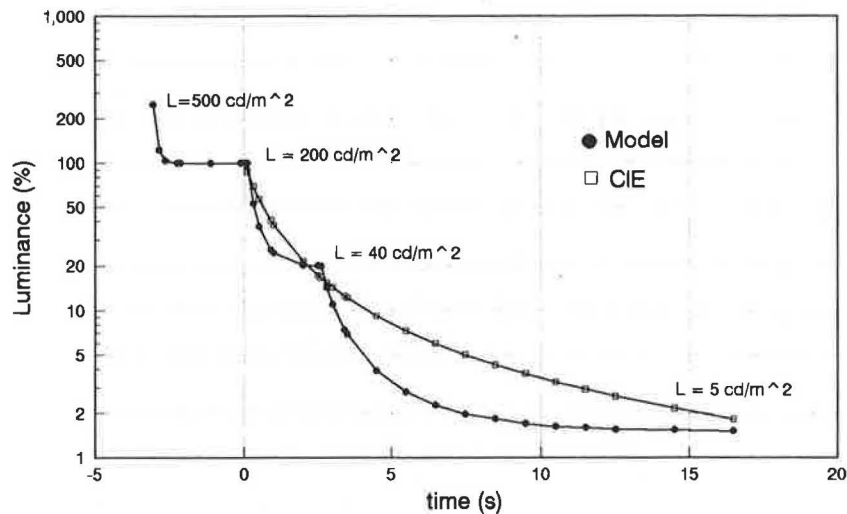


FIGURE 8 CIE transition and calculated functions following a two-step transition.

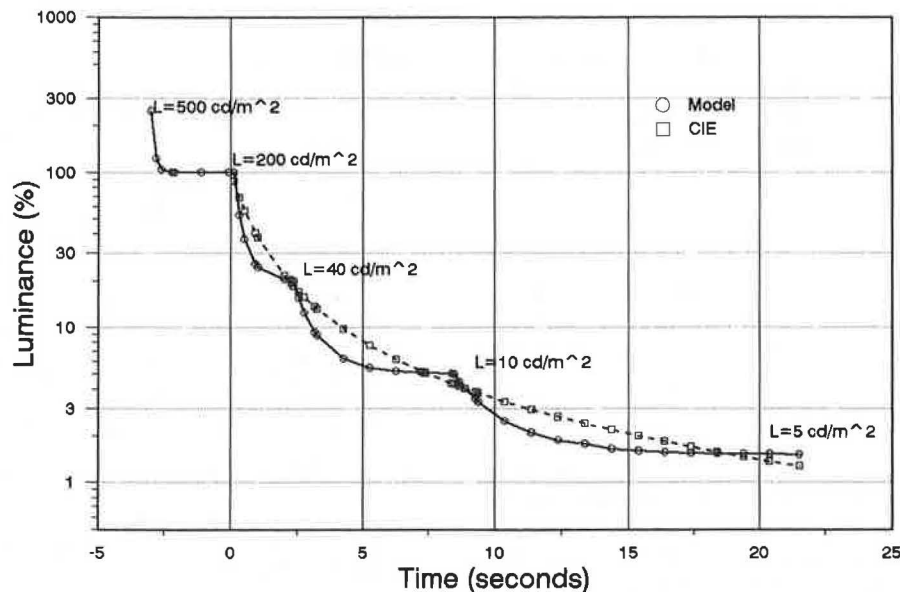


FIGURE 9 CIE transition and calculated functions following a three-step transition.

lower than suggested by CIE or DIN. This might be because an abrupt  $L$ -transition from the adaptation luminance of 500 to 3  $\text{cd/m}^2$  was assumed to occur at the end of the entrance zone, the length of which must measure one stopping distance. Over that distance a constant luminance level must be provided. Such an abrupt change, however, never occurs in practice. The continuously decreasing  $L$ -level must be approximated stepwise instead.

A first attempt is made in Figure 8 using two steps from the level in the entrance zone to the interior level. The first part shows the adaptation transition from  $L_A$  (500  $\text{cd/m}^2$ ) to the level in the entrance zone (200  $\text{cd/m}^2$ ). At the beginning of the transition zone, the luminance level is assumed to drop to 40  $\text{cd/m}^2$  and then to 3  $\text{cd/m}^2$ . The section of the curve (200 to 40  $\text{cd/m}^2$ ) was truncated at the time the  $\Delta L/\Delta L_o$  ratio reached

1.02 of its steady-state value, or when the increment was only 2 percent.

In Figure 9 the same calculation was carried out approximating the transition in three luminance steps, from 200 to 40, 40 to 10, and 10 to 3  $\text{cd/m}^2$ . As can be observed from the graph, the calculated course of the luminance comes very close to that of CIE, which was derived from experiments in models (2).

Figure 10 allows us to compare the transition steps contained in the North American Standard Practice RP22 and the calculated transition using the same luminance level of each step. According to the recommendation, the interior level of 5  $\text{cd/m}^2$  can be reached in 6 sec (165 m, 99 km/hr) after the end of the entrance zone having a luminance of 330  $\text{cd/m}^2$ . It is obvious that the adaptation transition takes longer

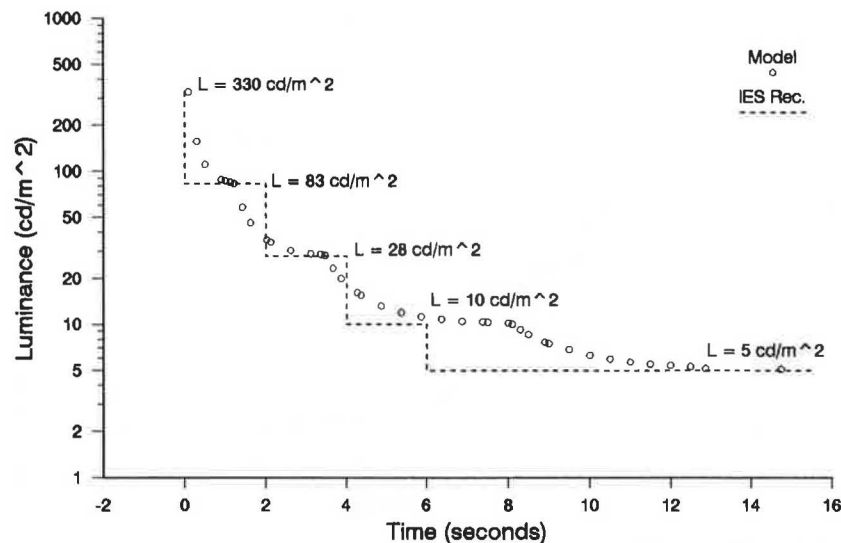


FIGURE 10 Calculated function for transient adaptation and steps proposed in IESNA RP22.

and that an observer entering a tunnel with such specifics would not be able to follow the rapid changes of interior luminance. The required distance to accommodate such a transition must be approximately twice as long.

## CONCLUSION

The purpose has been to investigate the adaptation of the eye following changes in luminance of the visual field. The criterion used for the adaptation in the transition from one luminance level to the other was the perceptibility of a defined, internationally used target to describe the visual task of a driver.

The calculation of the time required for transient adaptation was based on equations used by Fry (5) describing the kinetics of the chemical and physiological processes in the retina.

In conclusion, it appears reasonable to adopt the CIE suggestions in respect to the course of the luminance in the transition zone, provided that the starting point is 100 percent at the end of the entrance zone and not—as CIE allows—truncated function to start at 40 percent of the entrance  $L$ -level.

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