## Annex E: Tunnel lighting

### E.1 Introduction and summary

Tunnel lighting gained importance during the 1960's and was taken up by the CIE on the basis of early work in the Netherlands, among else by Duco Schreuder with a thesis for a doctor's degree at the at the Technical University of Eindhoven, "The lighting of vehicular traffic tunnels", 1964. Figure E.1 shows a photo from this report.

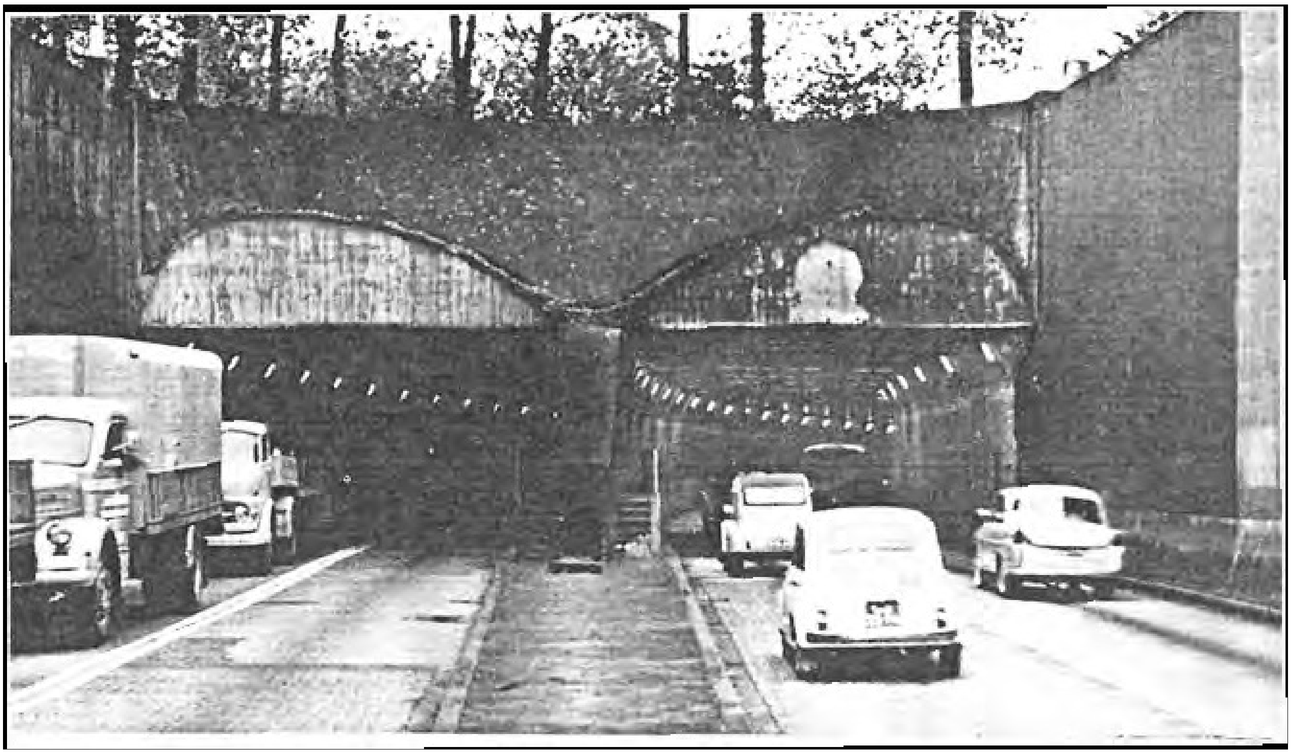


**Figure E.1: Photo from the 1960's of a tunnel.**

The international development of tunnel lighting is accounted for by means of CIE 26:1973, "International recommendations for tunnel lighting",. CIE 61:1984, "Tunnel entrance lighting – A survey of fundamentals for determining the luminance in the threshold zone", CIE 88:1990, "Guide for the lighting of road tunnels and underpasses" and CIE 88:2004 "Guide for the lighting of road tunnels and underpasses".

There is a large amount of literature on theoretical and practical aspects of tunnel lighting that is not referenced in the following. Some can be found on nmfv.dk.

The CIE reports define more than one principle for the design of tunnel lighting, all of which survive to varying degrees in national standards for tunnel lighting.

The European CEN organisation made an attempt – in CEN/TC 169 for lighting applications – to define a single approach for European countries. This was not successful and the final document in the form of a CEN technical report CEN/CR 14380: 2003 "Lighting applications – Tunnel lighting" include some of the principles applied in European countries. A new attempt in CEN/TC 169 later in the 2000's was abandoned without any publication.

A joint work in the Nordic countries in NVF (Nordisk Vejteknisk Forbund) resulted in an NVF Report No. 4: 1995 ”Belysning af vejtunneler” (in Danish) based essentially on CIE 88:1990. This report has been the basis for tunnel lighting in the Nordic countries.

The CIE publications aim primarily on long tunnels and consider only briefly short tunnels and underpasses that drivers can see through. The general idea is that short tunnels and underpasses need no special tunnel lighting, but may have optical guidance by means of rows of light signal or luminous road studs. On old idea of providing a band of light in the middle of a short tunnel has gained more attention in recent years. The band of light is called ”lichtschleuse” by a German type word (translates to ”lyssluse” in Danish).

The CIE reports and other publication provide several criteria for when a tunnel is long or short. Only long tunnels are considered in the following.

The main lighting criteria are based on the road surface luminance. Other aspects of lighting are sometimes considered to be important, such as to provide luminance of the lower parts of the tunnel walls - by a combination of a light colour and illumination - so that they give contrast to other road users and a feeling of the space inside the tunnel. Some very long tunnels have wider spaces at intervals with particular illumination or art in order to serve as landmarks. Some tunnels also have optical guidance of the same nature as used for short tunnels.

The equipment used for tunnel lighting is of the same nature as the equipment used for road lighting. As for road lighting, LED light sources are currently being introduced.

It is a particular consideration that conditions in tunnels are rough and dirty, which dictates that lighting equipment must be resistant to corrosion and to cleaning by high pressure hosing.

Luminaires are normally suspended in one or more rows under the tunnel ceiling. It is another particular consideration that luminaire spacings should not lead to flicker frequencies in the range from 2,5 to 15 Hz at the typical driving speed in the tunnel.

EXAMPLE: A driving speed of 90 km/h equals 25 m/s for which the luminaire spacing should then be less than 1,67 m or larger than 10 m.

The 1999 fire in the Mont Blanc tunnel led to the Directive 2004/54/EC on minimum safety requirements for tunnels in the trans-European road network. The directive does in itself include all aspects of safety requirements, but was supplemented by EN 16276: 2013 ”Evacuation lighting in tunnels” by CEN/TC 169. EN 16276 describes the lighting of specific areas under emergency circumstances in more detail.

Evacuation lighting is, therefore, an integral part of tunnel lighting. However, reference is made to the directive and to EN 16276.

Tunnels are traditionally divided into zones with regard to the tunnel lighting. These zones and their lengths are introduced in E.2.

The lighting of the first zone within the tunnel, the threshold zone, is discussed in E.3. Lighting in this zone is intended to overcome the ”blackhole effect”, which is that a driver approaching a poorly lit tunnel cannot see into the tunnel through the tunnel opening.

A historical account given in E.3.1 shows that the cause of the effect was first assumed to be adaptation of the eye, but later understood to be disability glare. This led to the development of two different methods of measuring the level of glare and selecting the luminance level in the entrance zone necessary to overcome the glare.

One method (the $L_{20}$ method) has a simplified evaluation of the glare and a simple way of selecting the luminance level in the threshold zone (as fraction of $L_{20}$). The other method (the $L_{seq}$ method) has a more accurate evaluation of glare, but a mysterious way of selecting the luminance level in the threshold zone (perceived contrast of an object).

On this basis disability glare is considered more closely in E.3.2. It is then shown in E.3.3 that the two methods can be combined so that the accurate evaluation of glare can be used together with the simple way of selecting the luminance level in the threshold zone.

This is actually a proposal for a new method. It is mentioned that the method also can lead to an objective determination of the permissible reduction of the luminance level along the threshold zone.

The lighting of the second zone within the tunnel, the transition zone, is discussed in E.4. Lighting in this zone decreases from the high level at the end of the threshold zone to the constant level in the third zone, which is the interior zone. The decrease should follow a curve that allows a driver to pass the change of luminance level without too much inconvenience.

A historical account is given in E.4.1. A particular curve, which can be identified as a curve in the thesis report of Duco Schreuder, is used in CIE 26:1973. This curve is replaced in CIE 88:1990 and CIE 88:2004 by another curve.

The curves are discussed in E.4.2.

The curve provided by Duco Schreuder is based on an experiment in which observers reduce the luminance of a screen at a rate where after-images are avoided and an object stays visible. However, it is shown that the curve is in contradiction to the practical and commonplace design of tunnel lighting and questionable in itself.

As the curve in CIE 88:1990 and CIE 88:2004 has a much slower rate of reduction, it is concluded that it cannot serve the above-mentioned purposes, but some other purpose that is described as comfort in the CIE reports.

In E.4.3 it is pointed out that a driver is affected by the glare from nearby luminaires, and that this glare is more serious because the driver is looking ahead into the transition zone where the luminance level is lower. On this basis it is assumed that the transition has the purpose of avoiding that glare becomes excessive.

A family of curves is then derived corresponding to an exponential decline of the luminance level. The curves are distinguished by the constant value of a factor f by which the luminance level decreases for each stopping distance ahead.

This is a proposal for curves for the transition zone that are relevant for glare limitation. The proposal is not quite worked out as the value of f may be set to vary along the transition zone in accordance with some visibility criterion.

However, it is important to verify/reject that glare is the dominating concern in the transition zone.

The lighting of the two last zone, the interior zone and the exit zone, is briefly introduced in E.5.

### E.2 Zones in tunnel lighting and their lengths

The zones and the lengths of the zones that are normally considered in tunnel lighting are shown in figure E.2.

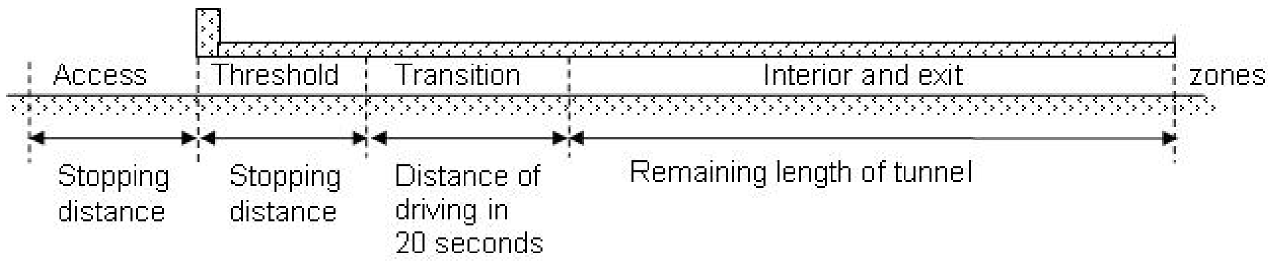



**Figure E.2: Zones in tunnel lighting and their lengths.**

The access zone lies in front of the tunnel entrance and has the length of the stopping distance at a given design driving speed V for the tunnel and its lighting measured in km/h.

With a reaction time of the driver of t measured in seconds and a driving speed of V measured in km/h, the reaction distance is t×(V/3,6) measured in metres. Further, when braking with a constant deceleration of D measured in $m/s^2$, the breaking distance is $0{,}5\times(V/3{,}6)^2/D$ measured in metres. The stopping distance is the sum of the two.

With common assumptions that t equals 2 seconds and D equals 5 $m/s^2$, the stopping distance becomes as shown in table E.1 at various design driving speeds.

The first zone within the tunnel is the threshold zone, which also has the length of the stopping distance shown in table E.1.

The second zone within the tunnel is the transition zone with a length equal to the distance of driving in 20 seconds at the design driving speed. This distance is found by 20×(V/3,6) measured in metres and is also indicated in table E.1.

The total lengths of the threshold and transition zones are also indicated in table E.1. These are quite long, ranging from 325 m to 925.

The two remaining zones are the interior and the exit zones, which take up the remaining length of the tunnel.

**Table E.1: Stopping distance, distance of driving in 20 seconds and total length.**

| Design driving speed km/h | Stopping distance m | Distance of driving in 20 seconds m | Total length m |
|---|---|---|---|
| 50 | 47 | 278 | 325 |
| 60 | 61 | 333 | 394 |
| 70 | 77 | 389 | 466 |
| 80 | 94 | 444 | 538 |
| 90 | 113 | 500 | 613 |
| 100 | 133 | 556 | 688 |
| 110 | 154 | 611 | 766 |
| 120 | 178 | 667 | 844 |
| 130 | 203 | 722 | 925 |

## E.3 Lighting of the threshold zone

### E.3.1 Historical account of methods

The first CIE publication on the subject is CIE 26, ”International recommendations for tunnel lighting”, 1973.

The problem in threshold zone is described as a ”blackhole” effect in daytime conditions, meaning that a driver in the access zone approaching a tunnel cannot discriminate anything inside a poorly lit tunnel. The problem is assumed to be that the driver is adapted to the high ambient luminance levels in front of the tunnel and that this prevents his discrimination of objects at the much lower luminance levels inside the tunnel.

The ambient luminance levels are estimated to be up to 8.000 $cd/m^2$ in bright summer conditions and even up to 10.000 $cd/m^2$ in snow covered areas. The remedy is stated to be lighting of the road surface in the threshold zone to levels of luminance of 0,1 times the ambient luminance levels; i.e.: up to 800 or 1000 $cd/m^2$.

A method of establishing the ambient luminance level is also provided in CIE 26:1973. It is to measure the average luminance within a circular field of view subtending an angle of ±10° centered on the direction of driving along the approach road to the tunnel. This is to be done at distances of 250 m, 150 m and 50 m from the tunnel opening followed by the formation of a weighted average of the measured luminance values with weights of respectively 1/6, 1/3 and 1/2 for the three distances. This kind of averaging is intended to account for the gradual adaptation of the driver during his approach to the tunnel.

The methods of CIE 26:1973 lead to the above-mentioned high luminance levels in the thresholds zone corresponding to lighting levels of 10.000 lx or more. The methods were not accepted in practice because of the high expense to the lighting and a feeling that less would be sufficient.

The CIE pondered about this for years. A report CIE 61, ”Tunnel entrance lighting – A survey of fundamentals for determining the luminance in the threshold zone”, was issued in 1984, while new recommendations in CIE 88, ”Guide for the lighting of road tunnels and underpasses”, were issued in 1990.

CIE 88:1990 recognises that the problem is not adaptation, but disability glare from the bright surroundings in front of the tunnel opening.

However, the above-mentioned method of measuring – or calculating – the luminance within ±10° is maintained. The value is called $L_{20}$, it is determined from a distance equal to the stopping distance from the tunnel opening only and is used to determine the average road surface luminance in the threshold zone, $L_{th}$ as a fraction of $L_{20}$.

Two methods are offered for the determination of $L_{20}$ in the design stage. The fraction is indicated as either 0,05; 0,06 or 0,10 for stopping distances of respectively 60, 100 or 160 m.

CIE 88:1990 does hardly in itself lead to savings compared to the older recommendations, unless the stopping distance is short – 60 or 100 m. These cover design speeds up to 80 km/h and are not relevant for motorway tunnels. The longer stopping distance of 160 m covers design speeds up to 110 km/h, refer to table E.1.

As counter beam lighting had been developed in the meantime, the report provides additional and lower values for the fraction as 0,04; 0,05 and 0,07 for the three stopping distances respectively.

Counter beam lighting means lighting with the light directed at a relatively high angle towards the oncoming traffic. Such lighting is more effective in producing road surface luminance than normal symmetrical lighting,  because lighting is predominantly in directions of specular reflection. Hence counterbeam lighting is more energy efficient than symmetrical lighting.

The above-mentioned fractions, labelled k are presented in table E.2.

**Table E.2: Fractions $k = L_{th}/L_{20}$ recommended in CIE 88:1990.**

| | Symmetrical lighting | Counter beam lighting |
|---|---|---|
| Stopping distance | $k = L_{th}/L_{20}$ | |
| 60 m | 0,05 | 0,04 |
| 100 m | 0,06 | 0,05 |
| 160 m | 0,10 | 0,07 |

The indication of lower fractions for counterbeam lighting provides it with an additional advantage and an even higher energy efficiency compared to symmetrical lighting. The additional advantage is granted on the basis that objects on the road are assumed to be predominantly darker than the road surface, so that counterbeam lighting enhances their negative contrast to the road surface.

In total, CIE 88:1990 offers savings by the use of counterbeam lighting in addition to the savings inherent in the method. These additional savings are questionable and are probably no longer applied on a national basis.

CIE 88:1990 does also offer a method based on the equivalent veiling luminance for disability glare, $L_{seq}$. The method includes an evaluation of $L_{seq}$ by summation of the luminances in zones shown in a polar diagram. Alternatively it is stated that $L_{seq}$ can be measured with luminance meters equipped with a ”glare lens”. The need for road surface luminance in the threshold zone is accounted for by means of a selected object that is to maintain a perceived contrast in spite of the glare.

The $L_{20}$ method is clearly the favourite of CIE 88:1990, which places the $L_{seq}$ method in a short annex A, provides warnings against the use of this method and does not explain how $L_{seq}$ and $L_{20}$ compare to each other.

A later CIE report, CIE 88:2004 ”Guide for the lighting of road tunnels and underpasses” is intended to replace CIE 88:1990. The later CIE report is based solely on the $L_{seq}$ method.

The $L_{seq}$ method allows consideration of further veiling luminance caused by scattering in the air and in the car windscreen. CIE 88:2004 offers the empirical values shown in table E.3

**Table E.3: Veiling levels of CIE 88: 2004.**

| Veiling levels | High | Medium | Low |
|---|---|---|---|
| Atmospheric veiling luminance (cd/m$^2$) | 300 | 200 | 100 |
| Windscreen veiling luminance (cd/m$^2$) | 200 | 100 | 50 |

Some countries have adapted to the $L_{seq}$ method of CIE 88:2004, but most have probably remained with the $L_{20}$ method of CIE 88:1990.

The weakness of the $L_{seq}$ method of CIE 88:2004 lies in the seemingly random assumptions regarding the object (a reflectance of 0,2), a contrast revealing coefficient (0,2 for symmetrical lighting and 0,6 for counterbeam lighting) and a minimum required perceived contrast (-28 %). A change of any of these values would result in a change of the calculated value of the road surface luminance in the threshold zone, $L_{th}$.

The truth is that the $L_{20}$ method of CIE 88:1990 involves fractions that also reflect random – although hidden - assumptions. Lighting of the threshold zone can for economic reasons not be provided in levels that will make all objects and obstacles visible.

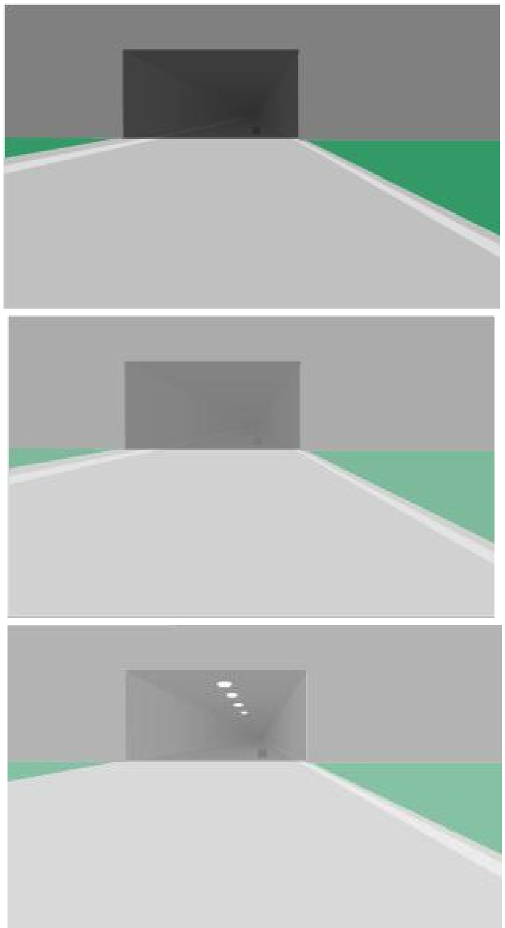
In CIE 88:1990 and CIE 88:2004 it is prescribed that the road surface luminance in the threshold zone, $L_{th}$ is to be maintained through half the length of the threshold zone, but then to be reduced in a linear manner with the distance to 40 % at the end of the threshold zone (to $0{,}4 \times L_{th}$).

This seems not to be well supported, as the veiling luminance can mostly be expected to drop steadily as the driver approaches the tunnel opening. The reduction of the road surface luminance should depend on the circumstances both concerning when to start and to what level to drop.

### E.3.2 Introduction to disability glare

CIE 88:1990 and CIE 88: 2004 both establish that the problem of seeing into the tunnel during the approach is disability glare from the bright surroundings in front of the tunnel opening. It is, therefore, worthwhile to consider disability glare in more detail.

The cause of disability glare is scattering of light in the human eye. The scattering produces a veil of light overlaying the field of view and thereby reduces the contrasts. This is illustrated in figure E.3 for a poorly lit tunnel. The figure also illustrates the re-establishment of contrasts by improved lighting.



**A: Poorly lit tunnel opening with an object**

**B: Tunnel opening with overlay of a veil**

**C: Tunnel opening with improved lighting**

**Figure E.3: The reduction of contrasts by disability glare and the re-establishment of contrast by improved lighting.**

Disability glare is described by the equivalent veiling luminance, $L_{seq}$ that indicates the luminance of the veil. In CIE 88:1990 the calculation of glare is based on a ”modified Holladay-Stiles formula:

$$L_{seq} = 9{,}2 \times \sum_{i=1}^{n} \frac{E_i}{\theta_i^2}$$

where $E_i$ is the illuminance produced at the eye by glare source i
and $\theta_i$ is the angle between the line of sight and the glare source.

CIE 88:1990 also provides a polar diagram showing zones in which the luminance produces equal contributions to the $L_{seq}$. The intention is that the luminance is estimated in each zone, the sum of these luminance values is formed and the sum is multiplied by $0{,}513 \times 10^{-3}$. This polar diagram is shown in figure E.4. The diameters of the rings limiting the zones are given in table E.4.

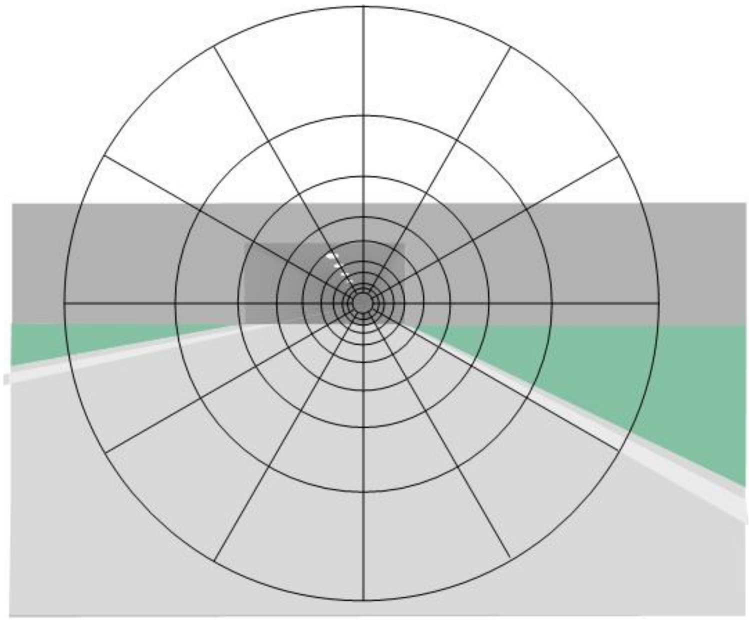


**Figure E.4: Polar diagram showing zones in which the luminance produces equal contributions to the equivalent veiling luminance.**

**Table E.4: Diameters of rings limiting zones.**

| Ring | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Diameter | 2,0° | 3,0° | 4,0° | 5,8° | 8,0° | 11,6° | 16,6° | 24,0° | 36,0° | 56,8° |

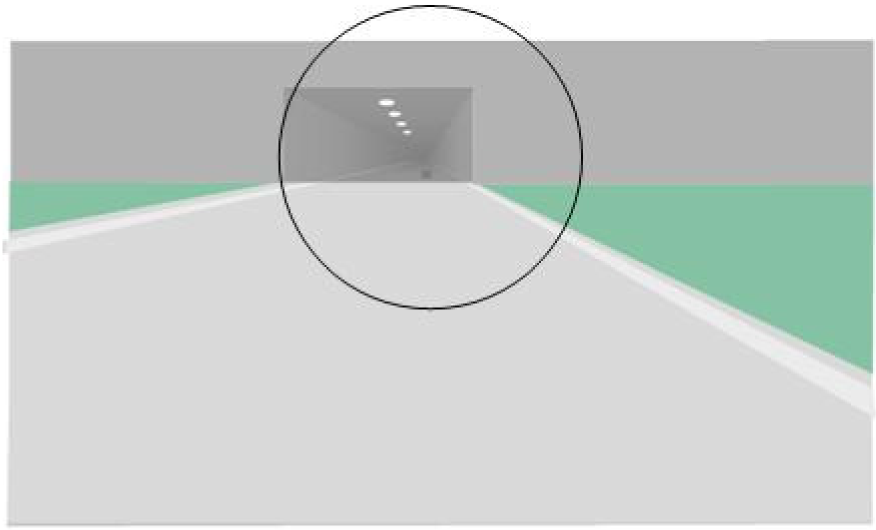
### E.3.3 A factor method based on $L_{seq}$

As it is established that the problem of seeing into the tunnel during the approach is disability glare, the equivalent veiling luminance $L_{seq}$ is in principle the correct parameter for the determination of the lighting of the threshold zone. The $L_{20}$ is of course a simplified representation of $L_{seq}$.

It is obvious that $L_{20}$ is not in the scale of a veiling luminance. Consider a field of a uniform luminance L that covers both the $L_{20}$ field and the field for the $L_{seq}$ as shown in figure E.5. For this field, the value of $L_{20}$ is L, while the value for $L_{seq}$ is 0,0554×L. In this case, the value of $L_{20}$ should be multiplied by 0,0554 in order to represent glare.

However, there is no fixed factor that can translate an $L_{20}$ value into an accurate representation of $L_{seq}$. This is obvious when comparing the zone used for the $L_{20}$ value shown in figure E.5, with the zones used for the $L_{seq}$ value shown in figure E.4. In most cases the factor value should probably be somewhat larger than the above-mentioned value of 0,0554 because the zones for $L_{seq}$ would tend to include some of the open sky above the tunnel. However, the variation is probably not large, as several small inner zones for $L_{seq}$ include the tunnel opening and its immediate surroundings.

**Figure E.5: Field of ±10° used for the $L_{20}$ value.**



Assume that a typical ratio $L_{seq}/L_{20}$ is 0,06, which means that the fractions $k = L_{th}/L_{20}$ provided in table E.2, can be converted to factors $L_{th}/L_{seq}$ by division with 0,06. The results are provided in table E.5.

**Table E.5: Fractions $L_{th}/L_{seq}$.**

| | Symmetrical lighting | Counter beam lighting |
|---|---|---|
| Stopping distance | $L_{th}/L_{seq}$ | |
| 60 m | 0,83 | 0,67 |
| 100 m | 1,00 | 0,83 |
| 160 m | 1,67 | 1,17 |

This, on the other hand, shows that $L_{seq}$ does not have to be connected to a mysterious calculation of perceived contrast, but can be used as well with factors in the same way as $L_{20}$.

The factor values vary about one, which shows that the $L_{th}$ has to be comparable to the $L_{seq}$. This natural when the effects of glare are to be significantly reduced.

This hints at a method, in which $L_{seq}$ replaces $L_{20}$ as a measure of glare, while using a table of factors for determining the $L_{th}$ value. Such a method provides some advantages compared to the $L_{20}$ method:

- a better measure of the glare,
- natural values of the factors,
- the possibility for inclusion of other sources of veil (by scattering in the air and in the car windscreen).

$L_{seq}$ as well as $L_{20}$ is to be measured or evaluated at the actual stopping distance (related to the design driving speed). In this connection it should be noted that the factors of tables E.2 and E.5 increase with increasing stopping distance. This is natural as it is harder to see an object at a longer distance.

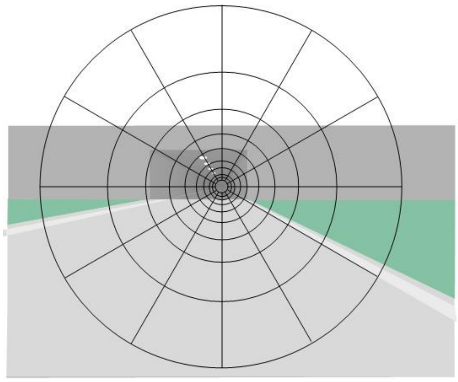
It is actually a lack of the $L_{seq}$ method of CIE 88:2004 that it deals only with perceived contrast and does not take the stopping distance into account.

The reduction of the road surface luminance in the last half of the threshold zone from $L_{th}$ to $0,4 \times L_{th}$ is prescribed CIE 88:1990 and CIE 88:2004.

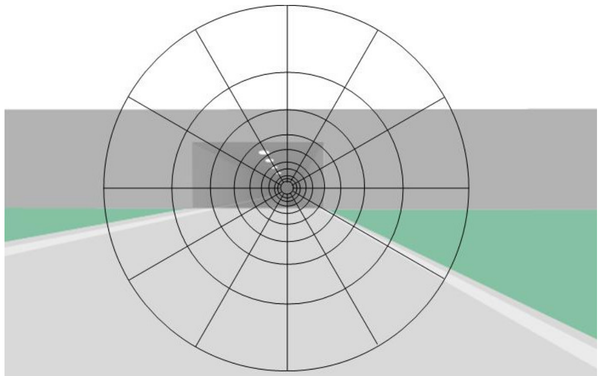
However, the $L_{seq}$ does in practice decrease gradually during the approach to the tunnel, as the tunnel opening and its immediate surrounds take up more of the zones. This is illustrated in figure E.6.

Therefore, it should be a sound procedure to evaluate or measure the $L_{seq}$ value at more than one distance in front of the tunnel opening and reduce the road surface luminance at the stopping distance inside the tunnel in proportion to the $L_{seq}$ value.

**A: at the stopping distance from the tunnel opening**



**B: Closer to the tunnel opening**



**C: Even closer to the tunnel opening**

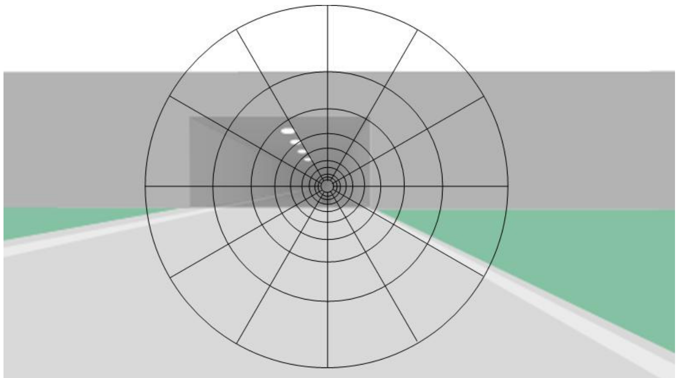


**Figure E.6: The $L_{seq}$ value decreases gradually during the approach to the tunnel opening.**

## E.4 Lighting of the transition zone

### E.4.1 Historical account

CIE 26:1973 provides the curve for the decrease of the road surface luminance within the transition curve shown in figure E.7.

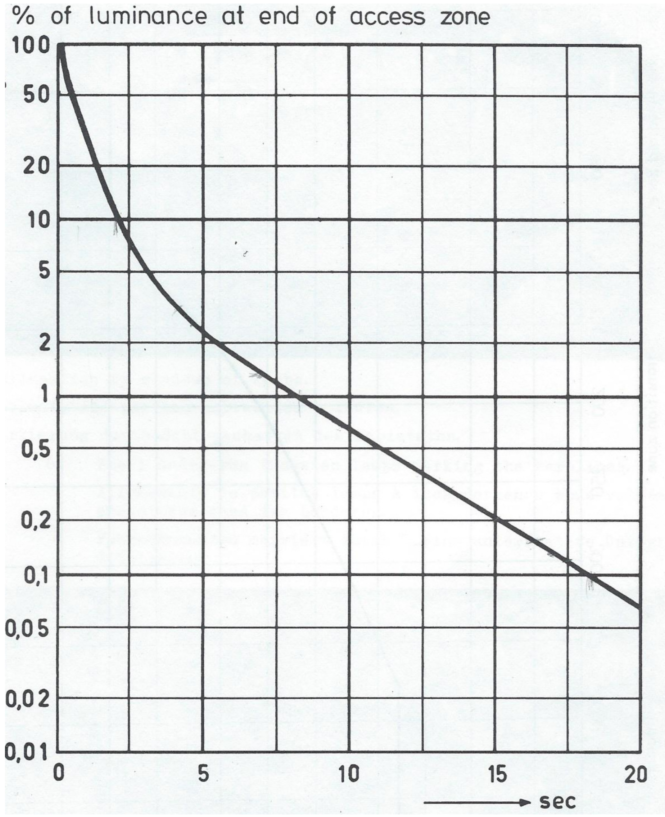



**Figure E.7: Relative decrease of the luminance in the transition zone as a function of driving time in seconds.**

A curve of much the same nature, although not identical, is provided in both CIE 88:1990 and CIE 88:2004. This curve is given by this formula:

$L_{tr} = L_{th} \times (1,9+t)^{-1,4}$

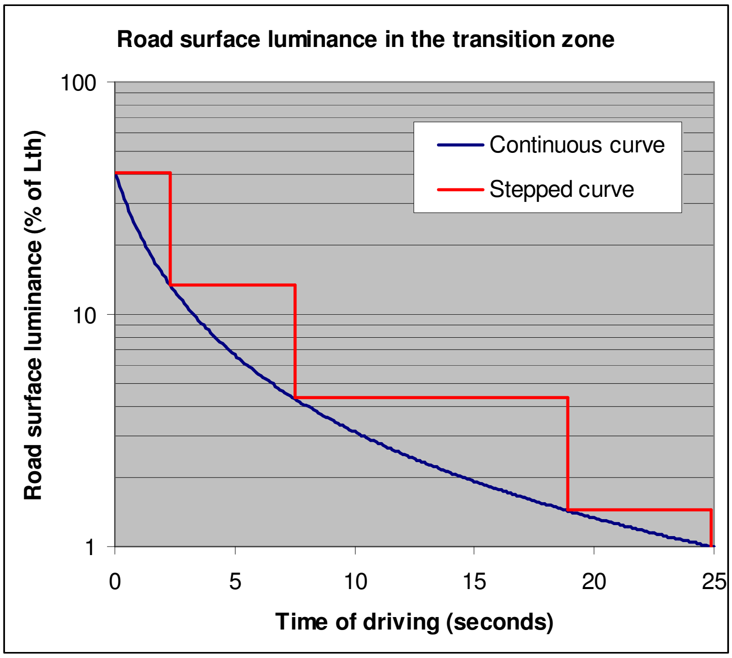
where $L_{tr}$ is the road surface luminance in the transition zone,
$L_{th}$ is the road surface luminance in the threshold zone,
and t is the driving time in seconds.

The curve for $L_{tr}$ in percent of $L_{th}$ is shown in figure E.8. It is permitted that the curve is approximated by a stepped curve provided that the steps do not exceed a factor of three and that the steps never fall below the continuous curve. A stepped curve with steps of a factor of 3 is also indicated in figure E.8.

It is to be noted that the curve starts at 40%. The reason is that the reduction from 100% to 40% is assumed to have taken place in the last half of the entrance zone.

NOTE: It is a bit annoying that the above-mentioned formula produces a value of 0,407 at t = 0 instead of 0,40.

Figure E.8: Road surface luminance in the transition zone as provided in CIE 88:1990 and CIE 88:2004.




The curve is in principle to be followed until the road surface luminance in the transition zone $L_{th}$ reaches the road surface luminance requested in the interior zone $L_{in}$. The necessary driving time in the transition zone is then given by:

$t_{tr} = (L_{in}/L_{th})^{-0,714}-1,9$ seconds

The necessary driving time $t_{tr}$ can also be read of the diagram in figure E.8 at the relevant value of $L_{in}$ expressed as percentage of $L_{th}$.

When $L_{in}$ is 1% of $L_{th}$, the driving time in the transition zone is as long as 25 seconds. When 2% or 3%, the time is reduced to respectively 14,4 s and 10,3 s. The necessary length of the transition zone is found by multiplication with the driving speed in m/s (found as the driving speed in km/h divided by 3,6).

This shows that the transition zone can be quite long, but that it depends on both the road surface luminance in the interior zone in addition to the driving speed.

The first step of reduction by at factor of three of the stepped curve in figure E.8 occurs after only 2,3 seconds of driving, the second step after additional 5,2 seconds of driving and the third step after further 11,4 seconds. This shows that the continuous curve is steep at the start of the transition zone and then flattens out.

### E.4.2 Adaptation, after-images and comfort in the transition zone

The doctor thesis report of Duco Schreuder provides the curve shown in figure E.9. It has been obtained in this way (quote from the report): “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”.

The report contains a discussion of adaptation, stating among else that ”In fact, under the conditions related to tunnel lighting, the "general adaptation" can be regarded as being instantaneous”. That was the reason that the focus was placed on after-images and comfort. Nevertheless, the word ”adaption” is used in a general way in the following.

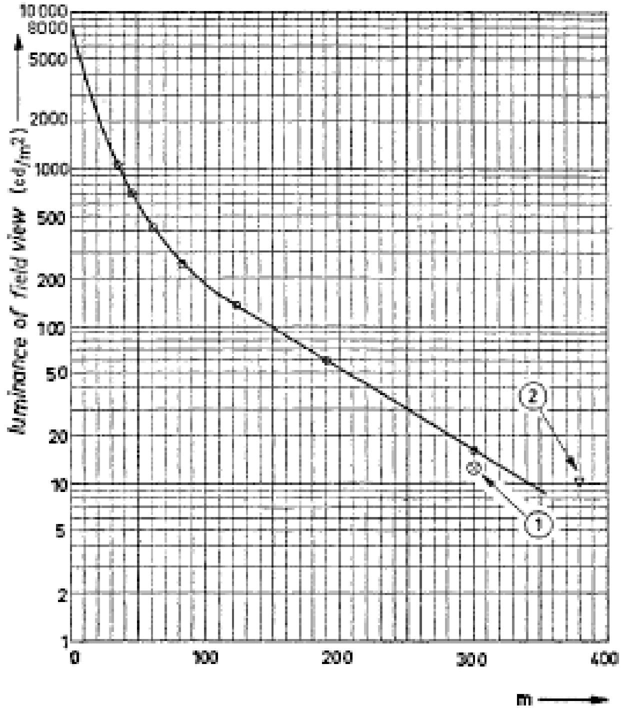



**Figure E.9: Curve provided by Duco Schreuder.**

As can be seen from figure E.9, the luminance of the screen was reduced from 8.000 cd/m$^2$ corresponding to bright outdoor conditions down to approximately 10 cd/m$^2$ corresponding to conditions near the end of the transition zone. The two point marked 1 and 2 are the results of simulated tunnel driving experiments.

What was measured was really time elapse, but the diagram is expressed in distance at a driving speed of 72 km/h. It can be converted back to time by dividing the distance by 20 m/s. Such a diagram is shown in figure E.10, where the scale is also converted to percentage.

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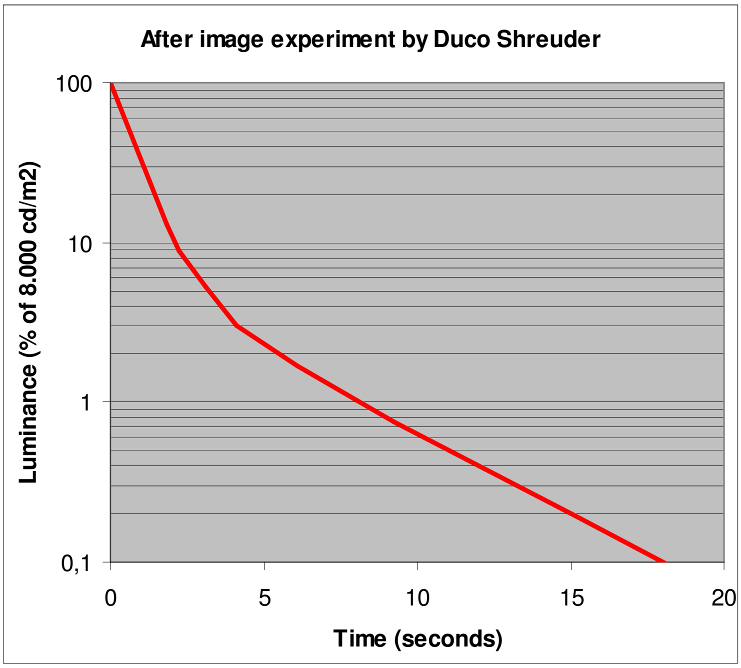



**Figure E.10: After image experiment by Duco Schreuder.**

The curve in the diagram can be identified with the curve included in CIE 26:1973. Compare figures E.7 and E.10.

However, the experimental method is based on a large uniform screen and gradual adjustment of the luminance by the observers and do not reflect a tunnel situation. Refer to figure E.11, which shows locations of a driver in the access zone and the stopping distance ahead at which he needs to see objects.

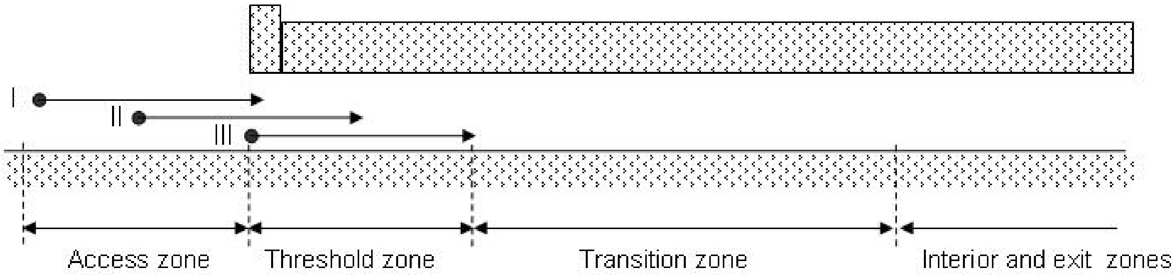



**Figure E.11: Locations of a driver in the access zone and the stopping distance ahead at which he needs to see objects.**

At location I, the driver is adapted to the full ambient light level of $L_{20}$, but looks into the threshold zone with a luminance level of $L_{th}$ of typically 5% of $L_{20}$. Refer to table E.2.

At location II, the ambient light level may be somewhat reduced compared to location I, because the tunnel opening is more close. The driver may be adapted to the reduced level which, however, is still far above $L_{th}$.

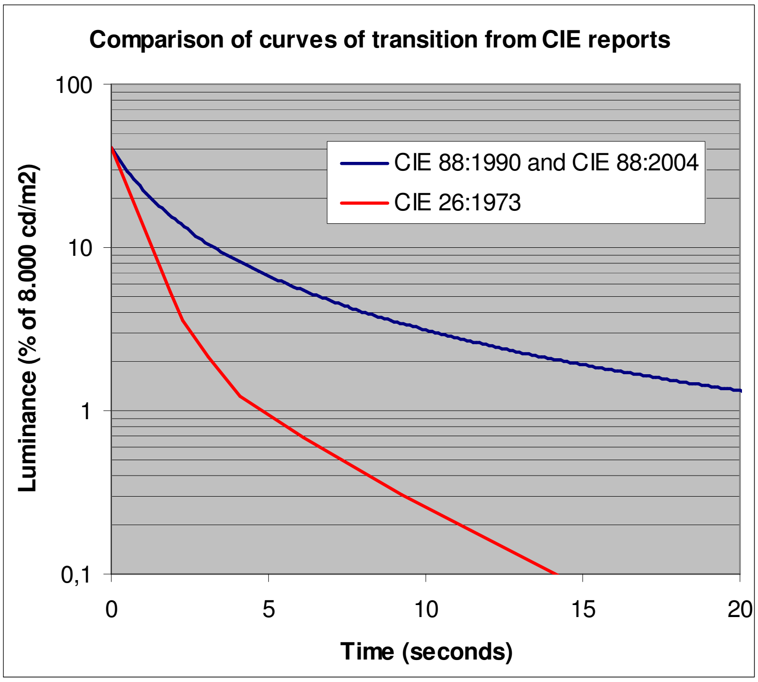
At location III, the ambient light level is the one of $L_{th}$. However, the driver has had only a couple of seconds of adaptation since position II and should have an adaptation level of approximately 10% of the previous level. This is higher than the level at the start of the transition zone of typically 2% of $L_{20}$.

This shows that the driver does not achieve adaptation in the sense of the above-mentioned experiment while driving in the access zone. He should be well into the threshold zone or transition zone before achieving adaptation, if he does that at all before entering the interior zone.

Therefore, the practical and commonplace design of tunnel lighting is in contradiction to the results of the experiment. The curve itself is, therefore, questionable. It is also questionable that it can be applied for the luminance in the transition zone in the way described in CIE 26:1973. After all, it has been derived for an initial luminance of 8.000 cd/m$^2$, and not for the much lower initial luminance in the threshold zone.

The diagram in CIE 26:1973 was replaced with a different diagram in CIE 88:1990 and CIE 88: 2004. The two curves are compared in figure E.12 after bringing them on the same scale. It is seen that the curve of CIE 88:1990 and CIE 88:2004 has a very slow rate of reduction and thereby causes a considerable length of the transition zone.

**Figure E.12: Comparison of curves from CIE reports.**




The author does not know why the curve of CIE 26:1973 was replaced nor how the newer curve was derived. There is no clue to that in CIE 61:1984.

However, the curve cannot represent adaptation nor the action of after-images as its decrease is much more slow than the curve of CIE 26:1973.

CIE 88:1990 mentions briefly that the curve corresponds to a situation of little visual discomfort and there that is more visual discomfort if a steeper curve is used.

That is dubious. Why should the driver be offered such a slow change of luminance level for comfort after his hardships of a dramatic change at the tunnel entrance ? Is there a need for such a slow change based on comfort at all ?

It is normal to accept changes of luminance level of a factor of 10 or more without hesitation or delay. This can for example be when stepping from a well lit office into a corridor. Most people do that without hesitation.

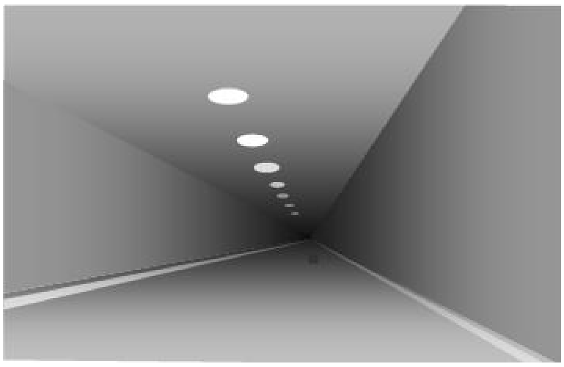
An explanation is offered in the next section.

### E.4.3 Glare in the transition zone

The characteristic matter in the transition zone is that the driver is at a location with a relatively high illumination that is associated with a relatively high value of the equivalent veiling luminance $L_{seq}$. This veiling luminance overlays the scenery one stopping length ahead, where he needs to be able to detect objects, and where the illumination is reduced. This is illustrated in figure E.13.

EXAMPLE 1: Assume that a driver is at a certain location in the transition zone with a local luminance level of 100 cd/m$^2$ and an equivalent veiling luminance of 20 cd/m$^2$ (this corresponds to a value of the Threshold Increment TI of 15%). The driver looks a stopping distance of 113 m ahead (corresponds to a driving speed of 90 km/h), where the luminance level is reduced to 20 cd/m$^2$. Therefore, the level of glare is actually high.

**A: Scene in the transition zone with decreasing luminance level**



**B: The same scene with overlay of an equivalent veiling luminance.**

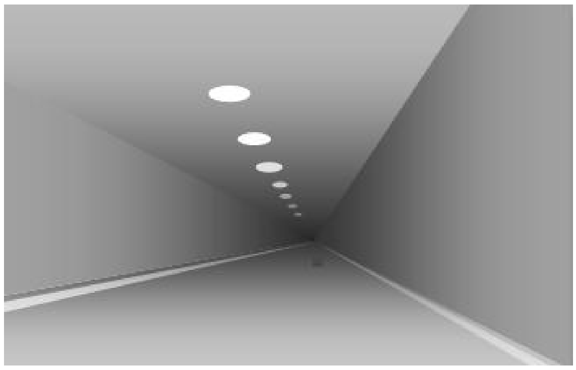


**Figure E.13: Glare has a stronger effect in the transition zone because the luminance level is decreasing.**

The effect is a virtual amplification of glare from levels that are relatively high in tunnel and road lighting compared to other forms of lighting. Therefore, luminance level cannot be stepped down dramatically over the time it takes to drive the stopping distance – which is 4 to 5 seconds for the most relevant driving speeds.

The author thinks that this is the reason that the transition zone needs to of a considerable length. This is probably a novel point of view that may not to have been debated in the CIE. However, the basis for designing the luminance reduction in the transition zone is outlined in the following.

When the driver is at a certain location, he experiences a certain value of $L_{seq}$ and a certain luminance level $L_{tr}$. The ratio is D equal to $D = L_{seq}/L_{tr}$. However, the driver looks ahead one stopping distance to a location where the luminance level is reduced by a factor f with a value smaller than one. The relevant value of D is, therefore, $D^* = D/f$.

When the driver has moved one stopping distance ahead, to where the luminance level has been reduced by the factor f, both $L_{seq}$ and $L_{tr}$ has been reduced by the same factor f. Therefore, the same value of D applies, and the same value of the factor f can be applied to provide the same value of D*.

This is repeated for more stopping distances, always providing a constant value of D* for a constant value of f.

Therefore, when using a fixed value of D* as the criterion for the selection of the factor f, the luminance level follows the function $f^x$, where x is the number of stopping distances.

D* is a sensible criterion for glare, as it measures the ratio between the equivalent veiling luminance and the road surface luminance at the location, where the driver is looking. The function $f^x$ is an exponential function given by $f^x = \exp(x \times \ln(f))$. The term ln(f) is negative because f is smaller than one.

NOTE: The ratio between $L_{seq}$ and the average road surface luminance was actually used as a measure of glare in road lighting before the Threshold Increment TI was introduced. It was called the degree of glare, D.

The value of the factor f is found by $f = D/D^*_{max}$, where $D^*_{max}$ is a selected maximum permissible value of D*.

EXAMPLE 2: Assume that $L_{tr}$ is 100 cd/m$^2$ and that $L_{seq}$ is 20 cd/m$^2$. A value of $D^*_{max}$ of 0,4 then leads to $f = 20/(100\times0,4) = 0,5$.

If taking for granted that the initial road surface luminance in the transition zone is $0,4\times L_{th}$ and that the road surface luminance needs to be reduced to the value of $L_{in}$ applied for the interior zone, the total reduction factor is $L_{in}/(0,4\times L_{th})$. The length of the transition zone is then found by $\exp(x\times\ln(f)) = L_{in}/(0,4\times L_{th})$ or $x\times\ln(f) = \ln(L_{in}/(0,4\times L_{th}))$; giving $x = \ln(L_{in}/(0,4\times L_{th})/\ln(f)$ measured in number of stopping distances.

EXAMPLE 3: Assume that $L_{th}$ is 400 cd/m$^2$, $L_{in}$ is 4 cd/m$^2$ and that f is 0,5. The number of stopping distances is then 5,32. With a stopping distance of 113 m a (corresponds to a driving speed of 90 km/h), the length of the transition zone becomes a considerable 600 m.

Exponential functions are straight lines in a logarithmic diagram. Some examples for different values of f are shown in figure E.14 expressed as percentage of $L_{th}$ and as functions of driving time at a speed of 90 km/h.

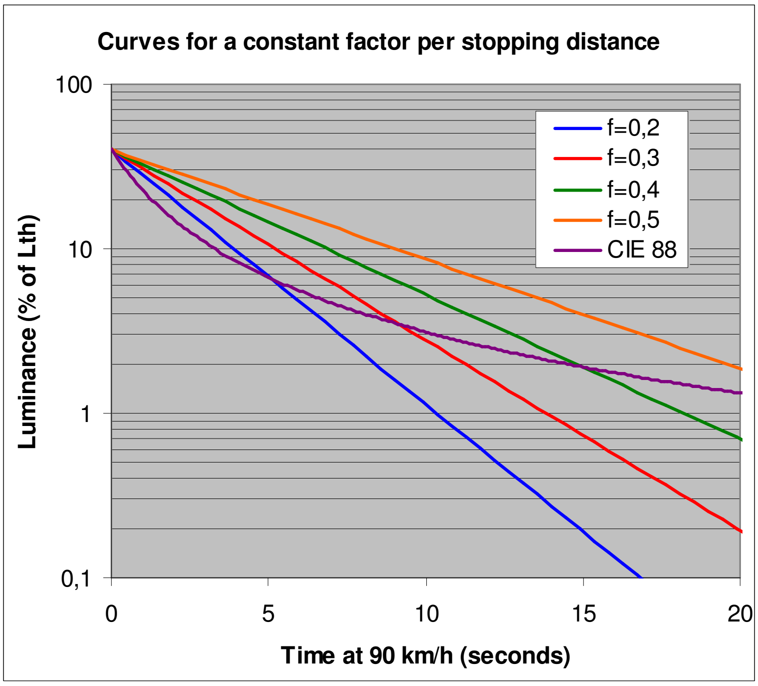



**Figure E.14: Curves for constant factor per stopping distance and the CIE 88 curve for comparison.**

The curves in figure E.14 are not quite independent of the driving speed, as the driving time for a stopping distance increases gradually with the driving speed. Therefore, the diagram in figure E.14 is not well suited for practical use, but the curves are directly comparable to the curve of CIE 88:1990 and CIE 88:2004. This curve is, therefore, also entered.

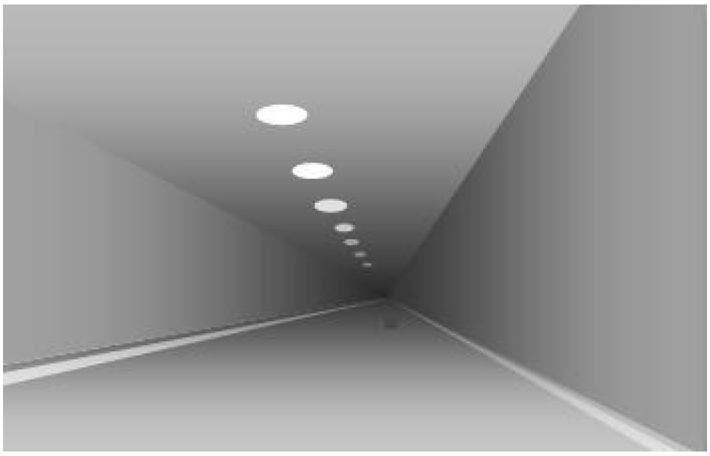
The factor need in practice to be less than 0,4 in order that the curves lead to a length of the transition zone shorter than for the CIE curve. Small values can be set for installations with little glare (low values of D).

It is not unreasonable to let the factor have a relatively small initial value and then increase it gradually. The justification is that a high fraction of glare has less effect on visibility at the initial high luminance levels. This would make the lines curve in a manner similar to the CIE curve and shorten the length of the transition zone. However, the CIE curve corresponds to very strong variation of the factor that cannot be reproduced by any visibility criterion..

In total, an approach as described in the above would produce results similar to those of the CIE curve. However, it would place emphasis on glare from the lighting installation, which is thought to be the dominating factor, and it would allow savings when introducing better control of glare.

It requires some form of justification that glare is the dominating factor before it is worthwhile to develop the approach into a design method. Some simple experiment, where observers judge the tunnel scene without and with a glare reducing screen. Refer to figure E.15 for a simple illustration.

**A: Without glare reduction**



**B: With glare reduction by means of a screen**

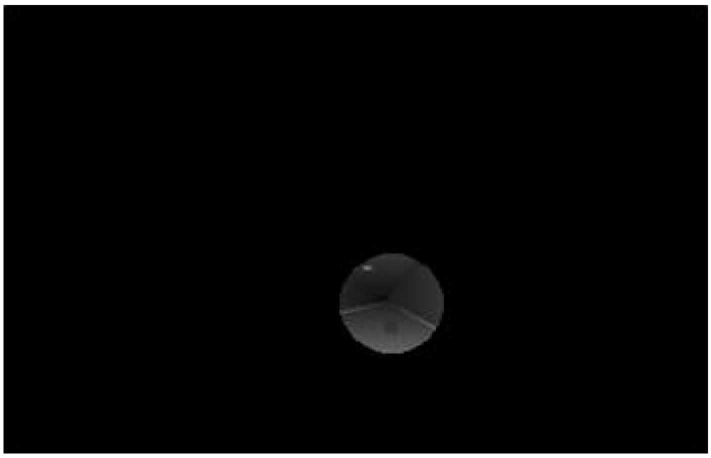


**Figure E.15: A tunnel scene observed without and with a glare reducing screen.**

## E.5 Illumination of the interior zone and the exit zone

The CIE reports provide the advice for lighting of the interior zone during daylight shown in tables E.6, E.7 and E.8.

**Table E.6: CIE 26:1973.**

| Type of tunnel | Average road surface luminance |
|---|---|
| Urban tunnels | 10 to 20 cd/m$^2$ |
| Rural tunnels | 5 to 10 cd/m$^2$ |
| Very long tunnels or tunnels with a speed limitation or on roads with little traffic | 3 to 5 cd/m$^2$ |

**Table E.7: CIE 88:1990.**

| Stopping distance | Traffic flow | | |
|---|---|---|---|
| | Low<br>≤100 vehicles/h | Medium<br>>100 vehicles/h<br>≤1000 vehicles/h | Heavy<br>≥1000 vehicles/h |
| | Average road surface luminance | | |
| 160 m | 5 cd/m$^2$ | 10 cd/m$^2$ | 15 cd/m$^2$ |
| 100 m | 2 cd/m$^2$ | 4 cd/m$^2$ | 6 cd/m$^2$ |
| 60 m | 1 cd/m$^2$ | 2 cd/m$^2$ | 3 cd/m$^2$ |

**Table E.8: CIE 88:2004.**

| Stopping distance | **Long tunnels**<br>Traffic flow (vehicles/hour/lane) | |
|---|---|---|
| | Low | Heavy |
| | Average road surface luminance | |
| 160 m | 6 cd/m$^2$ | 10 cd/m$^2$ |
| 60 m | 3 cd/m$^2$ | 6 cd/m$^2$ |

| Stopping distance | **Very long tunnels**<br>Traffic flow (vehicles/hour/lane) | |
|---|---|---|
| | Low | Heavy |
| | Average road surface luminance | |
| 160 m | 2,5 cd/m$^2$ | 4,5 cd/m$^2$ |
| 60 m | 1,0 cd/m$^2$ | 2,0 cd/m$^2$ |

NVF Report No. 4: 1995 “Belysning af vejtunneler” uses table E.7 with two modifications. One is that the stopping distance criterion has been replaced with a driving speed criterion (90-110, 70-90 and 50-70 km/h) and the other is that the average road surface luminance values of 5, 10 and 15 cd/m2 are replaced with the lower values of 4, 8 and 12 cd/m$^2$ respectively.

The reports provide lighting requirements for the night period that are similar to those that are applied for roads of similar driving speeds and traffic flows.

The exit zone is mostly to be illuminated in the same manner as the interior zone. However, in some specified cases it is recommended to raise the road surface luminance by a factor of 5.

The reports provide more details than accounted for in the above. Please refer to the reports themselves.

**E.6 Daylight screen**

For the purpose of reducing or elimination the need for powerful illumination in the entrance zone, the access zone in front of the tunnel opening can be covered with a daylight screen, which reduces the daylight below the screen. A daylight screen in the form of a louver with lamellae is illustrated in figure E.16. A daylight screen may also be a transmitting roof construction.

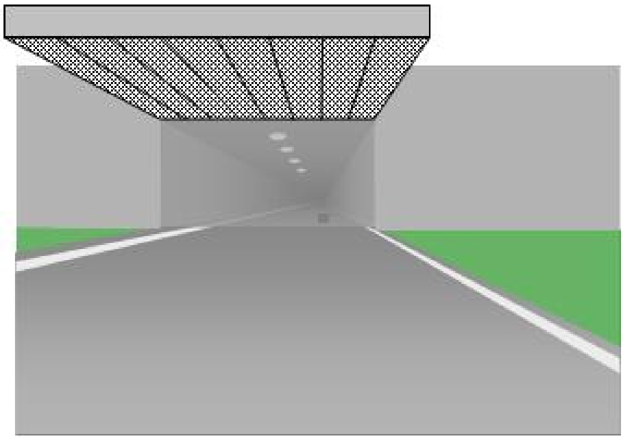


**Figure E.16: Daylight louver.**

An ideal daylight screen reduces the daylight level to the fraction that would be needed in the entrance zone. Refer to the tables E.2 and E.5. Use of such a screen corresponds to a conversion of the access zone into the threshold zone – and a conversion of the threshold zone into the transition zone. If the louver is sufficiently long and has a gradual decrease of the transmission, it can even replace some or all of the transition zone.

Roof constructions are not well suited for Nordic conditions because of snow and ice during the winter. Nevertheless, there is at least one example of use.

The disadvantage of louvers is that they may transmit patches of sunlight that are disturbing for the drivers. It is more easy to make a suntight construction the lower the sun is and this makes them more appealing for use in the Nordic countries. On the other hand, suntight construction has a transmission that is lower in sunshine than in clouded weather, and that tends to be too low.

A relatively open louver may have a sufficient transmission of 5% in sunshine and a too high transmission of 20% in clouded weather. If followed by a more closed and suntight louver the combination can be acceptable. There is at least one example of use of a combined louver. In part of the year, the relatively open louver transmits patches of sunlight, but this seems to be acceptable.

In Nordic conditions it is necessary to have means of avoiding collection of ice and snow on a daylight louver.

**Literature**

Duco Schreuder, The lighting of vehicular traffic tunnels, 1964, the Technical University of Eindhoven
CIE 26:1973 International recommendations for tunnel lighting
CIE 61:1984, Tunnel entrance lighting – A survey of fundamentals for determining the luminance in the threshold zone
CIE 88: 1990, Guide for the lighting of road tunnels and underpasses
CIE 88: 2004, Guide for the lighting of road tunnels and underpasses
CEN/CR 14380: 2003 Lighting applications – Tunnel lighting
NVF Report No. 4: 1995 Belysning af vejtunneler
Directive 2004/54/EC Minimum safety requirements for tunnels in the trans-European road network
EN 16276: 2013 Evacuation lighting in tunnels