Lighting of short tunnels during daytime

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Final Report

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Contents

Introduction

At the end of the year 2008, the BSI Committee for Tunnel Lighting (CPL/34/8/6) was looking for someone who is interested in conducting a research about short tunnel lighting during daytime. The reason was that practitioners find that for short tunnels the recommendations in the British Standards lack definition and can often result in considerable over-lighting. These recommendations can be found in BS 5489-2: 2003, *Code of practice for the design of road lighting –Lighting of tunnels*. I decided to conduct this research as the final report of my Light and Lighting (MSc) studies at the University College London in 2009.

The aim of this report is to investigate whether there are lighting approaches, which constitute an improvement over the lighting approach for short tunnels during daytime recommended in the current British Standard. Furthermore, the aim is to explore whether an overcast sky or an obstructed exit aperture provides a background of sufficiently high luminance to enable the 'silhouette effect' to operate.

Therefore, the final report is divided into four main parts:

First, the progress of short tunnel lighting research that has been developed over the years will be delineated.

Second, the research question stated will be defined in more detail.

Third, a new research about short tunnel lighting will be presented.

Fourth, the results of this research will be stated and analysed.

It will be concluded by arguing that the *Lichtschleuse*, a luminous band on the walls of a tunnel and LED strips on the wall of a tunnel are appropriate means to light a short tunnel. However, it will be also stated that there are still issues which could not be investigated due to the time frame of this final report.

The two key terms of the title of this work are 'daytime' and 'short'. Tunnels require a significantly different lighting during hours of daylight than during hours of night due to the different state of adaption of the user's eye. The term 'short' is not related to the absolute length of a tunnel, but to the necessity of lighting it artificially.

In this report, the term ‘short tunnel’ is defined as any kind of roofing over a road, whose exit is visible in front of the entrance.

This research focuses on short tunnels, which are used solely by motorised vehicles or by motorised vehicles and pedestrians/cyclists.

1.0 The state of knowledge about short tunnel lighting during daytime

In this section, the progress of research about ‘short tunnel’ tunnel lighting during daytime will be delineated. The steps of this progress will be described chronologically, and the progress will be appraised afterwards. This delineation also incorporates a summary of some recently published European guides and codes of practice concerning short tunnel lighting.
‘Short tunnel’ is termed as ‘underpass’ in some of the listed publications – however, the term ‘underpass’ as it is used in these publications do not conflict with the definition of ‘short tunnel’ as stated in the introduction.

1.1.1 The progress of lighting research

In 1955, Lossagk[1] pointed out that it would be important to consider the ‘silhouette-effect’ by lighting underpasses during daytime. Under certain circumstances obstacles (e.g. objects and people) in an underpass can be seen as silhouettes against the exit aperture. Lossagk stated that the luminance difference between an obstacle and the exit aperture is fairly big, and that it would be very difficult to achieve the same luminance contrast between the obstacle and its dark surroundings (e.g. the walls) by lighting the obstacle artificially. Therefore, he said “that promoting the ‘silhouette-seeing’ probably

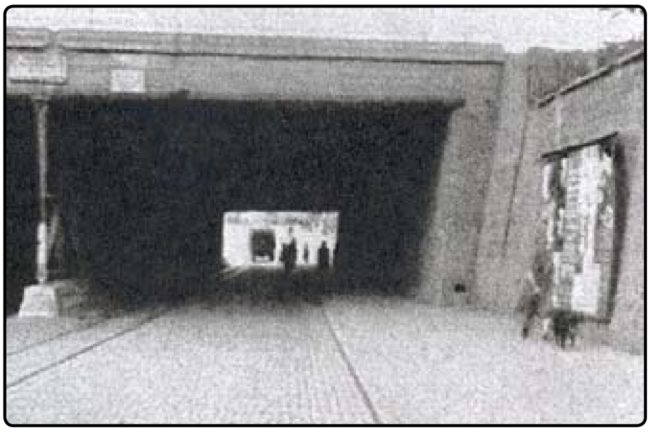

Figure 1: Obstacles can be seen as silhouettes against the exit aperture of a tunnel
(Source: Lossagk H. ‘Sehsicherheit bei Tageslicht in Unterführungen’. Lichttechnik, Vol 7, No 2 (1955) p50.)

1 Lossagk H. ‘Sehsicherheit bei Tageslicht in Unterführungen’. *Lichttechnik*, Vol 7, No 2 (1955) pp49-53.

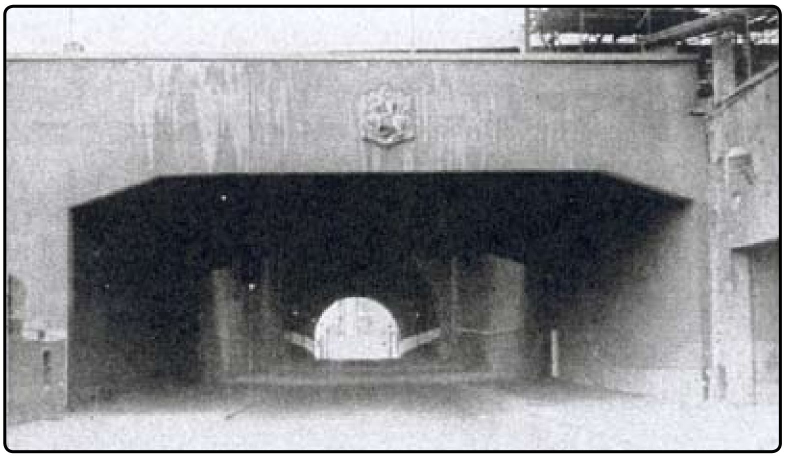

Figure 2: White strips on the walls improve the visibility of obstacles

(Source: Lossagk H. 'Sehsicherheit bei Tageslicht in Unterführungen'. Lichttechnik, Vol 7, No 2 (1955) p51.)

more improves the visual performance in underpasses than artificial illumination."[2] Furthermore, Lossagk stated that it would be desirable to use the light, which enters the exit aperture, to create high luminances on the surfaces inside the underpass. Therefore, he recommended equipping the walls with light finishes, for example white tiles - if these bright areas were interrupted by an obstacle, the driver would detect this obstacle. He supported this idea by means of a picture (see figure 2). This picture shows two white stripes, which are located on the walls in the rear of the underpass. Each of the stripes is 100 meters long and composed of tiles. Lossagk pointed out that the poles (of the street luminaires in the underpass) are visible as silhouettes against the white stripes, whereas they are "completely camouflaged"[3] against the grey walls – although the luminance of the stripes is only a small percentage of the luminance of the exit aperture. He suggested also other means to achieve this effect, for instance, specular rails. If daylight is not sufficiently provided in an underpass, this effect could be supplemented "without high expenses"[4] by directional artificial lighting.

Moreover, Lossagk proposed another approach, which was later called a *Lichtschleuse*[5]: an artificially lit area (e.g. a lit transparent surface), which covers the road, the foot-walk and the lower part of the right wall in the middle of the underpass, divides the underpass into two smaller ones.

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2 original text (German): "daß es zur Steigerung der Sehsicherheit in Unterführungen sinnvoller sein dürfte, daß 'Schattenrißsehen' zu fördern, als durch Ausstrahlung mit künstlicher Beleuchtung die Sehsicherheit erreichen zu wollen.“ (translated by David M. Kretzer) // *Ibid*. p50.

3 original text (German): "völlig getarnt“ (translated by David M. Kretzer) // *Ibid*. p53.

4 original text (German): "ohne großen Kostenaufwand " (translated by David M. Kretzer)" // *Ibid*. p53.

5 German: "light-lock" // (see figure 5)

	Favourable (no bends, no dense traffic, only motorised traffic)		Unfavourable (bends and/or dense traffic and/or mixed traffic)	
No lighting	Class 1a	0 to 50 m	Class 1b	0 to 25 m
Cross strip lit . . . . . . (to about 800 cd/m²)	Class 2a	50 to 80 m	Class 2b	25 to 40 m
Total length lit . . . . . . (to about 800 cd/m²)	Class 3a	80 to 100 m	Class 3b	40 to 100 m
Lighting according to recommendations for long tunnels	Class 4, more than 100 m			

Table 1: Recommendations of the NSVV (1963) for the lighting of short tunnels
(Source: Schreuder D A. The Lighting of Vehicular Traffic Tunnels. 2nd ed. Philips Technical Library, Eindhoven (1965) p60.)

In 1963, a paper about tunnel lighting was published by the 'Netherlands Foundation on Illumination'[6] (NSVV). In this paper, a distinction was introduced between 'short tunnels' and 'long tunnels'. A tunnel was defined as 'short', if its exit aperture is visible in front of the tunnel.[7] It was claimed that if the exit aperture is visible, the 'black hole effect'[8] occurs, and that this effect is the "same as with long tunnels"[9]; however, it would not be a 'black hole', but a 'black frame'. Obstacles, which are located within this black frame, "can not be perceived."[10] It was also stated that the adaptation of the eye would happen differently by entering a short tunnel than by entering a long tunnel, since the bright exit aperture would be in the centre of the field of vision. Therefore, no noteworthy adaptation to the luminance of the interior of the (short) tunnel would occur[11].

The authors published a table (see table 1), which should serve as guidance for the lighting of short tunnels. The recommendations were based on different parameters, namely traffic density, traffic composition, shape of the tunnel and length of the tunnel.

6 Nederlandse Stichting voor Verlichtingskunde (NSVV). 'Aanbevelingen voor tunnelverlichting'. *Electro-Techniek*, Vol 41, No 2 (1963) pp23-53.
7 *Ibid*. p28.
8 More information about this topic is given in: Boyce P R. '*Human Factors in Lighting*'. 2nd ed. Taylor and Francis, London (2003) pp374-375.
9 original text (Dutch): "dezelfde als bij lange tunnels" (translated by David M. Kretzer) // Nederlandse Stichting voor Verlichtingskunde (1963). op. cit. p28.
10 original text (Dutch): "niet kan worden waargenomen" (translated by David M. Kretzer) // *Ibid*. p28.
11 *Ibid*. p29.

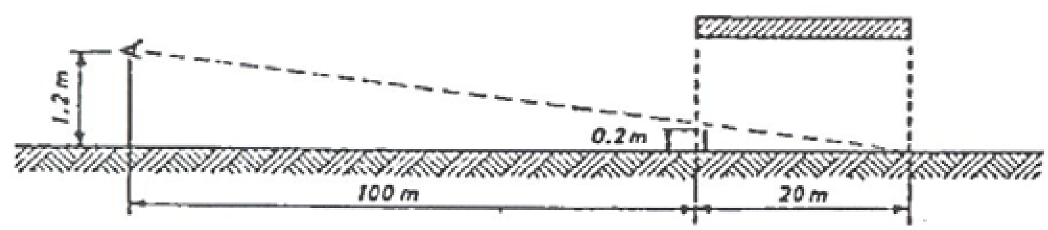


Figure 3: Geometrical drawing of the NSVV to support the recommendation for tunnels, which are up to 20 m long
(Source: Nederlandse Stichting voor Verlichtingskunde (NSVV). 'Aanbevelingen voor tunnelverlichting'. Electro-Techniek, Vol 41, No 2 (1963) p29.)

The authors stated that tunnels, which are up to 20 m long, do not need to be lit. This statement is based on a geometrical drawing (see fig. 3): it shows an observer's eye (eye height level: 1.2 m) located 100 meters in front of the tunnel and an obstacle (0.2 x 0.2 m) standing at the entrance of a tunnel. A line, which connects the eye and the upper edge of the obstacle hits the road 20 m behind the obstacle. If this tunnel were shorter than 20 m, the obstacle could partly be seen as a silhouette against the exit aperture. However, an unlit tunnel could even be longer than 20 m, if its walls and the road have a high luminance[12]. No reason was given for the distance and the height of the eye determined for the drawing.
It is stated that non-winding tunnels, which are longer than 50 m long, would need to be lit, because it could happen that a "lorry driving ahead in the tunnel shields almost the whole exit aperture, so that nothing is left for creating a silhouette [see figure 40 (page 90)]."[13]

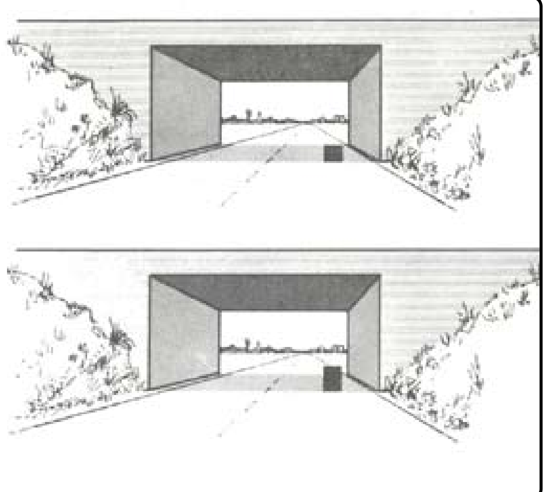


Figure 4: The size of an obstacles makes an impact on the visibility in tunnels: big obstacles stick out the 'black frame'
(Source: Schreuder D A. The Lighting of Vehicular Traffic Tunnels. 2nd ed. Philips Technical Library, Eindhoven (1965) p58.)

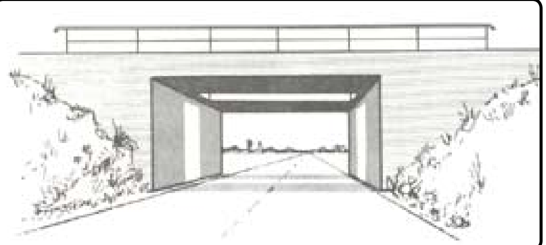


Figure 5: A *Lichtschleuse*
(Source: Schreuder D A. The Lighting of Vehicular Traffic Tunnels. 2nd ed. Philips Technical Library, Eindhoven (1965) p59.)

12 *Ibid*. p29.
13 original text (Dutch): "verderop in de tunnel rijdende vrachtauto vrijwel de gehele uit-

It was recommended to light tunnels, which are between 50 to 80 m (respectively 25 to 40 m) long, by creating a *Lichtschleuse* (a cross strip composed of light (see figure 5)) in the middle of the tunnel - because this would be economically attractive. By doing so, the obstacle is either seen against the *Lichtschleuse* or against the exit aperture. The Lichtschleuse could either be created by artificial or by natural light – a luminance of around 800 cd/m² was recommended.

> (In a later publication it is stated that "the luminance of the [short] tunnel interior must … be raised to at least 800 cd/m² in order to ensure 75 % visibility for an object of contrast 20 %."[14] This value was derived from an experiment about the black hole effect conducted by Schreuder[15]. It seems that the 'Netherlands Foundation on Illumination' derived the recommended luminance for the *Lichtschleuse* stated above from Schreuder's research).

The authors said that the *Lichtschleuse* should be at least 10 m long, however, 1/4 or 1/3 of the tunnel length would be desirable. No reason was given for the recommended length of the *Lichtschleuse*. It was advised against integrating more than one *Lichtschleuse* in one tunnel, since this would result in a confusing street scene.

It was recommended to light tunnels, which are between 80 to 100 m (respectively 40 to 100 m) long, by creating a luminance alongside the whole tunnel of around 800 cd/m².

Tunnels which are longer than 100 m were considered as 'long' tunnels.

Furthermore, for each category of the table (see table 1) an

Figure 6: Tunnel representing lighting class 3b: vertical tubular lamps form a bright background
(Source: Nederlandse Stichting voor Verlichtingskunde (NSVV). 'Aanbevelingen voor tunnelverlichting'. Electro-Techniek, Vol 41, No 2 (1963) p47.)

gang afschermt, zodat er van een silhouetwerking niets meer overblijft." (translated by David M. Kretzer) // *Ibid*. p29.

14 De Boer J B (ed.). *Public Lighting*. Philips Technical Library, Eindhoven (1967) p188.

15 More information about this research is given in: Schreuder D A. *The Lighting of Vehicular Traffic Tunnels*. 2nd ed. Philips Technical Library, Eindhoven (1965) pp6-11. & De Boer J B (ed.). *Public Lighting*. Philips Technical Library, Eindhoven (1967) pp158-166.

Figure 7a: One and the same tunnel can be regarded from one side as ‘long’...
(Source: Schreuder D A. ‘Short Tunnels’. International Lighting Review, Vol 16, No 3 (1965) p95.)

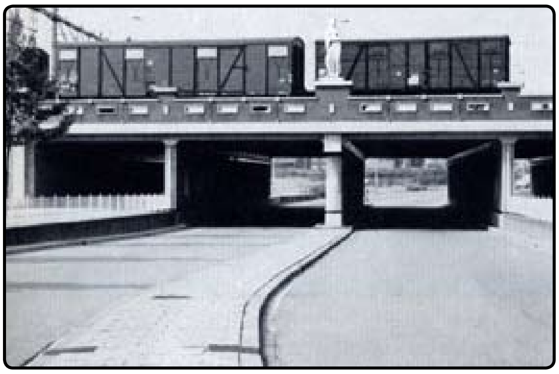


Figure 7b: ...and from the other side as ‘short’ (7a: exit not visible / 7b: exit visible)
(Source: Schreuder D A. ‘Short Tunnels’. International Lighting Review, Vol 16, No 3 (1965) p96.)

existing tunnel was presented, and its lighting reviewed. Vertical and horizontal illuminances and luminances were presented. Moreover, it was accounted for the lighting approach of each of these tunnels. Two of these approaches are special:

The tunnel representing class 1a was not lit - although it is 55 m long – due to the favourable traffic conditions[16].

The tunnel representing class 3b was lit by vertical tubular lamps, which form a bright background (see figure 6). The authors said that this approach would be economically very attractive. However, there were complaints about damage and dirt.[17]

In the 1960s, Schreuder wrote several publications[18] about short tunnel lighting. However, these publications were mainly summaries of the paper issued by the Netherlands Foundation on Illumination’s in 1963[19], but they also contained some supplemental information:

In 1964, Schreuder stated in his dissertation that an experimental tunnel lighting would have proven that a luminance of 150 cd/m² would not be sufficient for a

16 Nederlandse Stichting voor Verlichtingskunde (1963). op. cit. p47.

17 *Ibid*. pp47-48.

18 Schreuder D A. *The Lighting of Vehicular Traffic Tunnels*. 2nd ed. Philips Technical Library, Eindhoven (1965) pp57-64. & Schreuder D A. ‘Short Tunnels’. *International Lighting Review*, Vol 16, No 3 (1965) pp95-99. & Schreuder D A. ‘Über die Beleuchtung von Verkehrstunneln’. *Lichttechnik*, Vol 17, No 12 (1965) pp145-149. & De Boer J B (ed.). *Public Lighting*. Philips Technical Library, Eindhoven (1967) pp186-192.

19 Schreuder D A. *The Lighting of Vehicular Traffic Tunnels*. 2nd ed. Philips Technical Library, Eindhoven (1965) p48.

Lichtschleuse[20].

In 1965, he gave reasons for the observer's distance of 100 m on the geometrical drawing (see figure 3): "It is found in practice that it is generally sufficient if the obstacle … is seen 100 m away. Henceforth, 100 m will be taken as the minimum acceptable visibility-distance."[21] In this regard, it is worth mentioning how convinced Schreuder is about the minimum length of a lit tunnel: "tunnels of a length less than 20 meters, certainly require no lighting"[22] Furthermore, Schreuder demonstrated that a tunnel can be regarded from one side as long and from the other side as short, for instance, if there is a curve in front of one of the entrances (see figure 7a and figure 7b).

In 1985, Schreuder and Fournier conducted research[23] to find a better measurement to classify short tunnels than their length. They also intended to prepare a system for the classification of short tunnels. They brought forward the argument that classifying a tunnel on the basis of its length would not be appropriate:

> "In the past, one usually utilised the length of a tunnel itself for establishing such classifications, mostly measured along the centreline of the road. Thereby it became apparent that this approach does not work out. In real situations, there are tunnels, which are more than 100 m long and [only] need to be lit under certain weather or traffic conditions - then again, there are tunnels, which are only 20 or 25 m long, which would be very dangerous, if they were not fully lit."[24]

20 *Ibid*. p59.
21 De Boer J B (ed.) (1967). op. cit. p157.
22 Schreuder D A. 'Short Tunnels'. *International Lighting Review*, Vol 16, No 3 (1965) p95.
23 Schreuder D A. 'Een system voor classificate van korte tunnels'. R-85-59, Stichting Wetenschnappelijg Onderzoek Verkeersveiligheid SWOV, Leidschendamm (1985)
24 original text (Dutch): "In het verleden is men bij het opzetten van dergelijke classificaties gewoonlijk uitgegaan van de lengte zelf van de tunnel, meestal gemeten langs de wegas. Gebleken is dat deze manier niets opleverde. In de praktijk kan men tunnels van meer dan honderd meter tegenkomen die onder een enkele omstandigheid van weer of verkeer verlichting nodig hebben, maar ook tunnels van 20 of 25 meter die zonder een volledige verlichting zeer gevaarlijk ziin." (translated by David M. Kretzer) // Ibid. pp2-3.

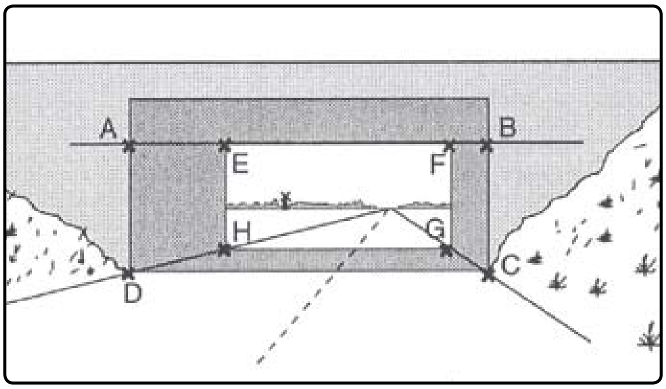


Figure 8: Points for the calculation of the through-view quotient
(Source: Schreuder D A. Road Lighting for Safety. Thomas Telford, London (1998) p272.)

Therefore, Schreuder and Fournier established the "doorzichtgetal"[25] [26] [27] (K) as the new measurement – it is defined as follows (for explanation see fig. 8):

$$K = \frac{EFGH}{ABCD} \times 10$$

The objective of the research was to investigate how tunnels of different lengths can be characterised by means of the through-view quotient. Therefore, pictures were taken of 26 tunnels of different lengths, which were "all 'more or less short'"[28]. These pictures were principally taken 50 m far from the tunnel entrance. Subjects should evaluate the tunnels using the photographs. Therefore, they were asked two questions:

1. "Imagine that the shown tunnel is located on a road - would you drive through the tunnel without reducing speed?"[29]
2. "Imagine that the shown tunnel is located on a road - would you be able to notice stationary cars and cyclists in the tunnel?"[30]

Both questions could be answered either "yes" or "no" or "uncertain".

The experiment was divided into two phases. In the first phase, 22 subjects had to answer a number of additional questions (, which are unfortunately not defined in Schreuder and Fournier's research paper); moreover, additional pictures, taken from different distances, were presented. In the second phase, 27 subjects did not have to answer the additional questions, and the pictures

25 Dutch: "through-view quotient"
26 Schreuder D A (1985). op. cit. p4.
27 This term is called 'look-through percentage' in the British Standard and in the CEN Report (see section 1.1.2)
28 original text (Dutch): "allemaal 'min of meer kort'" (translated by David M. Kretzer) // Schreuder D A (1985). op. cit. p5.
29 original text (Dutch): "Stelt u zich voor dat de getoonde tunnel in een autoweg is gelegen, zoudt u hier dan zonder snelheid te minderen doorheen rijden?" (translated by David M. Kretzer) // *Ibid*. p5.
30 original text (Dutch): "Stelt u zich voor dat de getoonde tunnel in een autoweg is gelegen, zoudt u dan een in de tunnel stilstaande auto of fietser tijdig waar kunnen nemen?" (translated by David M. Kretzer) // *Ibid*. p5.

presented were all taken from a distance of 50 m.
The results of both phases were summed up in the analysis - however, only the first question was considered. Thereby, “uncertain” answers were regarded as “no” answers.
Schreuder and Fournier presented the results as a table (see table 2). The tunnels are listed in the order in which they were presented to the subjects.
For each tunnel the yes/no (“Ja”/”Nee”) answers of the first (“Eerste proef”) and second phase (“Tweede proef”) are listed, and also the total (“Totaal”). The total of both yes and no answers is also expressed as one value (“Beordelling” (Dutch: “evaluation“)), which is based on the following equation:

$$\text{Evaluation} = \frac{\text{(total number of “yes” answers) x 10}}{\text{(total number of answers)}}$$

Hence, if the subjects answered unanimously “no”, the evaluation value is 0 – and if they answered unanimously “yes”, the evaluation value is 10. Moreover, the through-view quotient (“Doorzichtgetal K”) is stated, calculated from a distance of 50 m.
The data show “that there is indeed a certain correlation between the through-view quotient and the evaluation: a higher through-view quotient (a smaller black frame) corresponds generally with a higher evaluation [value] (more yes-answers).“[31] Schreuder and Fournier also presented the data in a graph (see graph 1), and pointed out that there are three clusters – although the through-view quotients are fairly equally spread. It would seem that in some cases the subjects are in doubt (cluster 2: evaluation value between 4 and 7.5) – the evaluation is not unanimous. In contrast, there are other cases were the evaluation was fairly unanimous (evaluation value between 0 and 2 (cluster 1) & 8.5 and 10 (cluster 3)) – the subjects agreed that there are very ‘good’ and very ‘bad’ tunnels.
Furthermore, the difference (regarding the through-view quotient (see graph 1)) between cluster 1 and 2 is “clearly not significant”,[32] whereas the difference

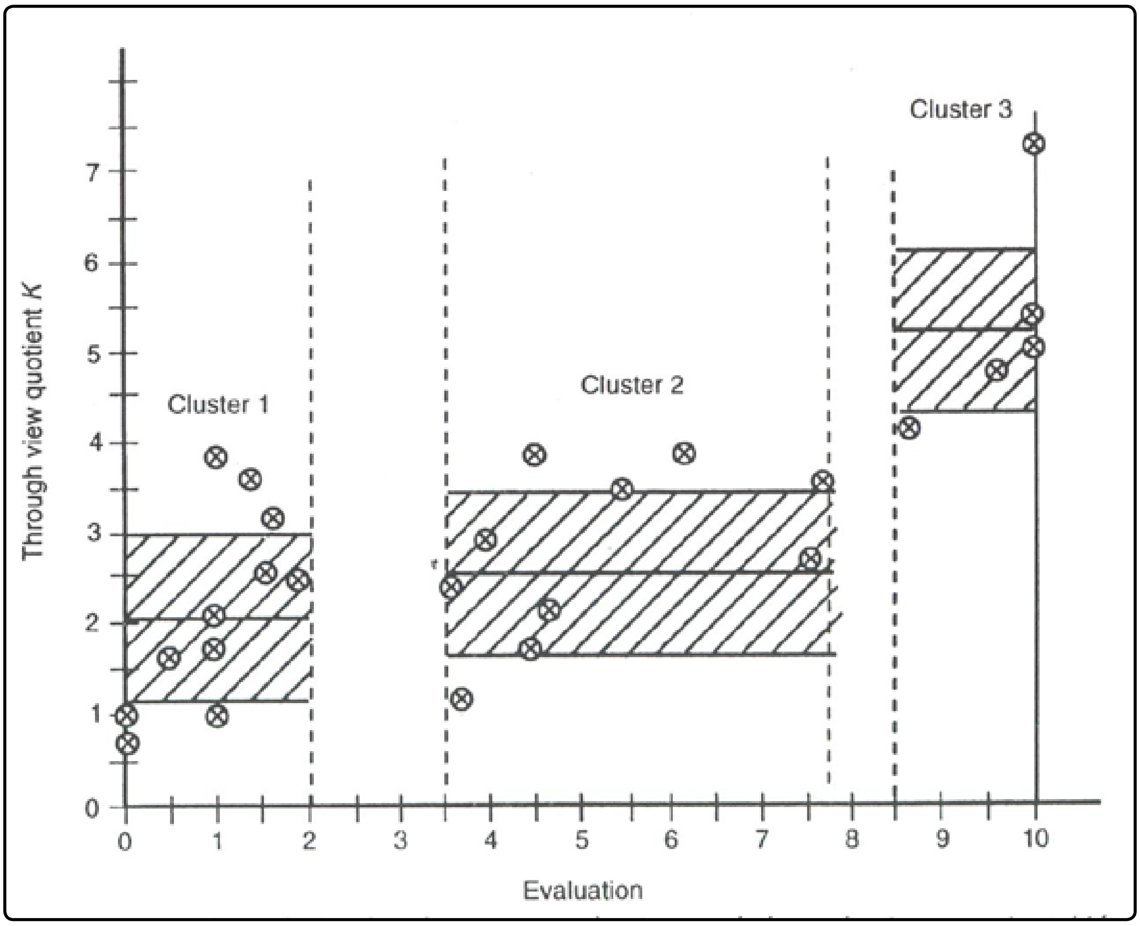
31 original text (Dutch): “dat er inderdaad een zekere samenhang te zien is tussen het doorzichtgetal en de beoordeling: een groter doorzichtgetal (een smallere zwarte lijst) correspondeert globaal met een hogere beoordeling (meer Ja-antwoorden).“ (translated by David M. Kretzer) // *Ibid*. p6.
32 original text (Dutch): “duidelijk niet-significant“ (translated by David Kretzer) // *Ibid*. p6.

Tunnel No.	Eerste proef Ja	Eerste proef Nee	Tweede proef Ja	Tweede proef Nee*)	Totaal Ja	Totaal Nee*)	Beoord.	Doorzicht getal K
1	0	22	5	22	5	44	1,020	2,1
2	14	8	24	3	38	11	7,755	3,4
3	6	16	12	15	18	31	3,673	2,5
4	8	14	18	9	26	23	4,694	2,4
5	1	21	20	7	21	28	4,286	3,8
6	4	18	4	23	8	41	1,633	2,4
7	10	12	12	15	22	27	4,490	2,0
8	2	20	3	24	5	44	1,020	3,6
9	16	6	21	6	37	12	7,551	2,8
10	4	18	5	22	9	40	1,837	3,1
11	6	16	3	24	9	40	1,837	2,4
12	20	2	22	5	42	7	8,571	4,4
13	2	20	6	21	8	41	1,633	3,4
14	22	0	27	0	49	0	10	6,8
15	22	0	27	0	49	0	10	5,1
16	22	0	27	0	49	0	10	5,3
17	0	22	0	27	0	49	0	0,75
18	0	22	0	27	0	49	0	0,8
19	3	19	16	11	19	30	3,878	1,3
20	21	1	27	0	48	1	9,780	4,7
21	8	14	19	8	27	22	5,510	3,4
22	13	9	18	9	31	18	6,327	3,8
23	0	22	2	25	2	47	0,408	1,65
24	4	18	1	26	5	44	1,020	1,8
25	0	22	6	21	6	43	1,224	0,9
26	4	18	16	11	20	29	4,082	3,0

*) inclusief Geen Mening

Table 2: Schreuder and Fournier‘ findings - table (1985)
(inclusief Geen Mening: including “uncertain”)

(Source: Schreuder D A and Fournier P. ‘Een System voor Classificatie van Korte Tunnels’. Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (SWOV), R-85-59, Leidschendam (1985) p11.)



Graph 1: Schreuder and Fournier's findings - graph (1985)
(Source: Schreuder D A. Road Lighting for Safety. Thomas Telford, London (1998) p272.)

between cluster 3 and the other ones is significant. Moreover, there is a tendency of increasing evaluation value subject to an increase of through-view quotient per cluster. However, Schreuder and Fournier said that further research is required to clarify whether this tendency is a systematic or a random one.[33] They inferred from this study that the look-trough quotient can give certain information to what extent a driver is going to face visual problems in a specific tunnel. However, <u>the outcome of their study would not be sufficient to derive recommendations for the lighting of short tunnels from it</u>, yet it can be used as a starting point for further investigations. Schreuder and Fournier recommended choosing 2 or 3 tunnels of each of the clusters mentioned above and investigating these with respect to the following points:

> "-cluster 1 (very bad) can give information about the optimal lighting of short tunnels which cause great visual problems;
>
> -cluster 2 (medium) can help answering the question, which 'short'

33 *Ibid*. p6.

tunnels are real short tunnels, and therefore do not need to be lit, and which ones need to be lit – if yes [if they need to be lit], how [how do they need to be lit]: as in cluster 1 or differently;
-cluster 3 (very good) can help answering the question, which facilities are desirable in short tunnels ('real short tunnels') which do not need to be lit during daytime."[34]

Schreuder gave additional comments on his and Fournier's paper (1985) in 1998. He stated that if the through-view quotient is around 2, observers expect visual problems,[35] and that a through-view quotient of around 5 "does not seem to give rise to visual problems."[36] However, he emphasised that "[t]his classification has … never been tested in practice."[37]

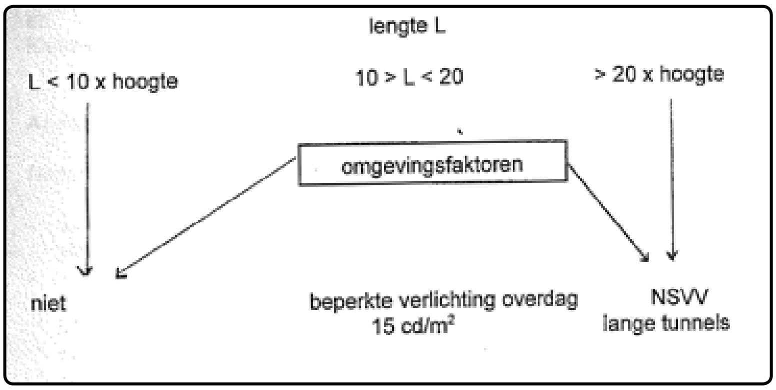


Figure 9: De Groot W A G and De Vlieger's recommendations (hoogte: height / niet: not / lengte: length / omgevingsfaktoren: criteria of the surroundings / beperkte verlichting overdag: limited daytime lighting / lange tunnels: long tunnels)
(Source: De Groot W A G and De Vlieger J A. 'Verlichten van onderdoorgangen en korte tunnels'. Congresdag 12 april 1994, Nederlandse Stichting voor Verlichtingskunde (NSVV), Amsterdam (1994) p12.)

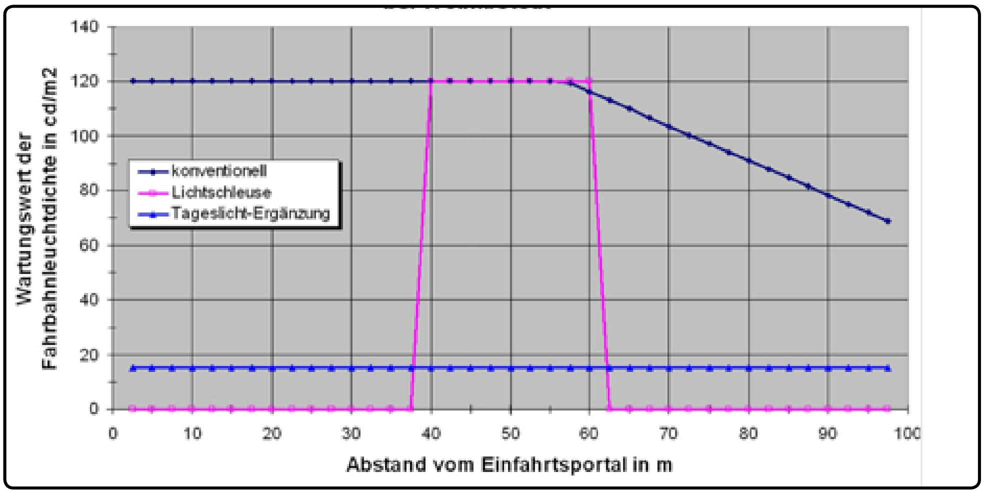
In 1994, a paper was published by de Groot and de Vlieger[38]. They introduced the height of tunnel as an assessment criterion: "All recommendations/ codes are based on the length of a tunnel. We do believe that the height of a tunnel

34 original text (Dutch): "- cluster 1 (zeer slecht) kan uitsluitsel geven over de optimale verlichting voor korte tunnels die grote visuele problemen opleveren;
- cluster 2 (middelgroot) kan verder uitsluitsel geven over de vraag welke 'korte' tunnels echt kort zijn en zonder verlichting kunnen blijven en welke wel verlicht moeten worden – zo ja, hoe: net als cluster 1 of anders;
- cluster 3 (zeer goed) kan uitsluitsel geven over de vraag welke voorzieningen gewenst zijn in korte tunnels ('echte korte tunnels') die overdag onverlicht kunnen blijven." (translated by David M. Kretzer) // *Ibid*. p8.
35 Schreuder D A. *Road Lighting for Safety*. Thomas Telford, London (1998) pp271-272.
36 *Ibid*. p272.
37 *Ibid*. p272.
38 De Groot W A G and De Vlieger J A. 'Verlichten van onderdoorgangen en korte tunnels'. *Congresdag 12 april 1994*, Nederlandse Stichting voor Verlichtingskunde (NSVV), Amsterdam (1994) pp9-14

should play a role, too."[39]

De Groot and de Vlieger claimed that a high tunnel would be "more see-trough"[40]. Their recommendation can be seen in figure 9. However, it is not stated whether the recommendations are confirmed by any research.

In 1998, Eberbach tested different lighting concepts for short tunnels[41]. He was sceptical whether the DIN at that time was appropriate. Therefore, he evaluated



Graph 2: Comparion of luminance requirements on the road surface of the tunnel in 'Wolmirstedt' (Germany): 'long' tunnel lighting (konventionell), Lichtschleuse and supplemental daytime lighting (Tageslicht-Ergänzung)
(Wartungswert der Fahrbahnleuchtdichte: maintained luminance on road surface / Abstand vom Einfahrtsportal: distance from tunnel entrance)
(Source: Eberbach K and Kaboth N. 'Pilotprojekt: Lichtschleusen-Beleuchtung im Straßentunnel bei Wolmirstedt'. Licht, Vol 57 (2005) p369.)

two existing tunnels, which did not need to be lit in according to the DIN – one of them was 100 m long, the other one 40 m. He evaluated the tunnels regarding the following parameter:

- the visual angle of the exit aperture seen from the stopping distance in front of the tunnel entrance
(Eberbach stated that the exit aperture needs to cover completely the 2° field of view – then it can be taken for granted that the bright adaptation

39 original text (Dutch): " Alle aanbevelingen/normen gaan uit van de lengte van de tunnel. Ons inziens dient echter ook de hoogte van de tunnel een rol te spelen." (translated by David M. Kretzer) // *Ibid*. p10.
40 original text (Dutch): "doorzichtiger" (translated by David M. Kretzer) // *Ibid*. p10.
41 Eberbach K. 'Die Beleuchtung von Kurztunneln - Kein Thema von morgen?', in: *Tagungsband zur 13. Gemeinschaftstagung der Lichttechnischen Gesellschaften Österreichs, Deutschlands, der Niederlande und der Schweiz*. Licht, Bregenz (1998) pp490-499.

remains largely stable[42].)

- the daylight factor in the middle of a tunnel

- the road luminance and the *Kontrastgüte-Koeffizient*

('Kontrastgüte-Koeffizient' is defined as $g_c = L_f/E_v$

L_f: road luminance; E_v: vertical luminance of the object seen by the observer)

-contrast of big obstacles (e.g. a stationary lorry) seen from the stopping distance

-visibility level[43] and 'Tarnzonen' for small obstacles with and without glare (Lseq: 0…200 cd/m² (equivalent veiling luminance)) during approach and crossing of a tunnel

(visibility level is defined as: VL = C_o x CE_e; 'Tarnzone' is an area of a road in which critical objects can not be detected)

Eberbach draw the conclusion from his investigation that "the waiving of artificial lighting of the tunnel, which is 100m long, [should] urgently be avoided."[44] Therefore, he compared three different concepts of short tunnel lighting: *'long' tunnel lighting*[45], *supplemental daytime lighting*[46] and the *Lichtschleuse*. *Supplemental daytime lighting* stands for an average luminance of 15 cd/m² along the whole road. 120 cd/m² was chosen experimentally for the *Lichtschleuse*. It was located in the middle of the road (see graph 2), and its length was 20 m[47]. Furthermore, Eberbach tested a combination of *supplemental daytime lighting* and the *Lichtschleuse.*

The comparison revealed that *'long' tunnel lighting* was the best solution. However, the combination of *supplemental daytime lighting* and the

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42 More information about this topic is given in: Adrian W and Eberbach K. 'On the relationship between the visual threshold and the size of the surrounding field'. *Lighting Research and Technology*, Vol 1, No 4 (1969) pp251-254 & Adrian W. 'Adaptation luminance when approaching a tunnel in daytime'. *Lighting Research and Technology*, Vol 19, No 3 (1987) pp73-79.

43 More information about this term is given in: Boyce P R. *Lighting for Driving: Roads, Vehicles, Signs, and Signals*. CRC Press, Boca Raton (2009) pp215-221 & Eberbach K. 'Neue Bewertungskriterien für die Straßen- und Tunnelbeleuchtung'. *Licht*, Vol 43, No 10 (1991) pp768-770.

44 original text (German): "von einem Verzicht auf eine künstliche Beleuchtung für den 100 m langen Tunnel dringend abzuraten [ist]." (translated by David M. Kretzer) // Eberbach K (1998). op. cit. p492.

45 original text (German): "Einsichtstrecken-Beleuchtung"

46 original text (German): "Tageslicht-Ergänzungsbeleuchtung"

47 Eberbach K and Kaboth N. 'Pilotprojekt: Lichtschleusen-Beleuchtung im Straßentunnel bei Wolmirstedt'. *Licht*, Vol 57 (2005) p369.

Lichtschleuse also provided “sufficient visual conditions for the traffic.”[48] Eberbach stated that further tests are required to determine whether the single components would also be sufficient. Moreover, further tests under traffic conditions would be necessary to check that 120 cd/m² are appropriate for the *Lichtschleuse*.

Beleuchtungskonzept	Anlagenaufwand	Energieverbrauch
a) Einsichtsstrecken-Beleuchtung	100 %	100 %
b) Tageslicht-Ergänzungsbeleuchtung	40 %	22 %
c) Lichtschleusen-Beleuchtung	32 %	28 %
d) Kombinations-Beleuchtung	60 %	47 %

Table 3: Comparison of costs for ‘long’ tunnel lighting (Einsichtsstrecken-Beleuchtung), supplemental daytime lighting (Tageslicht-Ergänzungsbeleuchtung), the Lichtschleuse (Lichtschleusen-Beleuchtung) and the combination of b and c (Kombinations-Bel.) (Beleuchtungskonzept: lighting approach / Anlagenaufwand: equipment costs / Energieverbrauch: energy consumption)

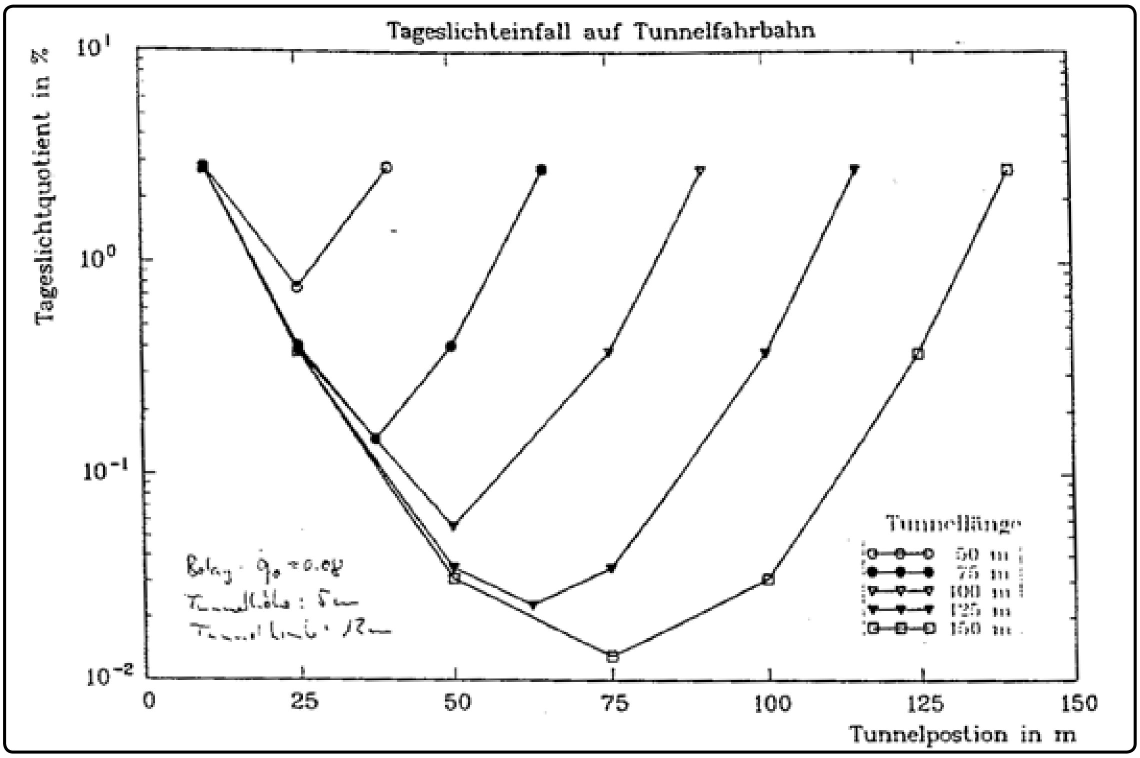
(Source: Bodmann H W. Quality of Interior Lighting Based on Luminance’. Transactions Illuminating Engineering society (London), Vol. 32, No 1 (1967) p23)

Eberbach demonstrated that *‘long’ tunnel lighting* is clearly the most expensive method of the ones tested – regarding equipment cost and energy consumption (see table 3).

In 1999, Eberbach gave information about tunnel research he had conducted before he made the comparison between the different concepts of short tunnel lighting[49] (mentioned before). He had analysed the daylight penetration of different tunnel length: 50 m, 75 m, 100 m, 125 m and 150 m (tunnel width: 12 m / tunnel height: 5 m). Eberbach had analysed the horizontal daylight factors (see graph 3) and the vertical daylight factors (see graph 4). He also calculated the *Kontrastgüte-Koeffizienten*[50] (see graph 5 (high values denote negative contrasts / low values denote positive contrasts)).
Eberbach observed that the daylight factors drop sharply within the tunnel –

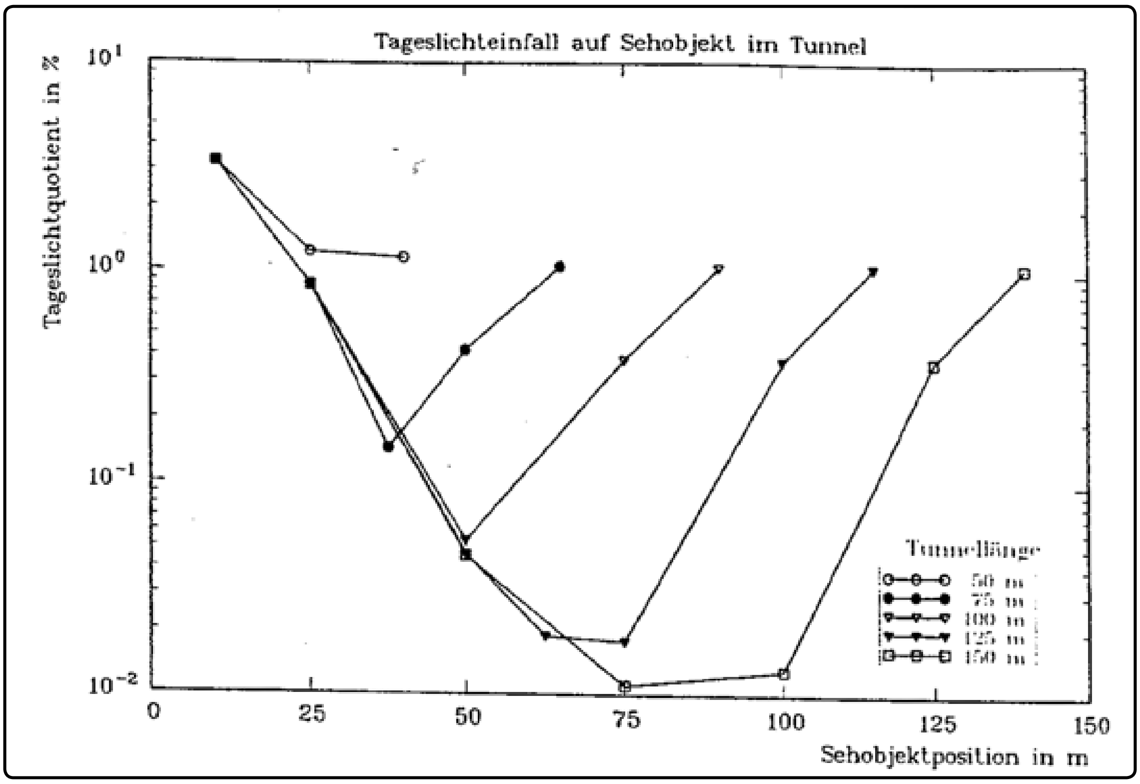
48 original text (German): “ausreichende Sichtverhältnisse für den Verkehr.“ (translated by David M. Kretzer) // Eberbach K (1998). op. cit. p498.
49 Eberbach K. ‘Lichtschleusen: Beleuchtung kurzer Tunnel’, in: *Tagungsband zur Sondertagung ‘Aktuelles zur Tunnelbeleuchtung’ der Bundesanstalt für Straßenwesen BAST und der Lichttechnischen Gesellschaften Deutschlands, Österreichs, der Niederlande und der Schweiz am 23. 9. 1999*. LitG, Bergisch Gladbach (1999) pp25-34.

50 *Kontrastgüte-Koeffizienten:* see page 20



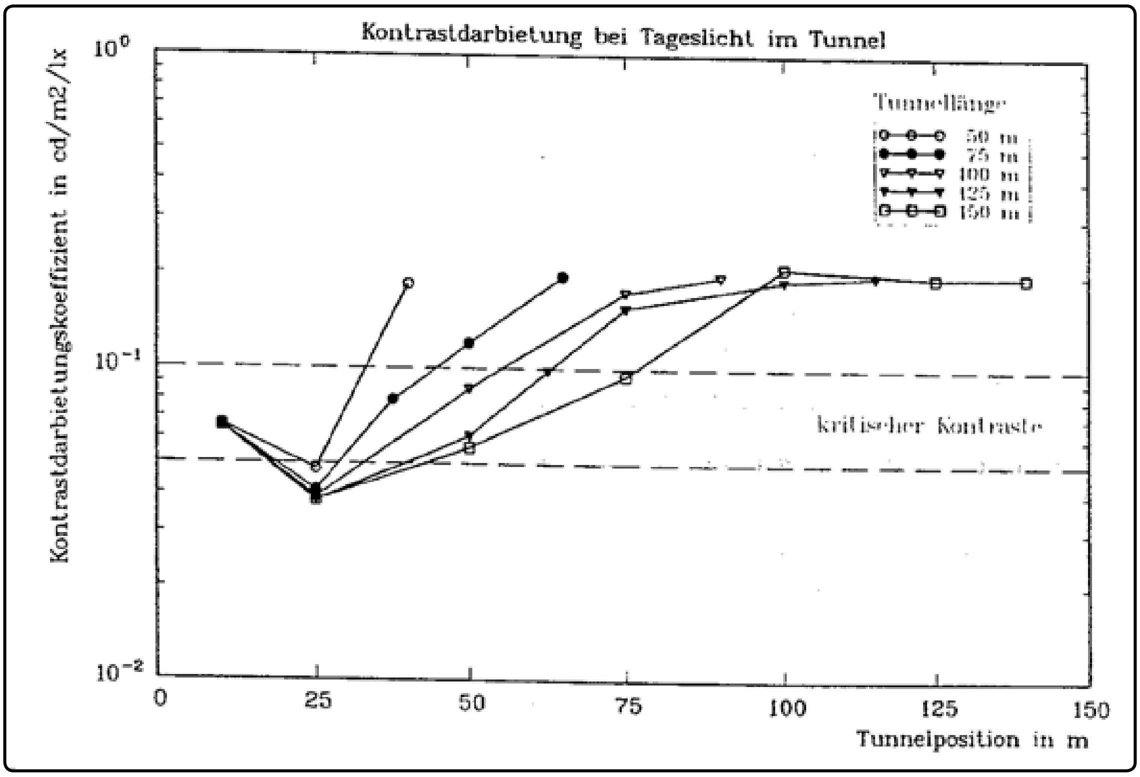
Graph 3: Daylight incidence on road surface in tunnels (Tageslichteinfall auf Tunnelfahrbahn): $q_0 = 0.08$ / tunnel height: 5 m / tunnel width: 12 m (Tageslichtquotient: daylight factor / Tunnellänge: tunnel length / Tunnelposition: position in tunnel)

(Source: Eberbach K. 'Lichtschleusen: Beleuchtung kurzer Tunnel', in: Tagungsband zur Sondertagung 'Aktuelles zur Tunnelbeleuchtung' der Bundesanstalt für Straßenwesen BAST und der Lichttechnischen Gesellschaften Deutschlands, Österreichs, der Niederlande und der Schweiz am 23. 9. 1999. LitG, Bergisch Gladbach (1999) p27.)



Graph 4: Daylight incidence on target (vertical) in tunnels (Tageslichteinfall auf Sehobjekt im Tunnel) (Sehobjektposition: target position)

(Source: Eberbach K. 'Lichtschleusen: Beleuchtung kurzer Tunnel', in: Tagungsband zur Sondertagung 'Aktuelles zur Tunnelbeleuchtung' der Bundesanstalt für Straßenwesen BAST und der Lichttechnischen Gesellschaften Deutschlands, Österreichs, der Niederlande und der Schweiz am 23. 9. 1999. LitG, Bergisch Gladbach (1999) p28.)



Graph 5: Contrast-performance in tunnels during daytime (Kontrastdarbietung bei Tageslicht im Tunnel) (*Kontrastdarbietungskoeffizient* (also called *Kontrastgüte-Koeffizient*) is defined as $g_c = L_f/E_v$ (L_f: road luminance; E_v: vertical luminance of the object seen by the observer) / kritischer Kontrast: critical contrast)
(Source: Eberbach K. 'Lichtschleusen: Beleuchtung kurzer Tunnel', in: Tagungsband zur Sondertagung 'Aktuelles zur Tunnelbeleuchtung' der Bundesanstalt für Straßenwesen BAST und der Lichttechnischen Gesellschaften Deutschlands, Österreichs, der Niederlande und der Schweiz am 23. 9. 1999. LitG, Bergisch Gladbach (1999) p28.)

however, the horizontal ones drop more sharply than the vertical. Furthermore, he commented on the *Kontrastgüte-Koeffizienten:* he said that values between 0.05 and 0.10 cd/m²/lx constitute a critical area – a contrast reversal occurs for obstacles, which have a reflectance of 0.15 – 0.30. Critical zones would rather be located in the front part of a tunnel, whereas a distinct silhouette-seeing with negative contrasts can be expected in the rear half of the tunnel.

Eberbach stated that the background of a big obstacle (e.g. a car) spans areas of a road, which would be normally longer than 40 m. A constant luminance would be unlikely on such a long area in a tunnel– especially in unlit tunnels. Therefore, it would be important to consider if an obstacle can be seen from the stopping distance as a silhouette against the exit aperture (or another bright area).[51]

51 Eberbach K (1999). op. cit. pp27-29.

Meanwhile, Eberbach installed eight Lichtschleusen in conjunction with *supplemental daytime lighting*[52] of 15 cd/m²[53] in existing tunnels (see, for example, figure 10) – he refers that the clients so far have been “very satisfied with this approach.”[54]

Figure 10: Combination of Lichtschleuse and supplemental daytime lighting in a tunnel in ‘Wolmirstedt’ (Germany)
(Source: Eberbach K and Kaboth N. ‘Pilotprojekt: Lichtschleusen-Beleuchtung im Straßentunnel bei Wolmirstedt’. Licht, Vol 57 (2005) p369.)

52 i.e. an average luminance of 15 cd/m² along the whole road
53 This value is required by the German ‘BASt (Bundesanstalt für Verkehrswesen)’, since there are no long term experience in *Lichtschleusen*-lighting . However, no reasons are given by the BASt for this value.
54 original text (German): “ sehr zufrieden mit diesem Lösungsansatz.“ (translated by David M. Kretzer) // personal correspondence with Eberbach (18 June 2009)

1.1.2 Selection of recently published European guides and codes of practice about short tunnel lighting

In 2000, the French ‘Centre D’études des Tunnels’ (CETU) published a guide about tunnel lighting[55]. It also contains a section about short tunnel lighting. In this guide, the main criterion to decide whether a tunnel needs to be lit is the length of the tunnel. Thereby, four different types of tunnels are considered[56]:

1. urban tunnels (see figure 11)
2. interurban tunnels - dense traffic and high speed
    a) two-way traffic (see figure 12)
    b) one-way traffic (see figure 13)
3. interurban tunnels – no dense traffic and no high speed (see figure 14)

However, the authors emphasised that someone should not rely solely on these four tree diagrams: “They allow to guide a first approach to the problem, but they do not release someone from the obligation to analyse the traffic and the geometry of the tunnel access …”[57]

Moreover, additional comments are stated:

Urban tunnels, which are used by pedestrians and cyclists and which are longer than 25 m, shall be treated as ‘long’ tunnels.[58]

It is forbidden to use the four diagrams for tunnels, which are used by vehicles which carry dangerous goods.[59]

None of the four tunnel types needs to be lit during daytime if less than 2000 vehicles pass trough the tunnel per day, and not more than 400 vehicles during the rush hour[60]. However, if such a tunnel is not lit, a sign needs to be mounted at the tunnel entrance. This sign shall inform the driver that the tunnel is unlit, and it shall ask for switching on the headlights. Furthermore, a specific visual

55 Centre D’études des Tunnels (CETU). *Dossier pilote des tunnels équipement*. Bron Cedex (2000).
56 The visibility of the entrance needs to be checked (in front of the tunnel entrance) at a distance equal to the stopping distance.
57 original text (French): “Ils permettent de guider une première approche du probléme, mais ne dispensent pas d’une analyse du trafic et de la géometrie des accès du tunnel ...“ (translated by David M. Kretzer) // Centre D’études des Tunnels (2000). op. cit. p27.
58 *Ibid*. p24.
59 *Ibid*. p27.
60 *Ibid*. p10.

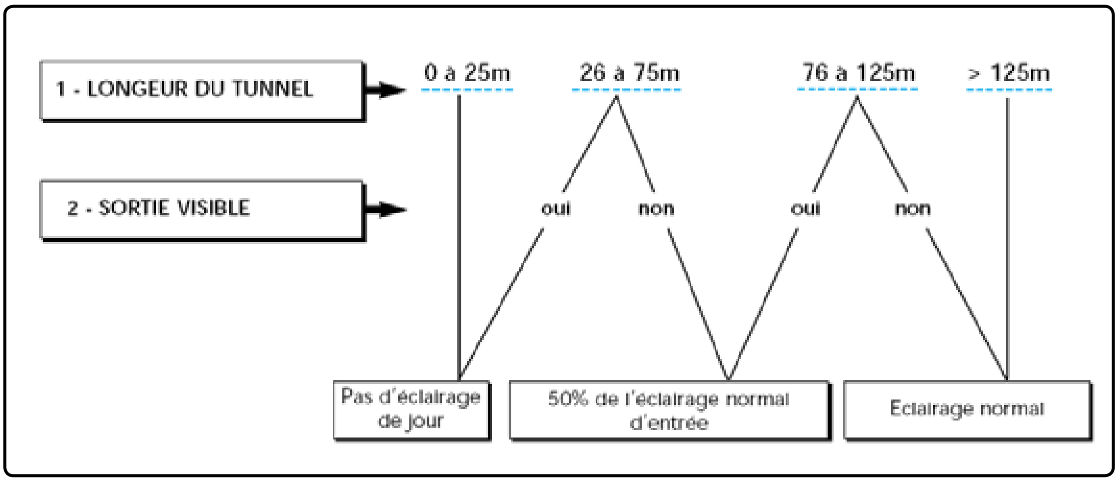


Figure 11: Recommendations of the CETU (2000): urban tunnels
(longeur du tunnel: tunnel length / sortie visible: exit aperture visible / pas d'éclairage de jour: no daytime lighting / 50 % de l'éclairage normal d'entrée: 50% of normal entrance (threshold) zone lighting / Eclairage normal: normal lighting (long tunnel lighting) / oui: yes / non: no)
(Source: Centre D'études des Tunnels (CETU). Dossier pilote des tunnels équipement. Bron Cedex (2000) p24.)

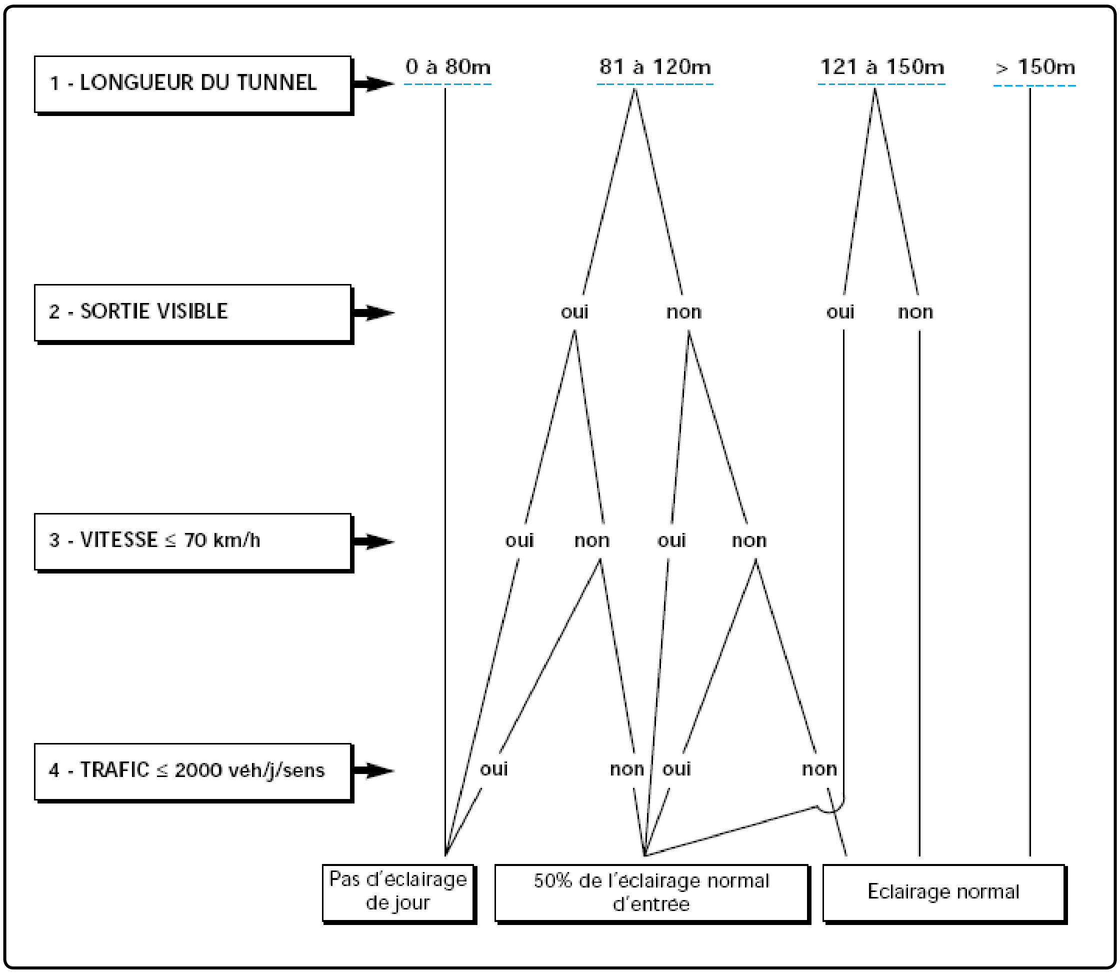


Figure 12: Recommendations of the CETU (2000): interurban tunnels: two-way traffic
(vitesse: speed / trafic ≤ 2000 véh/j/sens: traffic ≤ 2000 vehicles per day (annual average) per direction)
Source: Centre D'études des Tunnels (CETU). Dossier pilote des tunnels équipement. Bron Cedex (2000) p25.)

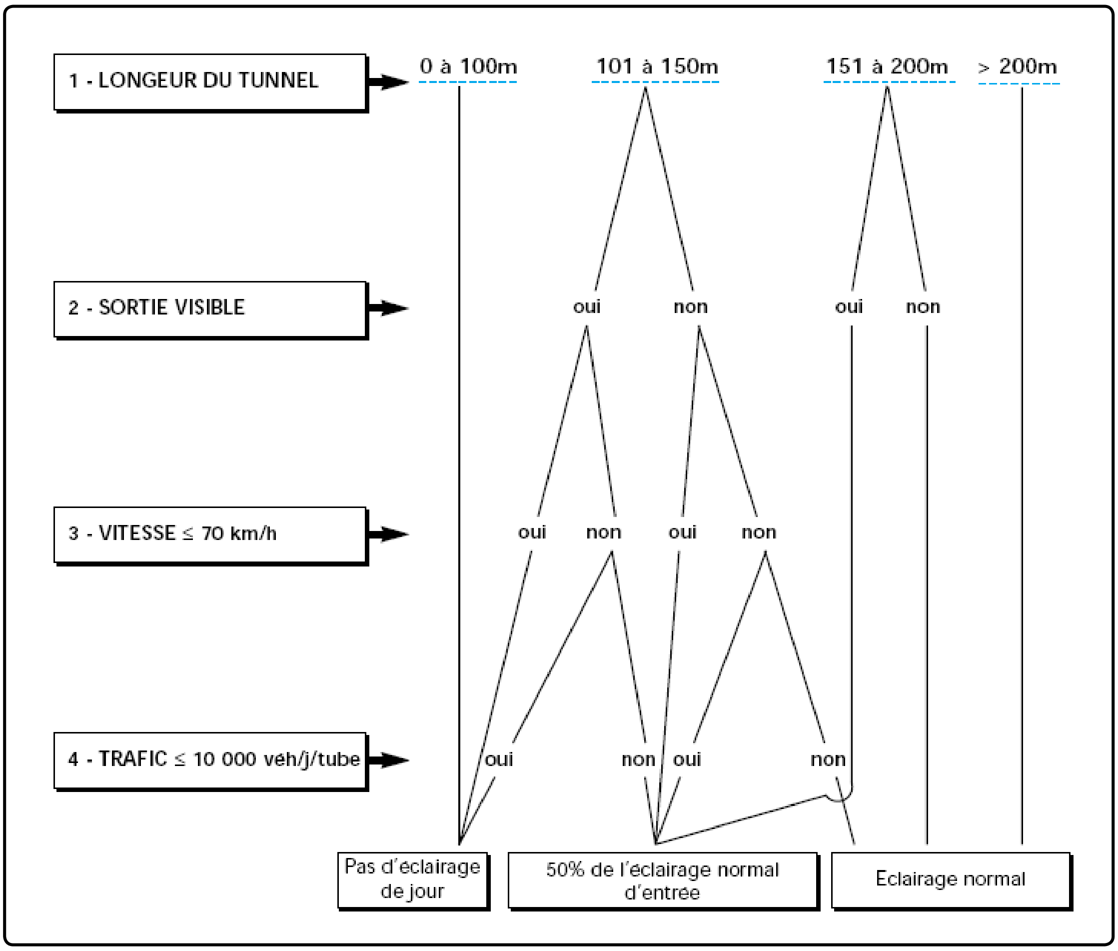


Figure 13: Recommendations of the CETU (2000): interurban tunnels: one-way traffic
(Source: Centre D'études des Tunnels (CETU). Dossier pilote des tunnels équipement. Bron Cedex (2000) p26.)

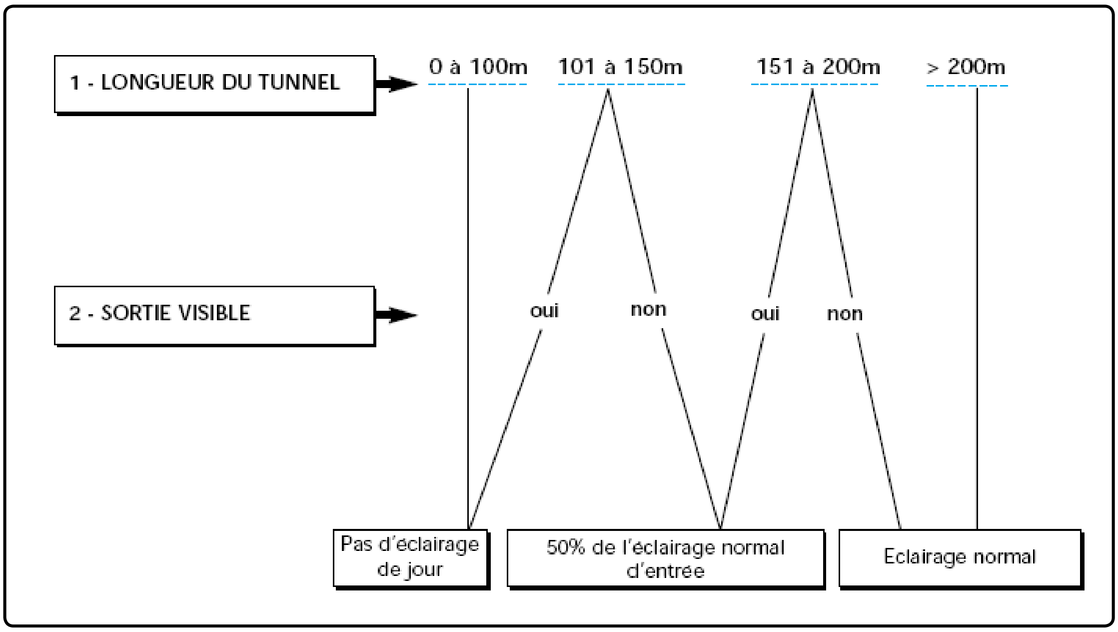


Figure 14: Recommendations of the CETU (2000): interurban tunnels: no dense traffic and no high speed
(Source: Centre D'études des Tunnels (CETU). Dossier pilote des tunnels équipement. Bron Cedex (2000) p27.)

guidance must be installed in the tunnel.[61]

The CETU didn't state whether any research confirmed its recommendations.

In 2002, the 'Netherlands Foundation on Illumination' published a guide for short tunnel lighting[62] during daytime. This guide is based on the work of Schreuder and Fournier (1985) – their research paper is listed in the bibliography. However, many new aspects were introduced.

The approach consists of two steps:

First, the 'through-view quotient' needs to be calculated (basically in the same way as Schreuder and Fournier had stated it). However, the observer's point is determined differently: the distance from the tunnel is equal to the stopping distance, 1.2 m above the road (standing in the middle of the lane). Furthermore, the influence of daylight is considered: the first 5m at the beginning of the tunnel and the last 10 m at the end of the tunnel can be disregarded for the calculation of the 'through-view quotient', since the daylight penetration would let the tunnel appear shorter[63] (due to the reflection of the walls and the road[64]).

It is considered that a tunnel might have a horizontal or a vertical curve. Therefore, drawings are provided to derive the 'through-view quotient' in such cases (see figure 15).

The authors claimed that the following recommendations would be "based on experiments":[65]

If the 'through-view quotient' is 50 % or more, the tunnel does not need to be lit.

If the 'through-view quotient' is 20 % or less, the tunnel needs to be lit.

If the 'through-view quotient' is between 20 % and 50 %, another method needs to be applied to find out whether the tunnel needs to be lit or not.

61 *Ibid*. p10.

62 Nederlandse Stichting voor Verlichtingskunde (ed.). *Verlichting van (korte) tunnels en onderdoorgangen: Kunstlicht voor onderdoorgangen voor snelverkeer en langzaam verkeer.* NSVV, Ede (2002).

63 *Ibid*. p9.

64 *Ibid*. p10.

65 original text (Dutch): "[o]p basis van de experimenten" (translated by David M. Kretzer) // *Ibid*. p11.

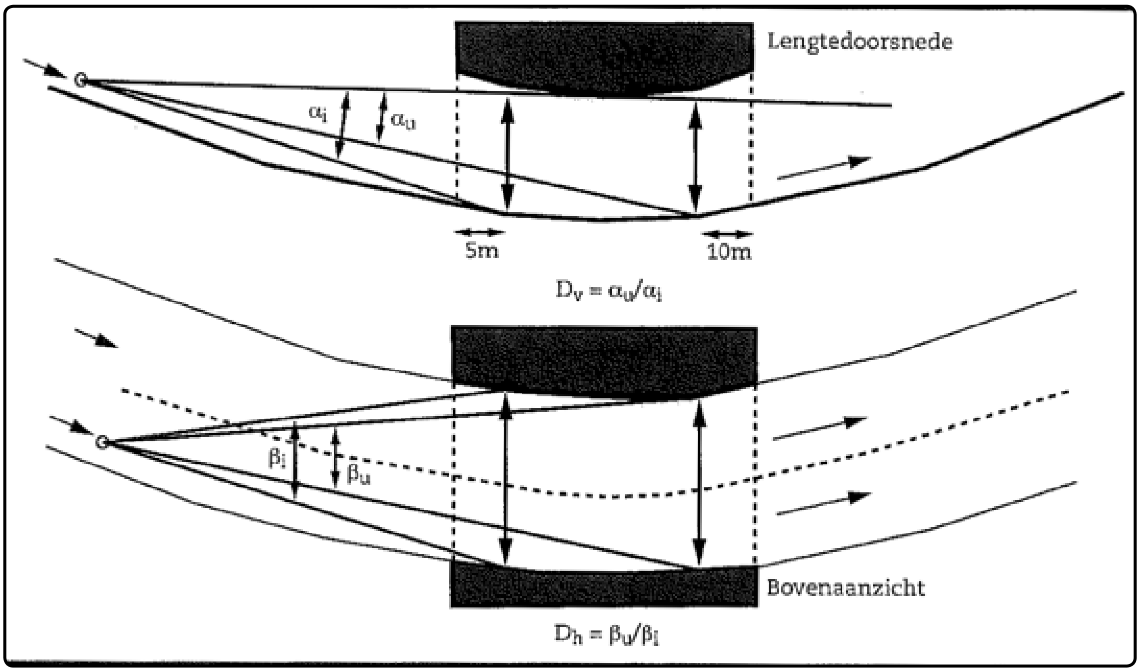


Figure 15: NSVV (2002): Drawing to explain the calculation of the through-view quotient of tunnels having a horizontal or vertical curve
(Lengtedoorsnede: elevation / Bovenaanzicht: plan view)
(Source: Nederlandse Stichting voor Verlichtingskunde (ed.). Verlichting van (korte) tunnels en onderdoorgangen: Kunstlicht voor onderdoorgangen voor snelverkeer en langzaam verkeer. NSVV, Ede (2002) p11.)

Second, if the 'through-view quotient' is between 20 % and 50 %, a critical obstacle needs to be incorporated. A plane of 1.6 x 1.4 m (representing a vehicle) needs to be used for tunnels which has only motorised traffic going through, and a plane of 0.5 x 1.8 m (representing a pedestrian or cyclist) needs to be used for mixed traffic tunnels (see figure 16). The obstacle must be placed in the middle of the lane (the distance between the tunnel entrance and the obstacle is not stated). If there are several lanes, the procedure must be repeated for every lane.

If at least 30 % of the obstacle representing the vehicle can be seen against the exit aperture, the tunnel does not need to be lit. If at least 50 % of the obstacle representing a pedestrian/cyclist can be seen against the exit aperture, the tunnel does not need to be lit.

Two methods were recommended to light a short tunnel[66]:

1. The tunnel is lit in the same way as a 'long' tunnel.
2. Luminance patterns are created on the surfaces of the tunnel by means of artificial or natural lighting. These patterns must be arranged in such a manner that obstacles can be seen from the stopping distance against

66 *Ibid*. p11.

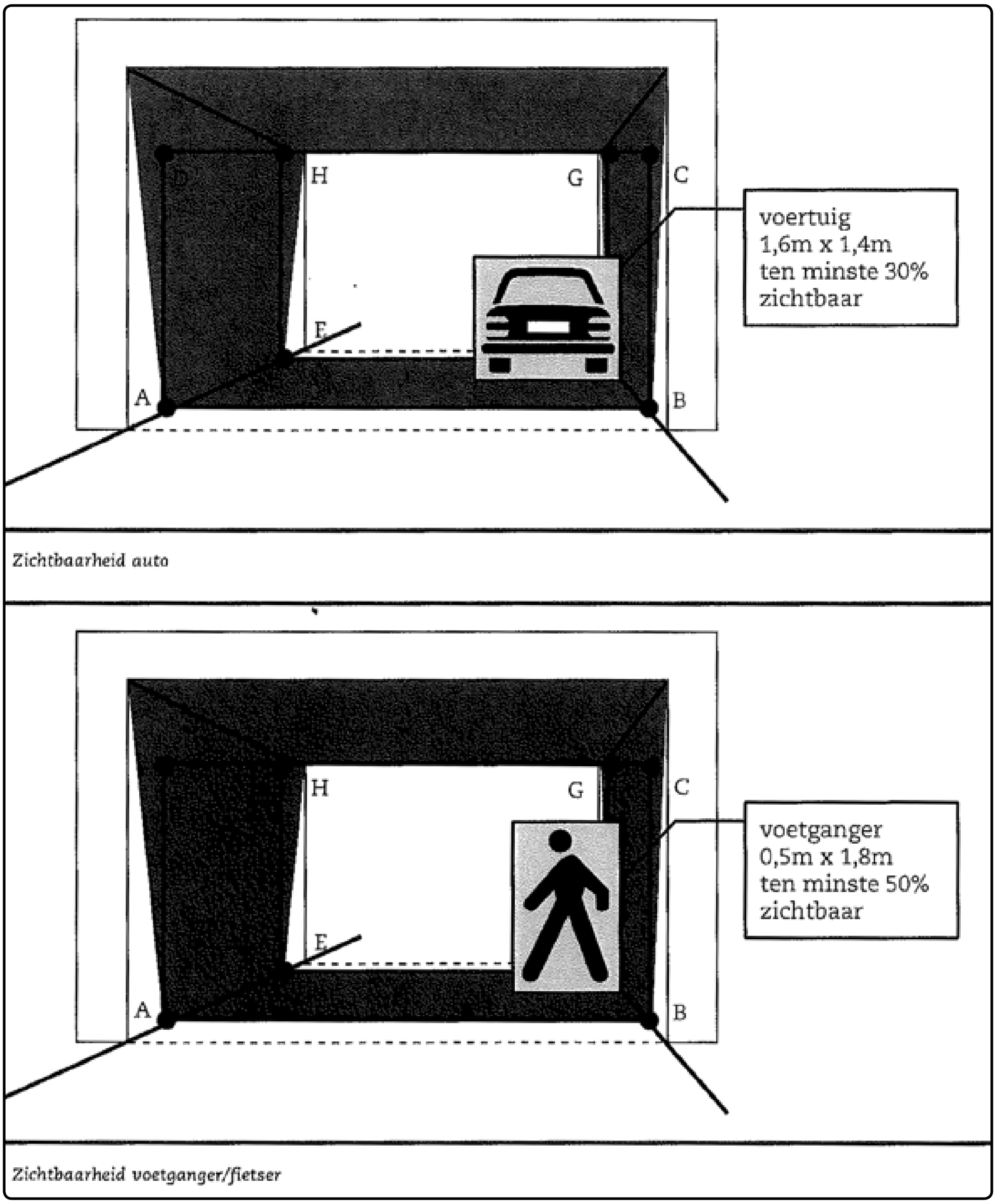


Figure 16: NSVV (2002): drawing to explain the calculation of the obstacle visibility
(voertuig: vehicle / voetganger: pedestrian / ten minste ...% zichtbar: at least ...% visible / zichtbaarheit: visibility / auto: car / voetganger: pedestrian / fietser: cyclist)
(Source: Nederlandse Stichting voor Verlichtingskunde (ed.). Verlichting van (korte) tunnels en onder-doorgangen: Kunstlicht voor onderdoorgangen voor snelverkeer en langzaam verkeer. NSVV, Ede (2002) p12.)

them – exact locations and luminance values are not stated. However, it is said that if a tunnel has a horizontal curve, the outer wall and the road needs to be lit.

Moreover, it is stated that tunnels longer than 200-250 m do always need daytime lighting, especially because of “adaptation problems”.[67] However, these “adaptation problems” were not specified.

Furthermore, it was stated that tunnels “shorter than 25 meters virtually do not need daytime lighting.”[68] However, no reasons were given for this statement.

The authors also pointed out the influence of lighting on crime prevention. They presented recommendations for tunnels, which are only used by pedestrians and cyclists, considering aspects such as facial recognition. They said that these recommendations should also be incorporated in mixed traffic tunnels[69]. However, they didn’t specify how to incorporate these recommendations – both approaches were significantly different[70].

In 2003, a CEN Report about tunnel lighting was published[71]. The recommendations and the approach for short tunnel lighting are almost exactly the same as the one published by the Netherlands Foundation on Illumination (2002). However, there are some differences:

It is stated that the guide of the ‘Centre D’études des Tunnels (CETU)’ (2000) can be used instead of the approach presented in the CEN Report[72]. This is worth emphasising, since the assessment criterion of the CETU guide is primarily the length of a tunnel – a completely different approach.

Furthermore it is interesting, how the formulation of the recommendation changed meanwhile. It is stated that for a ‘through-view quotient’[73] greater than 50 % “day-time lighting is <u>never needed</u>”[74]. However, Schreuder (1998) only said that a through-view quotient of around 5 “<u>does not seem</u> to give rise to visual problems.”[75] Furthermore, Schreuder emphasised that “[t]his classification has … never been tested in practice.”[76]

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67 Original text (Dutch): “ adaptatieproblemen” // *Ibid*. p13.

68 original text (Dutch): “korter dan 25 meter zullen overdag vrijwel nooit verlichting nodig hebben.” (translated by David M. Kretzer) // *Ibid*. p13.

69 *Ibid*. p6.

70 *Ibid*. p17.

71 European Committee For Standardization. *CEN Report CR 14380, Lighting applications – Tunnel lighting*. (2003)

72 *Ibid*. p54.

73 This term is called ‘look-through percentage’ in the British Standard and in the CEN Report.

74 European Committee For Standardization (2003). op. cit. p55.

75 Schreuder D A (1985). op. cit. pp 272

76 *Ibid*. p272

Moreover, short tunnels were restricted to 200 m due to adaptation problems (instead of 200-250 m). No reason was given for this alteration.
The luminance patterns on the tunnel surfaces, which may serve as lighting for short tunnels, were described in more detail in the CEN Report: "'light pools' at some places lengthwise, created by permitting daylight trough the roof or by artificial lighting; cars and other road users can be seen as dark objects against these 'light pools'.[77]"

In 2003, the British Standard Institution published their last Code of practice for Lighting of tunnels[78]. This recommendation was the reason for this final report. The parts which deal with short tunnel lighting are section 4.4 and Annex C (a copy of it can be found in this report (Annex B)).
This recommendation is almost exactly the same as the CEN Report (2003). However there are some differences and additions:
It is stated that for a through-view quotient greater than 80 % day-time lighting is generally not needed[79] (in the CEN Report the value is 50 %).
If a tunnel of length between 25 and 200 m needs daytime lighting, it has to be treated as a 'long' tunnel. It is not allowed for luminance patterns on the tunnel surfaces instead of applying long tunnel lighting.[80]
Furthermore, the transverse position of the critical obstacle is different: The position for tunnels, which carry multi-lane roads with an emergency lane, is on the left-hand side of the emergency lane. The position for tunnels, which carry multi-lane roads without an emergency lane, is on the left-hand side of the normal lane[81]. Single-lane roads are not mentioned.

> Moreover, it is stated that "[i]f full daytime lighting is not needed for tunnels of length between 25 m and 200 m, some limited daytime lighting can be provided for tunnels where the traffic flow is classified as "high" (see 5.2), when luminance levels within the tunnel are low, and during the periods immediately before dusk and after dawn, particularly

77 European Committee For Standardization (2003). op. cit. p56.
78 British Standard Institution. *British Standard BS 5489-2:2003+A1:2008, Code of for the design of road lighting – Part 2: Lighting of tunnels.* (2008)
79 *Ibid*. p20.
80 *Ibid*. p6.
81 *Ibid*. p20.

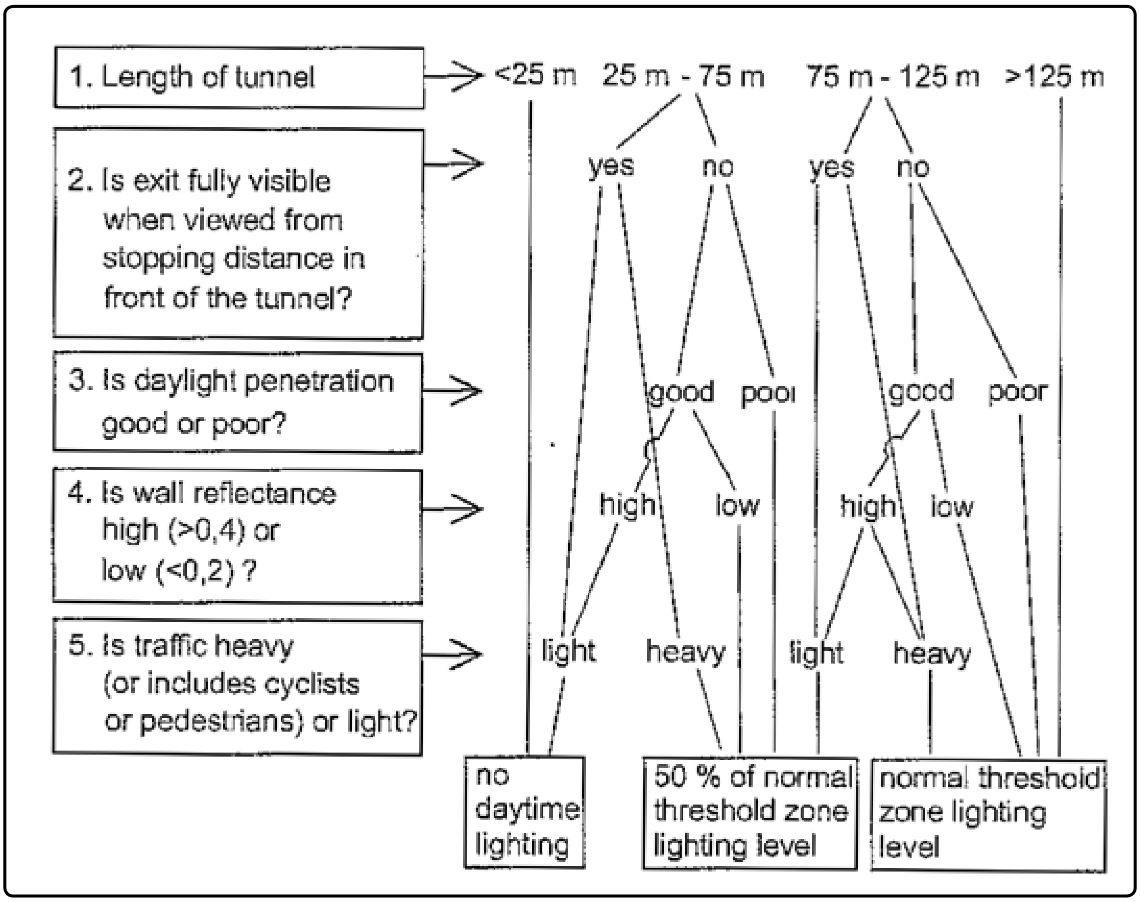


Figure 17: CIE (2004): Daytime lighting of tunnels for different tunnel lengths
(Source: Commision Internationale De L'eclairage. Technical Report – Guide for the lighting of road tunnels and underpasses. 2nd ed. CIE Central Bureau, Vienna (2004) p4.)

on overcast days. The decision to provide such limited daytime lighting is a matter for the highway authority.'"[82]

It is claimed that night-time lighting may be used for this purpose.[83] In accordance with this recommendation the "the night-time luminance inside the tunnel should be at least equal to the access road luminance, but not more than three times this value."[84]

In 2004, the CIE published a technical report about tunnel lighting[85]. The section about short tunnel lighting filled merely about half a page. It was basically a tree diagram (see figure 17). However, it is stated that this diagram "offers a first approximation. For a detailed lighting design, the possibilities to look through

82 *Ibid*. p6.
83 *Ibid*. p6.
84 *Ibid*. p11.
85 Commision Internationale De L'eclairage. *Technical Report – Guide for the lighting of road tunnels and underpasses*. 2nd ed. CIE Central Bureau, Vienna (2004)

the tunnel must be determined graphically”[86]. However, it is not explained how to do this graphical determination. Furthermore, no reason is given for the recommendations in the tree diagram.

In 2008, a new version of the German DIN 67524-1[87] was released. According to the DIN, a tunnel is considered as short if it meets two criteria:

1. The exit aperture needs to be “almost completely visible”[88] (seen from the stopping distance in front of the tunnel)
2. The field of vision formed by the exit aperture (seen from the stopping distance in front of the tunnel) should cover at least the fovea to maintain the bright adaptation of the driver[89] (two formulas, which constitute an approximation, are provided to calculate the threshold length of unlit tunnels[90]).

A short tunnel does not need to be lit during daytime if it meets two criteria[91]:

1. Sufficient daylight penetrates the tunnel (a formula is provided[92])
2. Obstacles standing at any position in the tunnel can be seen (from the stopping distance) at least partly as a silhouette against the exit aperture.

If a short tunnel does not meet these criteria, it has to be lit like a long tunnel or the *Lichtschleuse* can be applied.

86 *Ibid*. p4.

87 Deutsches Institut für Normung. *DIN 67524-1, Beleuchtung von Straßentunneln und Unterführungen – Teil 1: Allgemeine Gütemerkmale und Richtwerte.* (2008)

88 original text (German): “nahezu vollständig sichtbar“ (translated by David M. Kretzer) // *Ibid*. p10.

89 More information about this topic is given in: Adrian W and Eberbach K. ‘On the relationship between the visual threshold and the size of the surrounding field’. *Lighting Research and Technology*, Vol 1, No 4 (1969) pp251-254 & Adrian W. ‘Adaptation luminance when approaching a tunnel in daytime’. *Lighting Research and Technology*, Vol 19, No 3 (1987) pp73-79.

90 This formulas can be applied if the exit aperture is completely visible (seen from the stopping distance) and if the tunnel has neither a vertical nor a horizontal curve. For $b_{PA}/h_{PA} = 2$ the following formula is used: $LKT \leq ((A_{PA} / \pi)^{0.5} / TAN\ (1°)) - HSW$. For $b_{PA}/h_{PA} > 2$ the following formula is used: $LKT \leq ((0.8.h_{PA} / TAN\ (1°)) - HSW$. (HSW = Stopping distance / b_{PA} = exit aperture width / / b_{PA} = exit aperture height / A_{PA} = visible area of exit aperture)

91 Deutsches Institut für Normung (2008). op. cit. pp18-19.

92 $D \geq 0.3\ \%\ (0.08\ (cd/m^2)/lx)/q_0$.

The width and position of the *Lichtschleuse* has to be determined using a perspective drawing – it must be ensured that obstacles can always be seen against a bright background[93]. The bright strips on the wall have to be at least 2 m high. The luminance of the strips on the walls should be all about the same as the luminance of the strip on the road. The *Lichtschleuse's* luminance has to comply with the luminance of the threshold zone of long tunnels.
If a short tunnel does not meet the required daylight criteria[94], *supplemental daytime lighting*[95] has to be applied additionally to *Lichtschleuse*. Its luminance has to be 15 cd/m².

1.2 Appraisal and summary

Lossagk's paper (1955) served as starting point for short tunnel lighting research. It demonstrated that it is important to take into account that obstacles can be seen as a silhouette against a bright background such as the exit aperture. He also presented means to support this effect, for example, the *Lichtschleuse* and white tiles.

'Netherlands Foundation on Illumination' presented recommendations based on the length of tunnels. However, the justification for determining the minimum length of 20 m for lit tunnels is insufficient:
First of all, it was not taking into account that an obstacle could also be invisible against the dark walls of a tunnel. Second, it assumed that the driver's eyes were 1.2 m above the road – however, if a lorry approached a tunnel, the eyes would be higher and consequently, the minimum length of a lit tunnel would be shorter.
The justification of the maximum length was also insufficient: it is true that a lorry may cover the exit aperture of a tunnel, but it is not explained why this would limit an unlit tunnel to exactly 50 m. Moreover, the criteria, which tunnels of a length of between 25 and 50 m have to meet, are not adequately defined: the absence of bends/heavy traffic and the traffic composition are mentioned – however, according to the geometrical drawing an obstacle would be invisible

93 Deutsches Institut für Normung (2008). op. cit. p19.
94 D ≥ 0.3 % (0.08 (cd/m²)/lx)/q_0.
95 i.e. an average luminance of 15 cd/m² along the whole road

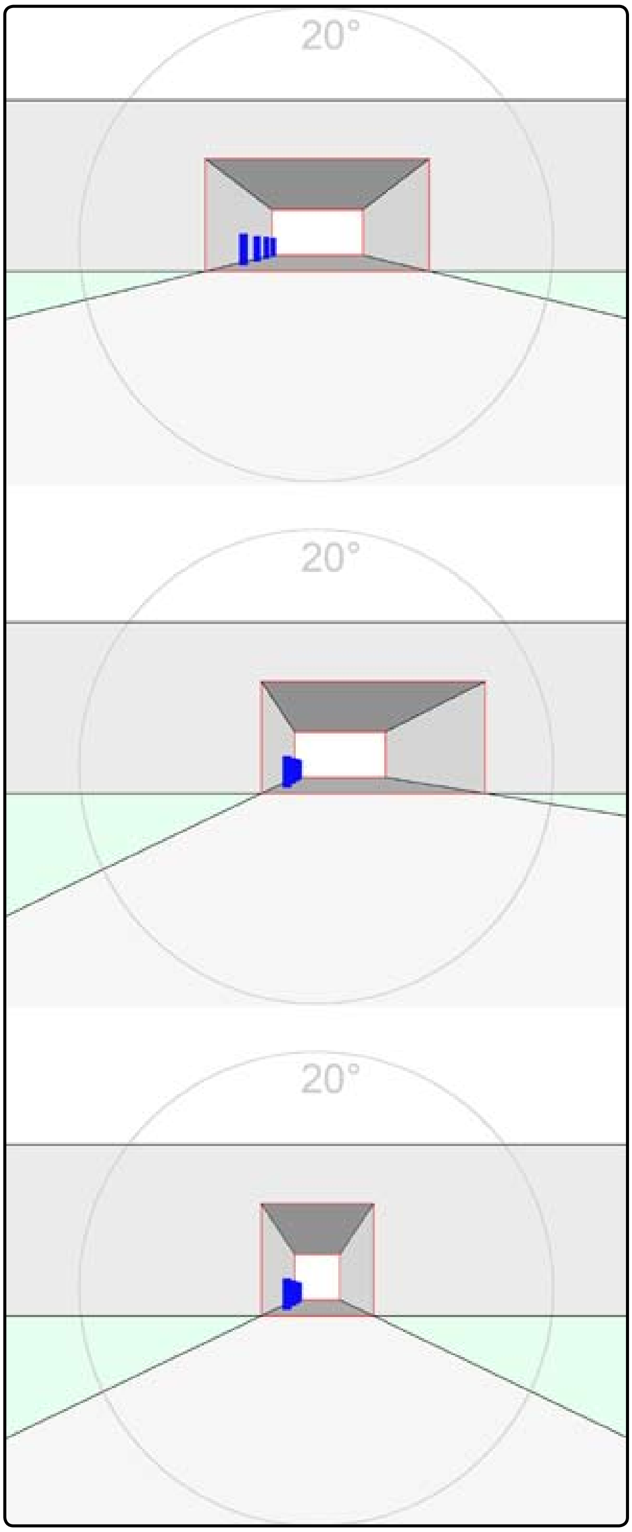


Figure 18: The through-view quotient of these three tunnels is exactly the same: 30 %.
However, the position of the observer (second tunnel) or the tunnel width (third tunnel) varies. As can be seen from the illustration, this variation makes an significant impact on the target visibility:
Only one target in the first tunnel is partly visible against the exit aperture, whereas three obstacles in the second and third tunnel are completely or partly visible against the exit aperture.
This demonstrates that the look-trough quotient does not provide sufficient information about the target visibility in tunnels.

anyway.

It seems that the recommended length of the *Lichtschleuse* had not been backed by research.

It is likely that the authors knew about Losagk's paper (1955).

Schreuder and Fournier's research (1985) constitutes a milestone, since they pointed out that classifying a tunnel on the basis of its length is not appropriate. However, several methodological aspects of this research are questionable:

First of all, no obstacles were shown on the pictures of the tunnels.

Second, additional pictures taken from different distances were shown to in the second phase – consequently, the subjects saw different through-view quotients of the same tunnel(s).

Third, the result of the survey was distorted, since "uncertain" answers were regarded as "no" answers.

Apart from that, even Schreuder and Founier stated that the outcome of their study can only be used as a starting point for further investigations.

Furthermore, a classification of tunnels based on the through-view quotient is generally disputable. The visibility of obstacles in tunnels can vary significantly depending on the position of the observer and the width of a tunnel - although the through-view quotient is the same: Figure 18 shows three tunnels having the same through-view quotient (30 %) and the same length (87.5 m); they are observed from the same distance (60 m) and also the spacing between the obacles is the same (17.5 m). Only the position of the observer or the width of the tunnel varies.
Schreuder and Fournier were aware of the publications of Lossagk and the 'Netherlands Foundation on Illumination'.

De Groot and de Vlieger (1996) pointed out that the height of a tunnel plays an important role. This is true, since the height influences the daylight penetration. However, de Groot and de Vlieger stated that the height would be important because high tunnels are more see-trough. But normally[96] only approximately the first two and half meters above the road need to be considered, since pedestrians/cyclists and cars tend to be smaller. Apart from that, it was not stated, whether the recommendations are backed by any research.
The authors did not refer to any other publication.

Eberbach was certainly not aware of Schreuder and Fournier's research (1985)[97] and it is uncertain whether he knew about the other research mentioned before. However, he introduced important new parameters for short tunnel lighting, especially the state of adaptation and the daylight penetration. He also created the recommendations of the current DIN[98]. Moreover, he investigated the suitability of the *Lichtschleuse* in conjunction with *supplemental daytime lighting*[99] of 15 cd/m² in several existing tunnels.

It is difficult to evaluate the recommendations of the CETU (2000) and the CIE (2004), since it is not stated how the different tunnel length recommendations

96 Inclined roads and roads carrying frequently high vehicles (such as a lorry) are an exception.
97 personal correspondence with Eberbach (18 June 2009)
98 personal correspondence with Eberbach (18 June 2009)
99 i.e. an average luminance of 15 cd/m² along the whole road

were derived and whether they are backed up by any research. It is questionable whether 50 % of normal threshold zone lighting provides sufficient contrast. However, it needs to be appreciated that it is clearly stated that these recommendations merely serve as a first approach.
The CETU made three important points: to distinguish between urban and interurban tunnels, to take into account if a tunnel is barely used, and to consider the transportation of dangerous goods.

The 'Netherlands Foundation on Illumination' (2002) contributed a lot to the current state of knowledge. Especially the introduction of obstacles by evaluating a tunnel was a milestone, since unique geometries of tunnels can be considered by this means – even tunnels which have horizontal and vertical curves. However, some aspects need to be improved:

1. It should be clearly stated that the obstacles have to be placed along the whole tunnel for its appraisal. If a tunnel had a curve, it could happen that an obstacle standing close to the entrance can be seen against the exit aperture, but an obstacle standing in the middle of the tunnel is covered by the wall.
2. The obstacle representing a pedestrian/cyclist should not be placed in the middle of the lane, but closer to the wall, since pedestrians/cyclists tend to travel close to the edge of the lane. The closer an obstacle is standing to the edge of a lane, the higher the probability that it will be seen against the wall of the tunnel.
3. It is questionable whether it is meaningful to check that an obstacle is visible 30 % (vehicle) and 50 % (pedestrian/cyclist) against the exit aperture, since the size of the retinal image depends on the distance. 10 % of an obstacle standing close can result in the same seize of retinal image, which emerges from 100 % of an obstacle standing far away.
4. The size of the obstacles is debatable. If a vehicle loses load, which is smaller than the obstacles specified, it would not be detected. A square plate of 20 cm is usually taken as a critical obstacle: "The justification for the choice of an object of this size is that an object 20 cm high will

just pass beneath most vehicles without hitting the underside."[100]

Moreover, the 'through-view quotient' is misleading as mentioned before (see figure 18). Apart from that, one may well ask why the 'through-view quotient'-method was incorporated, since the 'obstacle method' could just be used for the evaluation of every tunnel.
It is incomprehensible why the British Standard (2003) does not provide the opportunity to light 'short' tunnels by creating bright luminance patterns on the surfaces inside the tunnel – this opportunity had been presented before in both the guide of the 'Netherlands Foundation on Illumination' (2002) and the CEN Report (2003).

The DIN recommendation (2008) is fairly different than the ones discussed before:
The maximum length of a short tunnel is determined using a formula. Furthermore, the daylight penetration is considered, and a formula is provided to calculate it. However, the daylight is merely taking into account as an alternative for *supplemental daytime lighting*[101].
Moreover, the *Lichtschleuse* is presented as a means to light short tunnels, and its required dimensions and required luminance values are 'clearly'[102] defined.

Three comments concern all the guides and codes of practice mentioned above:
The first comment concerns the assessment position. The tunnel is assessed from a point in front of the tunnel entrance. The distance is equal to the stopping distance. The distance influences the assessment of the tunnel significantly. It is assumed that the driver looks at the stopping distance into the tunnel. But if this is not true, the assessment is misleading. Moreover, it is taken for granted that the driver looks from the assessment point through the tunnel at the exit aperture. However, this assumption also needs to be supported. Furthermore,

100 Boyce P R. *Lighting for Driving: Roads, Vehicles, Signs, and Signals*. CRC Press, Boca Raton (2009) p86.
101 i.e. an average luminance of 15 cd/m² along the whole road
102 The *Lichtschleuse* has to be designed so that obstacles standing at any position in the tunnel can be seen against it.

some documents state that the tunnel should be assessed at a point which is 1.2 m above the road (including the British Standard), others do not state a height (the CETU, the CIE and the DIN). However, the higher the driver's eye, the higher the possibility that an obstacle is seen against the road and not against the exit aperture. Consequently, a tunnel assessed 1.2 m above the road can be safe for a car but dangerous for a lorry.

The second comment considers the condition of the exit aperture and the sky. It is taken for granted that the luminance of the exit aperture is sufficient to make the obstacle visible as a silhouette. However, it is claimed in some publications that an overcast sky would not provide a background of sufficiently high luminance to enable the silhouette effect to operate.[103] Furthermore it might be that the exit is obstructed by a building or even by the road (if the tunnel has a vertical curve).

To sum up, it has been shown that the progress of research about 'short' tunnel lighting during daytime has not been linear. In several cases, the research was not based on previous findings. The reason might be that the different papers were written in different languages, and translations were barely available. This might also explain why the recommendations and guides of some countries differ significantly. Furthermore, the recommendations were rarely backed up by any research.

Moreover, it has been shown that it is more suitable to appraise the necessity of daytime lighting for 'short' tunnels by using a perspective drawing of a tunnel than by regarding solely the length of it. It seems that bright luminance patterns on the walls and on the road constitute an appropriate lighting approach for 'short' tunnels during daytime. By this means, an obstacle can be detected either against the exit aperture or against the bright luminance patterns.

103 See, for example, British Standard Institution. *British Standard BS 5489-Part 7:1992, Road lighting – Part 7: Code of practice for the lighting of tunnels and underpasses.* (1992) p12.

2. 0 Research question

The research question of this final report is whether there are lighting approaches, which constitute an improvement over the lighting approach for short tunnels during daytime recommended in the current British Standard[104]. Furthermore, the research question is whether an overcast sky or an obstructed exit aperture provides a background of sufficiently high luminance to enable the silhouette effect to operate.

An “improved approach” is primarily defined for this purpose as a lighting approach which consumes lower energy, but allows for at least the same safety though. Here, “safety” means travelling without running into somebody or something – however, aspects of safety associated with crime are disregarded. Therefore, the findings of this report should not be fully applied for tunnels which are merely used by pedestrians and cyclists.

The reason for this research is that “practitioners find that for short tunnels and underpasses the recommendations in … [the current British] Standard lack definition and can often result in considerable over-lighting.”[105]

It has been shown in the previous section that one of the main disadvantages of the current British Standard are the requirements for artificial lighting of short tunnels during daytime. The problem is that it is an ‘all or nothing’-approach: tunnels of length between 25 m and 200 m either don’t need to be lit at all or they need to be exactly treated as ‘long’ tunnels (tunnels which are longer than 200 m) - there is no ‘middle course’. Assumed there were two tunnels, one being 135 m and the other being 140 m long (both having the same elevation), and the shorter one were just regarded as ‘short’ and the other one were just regarded as ‘long’. The size of their exit aperture seen from the stopping distance would not appear significantly different. Consequently, if the bright area of the ‘long’ tunnel’s exit aperture were slightly enhanced by artificial means, obstacles would be as visible as in the other tunnel. The energy required

104 British Standard Institution. *British Standard BS 5489-2:2003+A1:2008, Code of for the design of road lighting – Part 2: Lighting of tunnels.* (2008)

105 personal correspondence with Tony Price (BSI Committee CPL/34/8/6 Tunnel Lighting Chair), 28 November 2008.

would be by far lower as lighting this tunnel as a ‘long’ tunnel. By lighting such a tunnel as a ‘long’ one, the potential of the bright exit aperture is disregarded completely.

For the experiment of this research, the basic approach recommended in the British Standard is adopted:
A tunnel is assessed using a perspective illustration of it, which is derived at a distance (in front of the tunnel) equal to the stopping distance, 1.2 m above the road in the middle of the lane. The target used to investigate the visibility of obstacle is greater than 0.2 m.
As mentioned before, it needs to be investigated whether it is reasonable to assume that a driver looks at this position into the tunnel. Furthermore, it needs to be discussed whether the height of 1.2 m (regarding lorries) and the target size is appropriate. However, due to the time frame of this final report it was not possible to investigate these issues, too. Therefore, the research question of this report focuses merely on the aspects mentioned above.

3.0 The experiment

Based on the result of the background research an experiment was developed, which consisted of two phases. Measurements of human performance were made to explore the effectiveness of three lighting settings for short tunnels, which differ from the current lighting approach in the British Standard. Furthermore, the aim was to investigate whether the ‘condition’ of the exit aperture alters the visibility of obstacles significantly.
This section deals with the description of this experiment. Firstly, a general description of the experiment is presented. It is followed by two subsections, which describe the experiment set-up and the experiment procedure. These two subsections are again subdivided into several subsections.

The experiment consisted of two phases:
In the <u>first phase</u>, obstacles standing at different positions in an unlit tunnel where presented to several subjects. The objective was to find zones in this tunnel, in which obstacles are unlikely to be seen. Moreover, those of the presented obstacles, which were visible against the exit aperture, were presented again in a different setting. The dimensions and properties of the tunnel remained the same – however, this time the exit aperture of the tunnel was completely obstructed by a building having a low reflectance. By doing so, it was tested whether the contrast of an obstacle seen against an obstructed exit aperture is still sufficient to make this obstacle detectable.
In the <u>second phase</u> of the experiment, the obstacles, which had generally not been detected by the subjects during the first phase of the experiment, were presented again – however, at this time three different lighting settings were applied. By doing so, it was checked that these lighting settings make the unseen obstacles in the tunnel visible. The first lighting setting was a *Lichtschleuse* (see figure 23), the second one a luminous band mounted on each wall of the tunnel (see figure 24) and the third one consisted of three LED-lines which were mounted at the same location as the luminous band (see figure 25). The dimensions and properties of the tunnel remained the same as in the first phase of the experiment. All of these three approaches

tend to consume significantly less energy than the current lighting approach recommended by the British Standard.

3.1 Experiment set-up

This section deals with the experiment set-up of this research. First, a general description of the set-up is presented. Afterwards three subsections describe the experiment set-up in more detail. The first one deals with the physical conditions of the analysed tunnel, its surroundings and the target used. The second subsection is concerned with the properties of the three tested lighting approaches. Finally, the third subsection deals with the different positions of the target within the tunnel.

Measurements of human performance were made to explore the effectiveness of the three lighting settings for short tunnels mentioned above:
A computer simulated image of an empty tunnel was presented to several subjects. Within this tunnel an obstacle flashed up for 300 ms - a typical glimpse between eye movements. The obstacle flashed up several times, and each time its position within the tunnel varied. After each time, when an obstacle was presented to the subject, he/she had to tell whether he/she had seen the obstacle and where he/she had seen it.
This method seems to be appropriate to analyse the visibility of targets within a tunnel – considering the procedure of visual perception:

> "Visual perception proceeds in a sequence of fixations and jumps (saccades) of the ocular axes most obvious in search and reading tasks. What we see is acquired during the fixational pauses (glimpses) lasting about 0.2 to 0.4 s. During this interval a target may be perceived foveally or extrafoveally. Detection of a target means to perceive its existence (for instance a signal light)."[106]

The computer simulated image showed the tunnel seen from a stopping distance of 60 m. The view angle of the observer was 20°. The stopping

106 Bodmann H W. '*Elements of photometry, brightness and visibility*'. Lighting Research and Technology, Vol 24, No 1 (1992) p33.

distance is recommended in the current British Standards to determine whether a tunnel is considered as long or short. A view angle of 20° was chosen, since it is widely believed that the "adaptation luminance of the driver approaching the tunnel portal…depends on the luminances in a 20° cone of vision…"[107]

The image(s) were calculated and simulated by the lighting software AGI32. This program processes in a deterministic way – consequently, the rendered images of different obstacle positions within the tunnel and the rendered image of the empty tunnel look exactly the same (apart from the position of the obstacle). Therefore, if an image of an empty tunnel is presented firstly, and afterwards the same tunnel having an obstacle inside, it appears as if an obstacle flashes up inside the tunnel.
The computer monitor gamma factor was set to 3.0 for the rendering of the *Lichtschleuse*-images to counter problems with the dynamic range. The rest of the images were rendered using a computer monitor gamma factor of 2.2. The size of each image was 1024 x 768 pixels.

3.1.1 Dimensions, reflectances, sky condition and target characterisation

In this section the physical condition of the analysed tunnel and its surroundings is defined and reasons are given for it. Furthermore, the character of the target, which represents an obstacle in a tunnel, is defined.

The dimensions of the tunnel were taken from a tunnel example in the current DIN (see figure 19), whose length was defined as just suitable if seen from a distance of 60 m. By doing so, the adaptation of the observer is supposed to remain stable (since the fovea is predominantly covered by the exit aperture[108]),

107 Simons R H and Bean A R. *Lighting Engineering: Applied Calculations.* Architectural Press, Oxford (2001) p404.

108 More information about this topic is given in: Adrian W and Eberbach K. 'On the relationship between the visual threshold and the size of the surrounding field'. *Lighting Research and Technology*, Vol 1, No 4 (1969) pp251-254 & Adrian W. 'Adaptation luminance when approaching a tunnel in daytime'. *Lighting Research and Technology*, Vol 19, No 3 (1987) pp73-79.)

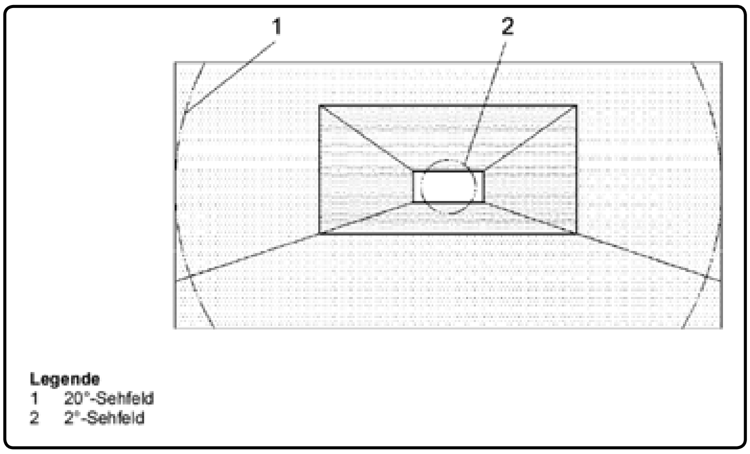


Figure 19: Tunnel geometry, whose length is defined as just suitable (if seen from a distance of 60 m) by the DIN (2008) - length: 169 m, width: 10 m, height: 5 m
(Legende: key / 20°-Sehfeld: 20° view angle / 2°-Sehfeld: 2° view angle)
(Source: Deutsches Institut für Normung. DIN 67524-1, Beleuchtung von Straßentunneln und Unterführungen – Teil 1: Allgemeine Gütemerkmale und Richtwerte. (2008) p11.)

besides – since the tunnel is quite long – there are zones in the tunnel in which obstacles are unlikely to be seen. This seemed to be a suitable setting for the experiment.
The width of this tunnel is 10 m, its height is 5 m and its length is 169 m (see figure 20 & page 59). The height of the construction, which is penetrated by the tunnel, is 10 m. The width of the road is 10 m. The stopping distance is defined as 60 m (in phase 2 the stopping distance was only 58.4 m instead of 60 m, since the observers position was moved accidentally; however, it is unlikely that this small change makes a significant impact on the results of the experiment). The road is divided into two lanes to simulate two-way traffic (contrary to the example in the DIN). The observer's position is on the middle of the left lane (2. 5 m away from either edge of the lane). The through-view quotient of the setting is 15. 5 %.
The object, which obstructs the exit aperture in the 2nd setting of the first phase is located 30 m behind the exit. Its length is 75 m, its width is 10 m and its height is 30 m. By doing so, the daylight penetration of the tunnel is not altered significantly (see figure 21 & page 60).

Every surface is a Lambertian diffuser.
7 % reflectance is chosen for the road (this is the same bulk reflexion factor as C2 road surface), 50 % for the tunnel walls and 30 % for the ceiling. The reflectance of the grass surrounding the road is 9 %.
Both the reflectance of the construction, which is penetrated by the tunnel, and the reflectance of the object which obstructs the exit aperture (in phase 1) is 20

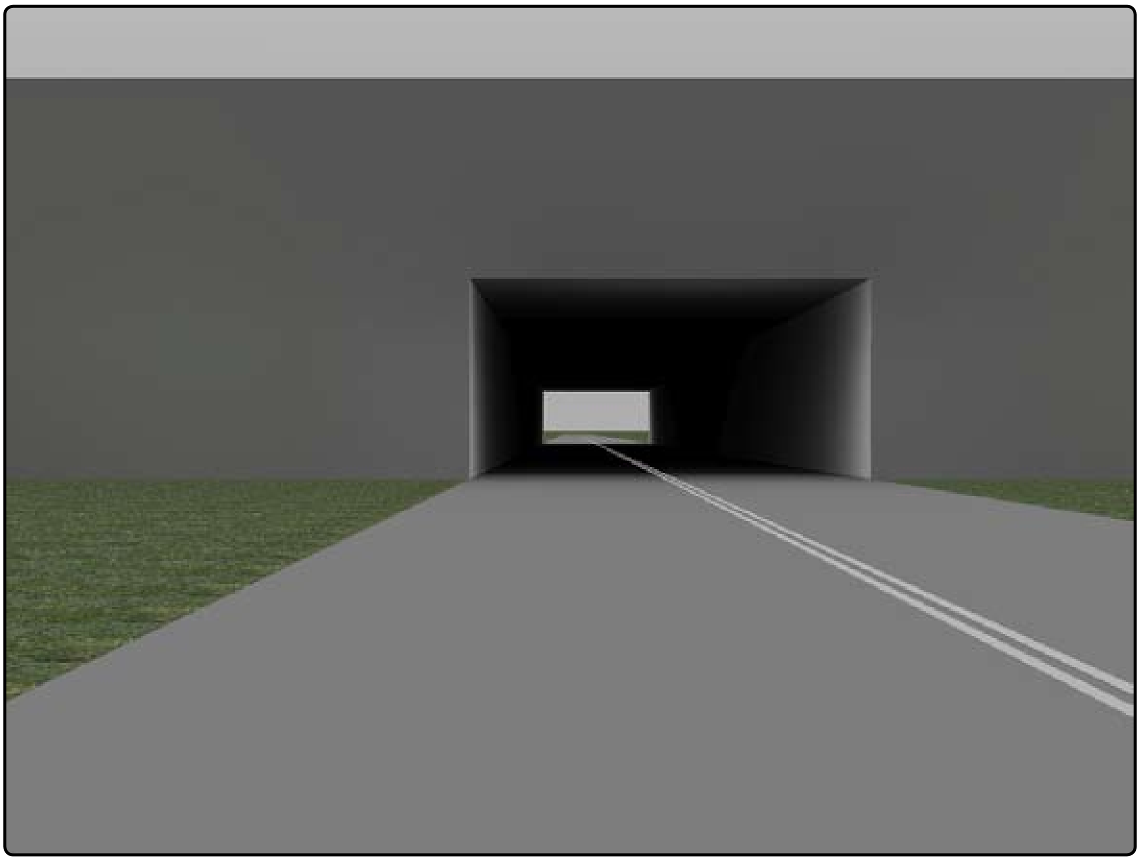


Figure 20: unlit tunnel (phase 1.1 of the experiment)

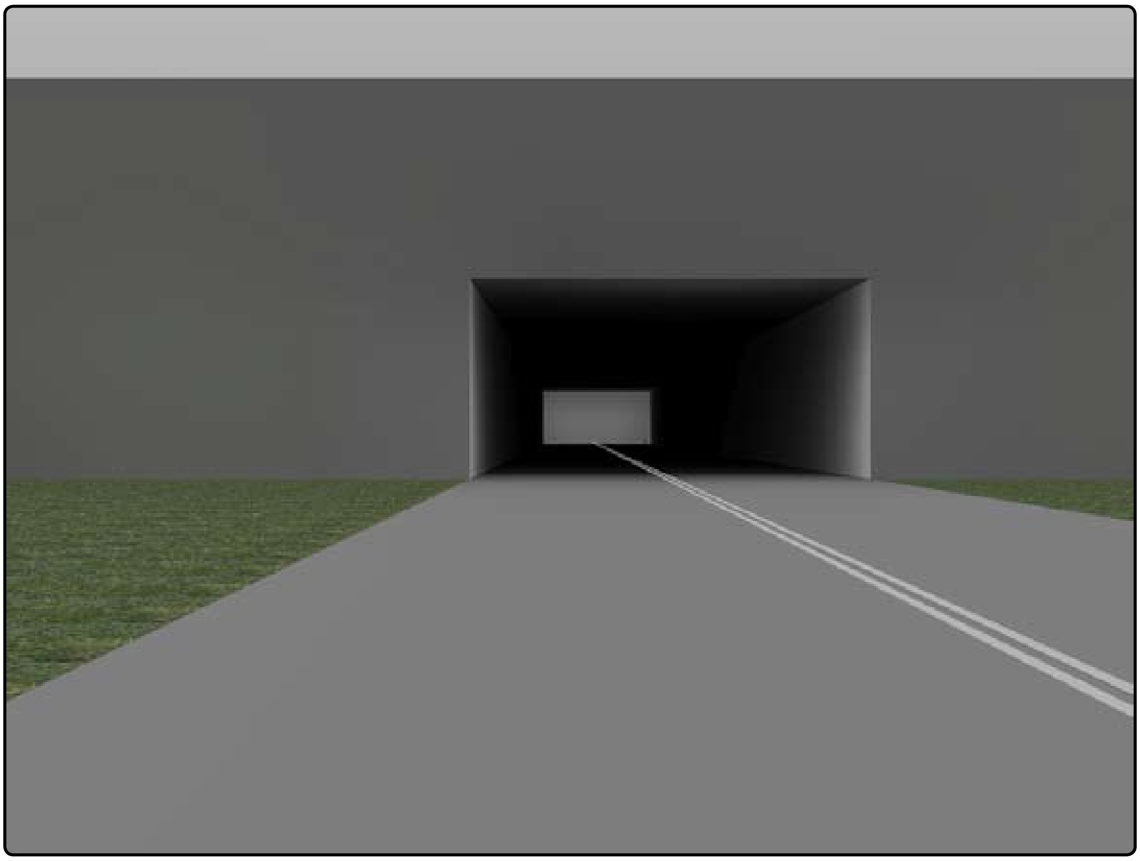
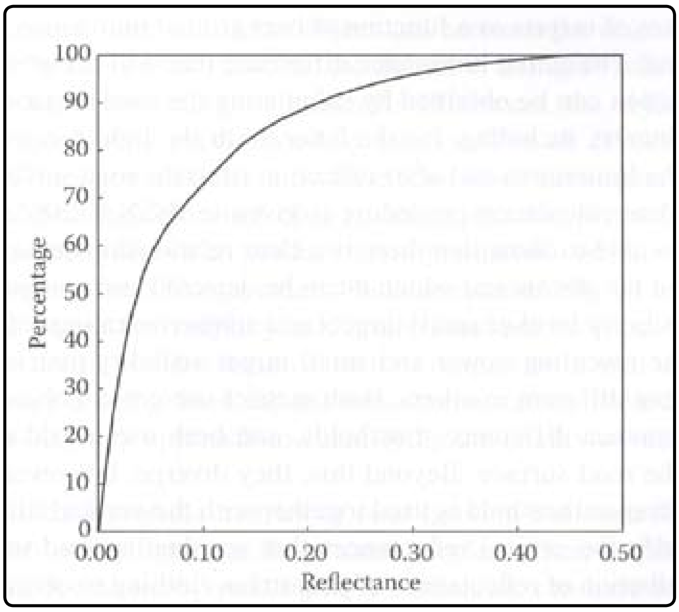


Figure 21: obstructed unlit tunnel (phase 1.2 of the experiment)

Figure 22: experiment set-up: tunnel reflectances

%. The reflectance of several common building materials in the United Kingdom (e.g. brickwork and concrete) is 20 % or more[109] – therefore, this value seems to be appropriate for investigating whether an obstructed exit aperture of a tunnel provides sufficient background luminance so that an obstacle can be seen as a silhouette against it. However, it should be taken into account that the reflection of an obstruction might even be lower (e.g. a dark grey painted house).

The daylight factor in the middle of the tunnel (measured 0 m above the centre of the road) is 0.007 %. The luminance distribution on the road and on the walls can be seen in figure 26.



Graph 6: The cumulative frequency of the reflectances of clothing worn by pedestrians (after Smith 1938)

(Source: Boyce P R. Lighting for Driving: Roads, Vehicles, Signs, and Signals. CRC Press, Boca Raton (2009) p87.)

Each of the obstacles tested is a cylinder. Its diameter is 0.2 m and it height is 1.5 m. The reflectance was determined as 25 % - this value was chosen, since the reflectance of 90 % of all pedestrian clothes is not more than 25 % (see graph 6). The colour of the obstacle was grey. This colour was determined to avoid the colour making a significant impact on the visibility, since “[i]t is possible to have a stimulus with zero luminance contrast that can still be detected because it differs from its background in

109 British Standard Institution. *British Standard BS 8206-2:2008, Lighting for buildings – Part 2: Code of practice for daylighting*. (2008) p33.

colour …”[110]

A cylinder was used instead of a plane obstacle, since “[t]he use of a plane target suffers from a number of disadvantages.”[111] First, a real obstacle is rarely plane. “Second, no light will reach the observed face of the target from luminaires behind the target, whereas in practice a solid object will appear to be lit from the side.”[112] Consequently, “a plane target is likely to give a misleading indication of the performance on an installation.”[113]

The dimensions of the obstacle were determined as mentioned above to focus on the visibility of the smallest user type of mixed traffic tunnels: pedestrians. Since big obstacles tend to be easier seen in short tunnels than small obstacles, it may be assumed that if a tunnel is safe for pedestrians, it is also safe for cyclists and motorized vehicles.

A CIE overcast sky, which produced an external (unobstructed) horizontal illuminance of 10000 lx, was applied for all settings. This condition is considered as the ‘worst case’, since the luminances of surfaces (outside the tunnel) are lower than lit by a clear sky and sunlight – apart from that, the luminances of an overcast sky itself are lower than the luminances of a clear sky. Therefore, the luminance contrast between the obstacle in a tunnel and its exit aperture is lower.

3.1.2 Properties of the three tested lighting approaches for short tunnels

This section deals with the properties of the tested lighting approaches. The reasons for using these lighting approaches are stated, and their technical and physical features are explained. Furthermore, the mounting positions within the tunnel are presented.

Three lighting approaches were developed, which are designed for tunnels,

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110 Boyce P R (2009). op. cit. p4.
111 Lecoq J. ‘Calculation of the visibility level of spherical targets in roads’. *Lighting Research and Technology*, Vol 31, No 4 (1999) p171.
112 *Ibid*. p171.
113 *Ibid*. p171.

whose exit aperture appears too small to make obstacles always visible against it, but covers the observer's fovea though. The field of vision formed by the exit aperture (seen from the stopping distance in front of the tunnel) should cover at least the fovea to maintain the bright adaptation of the driver[114]; this determines the maximum length of tunnels, which are in this report defined as 'short' (provided that the whole exit aperture can be seen from the stopping distance).

3.1.2.1 Lighting approach No 1: the *Lichtschleuse*

The first lighting approach tested is the *Lichtschleuse (*see figure 23)*.* As described in section 1.1.1, a *Lichtschleuse* is an artificially lit area in the middle of a tunnel, which covers the road and the walls. Viewed from outside the tunnel, it looks like a strip which divides the tunnel into two smaller ones. The objective is to provide an additional bright background area, so that an obstacle can either be seen against the exit aperture or against this artificially lit area. The *Lichtschleuse* was created using 75 conventional tunnel luminaires. The brand of these luminaires is called 'WRTL', and the type is called 'WRTL 2816 SNN 400W SON T' (see Annex C). The luminaires are spread in a regular array and they are ceiling mounted (see page 52).
The length of the *Lichtschleuse* is 39 m, and it is located exactly in the middle of the tunnel. The result of the first phase of the experiment (see section 4.1.1.1) had revealed that obstacles, which are standing 50.7 – 101.4 m behind the entrance of the tunnel, could not be detected by the subjects. To make all these obstacles in its entirety visible against the wall, the wall area from 55 – 151 m needs to be lit (because the observer is not standing parallel to the wall, but acute-angled). However, since this tunnel has two-way traffic going through, the distance between entrance and *Lichtschleuse* and between exit and *Lichtschleuse* needs to be the same. But in this case, the distance between the entrance and the *Lichtschleuse* needs to be 55 m, and the distance between the exit and the *Lichtschleuse* needs to be 18 m. This demonstrates

114 More information about this topic is given in: Adrian W and Eberbach K. 'On the relationship between the visual threshold and the size of the surrounding field'. *Lighting Research and Technology*, Vol 1, No 4 (1969) pp251-254 & Adrian W. 'Adaptation luminance when approaching a tunnel in daytime'. *Lighting Research and Technology*, Vol 19, No 3 (1987) pp73-79.

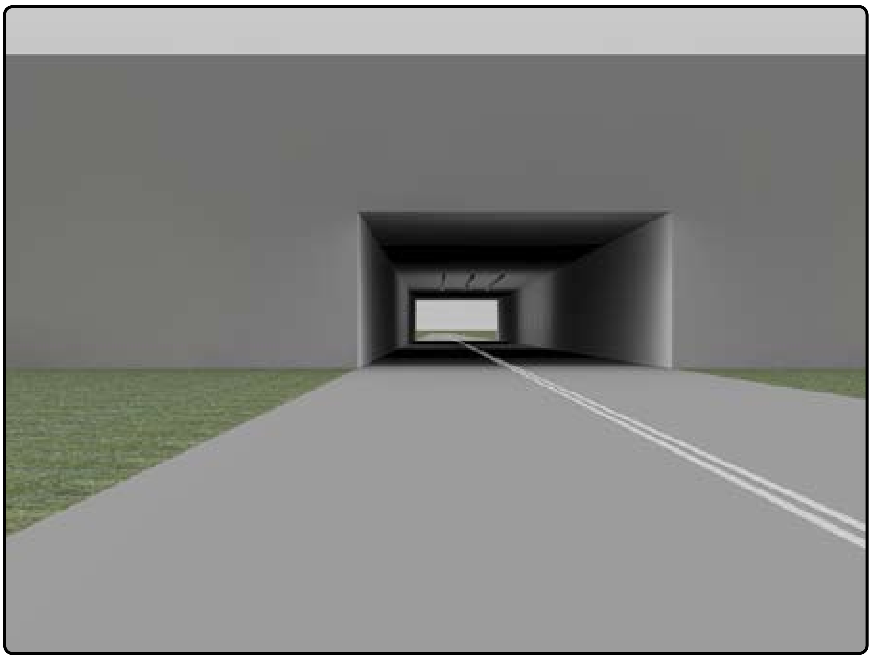


Figure 23: Lighting approach No. 1: <u>Lichtschleuse</u>

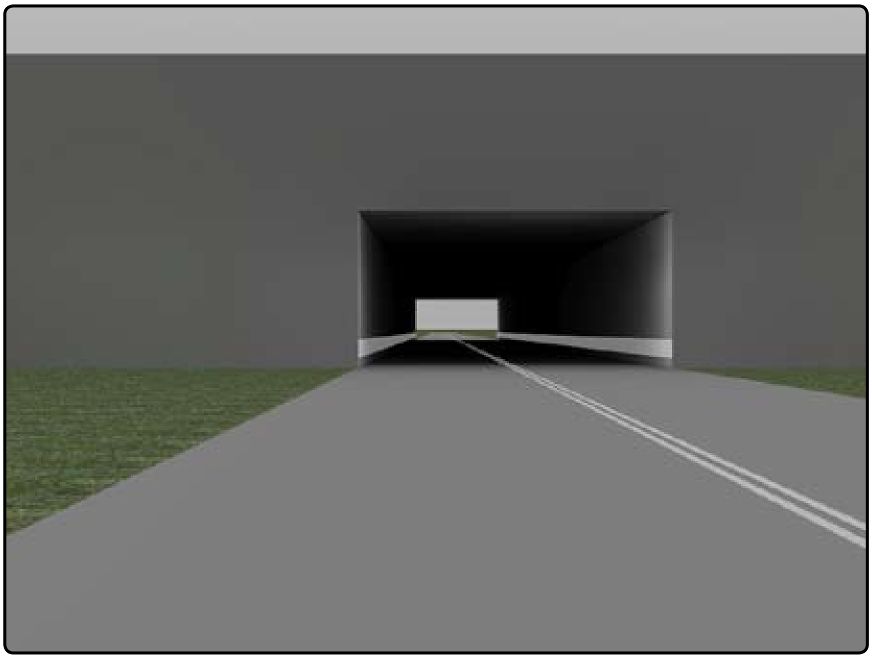


Figure 24: Lighting approach No. 2: <u>Luminous band</u>

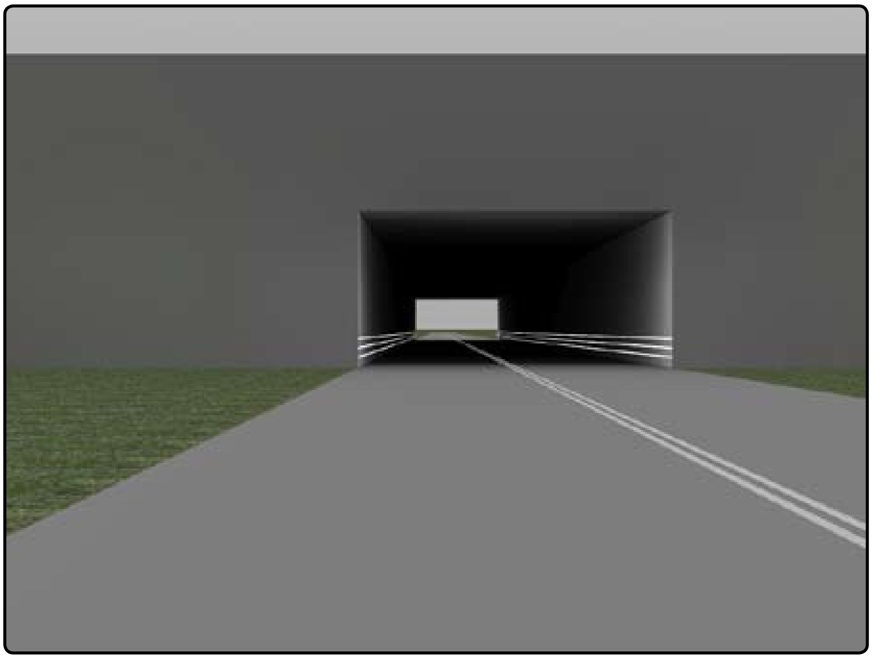
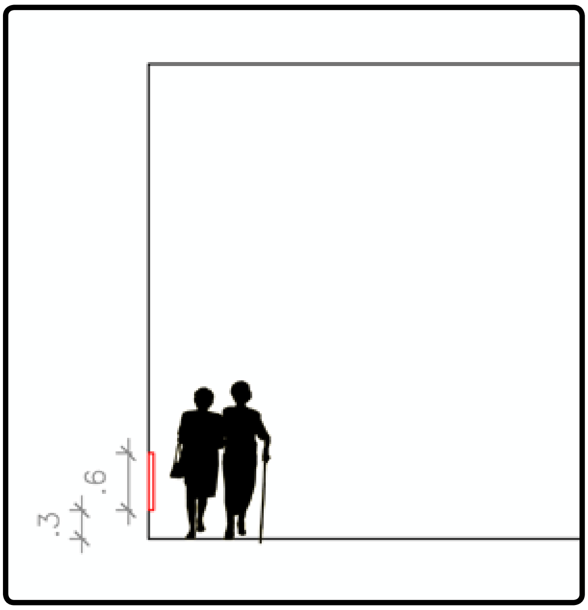
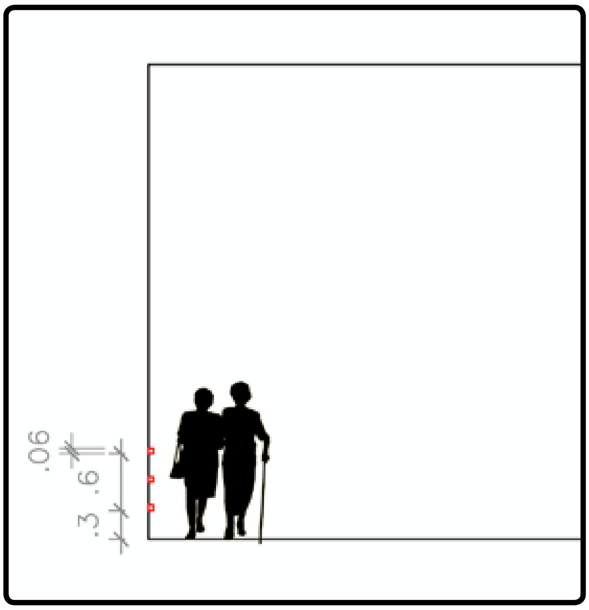


Figure 25: Lighting approach No. 3: <u>LED strips</u>

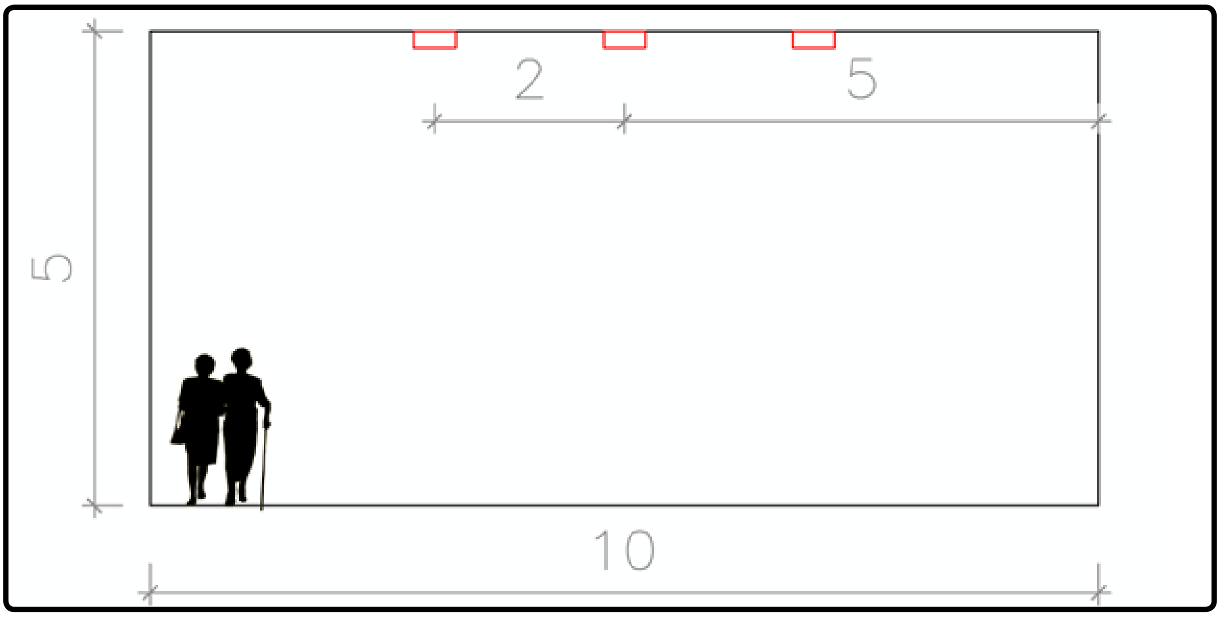
Lichtschleuse, luminous band and LED strips: mounting specifications



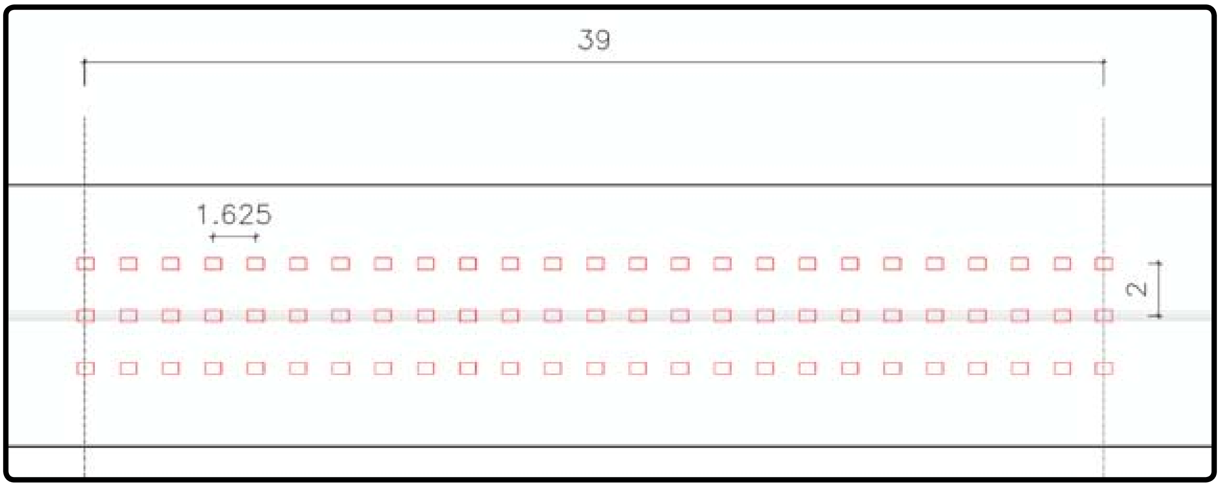
luminous band: elevation



LED strips: elevation



Lichtschleuse: elevation



Lichtschleuse - plan view (the Lichtschleuse is located in the middle of the tunnel)

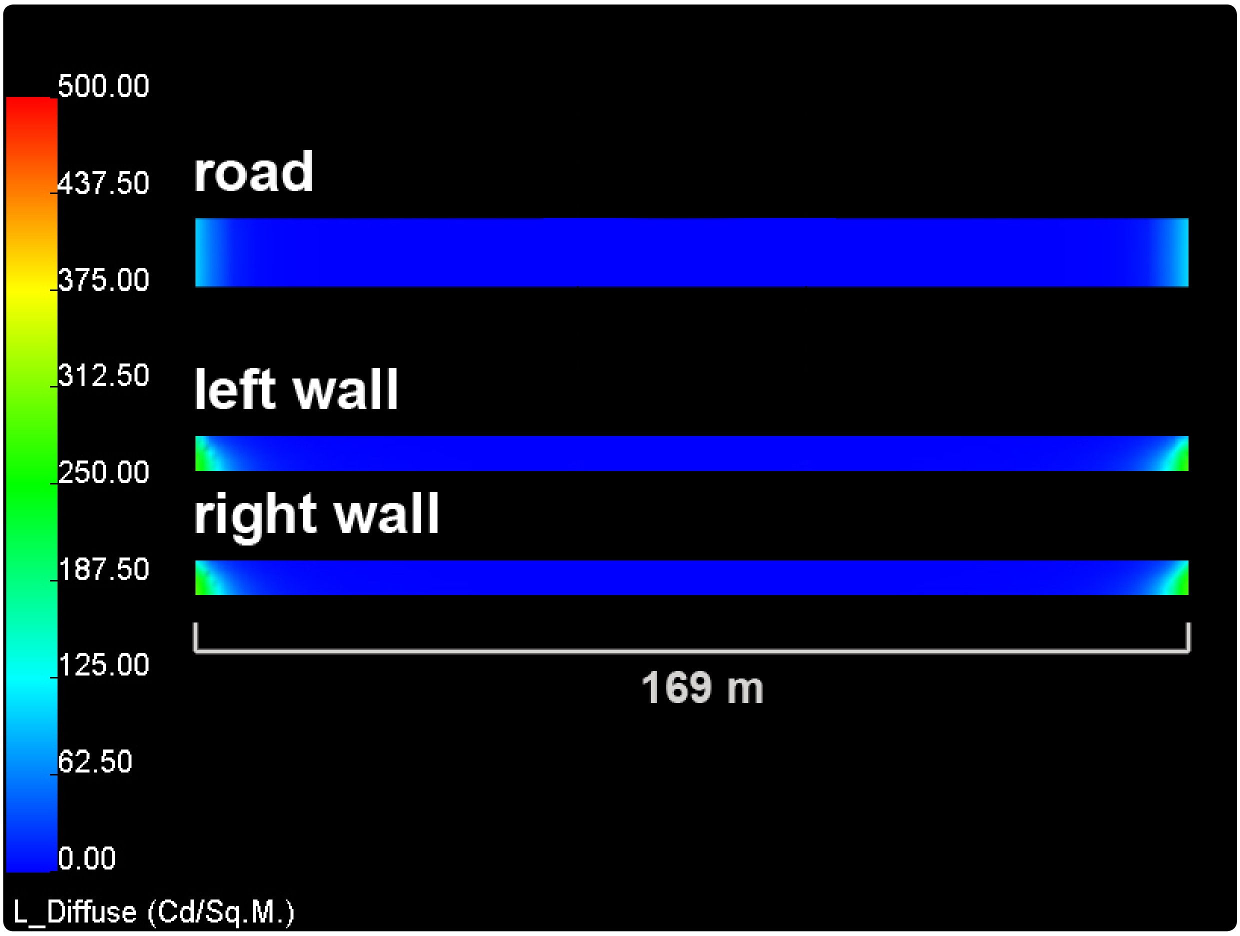


Figure 26: Luminances in the unlit tunnel (phase 1.1)

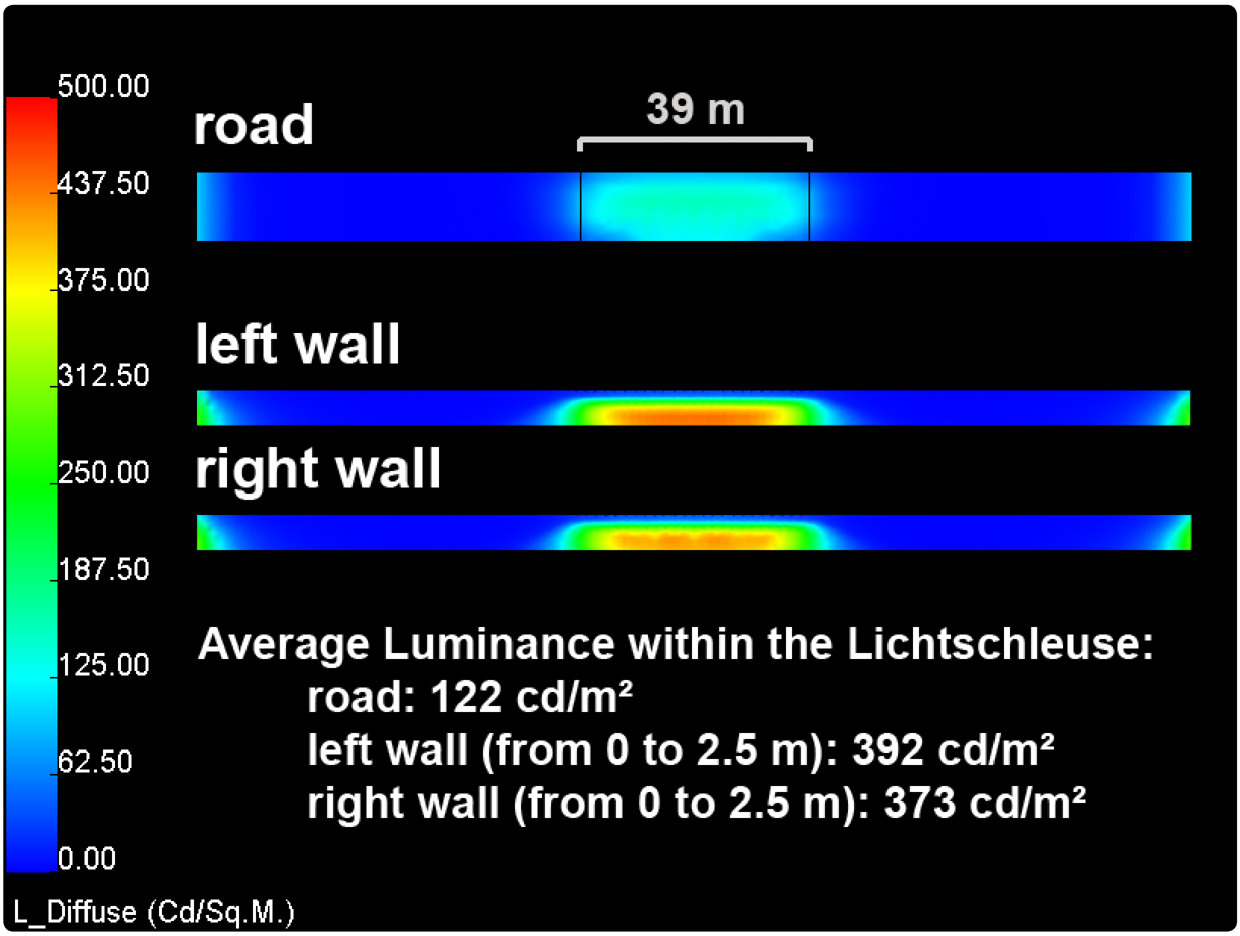


Figure 27: Luminance in the tunnel lit by the *Lichtschleuse* (phase 2.1)

the difficulty of applying the *Lichtschleuse* for two-way traffic tunnels, which are used by both motorists and pedestrians/cyclists. In this experiment, the *Lichtschleuse* was determined to be 39 m long, located exactly in the middle of the tunnel. Consequently, the distance between the *Lichtschleuse* and both the entrance/exit is 65 m. It was accepted that not every obstacle can be seen in its entirety against the *Lichtschleuse.* However, by doing so it can be investigated, how the visibility of the obstacles decreases when an obstacles 'moves' out of the *Lichtschleuse*.

On the one hand, Schreuder stated in his dissertation that an experimental tunnel lighting would have proven that a luminance of 150 cd/m² would not be sufficient for a *Lichtschleuse*[115]. On the other hand, Eberbach installed successfully a *Lichtschleuse*, whose luminance was 120 cd/m² [116]. Naturally, the required luminance of the *Lichtschleuse* must be determined regarding the acces zone luminance of the tunnel. Since there has not been conducted any research about the determination of the *Lichtschleuse's* luminance yet, the luminance of the *Lichtschleuse* was determined fairly high for this experiment. By doing so, it should be avoided that the result is altered due to too low luminance values. The average luminance on the walls (0 to 2.5 m above the road) was around 380 cd/m² and the average luminance on the road was 122 cd/m² (see figure 27). It would have been desirable to achieve the same value on both the walls and the road – however, since the reflectances of both surfaces are quite different (walls: 50 %; road: 7 %), this would be difficult to achieve with conventional tunnel luminaires.

A supplemental average luminance of 15 cd/m² along the whole road (*supplemental daytime lighting*) was not provided. It was assumed that this measure would not make a significant impact on the visibility of the obstacles. The lowest value on the road (in the centre of the road) was 0.1 cd/m² and the lowest value on the walls (2.5 m above the road) was 1.0 cd/m².

115 Schreuder D A. *The Lighting of Vehicular Traffic Tunnels*. 2nd ed. Philips Technical Library, Eindhoven (1965) p59.

116 Eberbach K and Kaboth N (2005). op. cit. p369.

3.1.2.2 Lighting approach No 2: a luminous band along the wall

The second lighting approach is a luminous band. It is mounted on the walls of the tunnel, 0.3 m above the road (see fig. 24 & page 52). It is as long as the tunnel and its height is 0.6 m. Consequently, the area of an obstacle starting at 0.3 and ending at 0.9 m above the ground can be seen as a silhouette against the luminous band. Therefore, it is also suitable for children. The luminous band was mounted on both walls of the tunnel, since this tunnel has two-way traffic going through.

The reason for developing this lighting approach is that the *Lichtschleuse* is rather suitable for motorised traffic tunnels than for mixed traffic tunnels. As described in section 3.1.2.1, the *Lichtschleuse* needs to be 96 m long to make the undetected obstacles completely visible against it. However, if this tunnel were treated as a long tunnel, its threshold zone would only need to be 60 m long[117]. This shows that the *Lichtschleuse* does not always saves much energy compared to the approach of long tunnel lighting. Furthermore, if a *Lichtschleuse* is designed too short, cyclists and pedestrians are likely to be invisible in some areas of the tunnel, because the dark parts of the walls do not provide sufficient luminance contrast (see figure 28). The important areas, which needs to be considered in mixed traffic tunnels are the walls (as long as the driver's eye height is assumed to be 1.2 m above the road). Under certain circumstances (e.g. a vertical curve), the road may be important, too. However, all the obstacles standing in the centre of the analysed tunnel (in the first phase of the experiment) could be seen against the exit aperture (see section 4.1.1.1). Since the exit aperture of the analysed tunnel

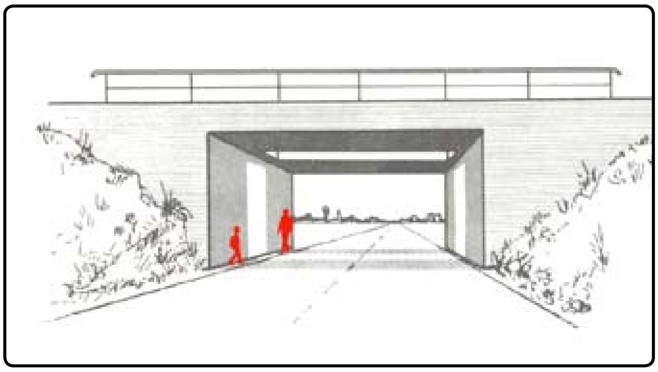


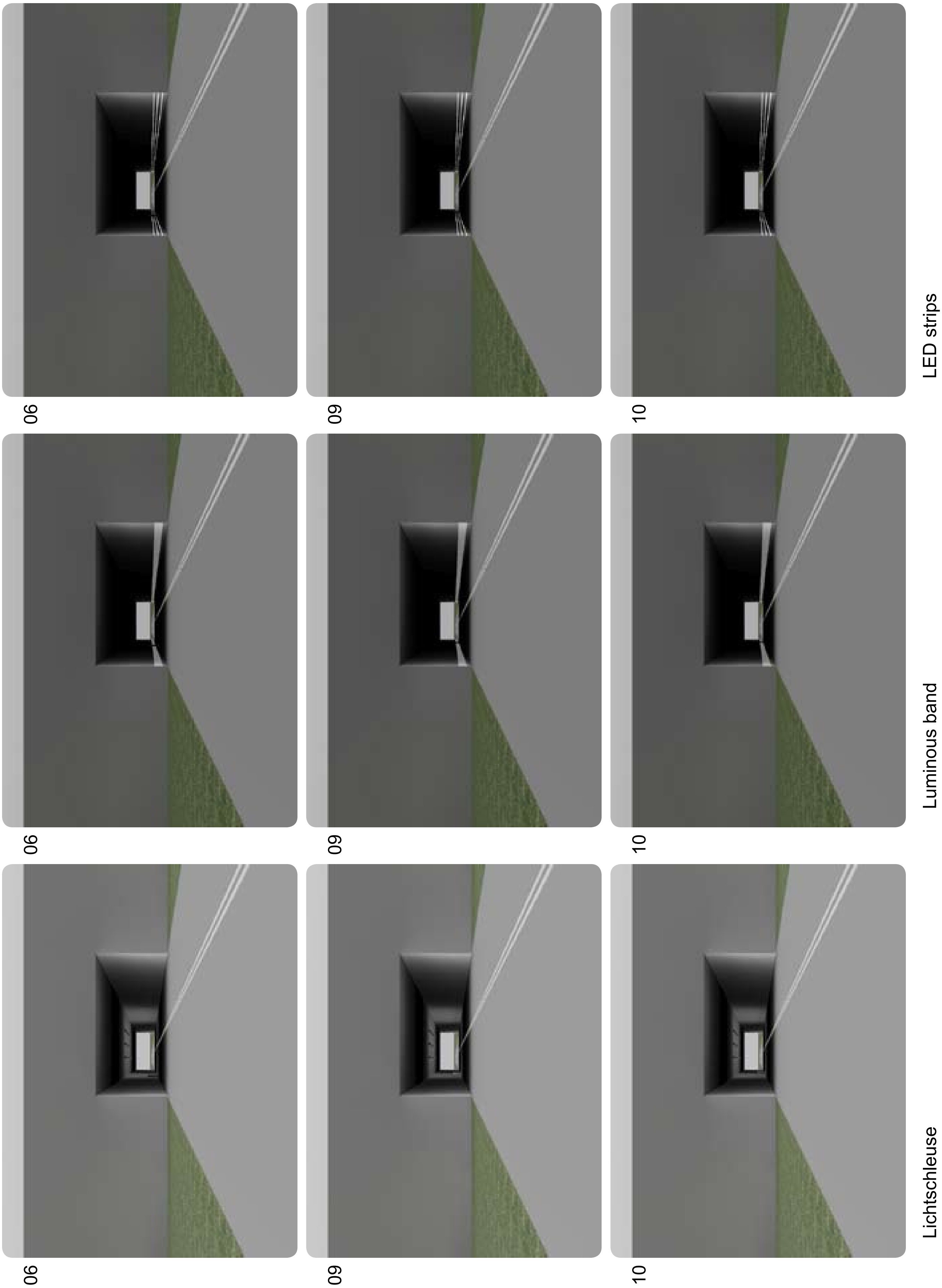
Figure 28: If a *Lichtschleuse* is designed too short, cyclists and pedestrians are likely to be invisible in some areas of the tunnel.

117 British Standard Institution. *British Standard BS 5489-2:2003+A1:2008, Code of for the design of road lighting – Part 2: Lighting of tunnels.* (2008) p8

covers the fovea just sufficiently (and hence, the tunnel is a limiting case), it can be assumed that the obstacles located in the centre can also be seen against the exit aperture in most other ‘short’ tunnels.
The luminous band can be created by using, for example, electroluminescent panels. The advantage of this kind of technology is that it is fairly thin. Therefore, it does not obstruct the way. If the band were significantly thicker, pedestrians and cyclists would travel closer to the centre of the lane, which would be more dangerous.
For this experiment, the luminance of the luminous band was determined being 200 cd/m². This value might be higher than required. However, for this experiment, it was intended to achieve rather a too high value than a too low value, since there has not been conducted any research about the determination of the required luminance for this lighting approach yet.
The light colour is daylight white.

3.1.2.3 Lighting approach No 3: three LED strips

The third lighting approach is similar to the second lighting approach. However, it is a reduction of the second one: instead of creating a single luminous area on the wall, which has the same seize as the luminous band, the area of the luminous band is outlined by two LED strips. Additionally, another LED strip runs between them. Each of the strips is 0.06 m wide (see figure 25 & page 52).
The objective of applying these LED strips was to reduce the energy required for the luminous band. It was assumed that a driver recognises if one or more of these strips are interrupted by an obstacle standing in front of it. However, it needed to be investigated whether the application of three 0.06 m wide LED strips (instead of a single 0.6 m wide luminous band) results in a lower detection rate of obstacles.
The simulation is based on a real product – an LED strip module called “Tallexx P111” (see Annex D). This strip module was integrated in a channel which is 60 mm wide and covered by an opal diffuser giving perfect cosine distribution. The strip module emits 250 lumens per linear meter – this creates a luminance of 1326 cd/m² on the opal coverage. The light colour is daylight white.



Comparison: obstacles No. 06/09/10 lit by the Lichtschleuse, the luminous band and the three LED strips

3.1.3 Positions of the obstacles

In this section the different positions of the target within the tunnel are defined and reasons are given for determining these positions.

3.1.3.1 Positions of the obstacles in the first phase of the experiment

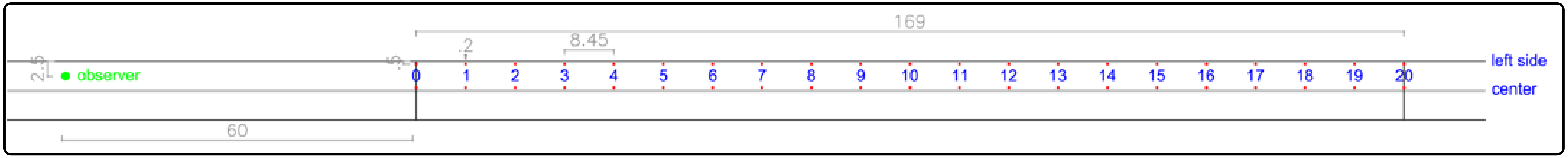
In the first phase of the experiment, two rows of obstacles are placed inside the tunnel (see pages 59). One row is located 0.5 m next to the left tunnel wall[118] and the other row is located 0.5 m next to the centre-line[119] (on the same lane). The obstacles on the left side of the tunnel represent non-motorised traffic (e.g. pedestrians and cyclists), whereas the obstacles in the centre represent motorised traffic[120]. The distance between each obstacle is 8. 45 m. The total number of obstacles (of each row) is 21. The first obstacle is designated “0” and it is standing at the beginning of the tunnel. Consequently, the tunnel is divided into 20 equal segments.

The objective of placing the obstacles in that way is to investigate two different kinds of visibility: several obstacles on the left side of the tunnel can not be seen against the exit aperture, but against the tunnel wall and the road. In contrast, all the obstacles in the centre can at least partly be seen against the exit aperture. It is predictable that the contrast of some obstacles at the beginning of the left side of the tunnel is positive, whereas the contrast of some obstacles in the rear of the tunnel is negative. It is assumed that all the obstacles in the centre can be detected either as positive or negative contrast. The first part of experiment is supposed to reveal the interval of the left side of the tunnel in which the obstacles are not visible. Moreover, it is checked that all of the obstacles in the centre are detectable. Although each of the obstacles in the

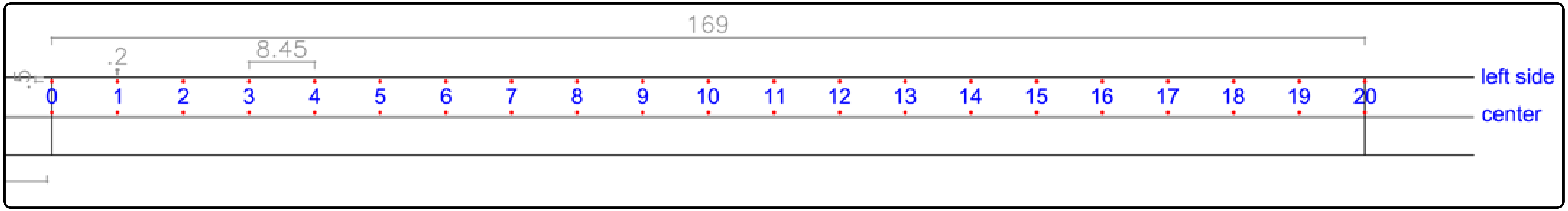
118 measured from the edge of the lane to centre of the obstacle

119 measured from the edge of the lane to centre of the obstacle

120 The row representing motorised traffic was not placed in the middle of the lane, since the distance between this row and the row on the left side would be fairly small. It would be difficult for the subject to distinguish clearly between left side and centre during the experiment. It is important that the subject can clearly distinguish the position of the obstacle (left side or centre), so that it can be checked whether he/she really saw the object or just guessed. However, the row in the centre of the lane (row C on the left side of the second phase of the experiment) can be seen (against the exit aperture) in the same way as the row in the centre of the road.



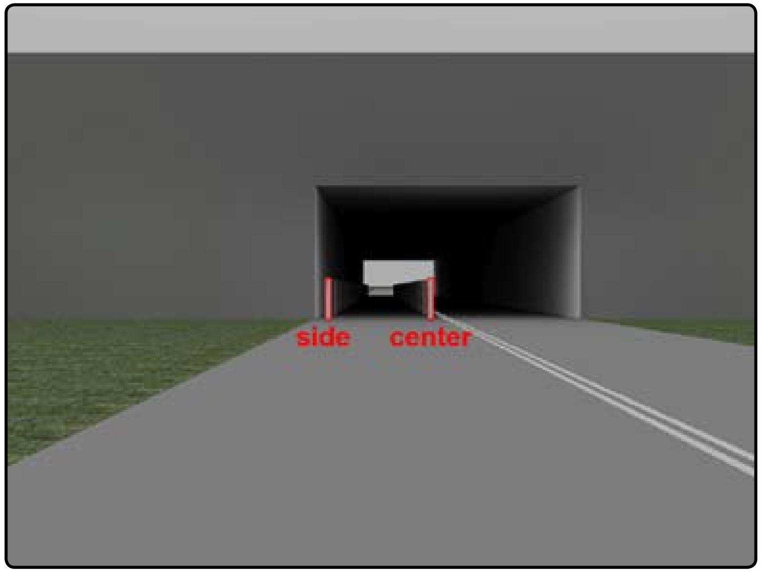
plan view

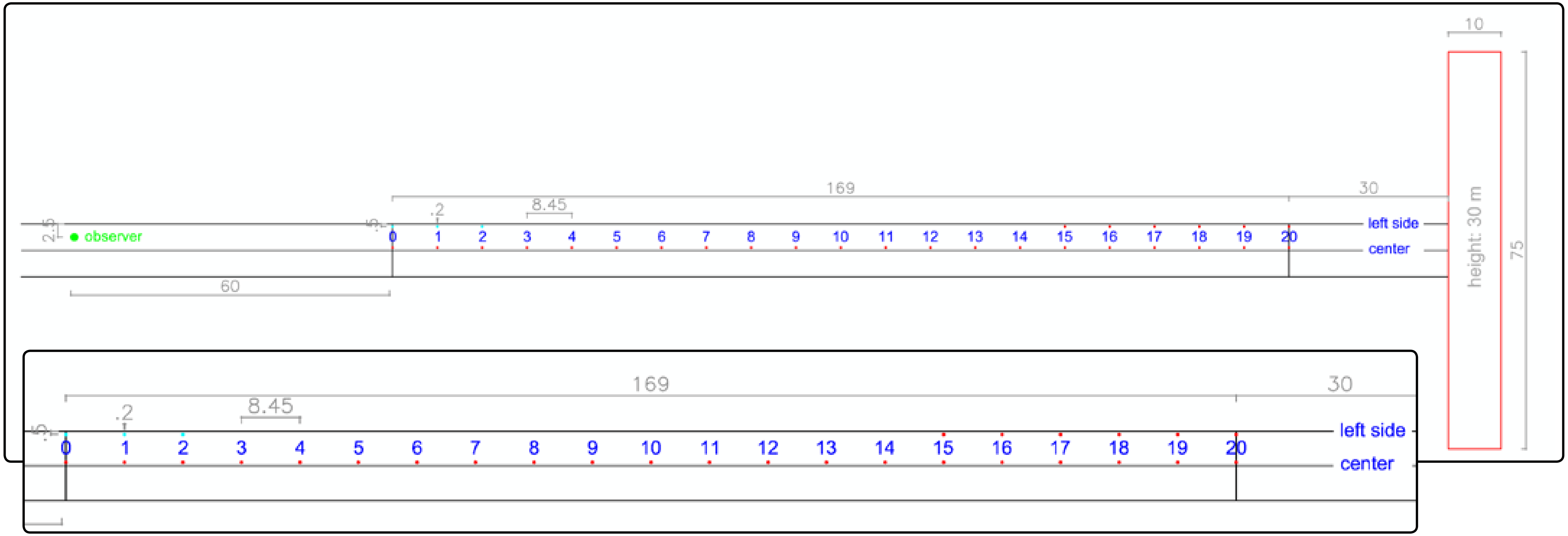


plan view: zoom

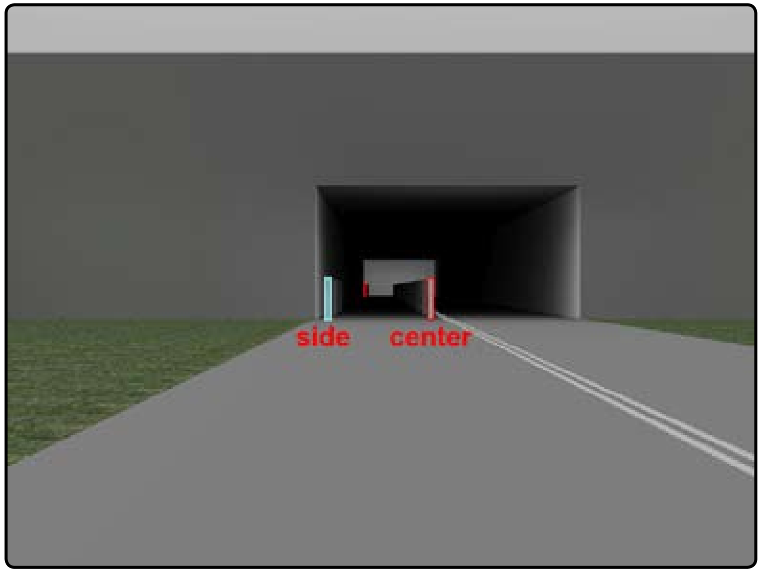
Positions - Phase 1.1 (unobstructed unlit)

The positions of the obstacle are coloured red.
The image shows the different obstacle positions all at once.





plan view and zoom



Positions - Phase 1.2 (obstructed unlit)

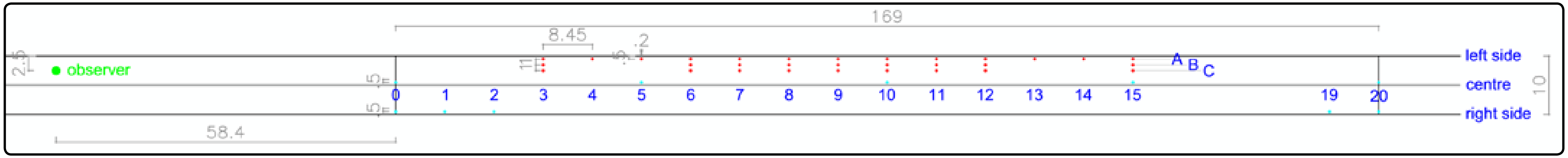
The positions of the obstacle are coloured red.
The positions, which were simply presented to check that the subjects did not guessed the positions of the obstacle, are coloured blue.
The image shows the different obstacle positions all at once.

centre can at least partly be seen against the exit aperture, it can not be taken for granted that they are detectable: Firstly, the size of the retinal image of the part of each obstacle which is visible against the exit aperture might be too small. Secondly, the contrast between the daylight lit obstacles (in the beginning of the tunnel) and the exit aperture might be to low.

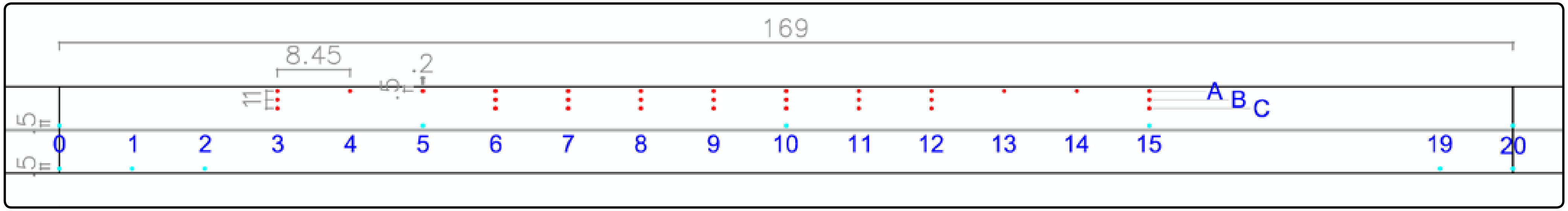
In the second part of the first phase of the experiment, the exit aperture is obstructed by an object, which is standing 30 m behind it (see page 60). The object's reflectance is 20 %.
The position of the each obstacle remains generally the same as in the first part of the first phase of the experiment. However, only those obstacles are presented, which are at least partly visible against the exit aperture. Obstacle No. 14 (left side) is not presented again, since it is partly standing in front of the tunnel wall - the result might be misleading, since the reflectance of the tunnel wall (50 %) is higher than the reflectance of the obstructing object (20 %). Obstacles No. 15 to 20 are presented on the left side and obstacles No. 0 to 20 in the centre.
Furthermore, three obstacles (No. 0-2) on the left side of the tunnel are introduced. The reason of incorporating these obstacles is to prevent the subjects focusing on the rear of the left row during the experiment. These obstacles are visible because they are lit by daylight.
The objective of this part of the experiment is to investigate whether an obstructed exit aperture provides a background of sufficiently high luminance to enable the silhouette effect to operate. In an urban area, for example, it might happen that objects (e.g. buildings) obstruct the exit aperture of a tunnel.

3.1.3.2 Positions of the obstacles in the second phase of the experiment

Phase 1 of the experiment revealed that within the area beginning at obstacles No. 3 and ending at obstacle No. 15 (on the left side of the tunnel) the percentage of detection dropped sharply (see section 4.1.1). The objective of the 2nd phase of the experiment is to investigate whether the three lighting



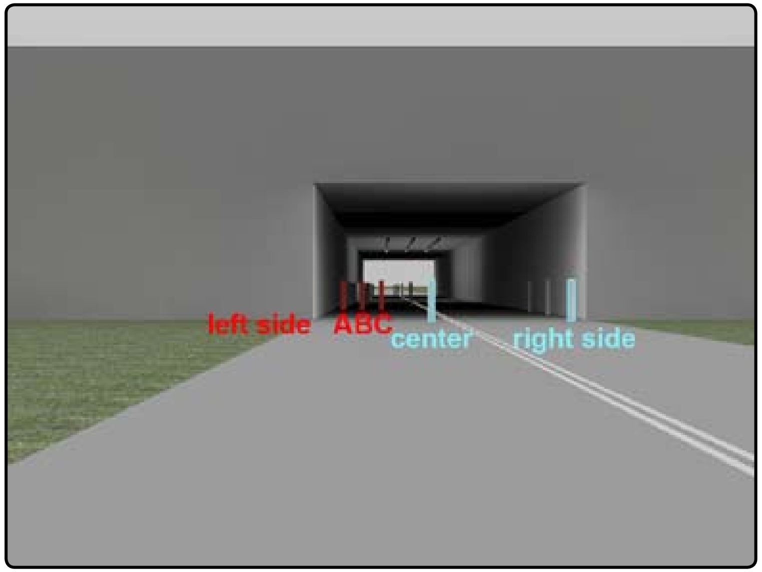
plan view



plan view: zoom

Positions - Phase 2 (lit)

The positions of the obstacles lit by the Lichtschleuse, the luminous band and the LED strips are the same.
The positions of the obstacle are coloured red.
The positions, which were simply presented to check that the subjects did not guessed the positions of the obstacle, are coloured blue.
The image shows the different obstacle positions all at once (the image of the Lichtschleuse is representative for each of the three approaches).



approaches described in section 3.1.2 make the obstacles within this area visible.
Therefore, the obstacles No. 3–15 on the left side of the tunnel are used again (see page 62 (row A)) for the 2nd phase of the experiment. Additionally, two new rows (row B and row C) of obstacles are introduced. The positions of these obstacles are crosswise the same as the positions of the obstacles mentioned before (No. 3-15[121] on the left side). However, the positions are lengthwise different: the second row of obstacles (row B) is placed 1.5 m next to the left tunnel wall and the third row (row C) is placed 2.5 m next to the tunnel wall.

The reason for incorporating row B and row C is to investigate whether obstacles, which are standing further away from the tunnel wall, can be detected by the driver. Row C is located in the centre of the lane; therefore, it represents motorised traffic (such as cars). Row B represents a 'threshold area', in which both motorised and non-motorised traffic can be found: a cyclist, for instance, might overtake a pedestrian, and scooters tend to drive closer to the edge of a lane.
Obstacles No. 4, 5, 13 and 14 are not incorporated in row B and row C.
The detection rate during the first phase of the experiment dropped at these positions, but it was not 0 %. The experiment focusses on the 'hard' positions to keep the duration of the experiment as short as possible. Otherwise it might happen that the subjects are bored during the experiment, and this might affect their attention.
Although every obstacle of row B and row C can partly be seen against the exit aperture (and hence are supposed to be detected by the driver), it needs to be examined whether the light, which is emitted by the three different lighting approaches, alters the visibility of the obstacles. Especially the *Lichtschleuse* changes the luminance contrast between an obstacle and the exit aperture, since it lights the walls/road and hence it also lights everything what is located between the walls/road and the light emitting luminaires. Consequently, it might happen that the *Lichtschleuse* lowers the luminance contrast between an obstacle and the exit aperture. Moreover, it might happen that the luminance

121 Obstacles No. 4, 5, 13 and 14 were left out.

contrast between the obstacle and the bright areas of the *Lichtschleuse* itself is not sufficient.
Furthermore, five obstacles in the centre of the tunnel and five obstacles on the right side of the tunnel are introduced. The reason of incorporating these obstacles was to prevent that the subjects focus exclusively on the left lane of the tunnel during the experiment. Moreover, by doing so it is revealed whether a subject really detected a subject or just guessed. Positions are determined, where the obstacles can easily be detected, to make sure that the reasons for undetected obstacles in the centre or on right side are inattention or guesswork.

3.2 Experiment Procedure

This section deals with the experiment procedure. The first subsection gives information about the subjects, and the second subsection is about the presentation of the simulated images and the task of the subjects.

3.2.1 The subjects

Both men and women participated in the experiment. The subject’s age ranged from 25 to 69 years in the first phase of the experiment, and from 24 to 50 years in the second phase. A total of six subjects participated in the first phase, and all in all 13 subjects participated in the second phase. The subjects’ nationalities were British, Indian, Taiwanese, Australian, Irish, German, Greek, Polish and Danish.
All subjects have a driver license. Therefore, it can be assumed that they are familiar with driving a vehicle. Consequently, they were able to observe the presented tunnel in an appropriate way.
The total number of six subjects in the first phase was regarded as sufficient because the results were fairly consistent (see section 4.1). However, the number of subjects was more than doubled in the second phase of the experiment to obtain a more meaningful result.

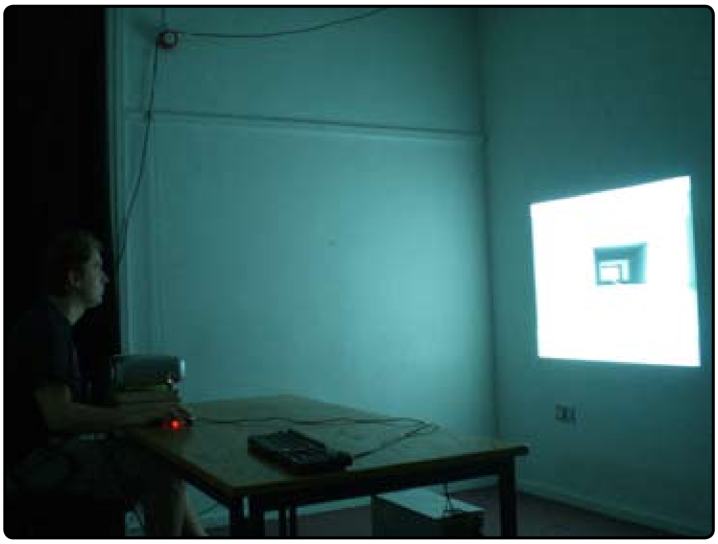


Figure 29: A subject participates in the experiment.

Figure 30: A subject participates in the experiment.

3.2.2 Presentation of the simulated images & and the task of the subject

The experiment was conducted in a windowless room in the basement of the “Wates House” (University College London).

The images, which had been simulated to analyse the tunnel and to investigate the properties of the three lighting approaches, were presented to the subject using a projector (see figures 29-30). A projector was used to effectuate that the distance between the subject and the presented image is as accurate as possible. The view angle of the simulated image is 20°. Therefore, the distance between the subject and the displayed image has to be 2.83 times the height of the displayed image to match this view angle.

If a screen, whose height is (for instance) 21 cm, were used, the required distance would be 56.6 cm. However, if the subject changed the position of his head just a little under this condition, the view angle would change significantly. Therefore a projector was used instead of a screen.

The size of the presented image was determined as big as possible to prevent that head movements of the subject make a significant impact on the view angle. The nature of the room allowed for an image seize of 108.5 x 81.5 cm. Consequently, the subject was sitting 2.3 m far from the displayed image (see figure 29).

The luminaires in the test room were switched off during the experiment – the

subject perceived solely the light emitted by the projector. The experiment normally took between 35 and 50 minutes, depending on the subject's pace and on the phase of the experiment.
201 images were presented in the first phase of the experiment and 267 images were presented in the second phase.

The presentation of each obstacle consisted of five steps:

<u>First</u>, the subject saw the empty tunnel and a command button in the right top corner of the screen (see figure 31). The subject was asked: "Are you ready?". As soon as the subject was ready, he/she needed to confirm this by pressing the "Ok"-button, which was located underneath the question "Are you ready?". The subject could take a break at this point – the time required for preparation didn't influence the procedure of the experiment and it was not taking into account in the analysis of the results. The command button was located in the right top corner of the screen to avoid that the exit aperture is covered by it. This would have affected the adaptation state of the subject significantly.
<u>Second</u>, the command button disappeared (see figure 32) and the subject saw merely the empty tunnel. The duration of this step varied between 1 and 3 seconds. By doing so, it prevented the subject from predicting the moment when the obstacle flashed up, since this would not comply with a real situation on a road.
<u>Third</u>, the obstacle flashed up for 300 ms (see figure 33). The sequence of presented obstacle positions was randomised to prevent the subject recognising a pattern, and hence foreseeing the upcoming position of the obstacle. Sometimes an empty tunnel was presented at this point. This blank image was incorporated to check that the subject really saw the obstacles – otherwise he/she might just have guessed.
<u>Fourth</u>, the obstacle disappeared, and the subject saw an empty tunnel (see figure 34). This step was randomised and took between 0.5 and 2.5 seconds (the random numbers of the second and fourth step were independent).
<u>Fifth</u>, the subject saw a command button in the right top corner of the screen (see figure. 35). The subject was asked: "Please click the appropriate button".

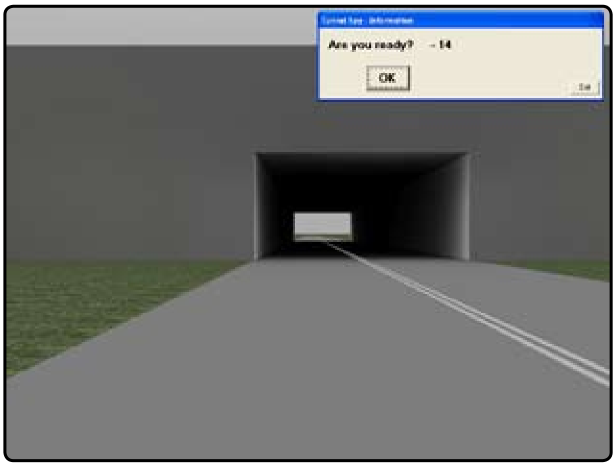


Figure 31: Step 1

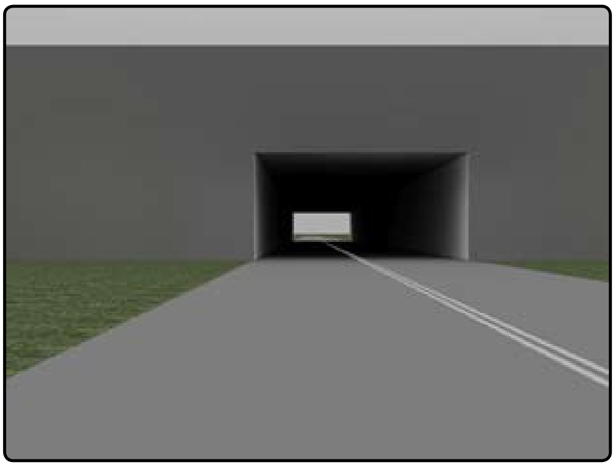


Figure 32: Step 2

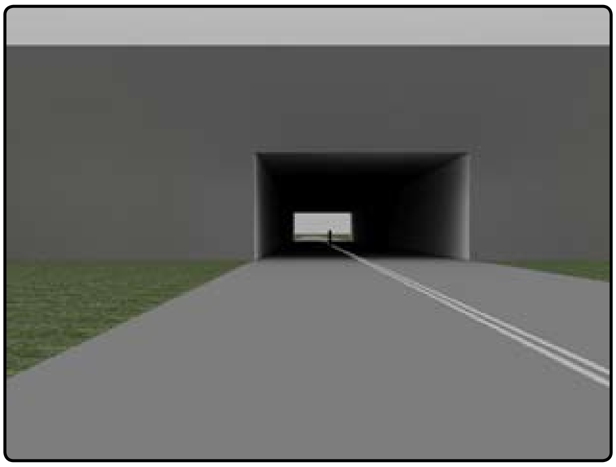


Figure 33: Step 3

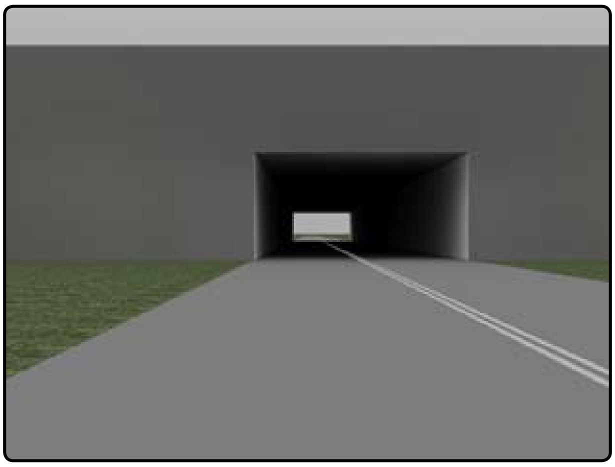


Figure 34: Step 4

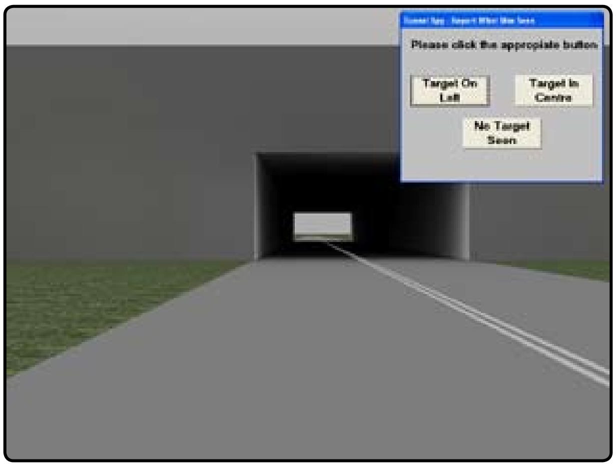


Figure 35: Step 5

The five steps of the presentation of an obstacle

He/she was given several choices to answer:
In the first phase of the experiment, the subject could answer “Target On Left” or “Target In Centre” or “No Target Seen”. “Target On Left” was supposed to be pushed, if an obstacle was detected on the left side of the left lane. “Target In Centre” was supposed to be pushed, if an obstacle was detected to the left of the centre line (but fairly close to the centre line).
In the second phase of the experiment, the subject could answer “Target On Left” or “Target On Right” or “No Target Seen”. “Target On Left” was supposed to be pushed, if an obstacle was detected on the left lane – this included every obstacle of row A/B/C and the obstacles right next to the centre line. “Target On Right” was supposed to be pushed, if an obstacle was detected on the right lane (these obstacles were standing close to the right margin of the left lane).
It was easy to assign the position of the obstacle to the correct button, since the distance between the obstacles referring to one button and the obstacles referring to the other button was fairly large.

The five steps described above appeared to the subject in a sequence. Consequently, if an empty tunnel was presented, the subject didn’t recognise any change during the second, third and fourth step.
The subject was asked by a command button to take a one minute break after every sequence of 20 obstacle positions. By doing so, it was avoided that eyestrain would affect the performance.
Each image (except the empty ones) was presented twice. By doing so, the result becomes more meaningful: Assuming that 10 subjects participate in the experiment and one of them would not detect an obstacle. If each obstacle were presented only once, the percentage of detection would be lowered by 10 %. However, if each obstacle were presented twice, the percentage of detection would be lowered by only 5 %.
The answers of the subjects were recorded automatically as a text file.
The subjects sometimes pushed accidently the wrong button. Therefore, they had the possibility to note this on a sheet of paper. These notes were taken into account by evaluating the answers.

4.0 Results of the experiment

In this section, the results of the two phases of the experiment will be presented and analysed. Therefore, this section is divided into two subsections. Each of them deals with one phase of the experiment respectively. These two subsections are again subdivided into several subsections.
The results of the experiment are generally shown as graphs. However, the detection rate of images, which were simply presented to check that the subjects did not guessed the positions of the obstacle[122], are just stated, since their exact position is not essential. The detailed answers of each subject can be found in Annex A.
The results of the subjects were fairly equal - it didn’t happen that one of the subjects performed extraordinarily better or worse than the others.
The y-axis of the graphs shows the percentage of detection of all subjects added together, the x-axis shows the distance between tunnel entrance and obstacle.

4.1 Results phase 1

This section deals with the results of the first phase of the experiment. It contains the results of the appraisal of the unobstructed unlit tunnel (phase 1.1) and of the unlit tunnel, whose exit is obstructed (phase 1.2).
Six subjects participated in the first phase of the experiment.
If an obstacle was once not detected during the first phase (1 out of 12), this lowered the percentage of detection by 8.33 %.

4.1.1 Presentation of results - unlit tunnel

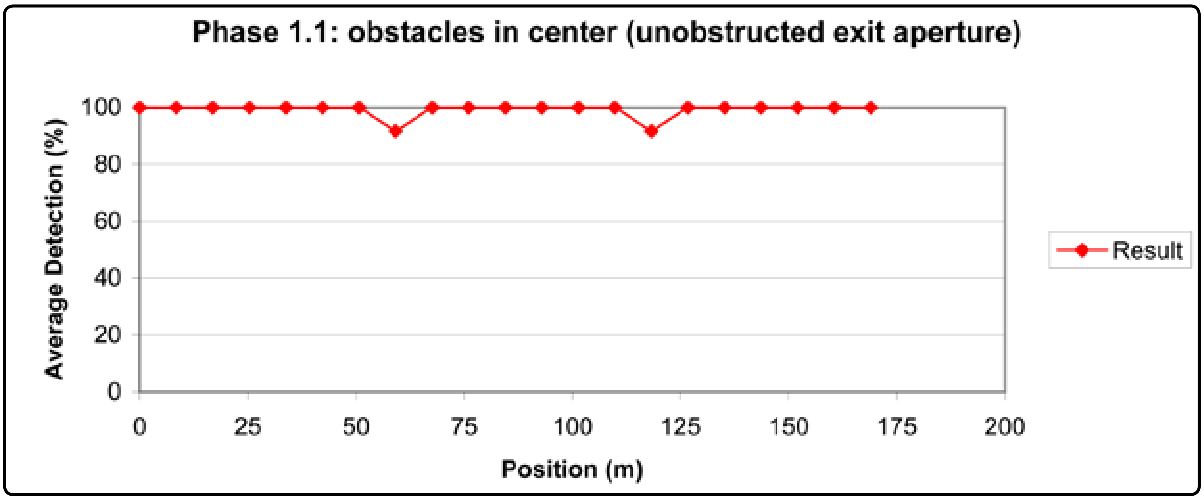
First, the results of the unobstructed tunnel will be presented and afterwards the results of the obstructed tunnel.

122 These are the empty images, and the images showing obstacles No. 1-2 (left side) in phase 1.2, and the obstacles in the centre (No. 0, 5, 10, 15, 20) and on the right side (No. 0, 1, 2, 19, 20) in phase 2.

4.1.1.1 Unlit tunnel - unobstructed

The empty image was 26 times presented to each of the observers in phase 1.1 of the experiment. Since six subjects participated, the empty image was altogether presented 156 times. The subjects detected this image 153 times.

The detection rate of the obstacles in the centre line of the unobstructed tunnel is shown in graph 7. The rate of detection is for almost every position 100 %. At two positions, the percentage decreases slightly to 91.6 %



Graph 7: Results of phase 1.1 of the experiment (row in centre)

The rate of detection of the obstacles on the left side of the unobstructed tunnel is shown in graph 8. The detection rate of the first 16.9 m behind the entrance is 100 %. At 16.9 m the rate of detection starts to drop sharply: 50.7 m behind the entrance it is 0 %. From 50.7 m to 101.4 m the detection rate does not exceeds

Graph 8: Results of phase 1.1 of the experiment (row on left side)

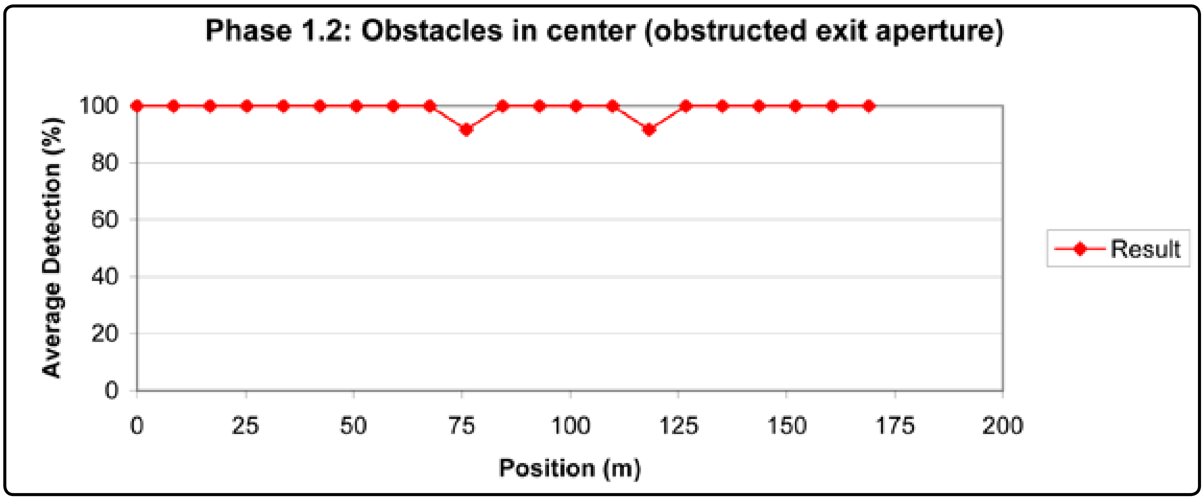
8.3 %. 101.4 m behind the entrance the graph starts rising significantly. From 118.3 m to 169 m the graph does not drop below 83.3 %.

.4.1.1.2 Unlit tunnel – obstructed

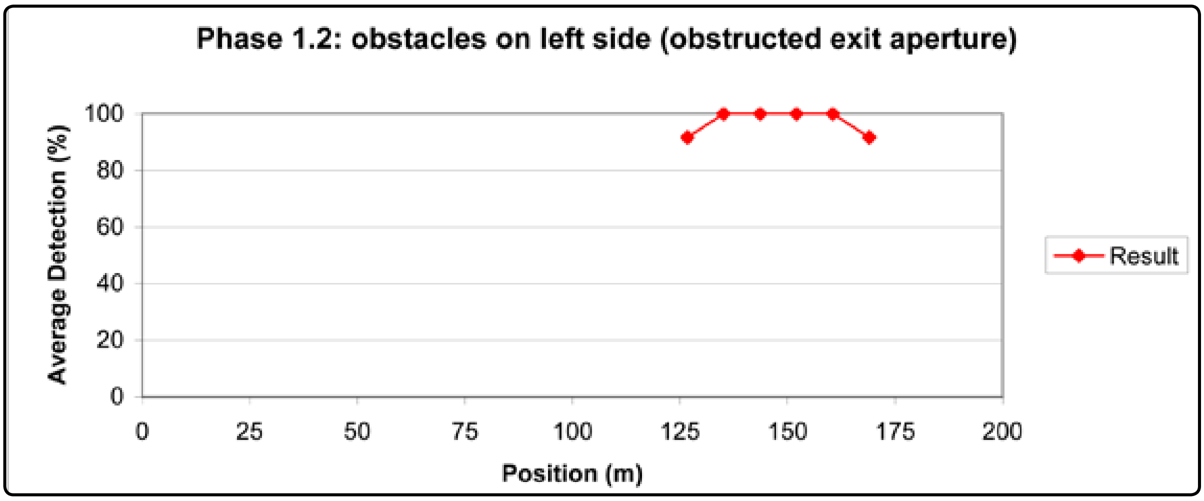
The empty image was 32 times presented to each of the observers in phase 1.2 of the experiment. Since six subjects participated, the empty image was altogether presented 192 times. The subjects detected this image 190 times. Obstacle No. 0-2 was presented twice to each subject. All of these obstacles were detected by each of the subjects.

The rate of detection of the obstacles in the centre line of the obstructed tunnel is shown in graph 9. The rate of detection is for almost every position 100 %. At two positions, the percentage decreases slightly to 91.6 %.

The rate of detection of the obstacles on the left side of the obstructed tunnel is



Graph 9: Results of phase 1.2 of the experiment (row in centre)



Graph 10: Results of phase 1.2 of the experiment (row on left side)

shown in graph 10. The rate of detection is at four positions 100 % and at two positions 91.6 %.

4.1.2 Analysis of results - unlit tunnel

For this phase of the experiment, 'sufficient visibility' of a target is defined as a detection rate of higher or equal 80 %. If a student conducts an experiment for more than 30 minutes and observes more than 200 images during that time, it might easily happen that he/she is distracted or inattentive at some of them – especially, since each obstacle is merely shown for 300 ms.
The detection rate of images, which were simply presented to check that the subjects did not guessed the positions of the obstacle[123], was fairly high in both phase 1.1 and phase 1.2. Therefore, it can be assumed that the subjects really saw the obstacles, which they indicated as detected.

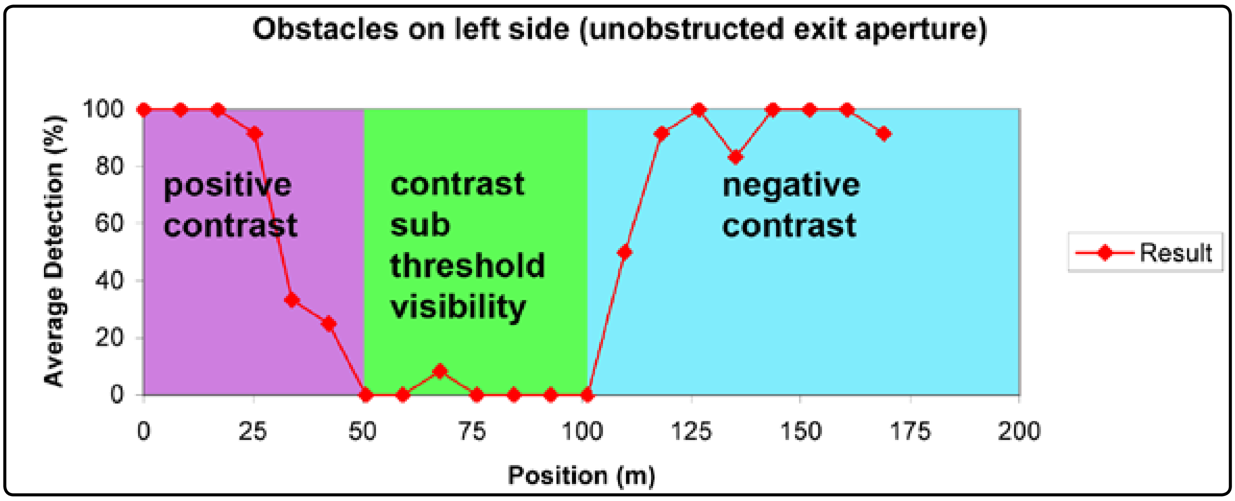
Phase 1.1 (unlit tunnel: unobstructed exit aperture):
The graphs of the unobstructed tunnel show clearly that the position of the rows within the tunnel makes a significant impact on the visibility of the targets. Every obstacle of the row in the centre was sufficiently visible, whereas several obstacles of the row on the left side were not detected at all.
All of the obstacles of the row in the centre are at least partly visible in negative contrast against the exit aperture. Furthermore, some of the first obstacles of this row (close to the entrance) are partly visible in positive contrast against the road, since they are lit by daylight.
The invisibility of several obstacles of the row on the left side can be explained as follows:

> Some obstacles, which are close to the entrance, are visible in positive contrast against the road and the wall due to daylight (see graph 11 & page 75-77). The bigger the distance between the obstacle and the entrance, the lower the positive contrast, because the daylight factor decreases[124]. From 50.7 m to 101.4 m the obstacles were generally

123 These are the empty images, and the images showing obstacles No. 1-2 (left side).
124 The daylight factor in the middle of the road (measured 0 m above the road) having the

not detected due to the low luminance values of the wall/road and the object. It is probable that the contrast is sub threshold visibility in this area of the tunnel. When the obstacles were at least partly visible against the exit aperture (at the end of the row), the subjects detected them in negative contrast.

Since the exit aperture of the analysed tunnel covers the fovea just sufficiently



Graph 11: Interpretation of the results of phase 1.1 of the experiment (row on left side)

(and hence, the tunnel is a limiting case), it can be assumed that tunnels, which are only used by motorised vehicles (which tend to travel in the middle of the road), don't need to be lit artificially. This demonstrates that the value for the through-view quotient in the current British Standard is misleading: the through-view quotient of the analysed tunnel is 15. 5 % - but in accordance to the British Standard it needs to be lit, since the through-view quotient is less than 20 %.

However, if a tunnel is used by pedestrians and cyclists, it might happen, that they are not visible against the exit aperture but against the wall and the road. If a tunnel is relatively long (but still regarded as a 'short' tunnel) it can be assumed that the daylight factor is not sufficient at several positions within the tunnel to make the pedestrian/cyclist visible.

same distance as obstacle No. 2 was 0.5 %, No. 3 was 0.2 %, No. 4 was 0.1 %, No. 5 was 0.1 % and No. 6 was 0 %.

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Phase 1.1: row of obstacles on left side (unobstructed exit) - page 1
(the position of the obstacle is stated in the left top corner of each image)


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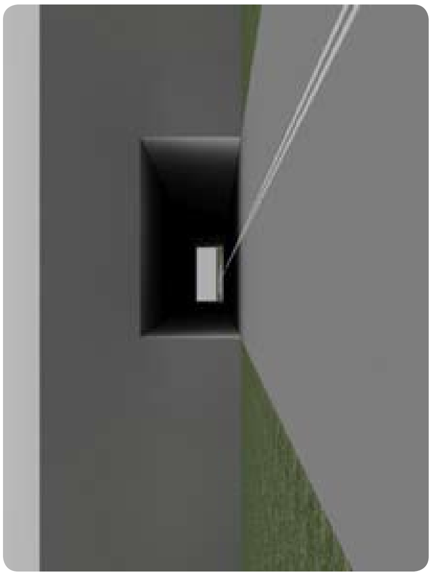
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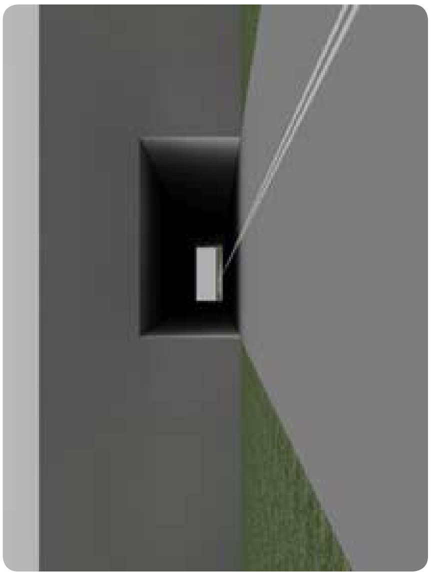
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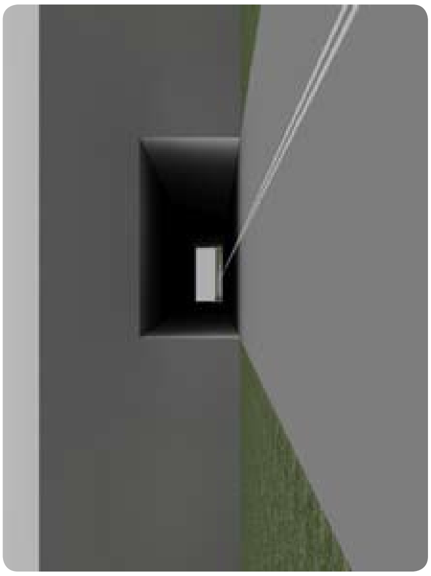
Phase 1.1: row of obstacles on left side (unobstructed exit) - page 2



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Phase 1.1: row of obstacles on left side (unobstructed exit) - page 3

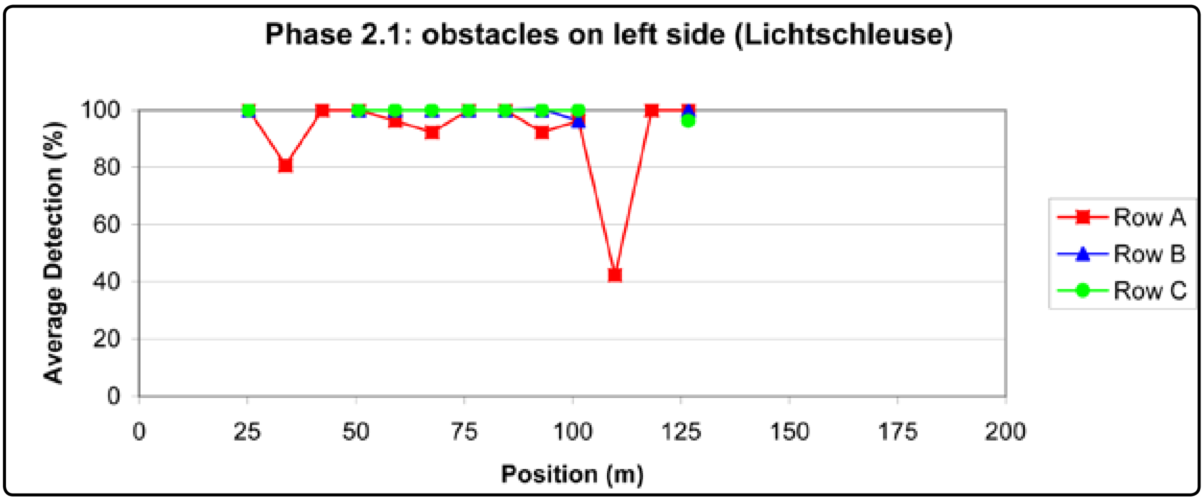
Phase 1.2 (unlit tunnel: obstructed exit aperture):
The detection rate of the obstacles presented in the obstructed tunnel (phase 1.2) was not significantly different than the ones presented in the unobstructed tunnel. The minimum percentage in the obstructed tunnel is not even lower than the minimum percentage in the unobstructed tunnel. Therefore, it can be said that the silhouette effect does not only operate if the sky is overcast but also if the exit aperture is obstructed (as long as the reflectance of the obstructing object is at least 20 %, and the surface is an Lambertian diffuser, and the obstructing object is not significantly obstructed by another object (since this would result in lower amount of received daylight)).

4.2 Results phase 2

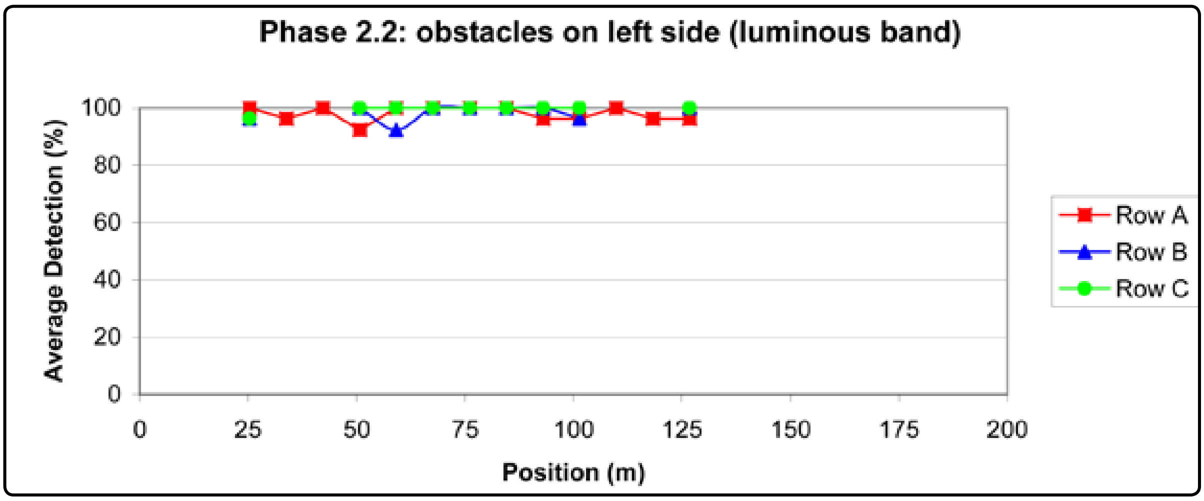
This section deals with the results of the second phase of the experiment. It contains the results of the appraisal of the applied *Lichtschleuse* (phase 2.1), the luminous band (phase 2.2) and the tree LED-strips (phase 2.3).
13 subjects participated in the second phase of the experiment.
If an obstacle was once not detected during the second phase (1 out of 26), this lowered the percentage of detection by 3.84 %.

4.2.1 Presentation of results - lit tunnels

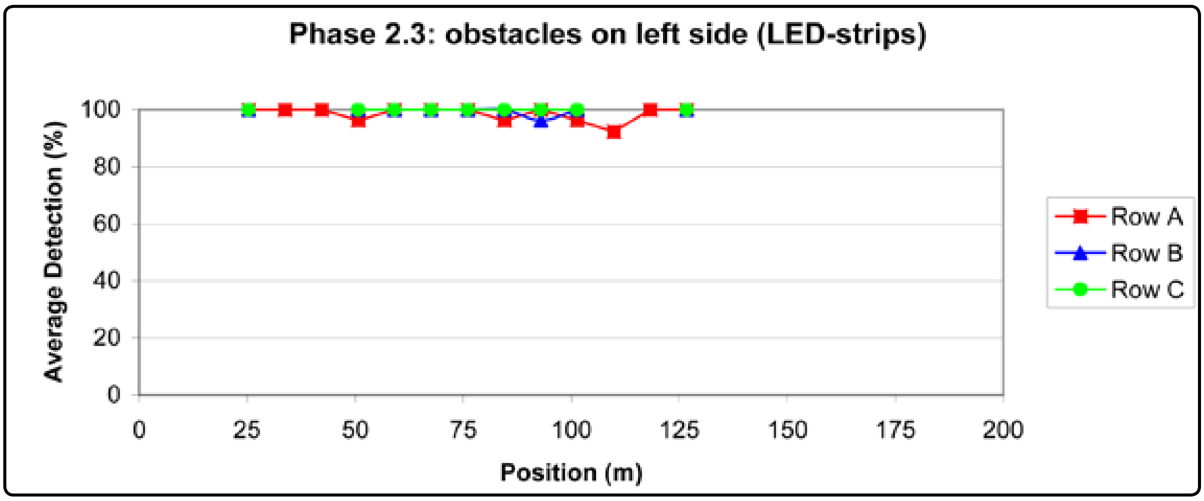
The empty image was 21 times presented to each of the observers in phase 2 (overall in phase 2.1, 2.2 and 2.3) of the experiment. Since 13 subjects participated, the empty image was altogether presented 273 times. The subjects detected this image 268 times.
Each of the obstacles of the row on the right side (No. 0-2 & No.19-20) and in the centre (No. 0, 5, 10, 15, 20) was presented twice. Altogether they were presented 260 times. The subjects detected these images 256 times.
First, the results of the applied *Lichtschleuse* will be presented and afterwards the results of the applied luminous band and the three LED strips.



Graph 12: Results of phase 2.1 of the experiment



Graph 13: Results of phase 2.2 of the experiment



Graph 14: Results of phase 2.3 of the experiment

4.2.1.1 Lit tunnel - *Lichtschleuse*

The detection rate of the obstacles of row A, row B and row C, which are lit by the *Lichtschleuse*, is shown in graph 12.
The graph representing row B and C never drops below 96.2 %.
The graph representing row A does not drop below 92.3 % at most of the positions. However, 33.8 m behind the entrance the detection rate drops to 80.8 %, and 109.8 m behind the entrance it drops to 42.3 %.

4.2.1.2 Lit tunnel - luminous band

The detection rate of the obstacles of row A, row B and row C, which are lit by the luminous band, is shown in graph 13.
The graph representing row C never drops below 96.2 %.
The graph representing row A and row B does not drop below 92.3 %.

4.2.1.3 Lit tunnel - three LED strips

The detection rate of the obstacles of row A, row B and row C, which are lit by three LED strips, is shown in graph 14.
The graph representing row A does not drop below 92.3 %.
The graph representing row B never drops below 96.2 %.
The graph representing row C never drops below 100%.

4.2.2 Analysis of results – *Lichtschleuse*, luminous band & three LED strips

For this phase of the experiment, ‘sufficiently visibility’ of a target is defined as a detection rate of higher or equal 80 % (for the same reason as given in section 4.1.2).
The detection rate of images which were simply presented to check that the

subjects did not guessed the positions of the obstacle[125] was fairly high in phase 2. Therefore, it can be assumed that the subjects really saw the obstacles, which they indicated as detected.

Lichtschleuse:

The obstacles of row B and row C are sufficiently visibility when lit by the *Lichtschleuse* – their detection rate does not drop below 96.2 %. Most of the obstacles of row A are also sufficiently visible (≥ 92.3 %)**.** But the detection rate of two obstacles of row A is significantly lower than the detection rate of the others: the detection rate of the obstacle standing 33.8 m (No. 4) behind the entrance is 80.8 %, and the detection rate of the obstacle standing 109.8 m (No. 13) behind the entrance is 42.3 %. However, as mentioned in section 3.1.2.1, it was accepted that not every obstacle can be seen in its entirety against the *Lichtschleuse* – the intention was to investigate how the visibility of the obstacles decreases when an obstacles 'moves' out of the *Lichtschleuse*. And this is what happens at these two positions: the obstacles standing 33.8 m and 109.8 m behind the entrance can not be seen in its entirety against the Lichtschleuse (see pages 82-83) – consequently, if the *Lichtschleuse* were designed longer, (it can be assumed that) these obstacles would be visible. The obstacle standing 33.8 m behind the entrance is mentioned above, although it is sufficiently visible (80.8 %) - however, also this obstacle demonstrates the interrelation between visibility and *Lichtschleusen* length.

It is worth emphasising what happens 84.5 m (No. 10), 92.95 m (No. 11) and 101.4 m (No. 12) behind the entrance: the obstacles can also not be seen in its entirety against the *Lichtschleuse* but against the dark part of the wall between the *Lichtschleuse* and the exit. However, they are sufficiently visible because they appear in positive contrast against the wall. This is due to the light emitted by the *Lichtschleuse*. It was taken into account that the *Lichtschleuse* lowers the luminance contrast between an obstacle and the exit aperture, furthermore, that the luminance contrast between an obstacle and the bright areas of the *Lichtschleuse* itself might be too low. However, in these cases the luminance contrast between obstacles and the wall is increased by the *Lichtschleuse* – it is

125 These are the empty images, and the obstacles in the centre (No. 0, 5, 10, 15, 20) and on the right side (No. 0, 1, 2, 19, 20).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Phase 2.1: row A of obstacles on left side *(Lichtschleuse)* - page 1
(the position of the obstacle is stated in the left top corner of each image)


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Phase 2.1: row A of obstacles on left side *(Lichtschleuse)* - page 2 a <u>positive contrast</u>. Further research may investigate how this additional effect can be taking into account for the application of the *Lichtschleuse* – it may lower the required energy.

S*upplemental daytime lighting* (average luminance of 15 cd/m² along the whole road) was not provided – nevertheless, the obstacles were sufficiently visible. Therefore, it seems that the *Lichtschleuse* works generally without s*upplemental daytime lighting*.

It has been shown that the *Lichtschleuse* improves significantly the visibility of obstacles in short tunnels: the detection rate of all the obstacles, <u>which can be seen in its entirety against the *Lichtschleuse*</u>, is higher or equal 92.3 %. According to this result, it can be said that the *Lichtschleuse* is an appropriate means to light short tunnels during daytime.

Luminous band:

The results show that the luminous band improves significantly the visibility of obstacles in short tunnels: the detection rate of every position tested is higher or equal 92.3 %. This value exceeds by far the minimum value of 80 %. According to this result, it can be said that the luminous band is an appropriate means to light short tunnels during daytime.

LED strips:

The results show that the three LED strips improve significantly the visibility of obstacles in short tunnels: the detection rate of every position tested is higher or equal 92.3 %. As stated before, this value exceeds by far the minimum value of 80 %. According to this result, it can be said that the three LED strips mounted on the tunnel wall constitute an appropriate means to light short tunnels during daytime.

<u>Comparison</u>:

None of the three lighting approaches performed significantly better than the others[126]. The detection rate varies slightly at different positions, but it is assumed that this is caused by some inattention of the subjects, since the results show no patterns which may be related to the features of the three approaches. It may be that the detection rates of the obstacles, which are lit by the *Lichtschleuse,* also vary because the luminance contrast between the obstacles and the *Lichtschleuse* varies (see page 82: position 5-9).

There is a tendency that the obstacles of row B and row C (of every approach) are slightly more visible than the obstacles of row A. However, every obstacle of row B and C is visible against the exit aperture and phase 1.1 (centre row) revealed that obstacles at those positions are even visible if the tunnel is unlit. The objective of incorporating row B and C was to investigate whether the light emitted by the luminaires of the *Lichtschleuse*, the luminous band and LED strips lowers the luminance contrast between the obstacles and the exit aperture to such a degree that they become invisible. However this experiment showed that this does not happen.

126 However, the *Lichtschleuse* is rather suitable for motorised traffic tunnels than for mixed traffic tunnels. As described in section 3.1.2.1 & section 3.1.2.2, the *Lichtschleuse* needs to be 96 m long to make the undetected obstacles completely visible against it. This lighting approach tends to consume too much energy, if applied in mixed traffic tunnels.

Conclusion

One of the main disadvantages of the current British Standard are the requirements for artificial lighting of short tunnels during daytime: it is an ‘all or nothing’-approach: tunnels of length between 25 m and 200 m either don’t need to be lit at all or they need to be exactly treated as ‘long’ tunnels - there is no ‘middle course’.
It has been shown that the progress of research about ‘short’ tunnel lighting during daytime has not been linear - in several cases, the research was not based on previous findings. However, a revision of the research papers about short tunnel lighting revealed that bright luminance patterns on the tunnel walls may serve as an appropriate daytime lighting for short tunnels. Therefore, three different lighting approaches, which were based on the idea of creating luminance patterns on the wall, were tested by means of an experiment: the *Lichtschleuse*, a luminous band and LED strips. The experiment revealed that each of these three lighting approaches constitute an appropriate mean to light short tunnels. However, further research is required to answer additional questions which are related to these approaches.

It may be argued that the methodology of this research is inappropriate, since it is based on images, which are simulated and presented by a computer. Certainly, the simulated images do not constitute an exact copy of what a driver would see in real situations. Especially the dynamic range is a problem: a screen or a projector does by far not produce luminance values, which someone normally encounters under the real sky dome during daytime. As mentioned in section 3.1, the computer monitor gamma factor even needed to be changed for the simulation of the *Lichtschleuse* to counter problems with the dynamic range. However, this methodology seems to be the most appropriate with respect to the technology currently available and the time frame of this research. Furthermore, the rate of detection of each obstacle of each lighting approach was much higher than required to be regarded as ‘sufficiently visible’ – therefore, even if the visibility of the obstacles would be slightly worse in a real situation, it is likely that they would still be ‘sufficiently visible’.

It is worth emphasising that the basic principles of the lighting approaches tested in this final report were already described in the very first research paper, which dealt with the lighting of short tunnels during daytime: Lossagk (1955) demonstrated the effect of a stripe on the tunnel wall composed of white tiles. Furthermore, he mentioned specular rails. These two proposals are similar to the luminous band and the LED strips. Moreover, he recommended creating a cross strip composed of light – *the Lichtschleuse*.

Nowadays, LED technology makes it possible to achieve easily the effect intended by Lossagk: creating bright luminance patterns on the tunnel walls so that obstacles can be seen as silhouettes against them.

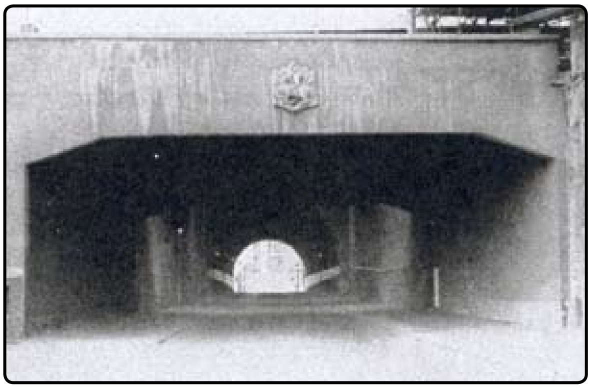

Figure 36: Lossagk 1955
(Source: Lossagk H. 'Sehsicherheit bei Tageslicht in Unterführungen'. Lichttechnik, Vol 7, No 2 (1955) p51.)

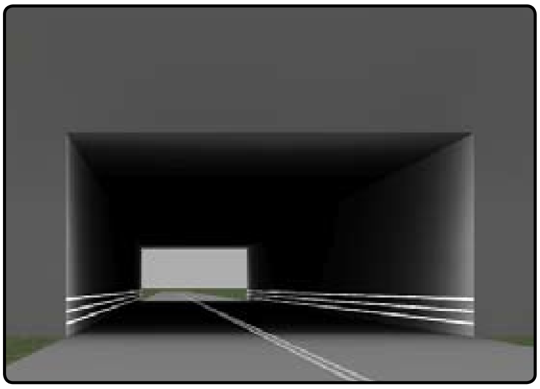

Figure 37: Kretzer 2009

The findings of this research may lead to the following refinement of the current British Standard about short tunnel lighting during daytime:

The tunnel is regarded in front of the tunnel entrance from a distance equal to the stopping distance, in the middle of the lane, 1.2 m above the road (if there are several lanes, the tunnel needs to be regarded for every lane separately):

1. If the exit aperture covers the fovea, step 2 is applied. If the exit aperture does not cover the fovea, the tunnel is treated as a 'long' tunnel.
2. If the tunnel is a mixed traffic tunnel, an obstacle representing a pedestrian is placed 0.5 m next to the left edge of the lane, along the whole tunnel (foreshortening needs to be taken into account). If the tunnel carries only motorised traffic, an obstacle representing a car

has to be placed in the middle of the lane[127] (foreshortening needs to be taken into account). If the tunnel carries an emergency lane, an obstacle representing a pedestrian is placed 0.5 m next to the edge of the emergency lane, along the whole tunnel (foreshortening needs to be taken into account).

3. If the obstacles are visible against the exit aperture (at every position from the beginning to the end of the tunnel), the tunnel does not need artificial lighting. If they are not visible against the exit aperture, the tunnel needs to be lit either by the *Lichtschleuse* or by a luminous band[128] or by the three LED stripes (see section 3.1.2). The choice depends on the geometry of the tunnel and on the traffic composition[129].

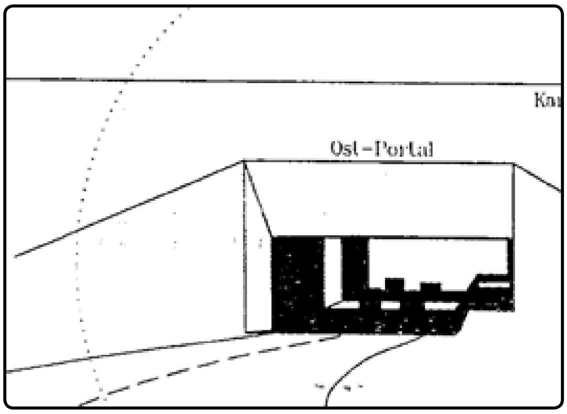

Figure 38: Drawing of a tunnel having a vertical curve (lit by a *Lichtschleuse*) in Olfen-Selm (Germany): obstacles can be seen against the *Lichtschleuse*
(Source: Eberbach K. 'Lichtschleusen: Beleuchtung kurzer Tunnel', in: Tagungsband zur Sondertagung 'Aktuelles zur Tunnelbeleuchtung' der Bundesanstalt für Straßenwesen BAST und der Lichttechnischen Gesellschaften Deutschlands, Österreichs, der Niederlande und der Schweiz am 23. 9. 1999. LitG, Bergisch Gladbach (1999) p31.)

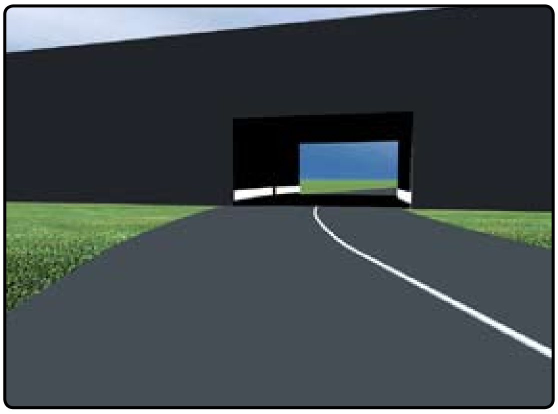

Figure 39: A luminous band or Led Strips are also applicable if a tunnel is a mixed traffic tunnel and/or this tunnel has a horizontal curve

127 A sign in front of the tunnel should ask motorised vehicles, which tend to drive close to the edge of the lane (e.g. scooters), to drive in the middle of the lane.

128 The luminous band does not necessarily need to be recommended, since it consumes more energy without performing better than the three LED strips.

129 A *Lichtschleuse* is particularly useful if a tunnel has a vertical curve, since also a part of the road is lit (in a tunnel having a vertical curve, it may happen that the road forms the background of an obstacle (see figure 38)). The length and position of the *Lichtschleuse* depends on the tunnel geometry.
A luminous band or Led Strips are particularly useful if a tunnel is a mixed traffic tunnel and/or a tunnel has a horizontal curve (see figure 39).

However, further research needs to be conducted to support this refinement. Several points could not be covered by this final report due to its timeframe. Especially the following points should be considered:

1. At present, a tunnel is assessed using a perspective illustration of it, which is derived at a distance (in front of the tunnel) equal to the stopping distance, 1.2 m above the road. The target used to investigate the visibility of obstacles is greater than 0.2 m.
As mentioned before, it needs to be investigated whether it is reasonable to assume that a driver looks at this position into the tunnel. Furthermore, it needs to be discussed whether the driver's eye height of 1.2 m (regarding lorries) and the target size are appropriate.

2. It needs to be investigated which minimum luminance value is required for the *Lichtschleuse*, the luminous band and the LED strips.

3. It seems to be useful to treat 'short' tunnels, which are barely used, in a special way. If there is (for example) a tunnel on the countryside, which is used by three vehicles per hour, it is questionable whether this tunnel needs to be lit all day long. The CETU (2000) guide may serve as a starting point to develop a method for such situations.

4. It needs to be investigated what seize of retinal image must be obtained by an obstacle (which can be (partly) seen against the exit aperture) to be detected.

5. It needs to be investigated what daylight factor is required so that an obstacle is visible in positive contrast without being artificially lit or without being seen against the exit aperture. The daylight factors stated in section 4.1.2 may serve as a starting point.

6. The current British Standard requires limited daytime lighting for tunnels where the traffic flow is classified as "high". This is important, since it can

happen that a vehicle covers (partly) the exit aperture and another vehicle is standing behind the vehicle at the same time (see figure 40) - and it is therefore not visible. However, it needs to be investigated whether the recommended “night-time luminance” is sufficient for this purpose.

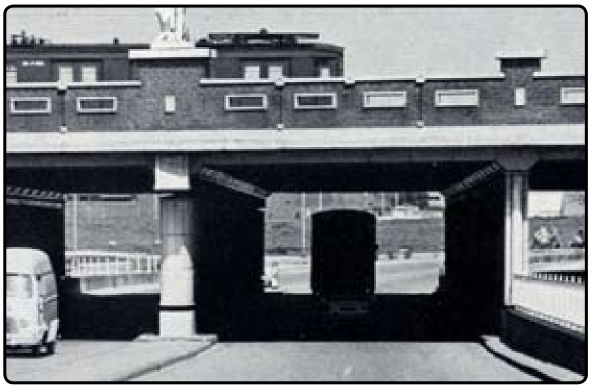

Figure 40: A lorry is covering the exit aperture while another car is driving behind it
(Source: Schreuder D A. ‘Short Tunnels’. International Lighting Review, Vol 16, No 3 (1965) p98.)

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Annex A

Annex A contains the results of each subject. The number of correct answers is listed. Each obstacle position was presented twice to each subject. The empty image in phase 1.1 was presented 26 times. The empty image in phase 1.2 was presented 32 times. The empty image in phase 2 was presented 21 times.

Key for phase 1:

CNB = row in centre – unobstructed exit
SNB = row on left side - unobstructed exit
NO-NB = no obstacle – unobstructed exit (empty image)

CWB = row in centre – obstructed exit
SWB = row on left side – obstructed exit
NO-WB = no obstacle – obstructed exit (empty image)

Key for phase 2:

LS-LA = Lichtschleuse – left side – row A
LS-LB = Lichtschleuse – left side – row B
LS-LC = Lichtschleuse – left side – row C
LS-C = Lichtschleuse – row in centre
LS-R00 = Lichtschleuse – row on right side

LB-LA = luminous band – left side – row A
LB-LB = luminous band – left side – row B
LB-LC = luminous band – left side – row C
LB-C = luminous band – row in centre
LB-R00 = luminous band – row on right side

LE-LA = LED strips – left side – row A
LE-LB = LED strips – left side – row B
LE-LC = LED strips – left side – row C
LE-C = LED strips – row in centre
LE-R00 = LED strips – row on right side

NO = no obstacle (empty image)

Results Phase 1

	Subject	1	2	3	4	5	6
	Age	**25**	**30**	**34**	**38**	**55**	**69**
	Gender	**M**	**M**	**F**	**M**	**M**	**M**
Position							
CNB00		2	2	2	2	2	2
CNB01		2	2	2	2	2	2
CNB02		2	2	2	2	2	2
CNB03		2	2	2	2	2	2
CNB04		2	2	2	2	2	2
CNB05		2	2	2	2	2	2
CNB06		2	2	2	2	2	2
CNB07		2	2	1	2	2	2
CNB08		2	2	2	2	2	2
CNB09		2	2	2	2	2	2
CNB10		2	2	2	2	2	2
CNB11		2	2	2	2	2	2
CNB12		2	2	2	2	2	2
CNB13		2	2	2	2	2	2
CNB14		2	2	2	1	2	2
CNB15		2	2	2	2	2	2
CNB16		2	2	2	2	2	2
CNB17		2	2	2	2	2	2
CNB18		2	2	2	2	2	2
CNB19		2	2	2	2	2	2
CNB20		2	2	2	2	2	2
SNB00		2	2	2	2	2	2
SNB01		2	2	2	2	2	2
SNB02		2	2	2	2	2	2
SNB03		2	2	2	1	2	2
SNB04		1	1	0	0	2	0
SNB05		1	1	0	1	0	0
SNB06		0	0	0	0	0	0
SNB07		0	0	0	0	0	0
SNB08		1	0	0	0	0	0
SNB09		0	0	0	0	0	0
SNB10		0	0	0	0	0	0
SNB11		0	0	0	0	0	0
SNB12		0	0	0	0	0	0
SNB13		1	1	1	1	0	1
SNB14		2	2	2	2	1	1
SNB15		2	2	2	2	2	2
SNB16		1	2	1	2	2	2
SNB17		0	2	2	2	2	2
SNB18		0	2	2	2	2	2
SNB19		0	2	2	2	2	2
SNB20		1	2	2	2	2	2
NO-NB		25	24	26	26	26	26
CWB00		2	2	2	2	2	2
CWB01		2	2	2	2	2	2
CWB02		2	2	2	2	2	2
CWB03		2	2	2	2	2	2

CWB04		2	2	2	2	2	2
CWB05		2	2	2	2	2	2
CWB06		2	2	2	2	2	2
CWB07		2	2	2	2	2	2
CWB08		2	2	2	2	2	2
CWB09		2	2	2	2	1	2
CWB10		2	2	2	2	2	2
CWB11		2	2	2	2	2	2
CWB12		2	2	2	2	2	2
CWB13		2	2	2	2	2	2
CWB14		2	1	2	2	2	2
CWB15		2	2	2	2	2	2
CWB16		2	2	2	2	2	2
CWB17		2	2	2	2	2	2
CWB18		2	2	2	2	2	2
CWB19		2	2	2	2	2	2
CWB20		2	2	2	2	2	2
SWB15		2	2	2	2	1	2
SWB16		2	2	2	2	2	2
SWB17		2	2	2	2	2	2
SWB18		2	2	2	2	2	2
SWB19		2	2	2	2	2	2
SWB20		1	2	2	2	2	2
NO-WB		32	32	31	31	32	32

Results Phase 2

	Subject	1	2	3	4	5	6	7	8	9	10	11	12	13
	Age	**24**	**24**	**25**	**26**	**26**	**27**	**28**	**29**	**30**	**30**	**31**	**47**	**50**
	Gender	**F**	**M**	**M**	**F**	**F**	**M**	**F**	**F**	**M**	**F**	**M**	**M**	**M**
Position														
LS-LA03		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA04		2	2	2	2	2	2	2	2	0	2	2	1	0
LS-LA05		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA06		2	2	2	2	2	0	2	2	2	2	2	2	2
LS-LA07		2	2	2	2	2	2	1	2	2	2	2	2	2
LS-LA08		2	2	2	2	2	2	2	1	1	2	2	2	2
LS-LA09		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA10		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA11		2	2	2	2	2	2	2	2	1	2	2	2	1
LS-LA12		2	2	2	2	2	2	2	2	2	2	2	1	2
LS-LA13		2	2	2	1	0	1	0	1	0	1	0	0	1
LS-LA14		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA15		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA16		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA17		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA18		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA19		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LA20		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB03		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB04		-	-	-	-	-	-	-	-	-	-	-	-	-
LS-LB05		-	-	-	-	-	-	-	-	-	-	-	-	-
LS-LB06		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB07		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB08		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB09		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB10		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB11		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB12		2	2	2	2	2	2	2	1	2	2	2	2	2
LS-LB13		-	-	-	-	-	-	-	-	-	-	-	-	-
LS-LB14		-	-	-	-	-	-	-	-	-	-	-	-	-
LS-LB15		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB16		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB17		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB18		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB19		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LB20		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC03		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC04		-	-	-	-	-	-	-	-	-	-	-	-	-
LS-LC05		-	-	-	-	-	-	-	-	-	-	-	-	-
LS-LC06		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC07		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC08		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC09		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC10		2	2	2	2	2	2	2	2	2	2	1	2	2
LS-LC11		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC12		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC13		-	-	-	-	-	-	-	-	-	-	-	-	-
LS-LC14		-	-	-	-	-	-	-	-	-	-	-	-	-

LS-LC15		2	2	2	2	2	2	2	1	2	2	2	2	2
LS-LC16		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC17		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC18		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC19		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-LC20		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-C00		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-C05		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-C10		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-C15		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-C20		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-R00		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-R01		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-R02		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-R19		2	2	2	2	2	2	2	2	2	2	2	2	2
LS-R20		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA03		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA04		2	2	2	1	2	2	2	2	2	2	2	2	2
LB-LA05		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA06		2	2	1	2	2	2	2	2	1	2	2	2	2
LB-LA07		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA08		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA09		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA10		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA11		2	2	2	2	2	2	2	2	2	2	2	1	2
LB-LA12		2	2	2	2	2	2	2	2	2	2	2	1	2
LB-LA13		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA14		2	2	2	2	2	1	2	2	2	2	2	2	2
LB-LA15		2	2	2	2	2	2	2	2	2	2	2	2	1
LB-LA16		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA17		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA18		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA19		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LA20		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB03		2	2	2	2	2	2	2	1	2	2	2	2	2
LB-LB04		-	-	-	-	-	-	-	-	-	-	-	-	-
LB-LB05		-	-	-	-	-	-	-	-	-	-	-	-	-
LB-LB06		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB07		2	2	2	2	1	1	2	2	1	2	2	2	2
LB-LB08		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB09		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB10		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB11		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB12		2	2	2	2	2	2	2	1	2	2	2	2	2
LB-LB13		-	-	-	-	-	-	-	-	-	-	-	-	-
LB-LB14		-	-	-	-	-	-	-	-	-	-	-	-	-
LB-LB15		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB16		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB17		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB18		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB19		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LB20		2	2	2	2	2	2	2	2	2	2	2	2	2

LB-LC03		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC04		-	-	-	-	-	-	-	-	-	-	-	-	-
LB-LC05		-	-	-	-	-	-	-	-	-	-	-	-	-
LB-LC06		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC07		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC08		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC09		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC10		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC11		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC12		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC13		-	-	-	-	-	-	-	-	-	-	-	-	-
LB-LC14		-	-	-	-	-	-	-	-	-	-	-	-	-
LB-LC15		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC16		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC17		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC18		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC19		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-LC20		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-C00		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-C05		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-C10		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-C15		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-C20		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-R00		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-R01		2	2	2	2	2	1	2	2	2	2	2	2	2
LB-R02		2	2	2	2	2	2	2	2	2	2	2	2	2
LB-R19		2	2	2	2	2	2	2	2	1	2	2	2	2
LB-R20		2	2	2	2	2	2	2	2	1	2	2	2	2
LE-LA03		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA04		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA05		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA06		2	2	2	2	2	1	2	2	2	2	2	2	2
LE-LA07		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA08		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA09		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA10		2	2	2	2	2	1	2	2	2	2	2	2	2
LE-LA11		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA12		2	2	2	2	2	2	2	2	2	2	2	2	1
LE-LA13		2	2	1	2	2	2	1	2	2	2	2	2	2
LE-LA14		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA15		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA16		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA17		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA18		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA19		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LA20		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB03		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB04		-	-	-	-	-	-	-	-	-	-	-	-	-
LE-LB05		-	-	-	-	-	-	-	-	-	-	-	-	-
LE-LB06		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB07		2	2	2	2	2	2	2	2	2	2	2	2	2

LE-LB08		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB09		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB10		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB11		2	2	2	1	2	2	2	2	2	2	2	2	2
LE-LB12		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB13		-	-	-	-	-	-	-	-	-	-	-	-	-
LE-LB14		-	-	-	-	-	-	-	-	-	-	-	-	-
LE-LB15		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB16		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB17		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB18		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB19		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LB20		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC03		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC04		-	-	-	-	-	-	-	-	-	-	-	-	-
LE-LC05		-	-	-	-	-	-	-	-	-	-	-	-	-
LE-LC06		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC07		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC08		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC09		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC10		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC11		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC12		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC13		-	-	-	-	-	-	-	-	-	-	-	-	-
LE-LC14		-	-	-	-	-	-	-	-	-	-	-	-	-
LE-LC15		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC16		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC17		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC18		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC19		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-LC20		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-C00		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-C05		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-C10		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-C15		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-C20		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-R00		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-R01		2	2	2	2	1	2	2	2	2	2	2	2	2
LE-R02		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-R19		2	2	2	2	2	2	2	2	2	2	2	2	2
LE-R20		2	2	2	2	2	2	2	2	2	2	2	2	2
NO		21	21	21	21	20	20	21	20	20	21	21	21	20

Annex B

Annex B contains the sections of the British Standard *BS 5489-2:2003+A1:2008,* which deal with the daytime lighting of short tunnels. These are section 4.4, section 5.7 and Annex C.

4.4 Lighting for different tunnel lengths

Lighting design for long and short tunnels differs according to the degree to which an approaching driver can see through the tunnel to the exit portal from a point at a distance equal to the stopping distance in front of the entrance portal.

The ability of a driver to see through a tunnel depends primarily on the length of the tunnel, although other design parameters also have an effect (width, height, horizontal and/or vertical curvatures, etc.).

The critical factor is whether approaching drivers can see vehicles, other road users or obstacles when their distance from the entrance portal is less than or equal to the stopping distance *SD* (see **5.1**). When the exit portal is a large part of the scene visible through the entrance, other road users and objects can easily be seen silhouetted against the lighter scene behind the exit portal. On the other hand, artificial lighting is needed when the exit portal is in a relatively large dark frame, in which objects can be hidden. This can happen when a tunnel is relatively long in relation to width, or when a tunnel is curved in such a way that only a part of the exit can be seen or the exit cannot be seen at all.

Tunnels shorter than 25 m do not normally need daytime lighting. Tunnels longer than 200 m should always have artificial daytime lighting, to avoid adaptation problems for road users. For tunnels of length between 25 m and 200 m, the method described in Annex C should be used to determine if daytime lighting is needed. If full daytime lighting is needed, it should conform to the recommendations given in Clause **5**.

If full daytime lighting is not needed for tunnels of length between 25 m and 200 m, some limited daytime lighting can be provided for tunnels where the traffic flow is classified as "high" (see **5.2**), when luminance levels within the tunnel are low, and during the periods immediately before dusk and after dawn, particularly on overcast days. The decision to provide such limited daytime lighting is a matter for the highway authority.

NOTE The night-time lighting as described in **5.7** may be used for this purpose. It can be controlled by a photocell so that it is switched on when illuminance on the road surface at the centre of the tunnel falls to the value at which the external illuminance is used to switch on the access road lighting, and switched off when the illuminance at the centre of the tunnel increases to this level. Alternatively, a luminance meter can be used as described in **5.10**, Note 2.

5 Tunnel lighting design

5.1 Determination of stopping distance

The stopping distance *SD* should be taken from Table 1, relative to the speed of the tunnel.

Table 1 — Stopping distances for various design speeds

Design speed[a] km/h	**Stopping distance (*SD*)** m
120	215
100	160
85	120
70	90
60	70
50	50

NOTE These values are extracted from Volume 6, Section 1, Part 1 of the Highways Agency publication DMRB TD9/93 [1].

[a] The design speed is that which is applicable to normal usage of the tunnel. In abnormal usage, such as contraflow operation, the design speed does not apply.

5.2 Tunnel lighting classification

The tunnel lighting classification should be based on the characteristics of the tunnel's known usage (for existing tunnels) or projected usage (for new tunnels). The main influencing factors are:

— traffic flow;

— traffic type and mix;

— visual guidance.

5.6 Tunnel walls

For class 4 tunnels, the average luminance of that part of the tunnel walls up to a height of 2 m should be not less than the average road surface luminance at the corresponding location.

For class 2 and 3 tunnels, the average luminance of that part of the tunnel walls up to a height of 2 m should be not less than 60 % of the average road surface luminance at the corresponding location.

For class 1 tunnels, no luminance recommendations are given for the walls. However, for such tunnels the average illuminance of that part of the tunnel walls up to a height of 2 m should be not less than 25 % of the average illuminance of the road surface.

5.7 Determination of night-time lighting levels

If the tunnel is on a section of illuminated road, the night-time luminance inside the tunnel should be at least equal to the access road luminance, but not more than three times this value.

If the tunnel is on a section of unlit road:

— tunnels shorter than 25 m do not normally need to be lit;

— for tunnels between 25 m and 200 m in length the decision to provide night-time lighting is a matter for the highway authority, taking account of matters including tunnel lighting class, type of usage at night and environmental considerations;

NOTE 1 For tunnels between 25 m and 200 m in length, if daytime lighting is provided (see **4.4** and Annex C), night-time lighting is normally provided as well.

— tunnels longer than 200 m should be lit at night to a luminance level of not less than 1.0 cd/m^2.

Where night-time lighting is provided to a tunnel on an otherwise unlit length of road, the decision to provide lighting on a short section of the access zone and parting zone is a matter for the highway authority. Where such lighting is provided, the length of this section should normally be not less than the stopping distance *SD* related to the tunnel design speed in Table 1, unless there are particular reasons such as environmental reasons for a reduced length.

NOTE 2 Recommendations for night-time lighting of roads are given in BS 5489-1.

The luminance uniformity of night-time lighting of a tunnel on an otherwise unlit road should be not less than the value given in Table 5 for the appropriate tunnel lighting class.

5.8 Flicker

The sensation of flicker can cause visual discomfort to drivers and in some cases can induce epileptic seizures. It is induced by periodic changes in luminance within the field of vision. Driving under incorrectly spaced luminaires within the tunnel or through an entrance zone with daylight louvres can give rise to this effect.

The degree of discomfort is dependent on:

a) total duration of the flicker experience;

b) contrast between the flicker source luminance and its background;

c) flicker frequency;

d) rate of change of luminance.

[A1] Where the duration of the flicker experience (i.e. the time taken to pass through the zone(s)) is no greater than 20 s, flicker can be ignored. Where the duration is greater than 20 s, the effect of flicker should be minimized by ensuring that:

1) unlit length between adjacent flashed areas in a luminaire row is less than the flashed length of a luminaire; and/or

2) flicker frequency falls outside the band 2.5 Hz to 15 Hz. [A1]

NOTE Flicker frequency can be calculated by dividing the speed, in metres per second (m/s) by the luminaire spacing [centre-to-centre, in metres (m)]. For example: for a vehicle speed of 60 km/h (= 16.6 m/s) and luminaire spacing of 4 m, the flicker frequency is 16.6/4 = 4.2 Hz.

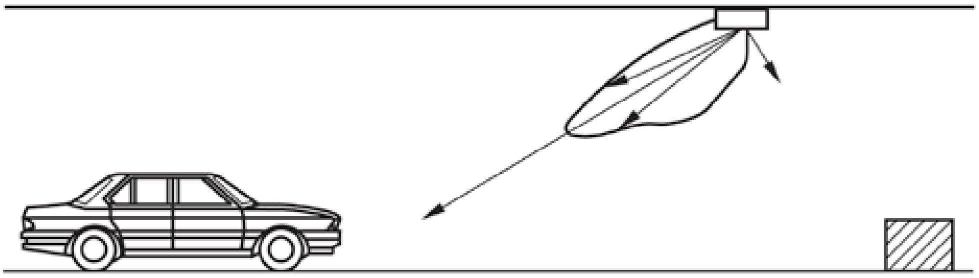


Figure B.2 — Counterbeam lighting system

Annex C (normative) Daytime lighting of short tunnels

C.1 Determination of look-through percentage

The look-through percentage *LTP* should be calculated using equation (C.1).

$$LTP = 100 \times \frac{\text{surface EFGH}}{\text{surface ABCD}} = 100 \times \frac{EF \cdot FG}{AB \cdot BC} = 100 \times \frac{EF}{AB} \cdot \frac{FG}{BC} \qquad (C.1)$$

where A, B, C, D, E, F, G and H are as shown in Figure C.1.

Since the angles are small, it can then be approximated using equation (C.2).

$$LTP = 100 \times \frac{\beta_u}{\beta_i} \cdot \frac{\alpha_u}{\alpha_i} \qquad (C.2)$$

where α_i, α_u, β_i and β_u are as shown in Figure C.2.

NOTE 1 The centre for the perspective drawing in Figure C.1 is:

— a point on a horizontal line 1.2 m above the road surface;

— in the middle of the driving lane (if more lanes are used to be determined for each lane);

— at the stopping distance *SD* from the daylight influenced apparent entrance portal, taken from Table 1.

NOTE 2 The ceiling is not taken into account, because it is not normally a background against which other road users or obstacles can be hidden.

NOTE 3 Daylight penetration shortens the apparent visual length of the tunnel. Therefore, an apparent entrance and exit portal is used when determining *LTP*. The apparent entrance portal is normally inset about 5 m inside the tunnel and the apparent exit portal about 10 m inside the tunnel. In practice it is difficult to estimate or measure the inset distances; the 5 m and 10 m figures represent good practice.

NOTE 4 The perspective situation can be based on drawings of the tunnel or on a photograph of an existing tunnel.

NOTE 5 In some cases a perspective drawing of the tunnel cannot be readily produced, especially when the tunnel has both a vertical and horizontal curve. In such cases, sufficient accuracy is given when the dark frame is based on drawings of the horizontal plane and vertical cross-section.

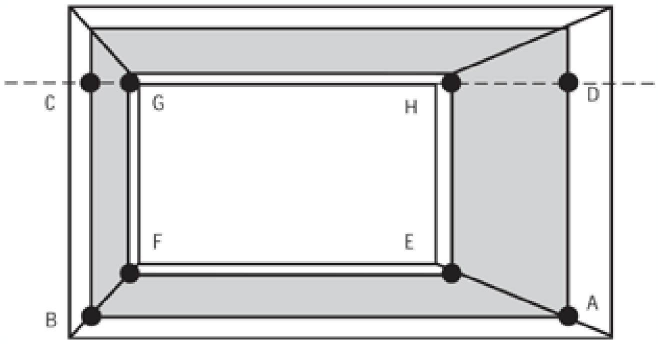
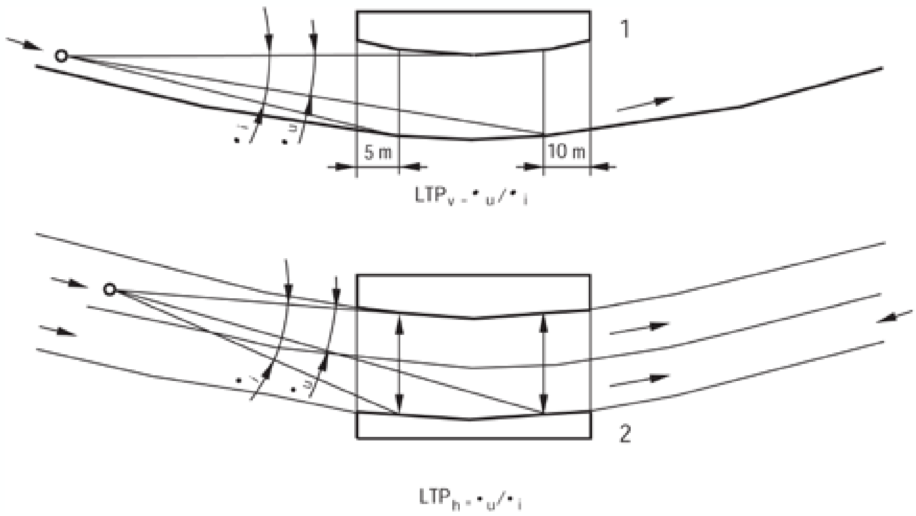


Figure C.1 — Look-through percentage



Key

1 Vertical plane
2 Horizontal plane

Figure C.2 — Visual angles

C.2 Determination of need for daytime lighting

C.2.1 *General*

Daytime lighting should be provided according to the *LTP* value, as follows:

— where *LTP* < 20 %, artificial daytime lighting should always be provided;

— where *LTP* > 80 %, artificial daytime lighting is generally not needed;

— where 20 % < *LTP* < 80 %, the need for artificial daytime lighting should be determined in accordance with **C.2.2**.

C.2.2 *Daytime lighting for LTP values between 20 % and 80 %*

Where the *LTP* value is between 20 % and 80 %, a critical object representing a car, pedestrian or cyclist should be observed against the apparent exit portal of the tunnel. The need for daytime lighting should then be determined according to the percentage of the critical object that can be seen against the apparent exit portal.

For tunnels intended for motor vehicles only, a critical object representing a car should be used. This should be a rectangle 1.6 m in width and 1.4 m in height.

For tunnels intended for mixed traffic, a critical object representing a pedestrian or cyclist should be used. This should be a rectangle 0.5 m in width and 1.8 m in height.

The longitudinal position for the observer should be the stopping distance *SD* from the apparent entrance portal.

The transverse position of the object and observer should be in accordance with Table C.1 for the appropriate type of road.

NOTE The visibility of the object in bi-directional tunnels should be considered in each direction of travel.

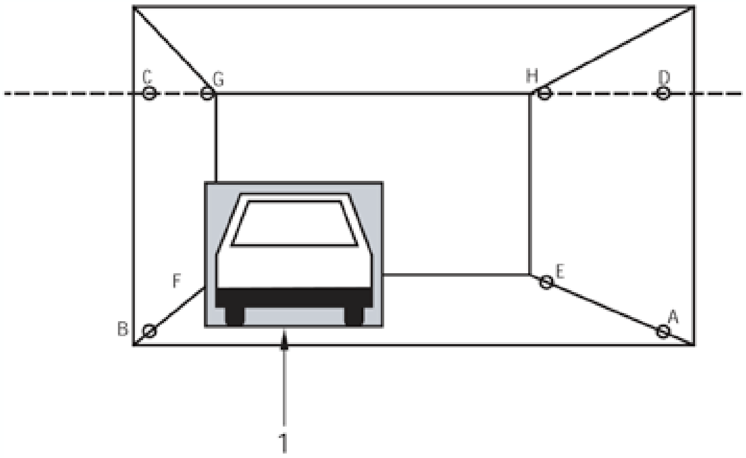
Table C.1 — Transverse position of object and observer

Type of road	Position of object	Position of observer
Multi-lane with an emergency lane	Left-hand side, emergency lane	Centre line, lane 1
Multi-lane with no emergency lane	Left-hand side, lane 1	Centre line, lane 1

Artificial daytime lighting should be provided when either:

a) less than 30 % of the critical object representing a car can be seen against the apparent exit portal (see Figure C.3); or

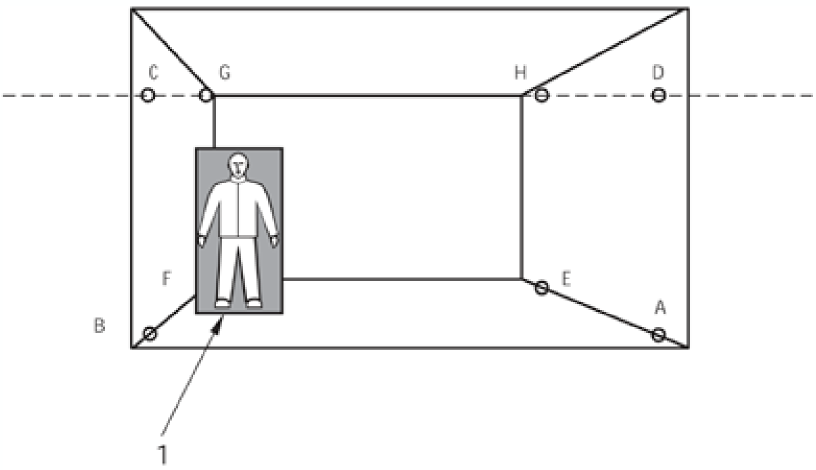
b) less than 50 % of the critical object representing a pedestrian/cyclist can be seen against the apparent exit portal (see Figure C.4).



Key

1 Vehicle
1.4 m × 1.6 m
30 % visible

Figure C.3 — Visibility of a car



Key

1 Pedestrian/cyclist
0.5 m × 1.8 m
50 % visible

Figure C.4 — Visibility of a pedestrian/bicyclist

Annex C

Annex C contains information about the features of the luminaire 'WRTL 2816 SNN 400W SON T', which is used for the *Lichtschleuse*.

WRTL exterior lighting

INDUSTRIA

2816 Series Tunnel Luminaire

technical datasheet

The 2816 tunnel luminaire is a proven guarantee for reliable, effective tunnel lighting. From short underpasses to major motorway works, the adaptability of the 2816 results in a practical solution every time. Formed from aluminium extrusion, the luminaire boasts excellent optical performance from its 3D pot optic, helping to reduce unit quantities and lending itself to cost effective solutions. The intelligent design also makes installation and maintenance a quick and simple exercise.

i-TunneL®

intelligent lighting solutions

Applications

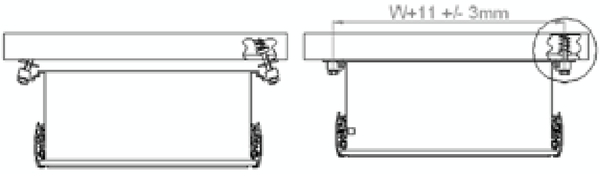
The 2816 luminaire series is best suited to road tunnels and underpasses requiring efficient lighting solutions using HID light sources. The luminaires can be mounted over-lane either against the tunnel soffit or on a hung support system. The luminaires are suitable for both interior and boost lighting applications, providing a complete and consistent lighting scheme.

Features & Benefits

- Fully compliant construction – designed and built to EN 60598
- HID types available
- Robust sealing technique provides assured IP66 protection
- Longitudinal closing system provides even pressure along length of luminaire
- Tool-free access
- Simple maintenance
- Impact resistant to IK09
- Universal mounting along full length of luminaire with front access
- Total isolation from support structure eliminates corrosion caused by dissimilar metals
- Extensive corrosion protection systems employed, including chromation to 6+ level
- Will accept i-TunneL® Lighting Control System if specified
- Excellent optical performance from symmetrical and asymmetrical optics
- Suitable for both symmetrical and counterbeam style installations
- Twin optic version available

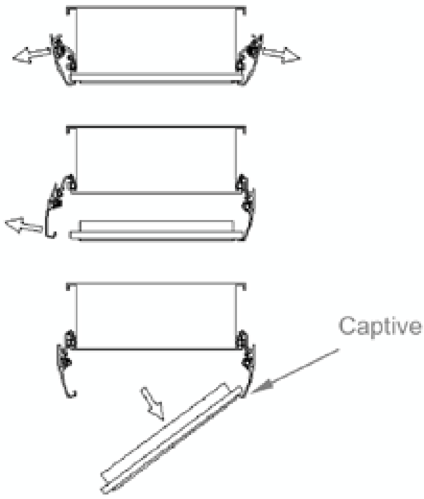
Mounting Details

Simple support structure formed from a proprietary channel system, with luminaire fixed from the front using the supplied clamps. The clamping system allows movement in two axis for accurate positioning (prior to fixing) and affords complete isolation from the support structure.



Opening & Closing

Fast opening and closing system with two latches running the length of the luminaire for tool-free access and life-time sealing.



Technical Data

Ingress Protection	IP66 – EN 60598/EN 60529
Impact Resistance	IK09 – EN 50102
Fire Resistance	Class 1 – NEN 6065
Housing	2.5mm extruded aluminium EN573-3, AlMg Si 0.5
Sealing	Silicone
Cover	Thermally toughened glass (DIN 12150) in an extruded/welded alum. frame
Filter	Polyamide, pressure equalising, filter (IP66)
Closing Clips/Hinge	Aluminium extruded closing latch, zinc coated stainless steel hinges, 1.4310 (DIN 17224)
Gear Tray	Thermally galvanised steel plate with keyhole slot fixings
Voltage	230VAC 50Hz Class 1
Cable Connection	3-5 x 6mm^2 terminal block
Lamps	HID 50-400W
Optics	High quality anodised aluminium, symmetrical and asymmetrical
HID Gear	Conventional ballast thermal cut-out, compensated (cos phi > 0.85)
Cable Entry	Polyamide gland M20, suitable for cable dia. 10-14mm
Finish	High quality pre-treatment and polyester powder coated, RAL 5007 (blue) minimum 65μm
Mounting	4 aluminium extruded clamps (AlMg Si 0.5) for M8 bolt
Ambient Temperature	-25°C to 40°C

Options

- Other lamps on request
- Reflector and lamp orientation and number
- Alternative cable entry positions & quantity
- Flying lead cable(s) pre-assembled
- Lamps supplied installed
- Electronic HID gear
- Preparation for control & monitoring system
- Coupling parts for mounting in continuous line
- Project specific luminaire coding
- Alternative RAL colours
- Inclusion of double pole cover switch

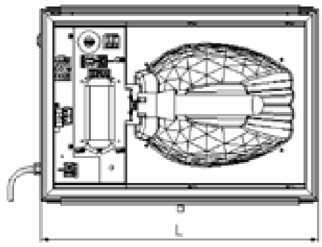
Lamp Codes:

HID High intensity discharge tubular 'T' or elliptical 'E'

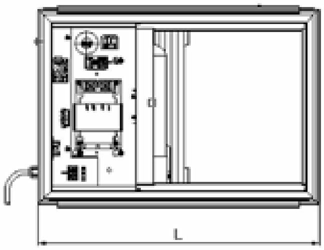
2816 Series Tunnel Luminaire

Dimensions & Range

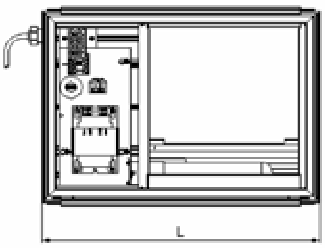
Symmetrical Optic



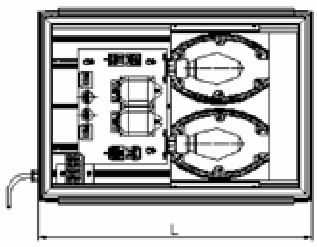
Counterbeam Optic 1



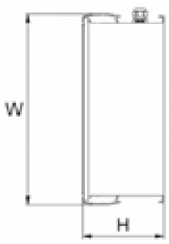
Counterbeam Optic 2



Twin Optic



End View (all types)



Type No.	Lamps	'L'	'W'	'H'	Weight (kg)
281622.nnn	1 x HID-50	618	442	180	12
281622.nnn	1 x HID-70	618	442	180	12
281622.nnn	1 x HID-100	618	442	180	13
281622.nnn	1 x HID-150	618	442	180	13
281622.nnn	1 x HID-250	618	442	180	14
281622.nnn	1 x HID-400	618	442	180	15

nnn – Last 3 digits define project specific requirements, e.g. optic type, wattage etc

Associated Products

2815 Series - Linear optic tunnel luminaire with multiple HID and fluorescent lamps

2811 Series - Low profile tunnel luminaire with linear optic and HID and fluorescent lamp options

WRTL Exterior Lighting Limited
Unit 33, Llys Edmund Prys
St Asaph Business Park
Denbighshire, LL17 0JA
Telephone – +44 (0) 1745 582918
Internet – www.i-tunnel.co.uk
E-mail – i-tunnel@wrtl.co.uk

WRTL is part of grupo INDAL lighting solutions

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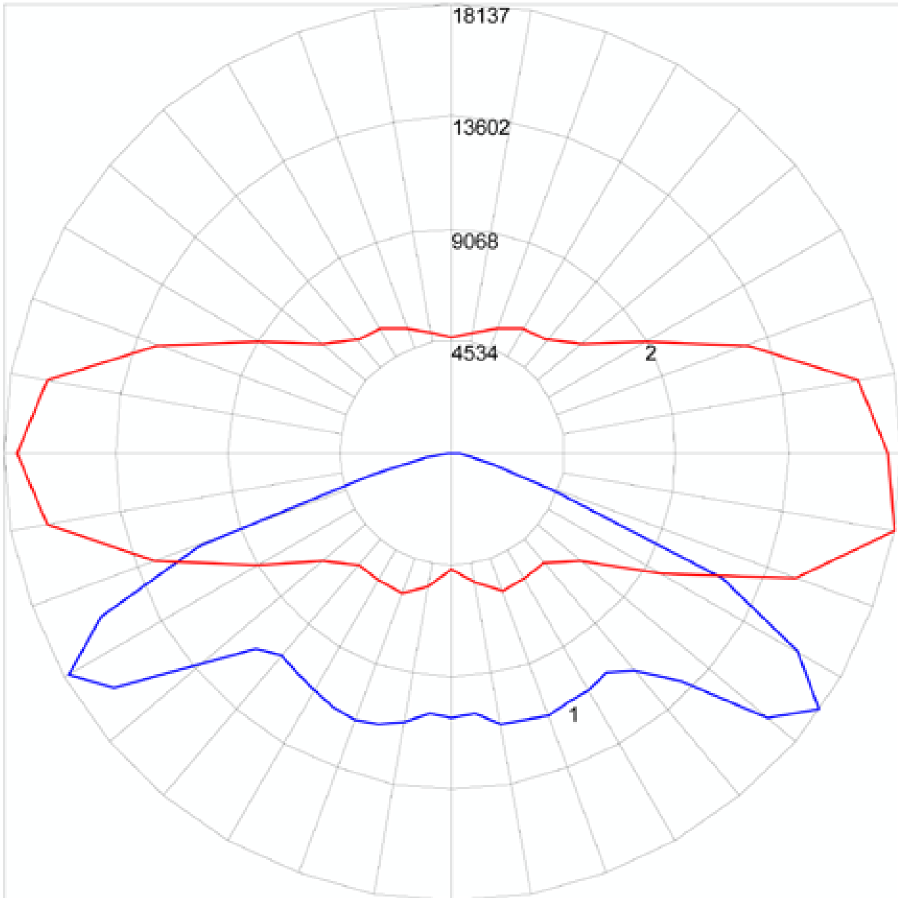
PHOTOMETRIC FILENAME : LUM3.IES

POLAR GRAPH



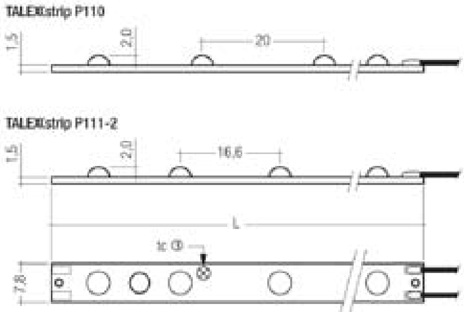
Maximum Candela = 18136.5 Located At Horizontal Angle = 350, Vertical Angle = 55
1 - Vertical Plane Through Horizontal Angles (350 - 170) (Through Max. Cd.)
2 - Horizontal Cone Through Vertical Angle (55) (Through Max. Cd.)

Annex D

Annex C contains information about the features of LED strip module called “Tallexx P111” (brand: Tridonic), which is used for the lighting approach No. 3.

TALEXstrip P110/111-2

RoHS



Applications:
- safety lighting, general lighting, effect lighting and shelf lighting
- accenting lines and edges and for side injection
- edge lighting of transparent or diffuse materials
- suitable for use with TALEXprofile Z200/201/202/203

Highlights:
- maximum possible beam angle for uniform illumination (thanks to COB technology)
- low profile

Properties:
- high-power LED in COB technology
- dimmable by pulse width modulation (PWM)
- colour temperature white: ④
  warm white (WW): 3,000 K
  neutral white (NW): 4,200 K
  daylight white (DL): 6,500 K
- integrated current source to stabilise luminous flux
- broad 140° light distribution for uniform illumination
- fixing: M4 plastic screw or double sided adhesive tape
- connection method: cable 200 mm
- identification of polarity: + red / – black

Notes:
- applying reversed polarity of the supply voltage may damage the TALEXstrip
- none of the components of the TALEXstrip (substrate, LED, electronic components etc.) may be exposed to tensile or compressive stresses
- for further information on installation please refer to the brochure entitled "TALEX installation instructions"

TALEX

type	article number	colour	wavelength colour temp. ④	light points per module	typ. luminous flux lm ①	voltage Vdc ②	power W ①	ta °C	tc point °C ③	length L mm	packing unit pieces/carton
P110 R	89600124	red	619–629 nm	10	22.0	24	1.56	-25 → +50	75	200±1	10
P110 A	89600125	amber	584–594 nm	10	18.0	24	1.56	-25 → +50	75	200±1	10
P111-2 G	89600327	green	530–540 nm	12	30.0	24	1.92	-25 → +50	75	200±1	10
P111-2 B	89600318	blue	465–475 nm	12	10.0	24	1.92	-25 → +50	75	200±1	10
P111-2 WW	89600343	warm white	3,000 K	12	38.0	24	1.92	-25 → +50	75	200±1	10
P111-2 NW	89600319	neutral white	4,200 K	12	41.0	24	1.92	-25 → +50	75	200±1	10
P111-2 W DL	89600320	daylight white	6,500 K	12	49.0	24	1.92	-25 → +50	75	200±1	10

all data for ta = 25 °C

① Tolerance range for optical and electrical data: ±15 %

② Exceeding the maximum operating voltage leads to an overload on the TALEXstrip.
This may in turn result in a significant reduction in lifetime or even destruction of the TALEXstrip.
Tolerance range for the supply voltage: 24 V: +2 V / -0 V

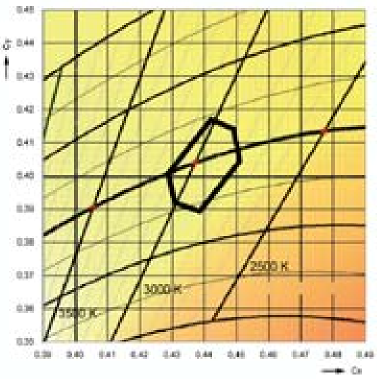
③ If the maximum temperature limits are exceeded, the life of the module will be greatly reduced or the module may be damaged.
The temperature of the TALEXstrip at the tc point in the thermally stable state by means of a temperature sensor or temperature-sensitive sticker (available for example from www.conrad.com, www.rs-components.com) as per EN60598-1.
For the precise position of the tc point see the above diagram.

④ For colour temperatures and tolerances – see page 2

TRIDONIC.ATCO

TALEX(strip P110/111-2

Corresponding colour temperature and CIE coordinates 3,000 K

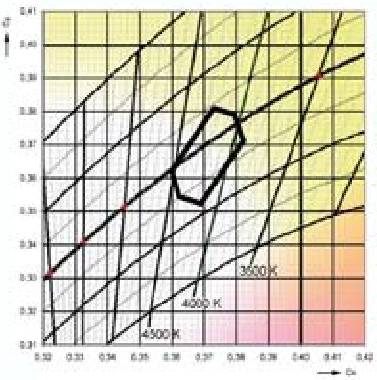


CIE coordinates: tolerance area

warm white, 3,000 K

	Cx	Cy
tolerance area	0.4309	0.3919
	0.4288	0.4006
	0.4421	0.4169
	0.4491	0.4141
	0.4510	0.4044
	0.4386	0.3893

Corresponding colour temperature and CIE coordinates 4,200 K

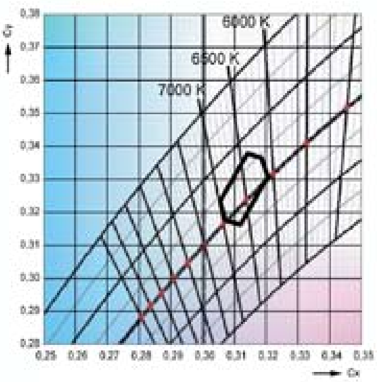


CIE coordinates: tolerance area

neutral white, 4,200 K

	Cx	Cy
tolerance area	0.3622	0.3545
	0.3599	0.3621
	0.3730	0.3809
	0.3794	0.3791
	0.3821	0.3711
	0.3690	0.3523

Corresponding colour temperature and CIE coordinates 6,500 K



CIE coordinates: tolerance area

daylight white, 6,500 K

	Cx	Cy
tolerance area	0.3074	0.3175
	0.3055	0.3233
	0.3141	0.3378
	0.3186	0.3365
	0.3205	0.3308
	0.3119	0.3162

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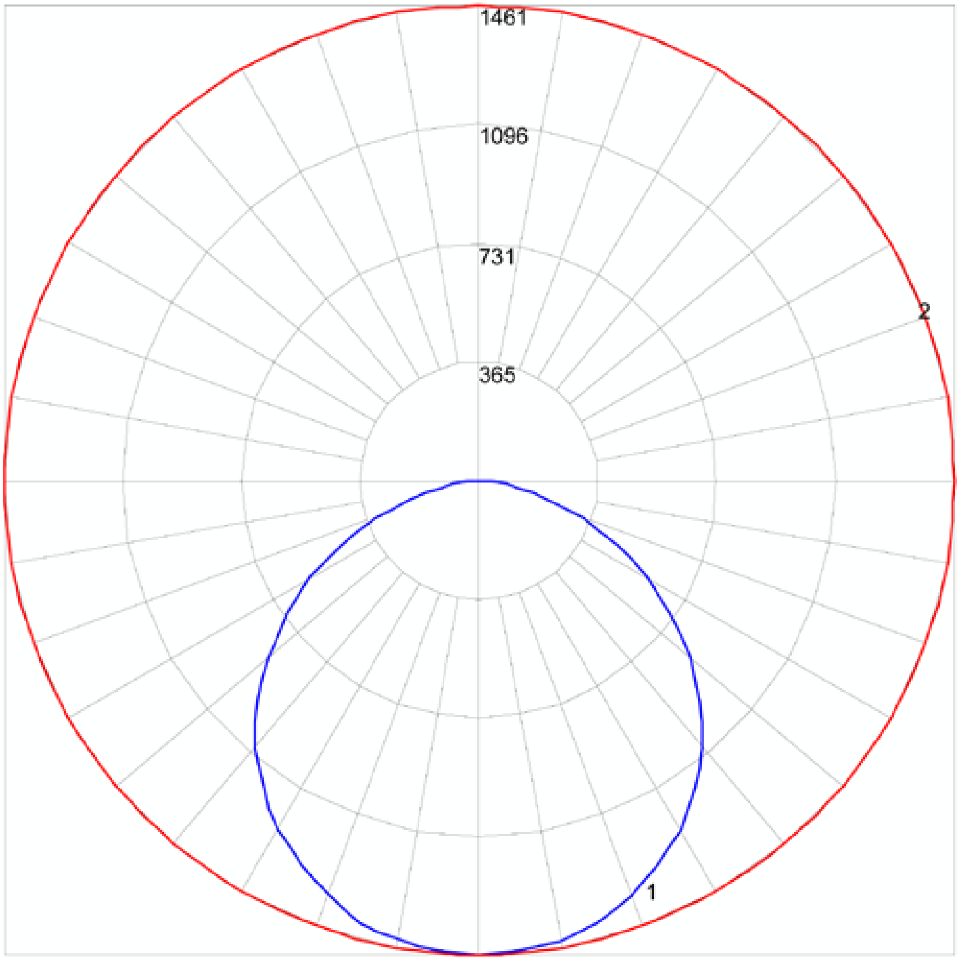
POLAR GRAPH



Maximum Candela = 1461   Located At Horizontal Angle = 0, Vertical Angle = 0
1 - Vertical Plane Through Horizontal Angles (0 - 180) (Through Max. Cd.)
2 - Horizontal Cone Through Vertical Angle (0) (Through Max. Cd.)