

Tunnel Lighting: Comparison and Tests of Symmetrical, Counter-Beam, and Pro-Beam Systems

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Three tunnel lighting systems—symmetrical, counter-beam (CBL), and pro-beam (PBL)—were compared under the same geometrical and weather conditions to determine their advantages and disadvantages in terms of visibility. The PBL system was found to have no advantages over the other two systems, and it should be used in combination with light, diffusing tunnel walls and road surfaces. The symmetrical system was found to provide good guidance when used with luminaires mounted in a continuous line, and the CBL system was found to ensure good perception of contrast and an acceptable level of glare, provided that certain conditions are met.

The main problem of tunnel lighting concerns the entrance zone extended over the length inside the tunnel corresponding to the safe stopping sight distance (SSSD).

The level of luminance L_{th} required in the threshold zone is defined in relation to the luminance level in the tunnel access zone L_{20} at a distance equal to the SSSD from the tunnel mouth, according to the ratio $k = L_{th}/L_{20}$, where L_{th} is the luminance in the threshold zone and L_{20} is the luminance within a field of 20 degrees measured in the access zone in the direction of the traffic, where the center of the field of measurement coincides with the center of the tunnel.

However, on examination of the different recommendations it can be seen that the ratio sometimes shows wide deviations between standards, and even within the same recommendation [e.g., depending on whether the lighting system used is symmetrical or asymmetrical with counter-beam lighting (CBL)].

For example, the values of k recommended in Commission Internationale de l'Eclairage (CIE) (International Commission on Illumination) No. 88 (1) are lower for CBL than for a system with symmetrical distribution.

How can there be such discrepancies between different standards? There are a number of explanations. If the tunnel is in use, the difficulties and dangers imposed by the traffic may make conducting experiments nearly impossible. Often the tests are carried out before the tunnel is opened, but this is even more irrelevant, and the time available is usually short. Many experiments are carried out at night in order to avoid traffic, but the conditions then are totally different from those during the day, and even when experiments are carried out during the day, it is difficult to get the same field of experimentation over a period long enough to be representative of different weather conditions. Thus, to take the different con-

ditions into account it is necessary to extrapolate from the results of laboratory experiments.

For example, the contrast quality factor of ≥ 0.6 for CBL cited in CIE 88, namely the ratio L_r/E_v , where L_r is the luminance of the road and E_v is the illuminance of the obstacle, can only be fully verified in the tunnel at night.

During the day, however, this factor is significantly less than 0.6, and may even be of the order of 0.4 in the first 40 m of the tunnel. This, in the opinion of the author, is mainly because the principle is based on theoretical notions that are insufficiently founded on daylight conditions in the tunnel entrance. The values put forward for the contrast quality factor are generally based on measurements carried out at night.

EXPERIMENTAL SITUATION

The experimental situation consists of a motorway tunnel that in 1975 was equipped with a symmetrical system of continuous strip lighting down the center of the ceiling. A second, asymmetrical, system—basically a CBL system—was installed in the threshold zone. The two types of lighting can be used alternatively. In 1990, the CBL system was converted to an asymmetrical system with the flux directed toward oncoming traffic by turning the luminaires through 180 degrees in azimuth.

The aim of the tests was to compare these three lighting systems in the tunnel under the same geometrical and weather conditions, and thus to deduce their advantages and disadvantages in terms of visibility, particularly to determine whether the three systems justified different choices for the ratio $k = L_{th}/L_{20}$.

EXPERIMENTAL SET-UP

Common Elements of Symmetrical and Asymmetrical Systems

The geometry of the experiments was as follows:

- Motorway tunnel, 2 unidirectional bores.
- Three traffic lanes, 3.75 m each.
- Total width: 14.25 m.
- Ceiling height: 5.50 m.
- Length of tunnel: 467 m.
- Speed of traffic: 120 kph.

The orientation was south to north for the bore under trial. The experiments were conducted under an open environment giving a luminance L_{20} of 4500 cd/m² (Figure 1).

The tunnel road surface was transversely corrugated concrete, light and highly diffusing, with $S1 = 0.16$ and $q_o = 0.10$. The tunnel wall surface was specular ceramic for the first 50 m of the tunnel entrance, with a coefficient of reflection of $\rho = 0.7$. The wall surface for the rest of the tunnel was light-colored concrete with a coefficient of reflection of $\rho = 0.5$.

Symmetrical Lighting System

The symmetrical lighting system was installed in 1977. The lighting units were mounted in two continuous lines on the ceiling: LPS 131 W for sunny conditions and fluorescent lamps for dark and night levels.

Asymmetrical Lighting Systems

In addition to the symmetrical system, four lines of luminaires with asymmetrical light distribution were installed on the out-

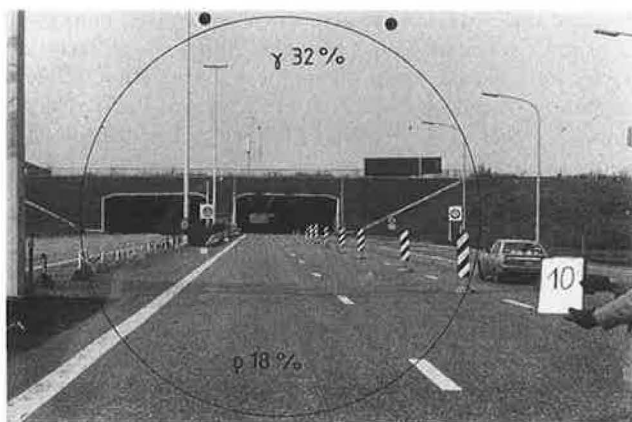


FIGURE 1 Wevelgem tunnel, 160 m from portal.

side of the existing lines. For the first 2 years these luminaires were oriented toward oncoming traffic (counter-beam lighting). In 1990, the units were rotated 180 degrees in azimuth to shine in the direction of traffic flow. This system is called pro-beam lighting (PBL). The lighting fittings were equipped with HPS 400 W sources. Figure 2 shows the levels measured at night for the three systems with the arrangement of the luminaires in the threshold zone. Figure 3 shows the polar diagrams I_{cd} for the three systems.

THEORETICAL CONDITIONS OF VISIBILITY OF OBSTACLES

If L_b is the luminance of the background, generally taken to be the luminance L_r of the road, and L_o is the luminance of the obstacle, the intrinsic luminance contrast (C_{int}) is then defined as follows:

$$C_{int} = (L_o - L_r)/L_r \quad (1)$$

This intrinsic contrast is defined at a short distance from the obstacle, without taking into account the various interference luminances, such as the veiling luminance (L_v), the atmospheric luminance (L_{atm}) or the windscreen luminance (L_{wscr}).



Depending on whether condition L_o is greater or less than L_r , the intrinsic contrast will be positive (from 0 to +∞) or negative (from -1 to 0).



When the absolute value of the intrinsic contrast is less than a certain value, conditions are below the threshold of visibility. That is, they are below the threshold contrast C_{th} , which in the particular case of tunnels is taken to be

$$|C_{th}| = 0.2 \quad (2)$$

If the simplifying assumption is made that obstacles are perfect diffusers, Equation 1 becomes

$$C_{int} = \frac{\rho \times E_v}{\pi \times L_r} - 1 \quad (3)$$

SYMMETRICAL LIGHTING SYSTEM					
	Horizontal illuminance road	Luminance road	Vertical illuminance road for H=0.3m	Walls Luminance	$\frac{L_r}{E_v}$
	E_h (lux)	L_r (cd/m ²)	E_v (lux)	L_w (cd/m ²)	
VERY SUNNY	5700	400	2400	510	0.15

COUNTER BEAM LIGHTING SYSTEM (C.B.L.)					
	Horizontal illuminance road	Luminance road	Vertical illuminance road for H=0.3m	Walls Luminance	$\frac{L_r}{E_v}$
	E_h (lux)	L_r (cd/m ²)	E_v (lux)	L_w (cd/m ²)	
VERY SUNNY	4900	400	590	510	0.68



PRO BEAM LIGHTING SYSTEM (P.B.L.)					
	Horizontal illuminance road	Luminance road	Vertical illuminance road for H=0.3m	Walls Luminance	$\frac{L_r}{E_v}$
	E_h (lux)	L_r (cd/m ²)	E_v (lux)	L_w (cd/m ²)	
VERY SUNNY	3900	380	3400	395	0.11

FIGURE 2 Lighting levels measured at night for three systems.

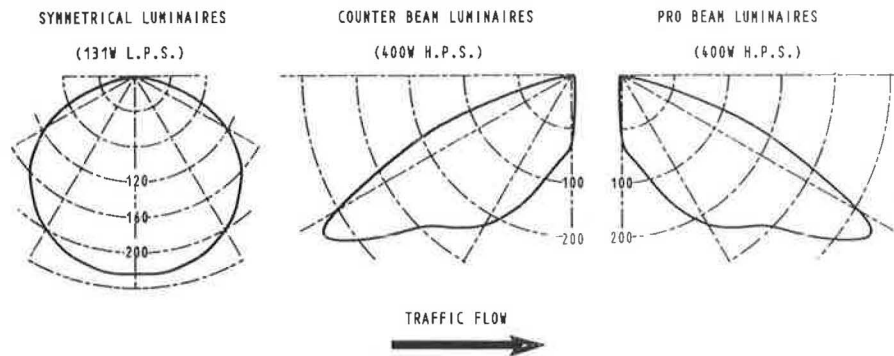


FIGURE 3 Polar diagrams I_{cd} for three systems.

where E_v is the vertical illuminance of the obstacle and is the coefficient of reflection of the obstacle.

The obstacle will be invisible when

$$-C_{th} < C_{int} < +C_{th} \quad (4)$$

From equations 3 and 4 it can be deduced that obstacles with coefficients of reflection ρ between the two following limits will be invisible.

$$\frac{\pi \times L_r}{E_v} (1 - C_{th}) < \rho < \frac{\pi \times L_r}{E_v} (1 + C_{th}) \quad (5)$$

For the three photometric distributions considered—symmetrical, CBL, and PBL—the L_r/E_v ratios were as follows for the Wevelgem tunnel (see Figure 2).

$$\text{Symmetrical distribution: } L_r/E_v = 0.15 \quad (6.1)$$

$$\text{CBL distribution: } L_r/E_v \geq 0.68 \quad (6.2)$$

$$\text{PBL distribution: } L_r/E_v = 0.11 \quad (6.3)$$

Symmetrical Lighting System

From equations 2, 5, and 6a, it can be deduced that obstacles with a coefficient of reflection (ρ) between 0.38 and 0.56 will have an intrinsic contrast (C_{int}) less than the threshold contrast (C_{th}). A light, diffusing surface that enables the ratio E_H/L_r to be made lower, thus lowering the lighting power required, would appear to be most suitable for a symmetrical system.

CBL System

From equations 3 and 6b it can be deduced that whatever the coefficient of reflection (ρ) of the obstacle is, the intrinsic contrast (C_{int}) will always be negative and greater than the threshold contrast (C_{th}). The lighter and more reflecting the surface (high $S1$), the more negative will be the contrast, giving the family of curves $R4$ with $q_o > 0.1$.

PBL System

From equations 2, 5, and 6c, it can be deduced that obstacles with a coefficient of reflection (ρ) between 0.25 and 0.38 will

have intrinsic contrast (C_{int}) less than the threshold contrast (C_{th}). A light, diffusing surface that enables the ratio E_H/L_r to be made lower, thus lowering the lighting power required, would appear to be the most suitable for a PBL system.

VISIBILITY OF OBSTACLES AT NIGHT

Practical verification of the first conclusions on the perception of contrast was carried out at night. Three 20- x 20-cm obstacles were placed across the highway, each with a different coefficient of reflection ($\rho = 0.16, 0.36$, and 0.75). The luminance values of the roadway (L_r) and of the obstacle (L_o) were measured for each obstacle.

Experiment I: Symmetrical Lighting System

For this experiment, $L_r = 400 \text{ cd/m}^2$ at night. For Obstacle 1, $\rho = 0.75$, $L_o = 580 \text{ cd/m}^2$, and $C = +0.45$. For Obstacle 2, $\rho = 0.36$, $L_o = 380 \text{ cd/m}^2$, and $C = -0.05$. For Obstacle 3, $\rho = 0.16$, $L_o = 270 \text{ cd/m}^2$, and $C = -0.32$. The tests confirmed that Obstacle 2, with a coefficient of reflection $\rho = 0.36$, is invisible (see Figure 4).

Experiment II: CBL System

For this experiment, $L_r = 400 \text{ cd/m}^2$ at night. For Obstacle 3, $\rho = 0.16$, $L_o = 90 \text{ cd/m}^2$, and $C = -0.77$. For Obstacle 2, $\rho = 0.36$, $L_o = 170 \text{ cd/m}^2$, and $C = -0.57$. For Obstacle



FIGURE 4 Targets at night under symmetrical lighting system.

1, $\rho = 0.75$, $L_o = 260 \text{ cd/m}^2$, and $C = -0.35$. The tests confirmed that the three obstacles are visible with negative contrast (see Figure 5).

Experiment III: PBL System

For this experiment, $L_r = 380 \text{ cd/m}^2$ at night. For Obstacle 1, $\rho = 0.75$, $L_o = 618 \text{ cd/m}^2$, and $C = +0.63$. For Obstacle 2, $\rho = 0.36$, $L_o = 400 \text{ cd/m}^2$, and $C = +0.05$. For Obstacle 3, $\rho = 0.16$, $L_o = 228 \text{ cd/m}^2$, and $C = -0.4$. The tests confirmed that Obstacle 2, with a coefficient of reflection of $\rho = 0.36$, is invisible (see Figure 6).

VISIBILITY OF OBSTACLES BY DAY

The test conditions were chosen to correspond with the actual situation of a driver who is approaching the mouth of a tunnel and must react to the perception of an obstacle on the road at a distance corresponding to SSD.

For each of the lighting systems, three series of measurements and observations were conducted, at distances of (a) 60 m from the obstacles, (b) 160 m from the obstacles, and (c) 160 m from the tunnel portal.

The 3 targets were moved successively from the portal of the tunnel to 70 m inside the tunnel in the threshold zone.

The series of measurements (L_r , L_o , E_v , L_{20} , and L_{atm}) were carried out mostly during good weather conditions (sunny and very sunny) with horizontal illuminance levels in the tunnel access zone on the order of 100,000 lux and luminances $L_{20} = 4,500 \text{ cd/m}^2$ and $L_{seq} = 230 \text{ cd/m}^2$.

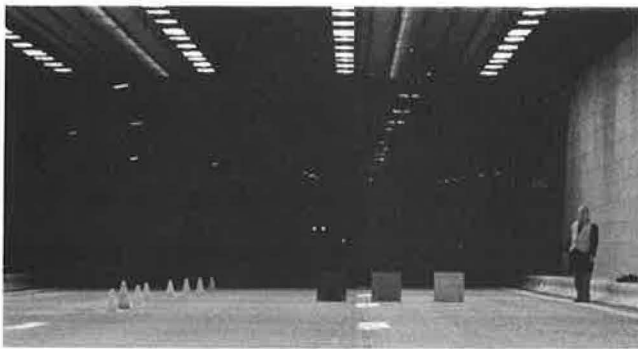


FIGURE 5 Targets at night under CBL system.



FIGURE 6 Targets at night under PBL system.

Atmospheric Luminance

Padmos (2) has shown that in Holland during at least 85 percent of the day $L_{atm} = 0.00152 d L_{20}$, where d is the distance measured from the mouth of the tunnel in the access zone. This gives the following value of contrast:

$$C = \frac{(L_o + L_{atm}) - (L_r + L_{atm})}{L_r + L_{atm}} \quad (7)$$

From equations 1 and 7 it can be deduced that

$$C = C_{int} = \frac{L_r}{L_r + L_{atm}} \quad (8)$$

The atmospheric luminance reduces the intrinsic contrast, without changing the sign.

Applying Padmos' formula for a distance of 160 m from the tunnel mouth and for luminances $L_{20} = 4,500 \text{ cd/m}^2$ measured at the site of the tunnel, $L_{atm} = 1,000 \text{ cd/m}^2$.

At 160 m from the tunnel mouth, values of $L_{atm} = 260 \text{ cd/m}^2$ were measured. For L_r values of 400 cd/m^2 in the threshold zone, the contrast C is reduced to 60 percent of the intrinsic contrast C_{int} .

Contribution of Daylight in Tunnel Entrance Zone

This factor has a significant effect in displacing the values of the ratio L_r/E_v downward. At 2 p.m., with external illuminance of 95,000 lux and $L_{20} = 5000 \text{ cd/m}^2$, the vertical illuminance was 50,000 lux at the tunnel mouth, 1,900 lux at 20 m inside the tunnel, 540 lux at 50 m, and 190 lux at 70 m. The following is derived from equations 3 and 8:

$$C = \left(\frac{\rho \times E_v}{\pi \times L_r} - 1 \right) \frac{L_r}{L_r + L_{atm}} \quad (9)$$

An obstacle that has a negative intrinsic contrast at night can take on a positive contrast or have a contrast below the threshold contrast.

Effect of Wall Lighting on Visibility in Threshold Zone

The Wevelgem tunnel walls are tiled for the first 50 m with light, specular ceramic with a coefficient of reflection of $\rho = 0.7$, and the walls of the interior of the tunnel are covered in light, diffusing cement with a coefficient of reflection of $\rho = 0.5$.

With CBL in particular, for which the vertical illuminance of obstacles should be as low as possible, one-third of the vertical lighting comes from the luminaires and two-thirds from the clear walls and the clear, diffusing roadway.

Results of Measurements

For the sake of clarity, the intermediate results for one series (a) of measurements only, at a distance of 60 m from the

obstacles, are given here. The differences in the results of the series are due entirely to L_{atm} increasing from series (a) to (c).

Figures 7a, 7b, and 7c show the following, for the symmetrical (7a), CBL (7b), and PBL (7c) systems, respectively.

For the three systems, L_r is greater than 1,000 cd/m² at the tunnel portal and is always greater than 400 cd/m² at 70 m (at night L_r 400 cd/m² in all three systems).

For the symmetrical system, the ratio L_r/E_v remains relatively constant at between 0.1 and 0.2 (at night $L_r/E_v = 0.2$); for CBL, L_r/E_v varies between 0.1 and 0.45, without reaching the ratio of 0.6 attained at night; for PBL, L_r/E_v remains relatively constant at between 0.05 and 0.1 (at night $L_r/E_v = 0.1$).

For the symmetrical system, the contrast (C) is positive up to approximately 5 m and remains positive for the obstacle

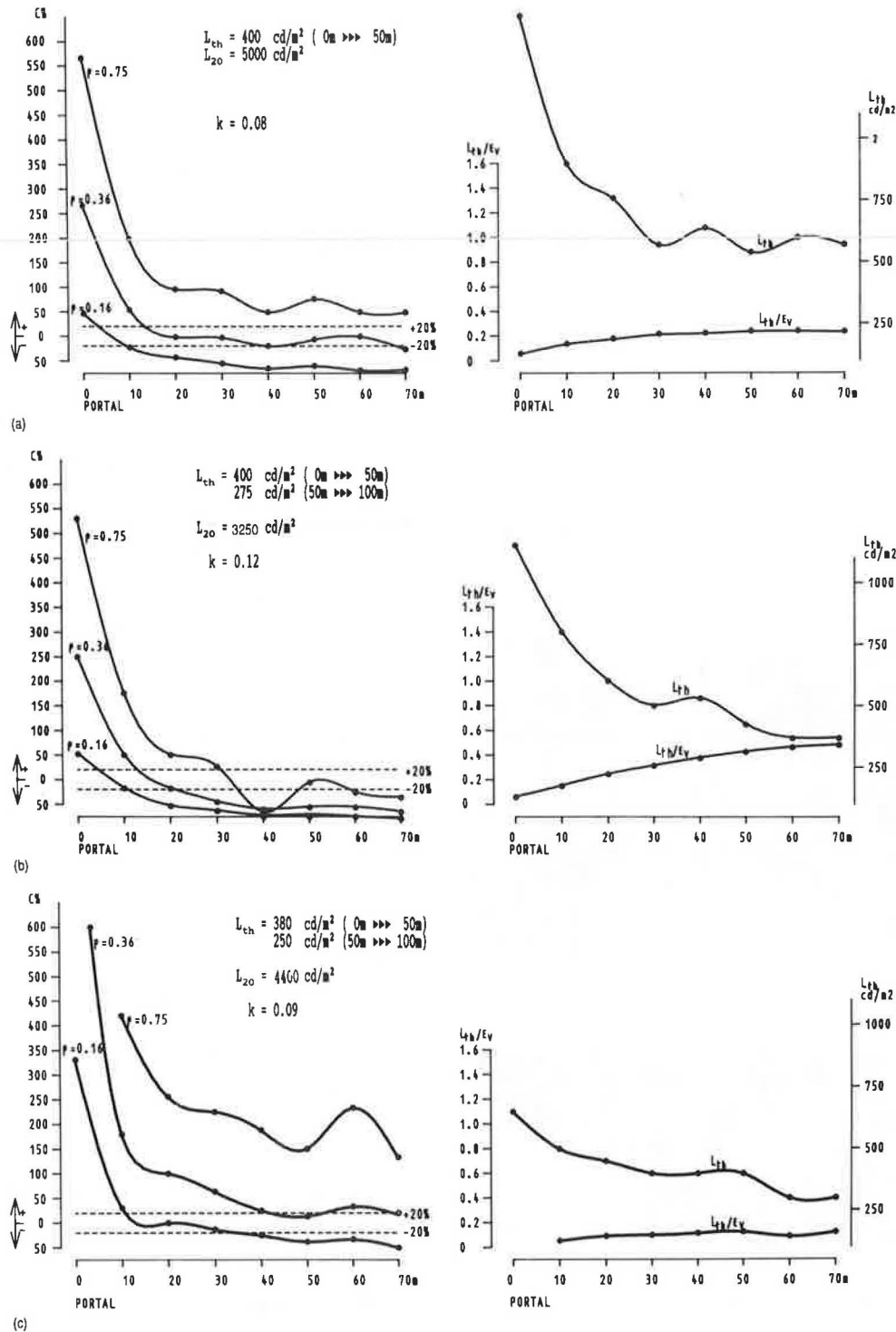


FIGURE 7 Results of measurement of visibility of obstacles by day for three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL.

with a coefficient of reflection of $\rho = 0.75$. The obstacle with a coefficient of reflection of $\rho = 0.36$ will become invisible at 15 m and remain invisible up to 70 m. The obstacle with a coefficient of reflection of $\rho = 0.16$ will remain invisible from 5 to 10 m and will become visible once more but with negative contrast beyond 15 m.

For CBL, the obstacle with a coefficient of reflection of $\rho = 0.75$ will have a contrast (C) that is positive from 0 to 30 m. It will be invisible between 30 and 40 m and will have negative contrast beyond 40 m.

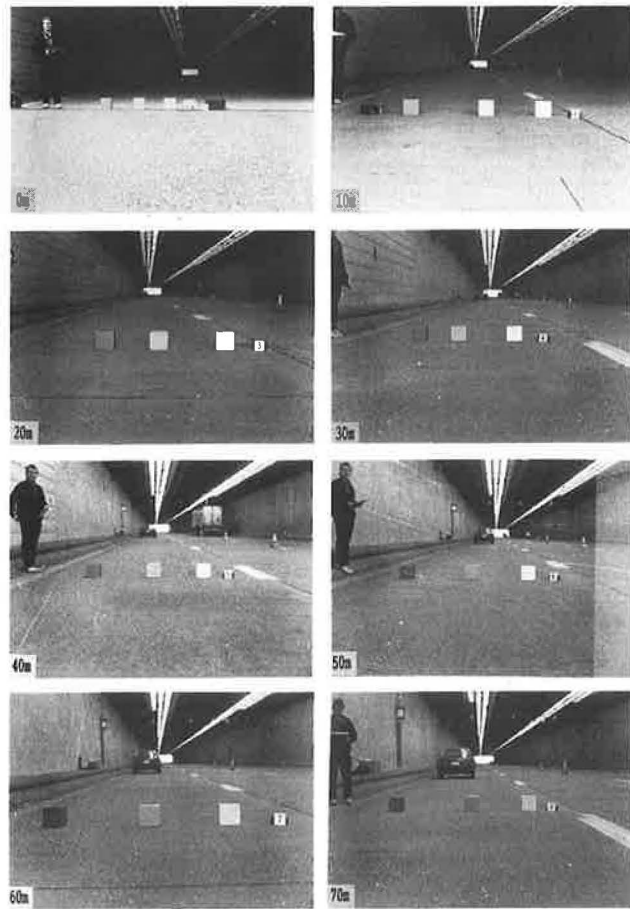
The contrast of the obstacle with a coefficient of reflection of $\rho = 0.36$ will change from positive to below the threshold contrast beyond 12 m; it will become visible once more with negative contrast at 22 m.

The obstacle with a coefficient of reflection of $\rho = 0.16$ will become invisible at 5 m and will become visible again, but with negative contrast, at 10 m.

For PBL, the values of contrast for the three targets from the tunnel mouth up to 70 m are similar to those obtained with the symmetrical system.

The obstacle with a coefficient of reflection of $\rho = 0.36$ is almost always invisible or at the limit of the threshold contrast (C_{th}).

Figures 8a, 8b, and 8c show the variation in contrast for the three systems. Note however that the photographs were taken from a shorter distance (5 m).



(a)

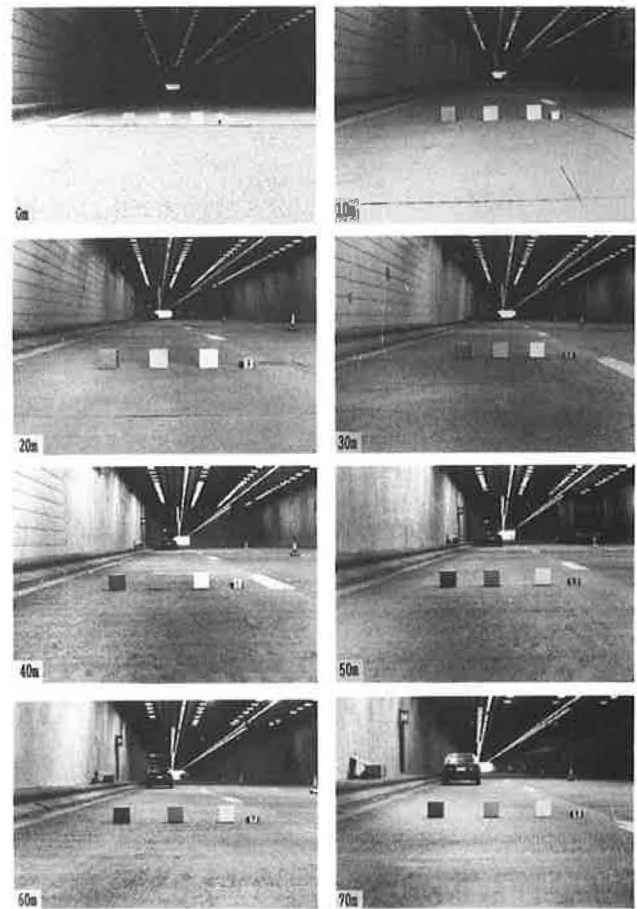
From these contrast measurements from the three targets, one can interpolate the contrast values for obstacles with coefficients of reflection between 0.75 and 0.16 and trace the invisibility zones $|C| \leq 2$ for obstacles with $0.16 < \rho < 0.75$ from the tunnel portal up to 70 m.

Figures 9a, 9b, and 9c show the invisibility zones for the three systems with the contrast measured at 60 m from the obstacle, from the tunnel portal up to 70 m inside the tunnel. For the symmetrical system (Figure 9a), the obstacle with a coefficient of reflection ρ between 0.3 and 0.5 is critical and will never be seen. For CBL (Figure 9b), for the same obstacle, whatever its coefficient of reflection (ρ), there will be a position at which it will be invisible or its contrast will be reversed. The light obstacle with $\rho > 0.7$ (statistically infrequent) will not be seen. For PBL (Figure 9c), the dark obstacle with coefficient of reflection ρ between 0.15 and 0.35 (statistically significant) is critical and will never be seen.

Figures 9–11 illustrate the effect of the viewing distance. Because the atmospheric luminance L_{atm} increases with distance, the invisibility zones also become greater with distance. This confirms the previous conclusion that the atmospheric luminance reduces the contrast.

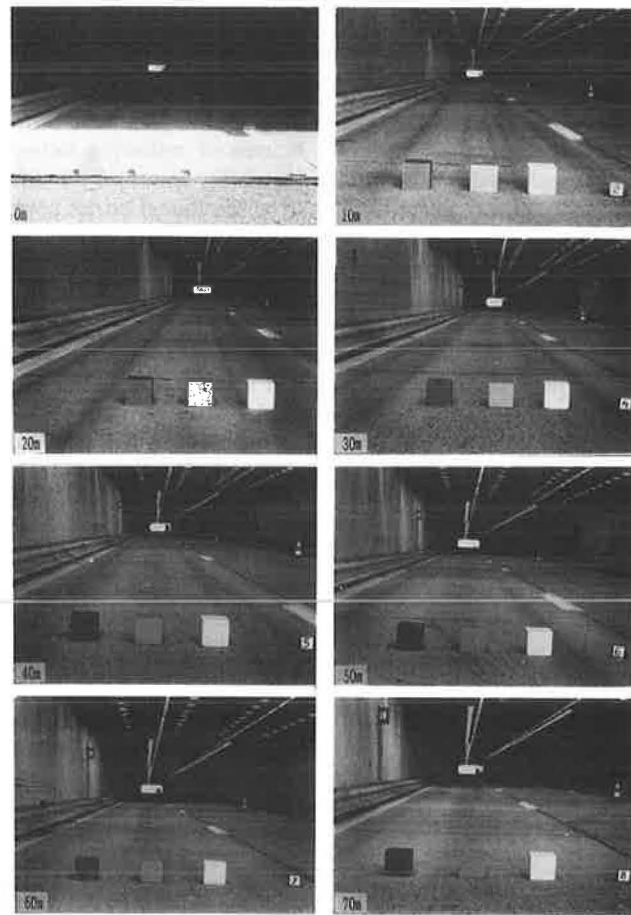
CONCLUSIONS

- L_{atm} is critical for all three systems. The only remedy is to lower the speed limit in order to reduce SSSD.



(b)

FIGURE 8 Three obstacles located up to 70 m from tunnel portal under three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL. (continued on next page)



(c)

FIGURE 8 (continued)

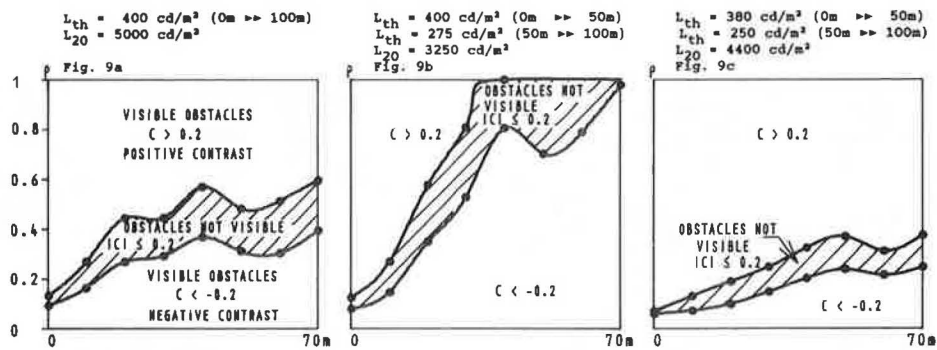


FIGURE 9 Zones of visibility 60 m in front of obstacles for three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL.

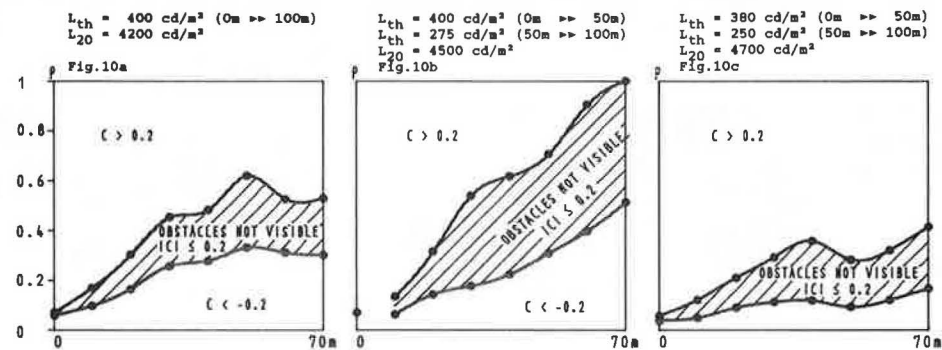


FIGURE 10 Zones of visibility 160 m in front of obstacles for three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL.

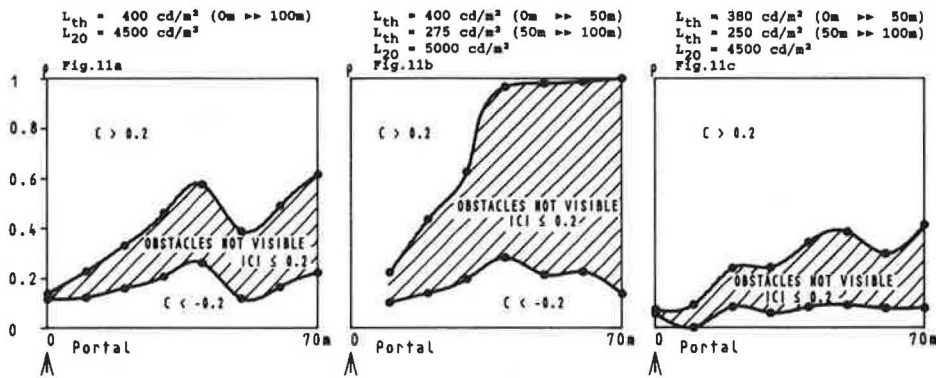


FIGURE 11 Zones of visibility 160 m in front of tunnel portal for three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL.

- There are, for all three systems, invisibility zones of similar importance. Accordingly, there is no justification for reducing the ratio $k = L_{th}/L_{20}$ for any of them.

- Preference for the PBL system is not justified because the system does not have any advantages over the symmetrical or CBL systems. Moreover, it demands higher installed lighting power. Dark obstacles (statistically frequent) have poor visibility as dark vehicles, especially because of the light distribution of the luminaires there is no perceptible flickering on the back windscreens.

- The PBL system should be used in combination with light, diffusing tunnel walls and road surfaces.

- The symmetrical system provides good guidance when it is used with luminaires mounted in a continuous line. A flickering effect on the rear windscreens is not distracting and ensures perception of moving vehicles. This system should be used in combination with light tunnel walls and a light, diffusing road surface.

- The CBL system ensures good perception of contrast, a reduction in installed power, and an acceptable level of glare, provided that certain conditions are met:

- The part of the walls with high luminance must be limited to a level of 1 m in order to reduce the E_v of the obstacles.
- The light intensity emitted by the luminaires in the direction of the traffic must be limited.
- A light, specular road surface must be used to enhance installed lighting power.
- The photometric distribution must be such that the vertical angle of the beam is as high as possible but not higher than 56 degrees, and the intensities between 70 and 90 degrees should be kept as low as possible to avoid glare.

REFERENCES

1. CIE Publication No. 88: *Guide for the Lighting of Road Tunnels and Underpasses*. International Committee on Illumination, Paris, France, 1990.
2. P. Padmos. Glare and Tunnel Entrance Lighting. *CIE Journal*, Vol. 3, No. 1, 1984.