fan arrangement was determined to be three fans per duct, each having three speeds. The number of fans will therefore be 6/ventilation section, 12/bore, or 48 for the total facility. Each of the two ventilation buildings will house 24 fans. Each exhaust fan will be mounted in a separate chamber with a removable wall or partition between the transmission drive and the fan. This will isolate the motors and drivers from the airstream in an environmentally controlled space and ensure system capability to operate during a tunnel fire.

CONCLUSION

The amount of air required to maintain a safe and comfortable environment in the Fort McHenry tunnel was determined by using the ASHRAE vehicular tunnel ventilation method. The distribution system was also determined by using the same method and resulted in selecting a fully transverse ventilation system comprised of three centrifugal supply fans and three centrifugal exhaust fans for each ventilation section, where each fan has three speeds. This results in a total of 48 fans in the completed facility; the ventilation system will deliver a maximum of 1608 L/s in the northbound and 1546 L/s in the southbound traffic tubes.

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Tunnel-Lighting Engineering for Traffic Safety: Theory Versus Practice

A. KETVIRTIS

The tunnel-lighting design criteria proposed by various authoritative technical societies on a worldwide scale are reviewed. The paper compares the recommended design practices with actual engineering and installation methods used in North America and in other parts of the world. A case study of the Thorold Tunnel is discussed, and the difficulties in designing tunnel lighting based on present methods are reviewed. Suggestions are made for possible practical solutions to meet the driver's needs with minimal energy consumption.

In daytime traffic, motorists passing through a tunnel or a long underpass will experience a visual disturbance caused by the sudden change in luminance levels at the tunnel entrance and in its interior. The degree of difficulty will depend mainly on the suddenness and magnitude of the reduction step in luminance levels. Thus, the problem is related to the ratio of outdoor luminance (L_1) and its level in the tunnel interior (L_2), as well as the speed of travel. Due to the presence of several independent variables that affect a driver's visibility, the question arises of how to determine the luminance levels at the tunnel entrance that would permit safe traffic flow in each specific situation.

National and international organizations, such as the International Commission on Illumination (CIE) (1) and the Permanent International Association of Road Congresses (PIARC) (2), offer practical methods and guides for achieving solutions in tunnel-lighting design. However, due to the varying opinions of individual researchers regarding eye performance under actual dynamic conditions, as well as the different economic factors that exist in various parts of the world, the suggested practices also differ. Furthermore, disagreement regarding the methods of determining the luminance ratios between outdoor (L_1) and tunnel interior (L_2) exists not only between individual engineers but also between technical societies.

DARK ADAPTATION

Eye Limitations to Dark Adaptation

The visual difficulties experienced at the entrance to a tunnel in daytime driving refer to the psychophysical aspects of dark adaptation. The majority of the information input required for driving is obtained in the form of visual data. A sudden change in the prevailing luminance levels may result in total or partial interruption of the flow of visual data, thus seriously affecting contact with the surroundings. In vehicular traffic, such a phenomenon is demonstrated in daytime driving when a vehicle enters a tunnel that has significantly lower luminance in the interior than the exterior.

When the motorist's eyes are presented with an abrupt change in luminance levels, a burst of retinal activity may cause a temporary interruption in the flow of visual information. The detection of objects will be impaired for a varying period of time until adjustment within the system of vision reaches a state of adequate stability. Although theoretically the human eye is capable of accommodating a very wide range of luminance levels (reaching a ratio of 1:10 000 000), a problem is created by the fact that such accommodation involves time. A complete adaptation from the daytime luminance to the starlight level will require about 30-40 min; however, partial adaptation occurs much faster. In the case of conditions at the tunnel entrance, therefore, partial adaptation can only be considered because, in most cases, when driving through a medium-length tunnel, the duration of the process is limited to a fraction of a minute.

Figure 1 (from Mathey) shows the dark-adaptation factor, which represents the average value and the maximum value for normal observers (3). (Note that in the figure the full-line curve represents average values and the broken-line maxima is for normal observers.) It is significant to note that in the first few seconds, adaptation is rapid; later, after a lapse of approximately 8 min, there is an intersection between two curves where the transition from cone (photopic) vision to rod (scotopic) vision takes place.

The time duration required for dark adaptation also depends on the luminance levels to which the eye was exposed prior to the beginning of dark adaptation. Dark adaptation has a pronounced influence on visual acuity, depth perception, and contrast sensitivity. All of these factors are of great importance in the visual process of night driving.

Adaptation Physiology

The immediate physical eye reaction to change in luminance levels is represented by pupillary dilation and contraction. From the size of the opening of the pupil, which varies between 2 and 8 mm in diameter, the quantity of light that reaches the retina will be determined. The quantity of light will influence the strength of signals generated within the retina following a photochemical reaction.

Although the pupillary change has specific significance in the adaptation process, the size of the opening does not represent the actual state of dark adaptation at any specific moment. In the first few seconds of adaptation, the process is very rapid (Figure 1). However, the time required for the pupil to open from 2 to 8 mm is of the order of 10 s. Although 10 s is not nearly of sufficient duration for reaching retinal stability, in practice it is believed that such time is of considerable significance (4).

In designing the tunnel-lighting system, the length of the supplementary zone is related by some researchers to the period required to achieve complete pupillary dilation. It is believed that the equivalent travel time from the beginning of the driver's fixation on the tunnel entrance (150 m) and the length of the supplementary lighting zone should be not less than 15 s.

Preadaptation and Transient Conditions

In analyzing the visual process that affects the adaptation state prior to the tunnel entrance, two specific positions should be noted. These are the fixation point and the adaptation point.

The first point describes the driver's position when he or she registers awareness of a visual obstacle. At a distance of 150-200 m [Figure 2 (5)], the dark outline of the tunnel entrance becomes a factor within the driver's visual field and begins to influence the state of adaptation (6,7). As the distance between the driver and the tunnel entrance is reduced, the relative size of the entrance outline increases, thereby forcing an adjustment in pupillary dilation.

The second point is when most of the principal field area is occupied by the tunnel opening, which affects the pupillary dilation, thereby resulting in definite and forceful adjustment. This position is often called the adaptation point. The adaptation point for a conventional-type tunnel will be at a distance of approximately 10-15 m from the entrance.

The degree of difficulty in visibility at this point will depend mainly on the conditions in the tunnel threshold zone. If the level of illumination in the tunnel interior is very low, adaptation will be difficult and the flow of visual information will be interrupted.

AMBIENT ILLUMINANCE LEVELS AND L_1:L_2 RATIO

The ambient illuminance levels were measured by Ketvirtis in 1972 for the months of June, July, and August. Four readings were taken (9, 11, 13, 15 h) every second day during these months. Figure 3 shows the results of the readings. From these readings, it is evident that the illuminance level can exceed 120 000 lx; with a reflectance coefficient of 25 percent, the ambient luminance may reach 10 000 cd/m². [Ed. note: For an approximate conversion of lux to footcandles, use a ratio of 10:1.]

EXISTING STANDARDS FOR TUNNEL-LIGHTING DESIGN

Because each tunnel design varies with respect to its geometry, material use, construction methods, traffic characteristics, and geographic location, visibility conditions also differ in each individual case. Thus, it may appear futile to attempt to establish even some generalized guides for lighting design. But, in spite of all these differences in visibility requirements, several national and international technical organizations offer recommendations that give quantitative values of photometric characteristics for tunnel-illumination systems.

CIE Recommendations

In 1973, the Committee TC-4.6 of CIE prepared International Recommendations for Tunnel Lighting (1). Figure 4 (1) shows the suggested luminance values in the tunnel threshold and transition zones.

The current CIE recommendations are based on Schreuder's (7) investigations in the 1960s, which were mainly derived from laboratory experiments. According to these recommendations, the ratio between L_1 and L_2 should not exceed 10:1.

Narisada and Yoshikawa (5) repeated Schreuder's experiments and verified his results. The comparison of research results is shown in Figure 5. Based on the results of these experiments for the L_1 value of 8000 cd/m², it would be necessary to obtain a threshold zone luminance of 800 cd/m², or approximately a 12 000-lx illuminance level.

PIARC Recommendations

At the XV Road World Congress in 1979, a report was published by a technical committee on road tunnels that outlined the design recommendations for tunnel lighting (2). This committee conducted extensive theoretical studies, as well as field observations, at existing tunnels around the world. Their recommended ratio of L_1 to L_2 (or Lsp to Lsp') falls in the range of 15:1 to 30:1 [Figure 6 (2)]. The recommended length of L_2 (Lsp') is 50-80 m. Comparing the levels based on PIARC with those of CIE, note that there is a considerable difference. For example, according to CIE recommendations, if the value of L_1 = 8000 cd/m², then L_2 should be 800 cd/m². However, the PIARC value based on, say, a 25:1 ratio is L_2 = 320 cd/m². The cost of the difference between these two recommendations for a two-way divided tunnel can be of the order of $400 000.

CASE STUDY: THOROLD TUNNEL ILLUMINATION

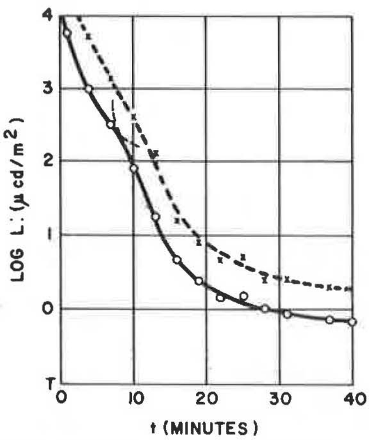
For the purpose of improving the illumination system at the Thorold Tunnel entrance, a study was conducted in 1976 by the Ministry of Transportation and Communications, Ontario, and Fenco Consultants, Ltd. The objective of this study was to investigate the practical lighting levels at the tunnel entrance and its interior related to the driver's visibility needs and sound economics (according to the Thorold Tunnel Visibility Study, 1976, an internal report by the Ministry of Transportation and Communications, Ontario, and Fenco).

Investigation of Existing Tunnel Lighting Prior to Thorold Tunnel Study

Prior to commencing the Thorold Tunnel study, a number of tunnels in Canada, the United States, Great Britain, and Western Europe were visited, and observations were made regarding the effectiveness of the lighting in the threshold zone.

Observations at the Vlake Tunnel, Holland, were carried out on October 5-6, 1976, with the permission of the Ministry of Transport, Holland. This

Figure 1. Adaptation curve.



Note: L = threshold illuminance and t = time.

Figure 2. Fixation, distance and frequency.

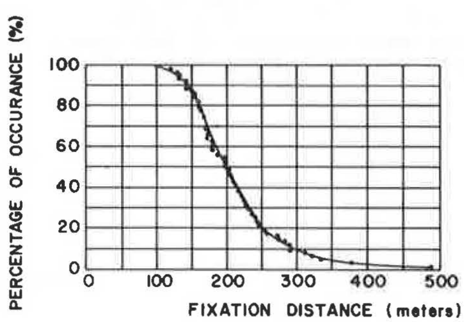


Figure 3. Horizontal illuminance distribution for June, July, and August 1972, 43° latitude.

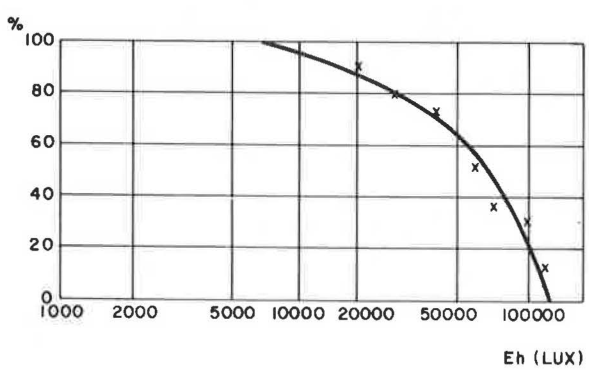


Figure 4. Recommended decrease of luminance values in entrance zone.

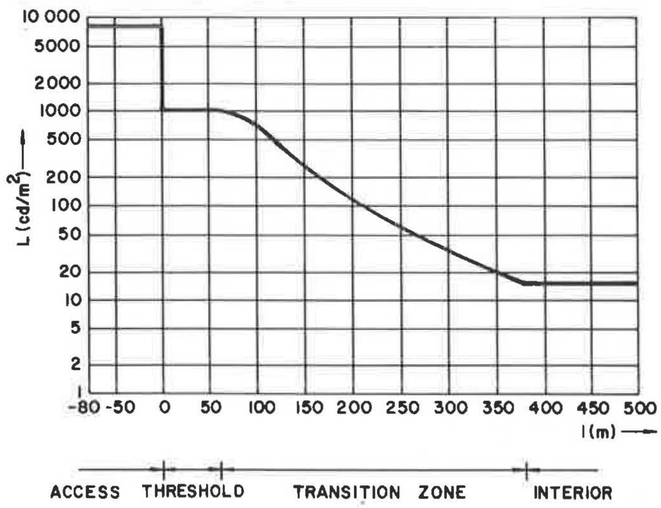


Figure 5. Ratio between L_1 and L_2.

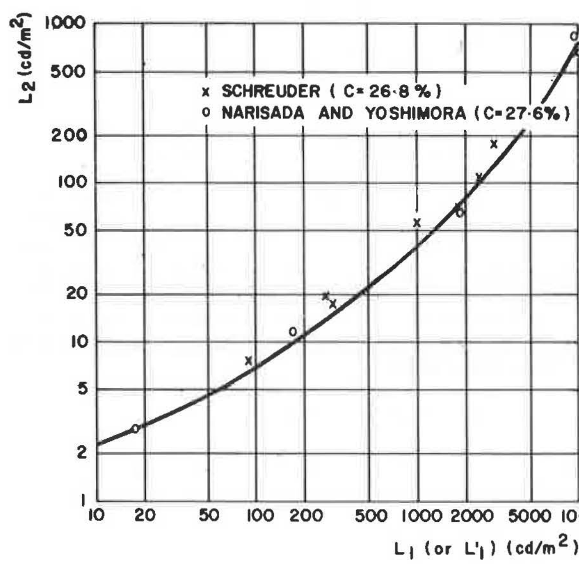
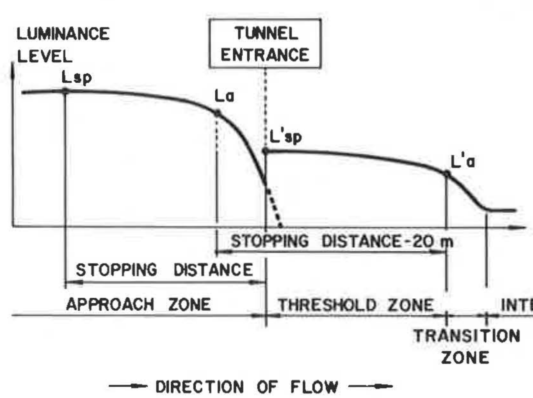


Figure 6. Recommended relation between Lsp and Lsp'.



tunnel was of particular interest to the investigators because of its similarity to the Thorold Tunnel (east-west orientation and the tunnel crossing a waterway).

The lighting system in the threshold zone for this tunnel is designed to provide the following lighting levels: 6200, 3000, 1500, 600, and 300 lx. With an outdoor illumination (L_1) of 48 000 lx, a brown compact car was observed in the tunnel interior from a distance of 100 m. The following table gives the results of the observations:

Lighting (lx)	Result
300	Car not visible in tunnel
600	Car not visible in tunnel
1500	Car barely visible
3000	Car clearly visible
6200	Visibility excellent, but improvement was not significant for observations on an overcast day

Observations and Measurements at Thorold Tunnel

The construction of the Thorold Tunnel, which crosses a shipping canal near St. Catharines, Ontario, was completed in 1968. It consists of two tubes, each carrying two-lane traffic, and has a posted speed of 72 km/h.

The initial illumination level (1968) in the threshold zone was approximately 1000 lx by using mercury vapor lamps for supplementary lighting and fluorescent lighting for the tunnel interior. In 1976, measurements were carried out at the tunnel site. A summary of the findings is given below:

1. The level of illumination in the threshold zone was measured at 300 lx. After cleaning the luminaires and relamping, the level was raised to 900 lx.
2. The visibility into the tunnel interior at the critical distances from the portal does not provide a 100-m safe stopping sight distance, particularly if the ambient luminance level is high (i.e., bright summer days).
3. Visibility distance is also reduced by a sharp vertical drop in the approach road (west end) and in the interior road alignment.
4. The white portal facing, which acts as a reflector in the morning at the east end and in the afternoon at the west end of the tunnel, has a negative effect on the driver's visual adaptation process.
5. The sun's low position in the morning and late afternoon penetrates the tunnel interior and interferes with the driver's vision.

After careful consideration of the results of the investigation, the following remedial measures were recommended to improve the existing conditions of the tunnel entrance and approaches:

1. The level of illumination in the threshold zone should be increased from the existing level of 900 lx to a maintained value of 3000 lx.
2. The tunnel portals at both ends should be treated with a dark, low-gloss paint.
3. When resurfacing of the approach roads is warranted, the concrete paving should be changed to a black high-friction type on the approaches and to a mix that has a high percentage of suitable white aggregate additive in the tunnel interior.
4. Planting suitable evergreens on the slopes near the entrance should be considered for the purpose of reducing reflectance of the snow-covered areas within the principal visual field.
5. Lighting equipment should be maintained in good operational condition.

SUMMARY OF DESIGN CRITERIA FOR NEW LIGHTING SYSTEM

As a result of the field measurements and observations, it was decided to redesign the tunnel-lighting system. In the process of establishing the design criteria for the new lighting system, the following factors were taken into account:

1. Traffic safety requirements (safe stopping sight),
2. Traffic operation requirements,
3. Possibilities of reusing existing lighting equipment,
4. Limitations in the existing transformer capacity,
5. Energy conservation,
6. Space limitations in the tunnel interior available for luminaire mounting,
7. Restriction in drilling of precast ceiling slabs and tunnel walls,
8. Need to wash the tunnel walls with high-pressure water hoses,
9. Pavement reflectance and skid characteristics, and
10. Maintenance factors and procedures.

From the visibility study by the Ministry of Transportation and Communications, Ontario, and Fenco, the requirement of the illuminance level for safe traffic operation in the threshold zone was determined to be 3000 lx. The total length of the threshold and transition zones was recommended to be 250 m. In order to meet the adaptation needs, it was necessary to design the system so that, for the first 80 m, the level was maintained at the same intensity of 3000 lx and the rest of the supplementary zone tapered off to meet the level of the tunnel interior lighting provided by the existing fluorescent lighting system. Supplementary lighting switching controls were implemented by photocell relays and arranged in three steps--3000, 2000, and 1000 lx. A review of the tunnel-type luminaires offered by the manufacturers and the light source analyses with respect to the efficacy and glare control led to conclusions that the most suitable source for this application was high-pressure sodium.

FIELD MEASUREMENTS OF ILLUMINANCE LEVELS: NEW SYSTEM

On November 30, 1979, field measurements were carried out at the tunnel threshold zone. The initial readings of illuminance levels are shown in Figure 7 (curve A). The estimated maintained illuminance level, with all luminaires energized (high level), is represented by curve B. Recommended values are indicated in curve C.

The values of maintained illuminance levels were arrived at by applying a maintenance factor of 0.4. Luminance readings were not taken at that time because the pavement resurfacing had not yet been carried out.

On April 1, 1980, a second field visit was made. The measurements of supplementary illumination indicated that the average level of lighting in the threshold zone dropped to approximately 5000 lx with all luminaires switched on. (The initial reading at the same location was 8000 lx. This indicates that the severe maintenance factor of 0.4 used in the calculation procedures is justified.)

SUMMARY OF OBSERVATIONS

On November 30, 1979, observations were carried out on the performance of the new lighting system, which included the following:

1. Observations of regular traffic flow and the patterns in change of speed, use of brakes, hesitation, and/or other irregularities at the Thorold Tunnel approaches and entrances;
2. The visibility conditions regarding eye adaptation from a moving vehicle;
3. Illuminance level measurements of the new supplementary lighting system; and
4. Photographic survey of visibility conditions at the approaches and tunnel interior.

From the observations and measurements conducted by a committee of lighting engineers, the following conclusions were made:

1. The new lighting system (at the time of observation) provides clear visibility into the tun-

Figure 7. Thorold Tunnel relighting.

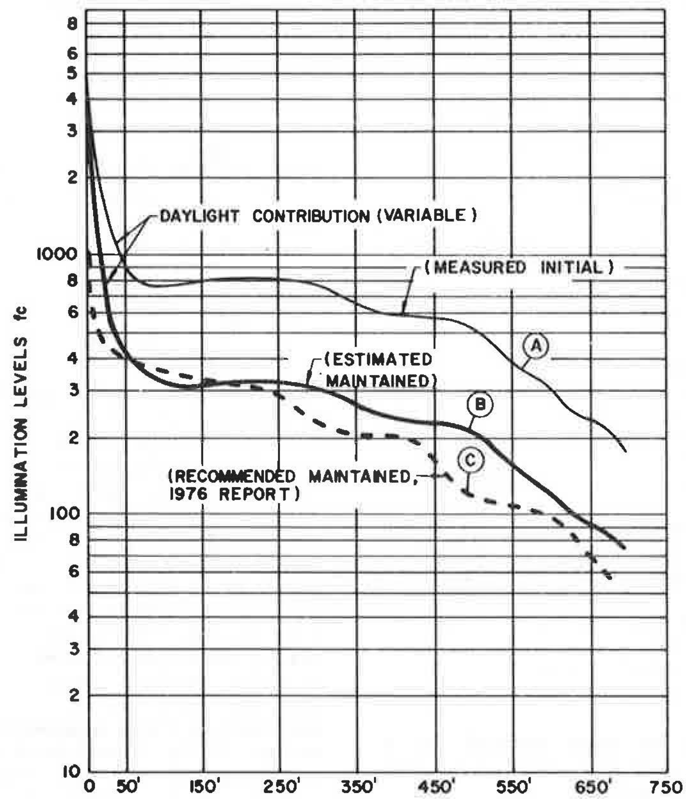
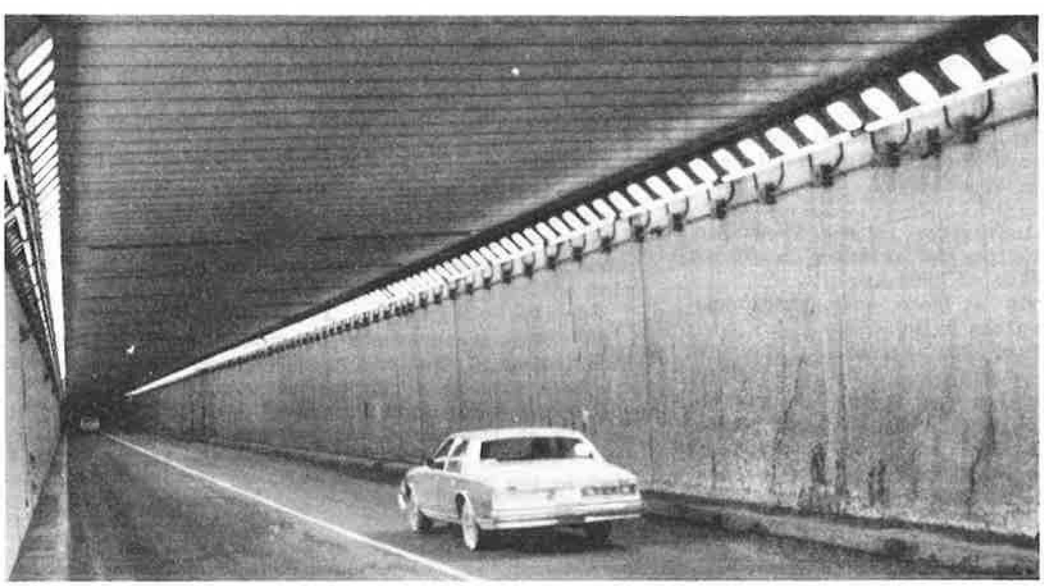


Figure 8. New lighting system in Thorold Tunnel.



nel, and an approaching driver with normal vision should have no problems in the eye-adaptation process (Figure 8) at the following lighting levels: L_1 = 68 000 lx and L_2 = 2600 lx; therefore, the L_1:L_2 ratio = 26:1.

2. The vehicles approaching the tunnel do not show any hesitation and very few drivers use their brakes at the tunnel approaches.

3. The new supplementary lighting system is acceptable from an aesthetic viewpoint.

4. The luminaire design features are compatible with tunnel operating conditions and maintenance procedures (i.e., washing with fire hoses).

5. The ambient (L_1) lighting level for this area exceeds 100 000 lx; therefore, with a maintained illuminance level in the threshold zone of the order of 3000 lx 95 percent of daytime, the ratio of L_1:L_2 is equal to 33:1. However, for short periods, the L_1:L_2 ratio may reach 40:1, but this is not considered too critical.

CONCLUSIONS

From the observations carried out at the Thorold Tunnel, it was concluded that a luminance level of 200 cd/m² or 3000 lx is adequate to secure clear visibility into the tunnel interior. On the very bright days of summer, therefore, the L_1:L_2 ratio may reach 40:1 without endangering the visibility conditions.

From these observations, it was learned that the value of the L_1:L_2 ratio changes with the increase of the L_2 value. At the lower ambient luminance levels (on cloudy winter days), the ratio between L_1 and L_2 should be lower (perhaps not exceeding 20:1). However, in the summertime when the L_2 value is higher, the ratio can reach 40:1.

In the design process, perhaps a ratio of 25:1 should be considered as reasonable and economically acceptable. It should be noted that this value also agrees with PIARC recommendations.

One further remark should be made regarding the basic principles currently used to describe tunnel lighting. The CIE and PIARC approaches refer to the ratio between L_1 and L_2 as the basis for tunnel-lighting design. Because the values of L_1 and L_2 are expressed in candela per square meter, it is desirable that the tunnel interior walls and pavement be painted as light a color as possible. However, the objects in the tunnel interior are seen by surface details; therefore, the most important lighting aspect should be vertical illuminance rather than the background luminance. The question then arises whether the current concept based on the ratio between L_1 and L_2 is correct. Perhaps a design based on vertical illuminance principles would offer a better assessment of visibility conditions in the tunnel interior.

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