ILLUMINATION DESIGN FOR VEHICULAR TUNNELS (ABRIDGED)

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1. Introduction

The decision to construct a tunnel for crossing a land obstacle is often dictated by economics or land usage policies, although aesthetic requirements may also play an important role, particularly in urban areas. On reaching a decision to build a tunnel it may appear that the basic problem is solved; however, as a result of such a choice other problems may be created.

Before selecting a tunnel for crossing waterways or mountains instead of other equivalent methods, the situation should be carefully analyzed in its proper perspective and assessment of tunnel functional operation regarding traffic safety must be made.

Visibility plays a particularly important role in the tunnel functional operation. It has far-reaching implications in its efficiency and overall traffic cost. The purpose of this paper is to analyze and compare the design methods offering solutions to the visibility problem and to explore the possibilities of improvements.

Many traffic engineers and highway administrators are still of the opinion that illumination of roads, bridges and even tunnels is an unavoidable nuisance, and adds little to the smooth traffic flow. Advocates of the opposite opinion often over-emphasize the importance of illumination and visibility, and are guilty of exaggeration. This is evident in some recent tunnel designs in Europe and on this Continent. There are cases where the use of so-called sun screens to improve visibility double the length of the tunnel and substantially increase the cost of the structure.

Without siding with any one of the extremists it is imperative to state that traffic conditions differ widely in a tunnel compared with the open highway, or a bridge. An accident in a tunnel may result in a chain of serious consequences, causing traffic breakdowns and sometimes endangering the lives of hundreds of motorists. It is therefore a necessity to accept that good visibility is one of the important aids in creating conditions where safe and efficient traffic functioning is assured.

2. Tunnel Functional Areas

For the purpose of assessment of visibility under widely varying day and night illumination conditions, it is advisable to identify specific functional areas related to the tunnel geometric arrangement (Fig. 1). These are the tunnel approaches, portal, interior and tunnel exit.

a) Considering the tunnel approaches with respect to visibility, vertical and horizontal road alignments, retaining walls, shoulders and various objects in the immediate surroundings should be appraised regarding their geometry and material characteristics.

The approach design should not only satisfy safe stopping sight distance, but it should also help the driver's eyes to accommodate to rapidly changing visibility conditions.

b) Tunnel portal geometry and materials are also very important, and greatly influence the motorist's eye adaptation process.

c) The tunnel interior layout has to be designed to satisfy sight distance requirements, visual field optics, noise control and ease of maintenance. Materials used for the walls and pavement should also be related to light reflective characteristics.

d) The exit needs to be identified not only as a geometric component, but also as one of the areas which calls for attention in the process of lighting level co-ordination between the interior and immediate exterior. Early morning and late afternoon sun positions may cause considerable visual difficulties at the exit.

3. Tunnel Geometric Design

Vertical and horizontal alignment of the tunnel tubes relative to approach road layout is of major importance when assessing the overall visibility conditions. For example, tunnels under rivers and canals normally take a sharp dip at the entrance, then level off for the required distance, and rise to the road level at the exit. In such a case, when approaching the entrance, the motorist will see the tunnel ceiling only up to the point where the vehicle reaches the crest of the hump near the tunnel portal. The ceiling, often poorly illuminated, offers little help to the approaching motorist's eye adaptation or guidance.

Vertical alignment in relation to approaches is basically different when a tunnel traverses a mountain. In such cases the tunnel interior pavement follows the approach road level. Under such conditions the motorist when approaching the tunnel entrance normally can see the floor and walls, assuming adequate illumination of the interior is provided.

The luminaire arrangement in the tunnel interior, as well as relative optics of the overall visual field, should be designed so that they help the motorist not only to obtain visual data for effective vehicle operation, but also provide adequate guidance through the facility (Fig. 2).

At certain periods of the day the sun may shine into the upturned tunnel entrance or exit. If the walls of the tunnel are glazed the sun may create considerable inter-reflections at the exit, preventing the motorist from identifying the tunnel outlines - see Fig. 3.

4. Traffic Characteristics & Illumination Levels

Traffic volume and speed are the basic parameters for tunnel lighting design. There is a great difference between a rural tunnel carrying local traffic of relatively low density compared with an urban facility carrying expressway traffic.

Urban conditions often limit the land availability, affecting the design of tunnel approaches. Merging or weaving traffic close to the tunnel portal often cannot be avoided. The quality of visual information at the tunnel portal under such conditions is much more critical.

Fig. 4 shows luminance levels suggested by the CIE Committee on Public Lighting. The levels of illumination shown can be used as a guide; however, the specific requirements for each tunnel lighting project should be determined according to the traffic density and speed. In practice, for speeds of 30 mph and 25,000 ADT supplementary lighting levels of the order of 150-250 fc may be acceptable. For speeds exceeding 30 mph, and with a volume higher than 25,000 ADT, levels of 400-500 fc are recommended.

Figs. 5 and 6 indicate the recommended levels of illumination adopted by the Roads and Transportation Association of Canada. Fig. 7 shows the luminance intensities recommended by the Japan Highway Public Corporation.

It is important to note that comparing CIE (Fig. 4) and Japanese (Fig. 7) recommendations there is a distinct difference between permissible ratios in approach luminance and tunnel threshhold zone. When CIE recommends the ratio of 10:1 Japanese permit approximately 40:1. Although theoretically these differences can be explained by the differences in the test parameters such as exposure time and contrasts of the test object in the tunnel interior, the basis for Japanese research and recommendations is perhaps closer to reality and actual tunnel illumination practice.

In order to satisfy most of these requirements for high speed and high volume tunnels, it is necessary to create levels of 400-500 fc by artificial means, employing a great number of luminaires installed on the tunnel walls or ceiling. High intensity sources would permit reduction in the number of units but the source glare may reach unacceptable limits.

Another solution for achieving successful eye adaptation is the use of natural light filtered through louvre type panels. In the following paragraphs the present design methods are reviewed and some improvements offered.

Sun Screen Method

One method of providing acceptable steps for eye adaptation at the tunnel entrance is the introduction of suitably designed sun screens as a method of light quantity control - see Fig. 8.

Sun screens normally consist of louvre type panels with rectangular openings of 10" to 15" and vertical or sloping walls - see Fig. 9. The depth of the louvre segments and orientation has to be co-ordinated with the sun's path in order to prevent direct sun rays from reaching the tunnel pavement or walls. Using high reflectance materials (aluminum or stainless steel) well designed louvres may permit up to 15% light penetration. However, the penetration does not depend on louvre geometric proportions only. Weather conditions - the content of moisture in the air, cloud formation and relative sun position - also have considerable influence.

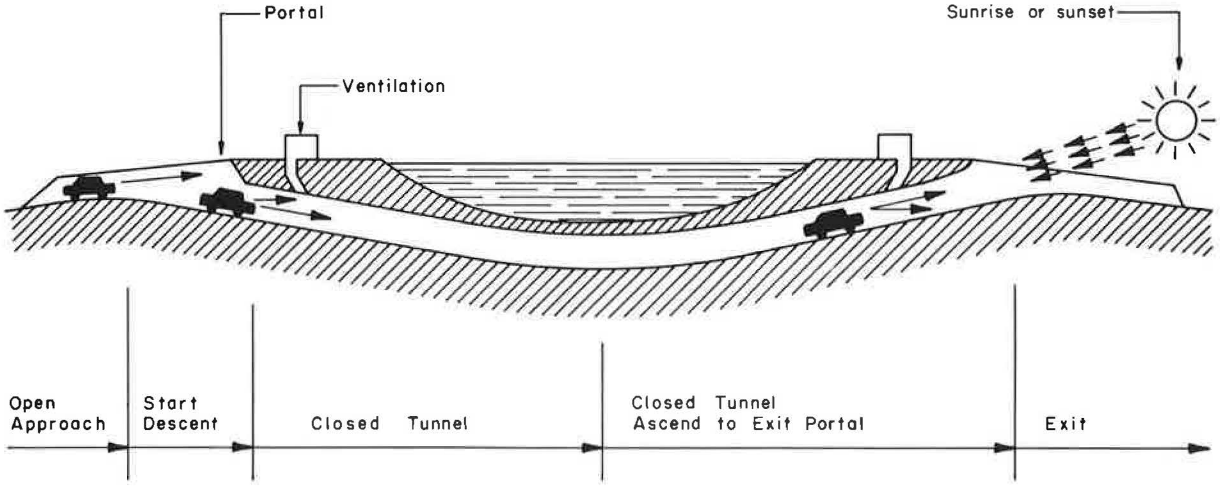

Figure 1. Tunnel functional areas.

Figure 2. Continuous luminaire rows provide guidance through tunnel (photo by Philips, Eindhoven).

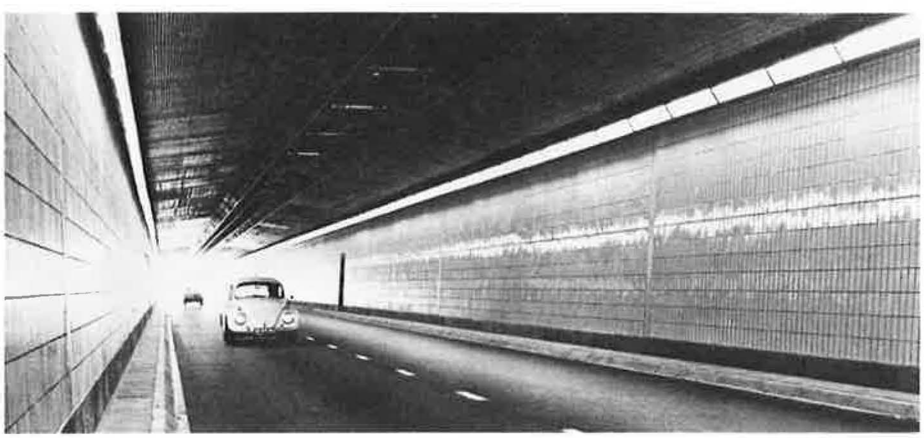

Figure 3. Glossy walls may cause difficulties in identifying tunnel outlines.

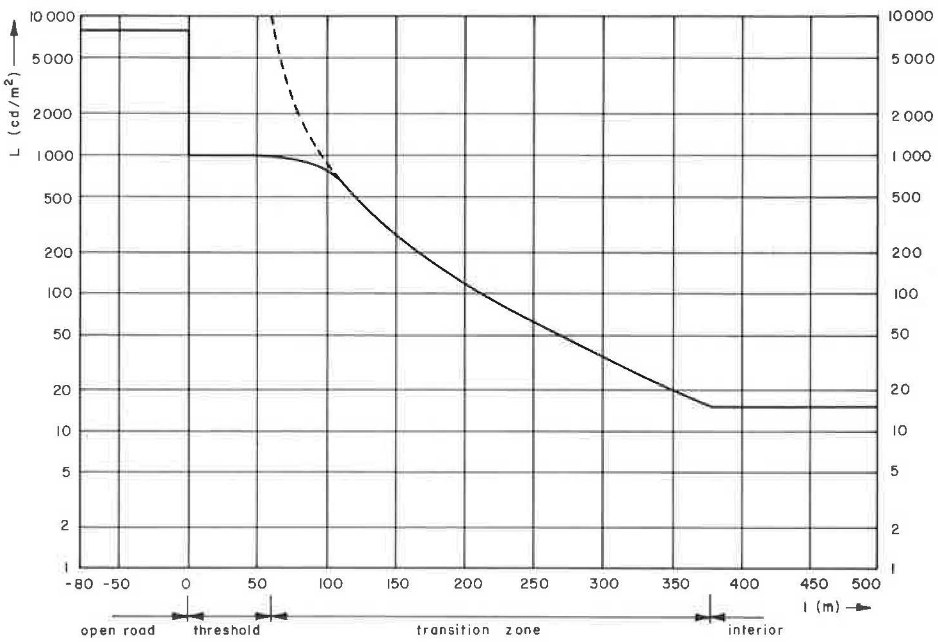

Figure 4. Proposed CIE tunnel entrance daytime luminance.

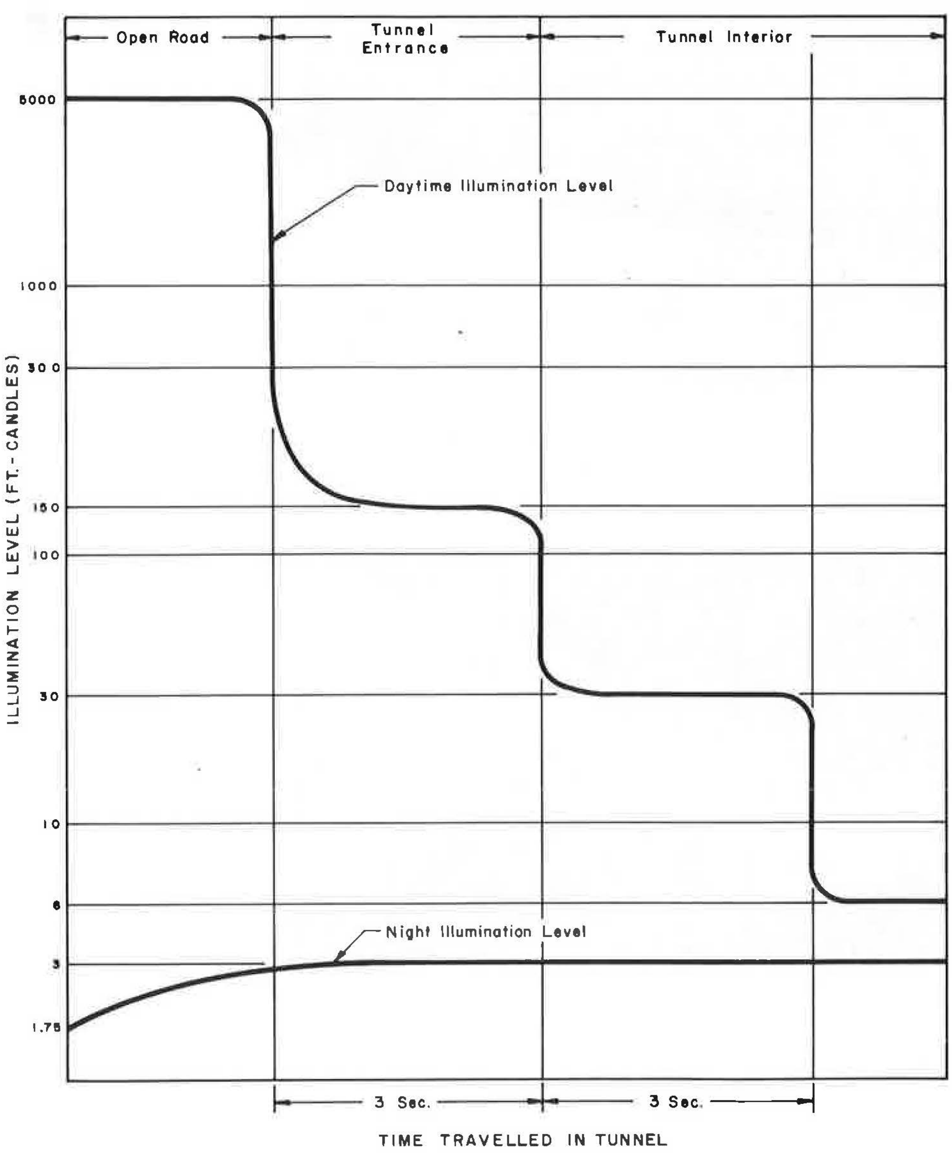

Figure 5. Typical illumination values for low speed, low volume tunnel entrances (RTAC).

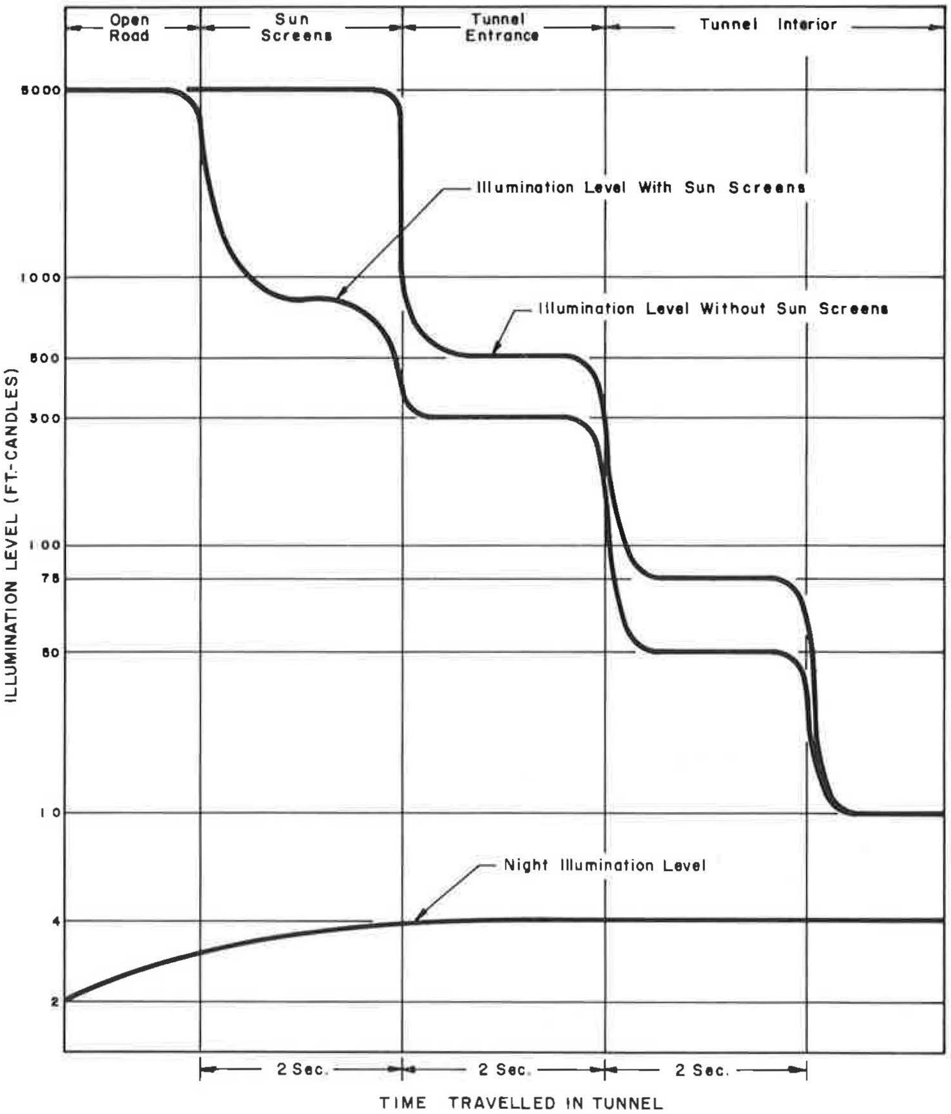

Figure 6. Typical illumination values for high speed, high volume tunnel entrances (RTAC).

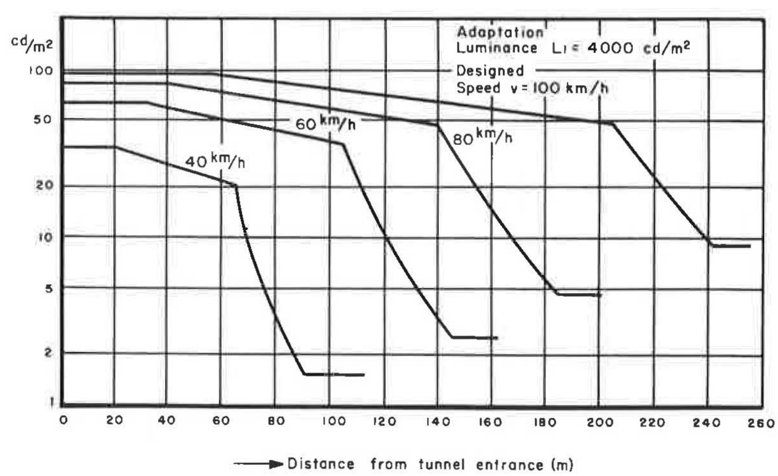

Figure 7. Tunnel entrance lighting curve (recommended by Japan Highway Public Corporation)

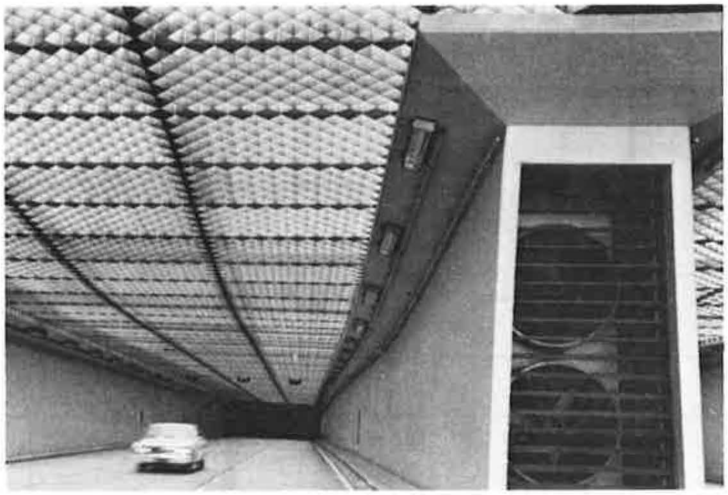

Figure 8. Sun screens are often used in Europe to provide smooth transition for eye adaptation.

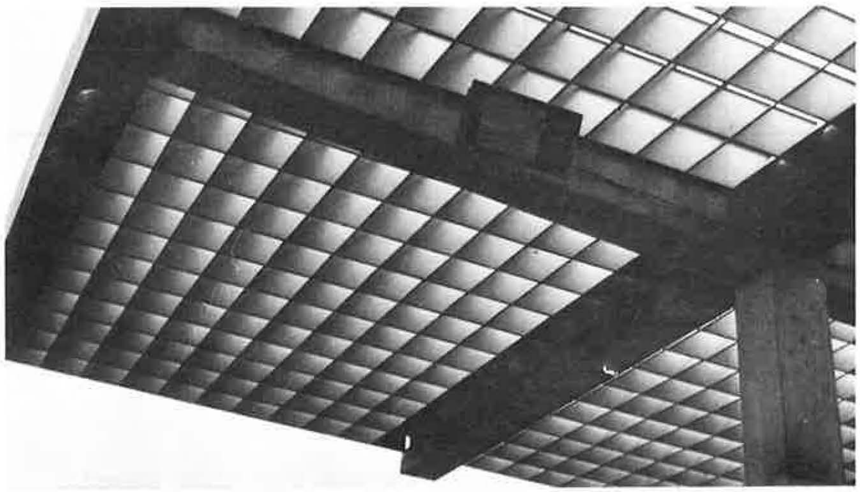

Figure 9. Sun screen detail.

Figure 10. Sun screens at the Schiphol tunnel entrance, Amsterdam (photo by Philips, Eindhoven).

Some of the latest tunnels (Coen, Benelux and IJ in Holland and La Fontaine, Quebec) are provided with such screens at both ends of the facility. Other tunnels (Schiphol) utilize sun screens only at the entrance (Fig. 10).

The pavement under the louvres should be provided with snow-melting equipment in areas where snow is a regular occurrence. It should be noted that in using sun screens there is a danger that freezing rain may accumulate ice on the louvre segments and, when thawing, will drop in large lumps through the openings, creating a traffic hazard.

The cost of sun screens is in the order of $10 to $15 per square foot. If such screens are used at both ends of the tunnel the overall expense may reach millions of dollars.

For night operation sun screens become an extension to the tunnel and therefore should be provided with adequate lighting. For tunnels in the range of 1000 to 2000 feet sun screens may add a substantial percentage to the overall length. Under urban conditions the use of sun screens is often restricted by the limited space available.

High Intensity Supplementary Illumination

In order to introduce an intermediate step between outdoor illumination and the tunnel interior a method of providing high intensity lighting at the tunnel entrance is often employed. This method is less expensive compared with sun screens. However, it requires mounting of multiple rows of luminaires on the tunnel walls and ceiling. High intensity sources such as mercury or high pressure sodium are not acceptable due to the high source glare, although smaller units may be tolerated if limited to 100 to 250 watts. On the other hand, using fluorescent lamps it is almost physically impossible to accommodate the number of luminaires required to reach a 500 fc level of illumination.

In such installations luminaire cleaning and relamping necessitate the use of maintenance vehicles, often creating a traffic hazard and reducing tunnel capacity. Due to the vulnerability of electrical wiring equipment, components mounted on the walls and ceiling prevent the successful use of mechanical cleaning vehicles in the tunnel interior.

Luminous Gallery Method

Good quality supplementary illumination at the tunnel entrance can be achieved by using high intensity light sources (mercury, high pressure sodium or metal hallide) if light beam intensities are dispersed before permitting them to enter the tunnel space. This can be accomplished by mounting luminaires behind translucent screens (Figs. 11, 12 and 13).

The screen material can be of the diffusing or refractorized type. The geometry of this arrangement may consist of a 6 ft x 3 ft walk-in gallery fitted in the upper corners of the tunnel. The advantages of gallery type illumination are such that in addition to increased visual comfort and motorist's guidance, the overall field optics can be successfully coordinated.

Maintenance of the tunnel walls is simplified and mechanical equipment such as rotating brushes may be successfully employed. Lighting equipment can be inspected and lamps changed without the use of vehicles. All work can be carried out from the gallery interior using electrician's tools only.

To make luminous galleries more effective, as an additional refinement in the design, the use of short sun screens is advisable (Fig. 14). Such an arrangement reduces contrasts between the tunnel interior and the portal by creating a shadow across the entrance opening and the entrance structure. In other words, it permits the motorist to view the entrance in the shade, thus increasing effectiveness of supplementary illumination.

The fume particles illuminated by the sun can result in a "screen" effect at the tunnel entrance. Short louvres in this case serve a double purpose. Firstly, they permit the exhaust smoke to rise through the screens and secondly, they prevent the fume from being directly exposed to the sun's rays.

The basic tunnel illumination may be provided by two continuous rows of fluorescent tubes on each side, with provision for dimming. This arrangement satisfies the general illumination needs for the tunnel interior - 10 to 12 fc for day and 4 to 5 fc for night. Two rows of luminaires on each side are recommended because of the required variety of intensities, and therefore switching combinations.

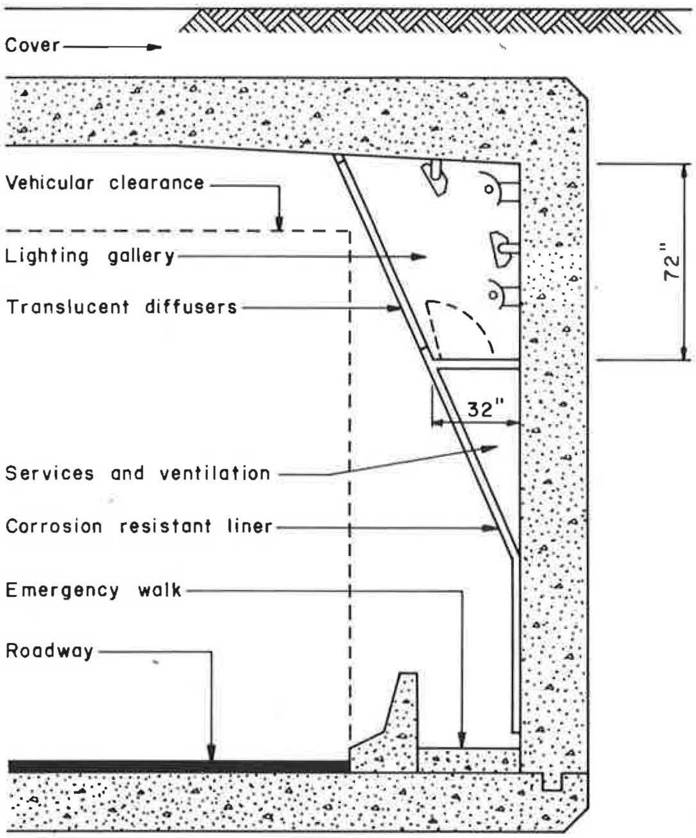

Figure 11. Surface mounted lighting gallery.

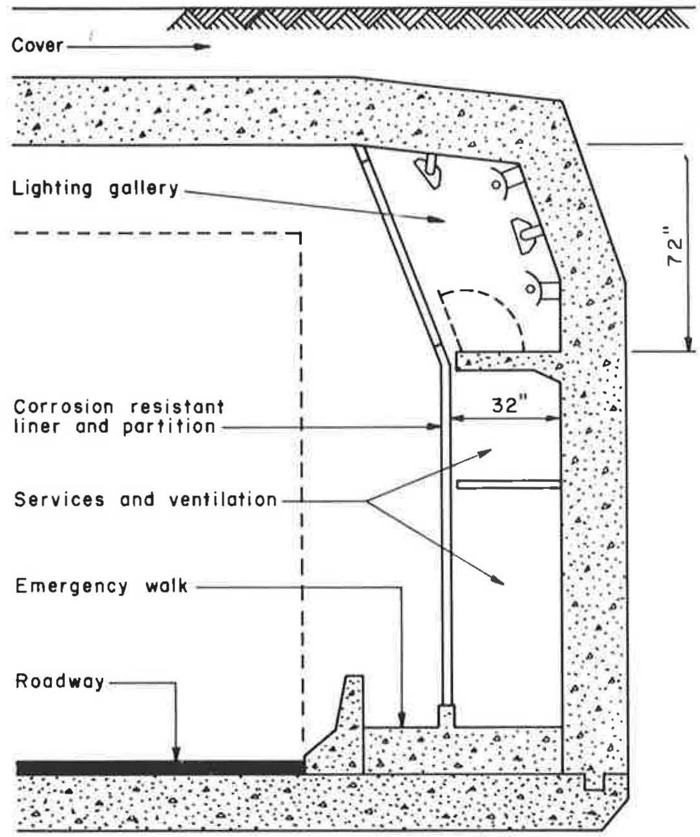

Figure 12. Semi-recessed lighting gallery.

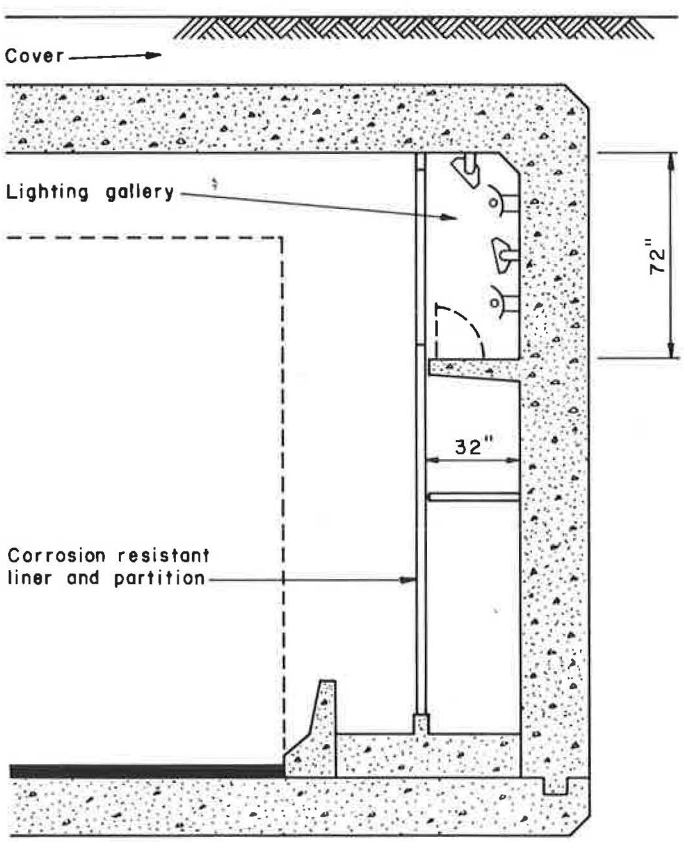

Figure 13. Recessed vertical lighting gallery.

Figure 14. William R. Allen Expressway (Toronto) Cedervale tunnel entrance (model).

Supplementary lighting in the adaptation zone of 150 to 800 fc may be achieved using high intensity lamps with simple reflector luminaires. The tapering off of the supplementary lighting can be accomplished by a combination of smaller sources and increase in luminaire spacing.

In connection with the William R. Allen Expressway development in Toronto, where three consecutive tunnels will be required within a stretch of 3 miles of road, a considerable amount of investigation has been carried out regarding the effectiveness of various types of tunnel illumination. After visiting a number of the latest tunnels in Europe and on the North American Continent, it was decided to use a somewhat new approach in tunnel lighting design - gallery type lighting appeared to be the most attractive solution. To test the feasibility of gallery type lighting a full scale model was constructed to take various readings and to make observations. This model contained two rows of continuous fluorescent lamps operated at 600 mA and 300 mA, and two rows of 400 watt mercury units spaced at 18" centres. Using this type of equipment it was learned that levels of illumination between 5 fc to 800 fc were feasible.

5. Visibility in the Tunnel Proper

The visibility problem is by no means solved by providing solutions for the tunnel entrance and transition zone. Once the motorist crosses the treated area he has to guide his vehicle through the tunnel safely and efficiently. The quality and characteristics of tunnel interior optics have specific significance, particularly with respect to co-ordination of its components.

Intensities of brightness within the visual field require co-ordination to avoid extremes in contrasts without sacrificing the motorist's guidance. For example, excessively bright luminaires mounted on a black ceiling may produce such extreme conditions. Black asphalt pavement, with high reflective wall treatment may also create poor visual environment. It is therefore desirable that brightness of walls, as well as pavement colour and texture, are brought into a reasonable scale of contrasts. Luminaire arrangements that may generate flickering frequencies of 3 to 18 cycles should be avoided. Brightness uniformity of the walls and pavement should be at least 2:1 or better.

In order to avoid specular glare low gloss wall textures are recommended. Ceramic materials or metallic panelling with a plastic coating, or high durability paints are most suitable for such applications. Paints applied on concrete walls often prove to be unsuccessful.

The tunnel pavement should have high reflectance characteristics combined with high friction requirements for safe stopping. To enhance reflective qualities natural baked flint used in England, or equivalent artificial materials employed on some European projects, can be used. Concrete, with the same additives, would perhaps produce almost ideal tunnel pavement material.

6. Visibility at the Tunnel Exit

Under day or night conditions the motorist leaving a tunnel will experience a new visual situation, often opposite to that at the entrance. Eye adaptation during the day will require adjustment from low levels in the tunnel interior to high intensities on the open road. The process of upward adjustment of the eyes, however, is considerably faster. Before the motorist leaves the tunnel his eyes are already partly adjusted to the new levels of illumination due to the fact that the high brightness at the tunnel exit begins to influence his vision while he is still some 600 feet from the exit (Fig. 15). For this reason louvres or supplementary artificial illumination at the exit are not effective and not justified in most cases.

At night the tunnel interior is illuminated at levels of 3 to 5 fc; however, the road lighting is often only 1 fc or even less. To reduce the step at the tunnel exit it is recommended that the road night illumination level is increased to approximately 3 fc, and then tapered off to a normal level within a range of 1500 feet.

7. Conclusions

Tunnels built in recent years in Europe and on this Continent vary considerably in respect to treatment of threshhold and transition zones, as well as the tunnel interior.

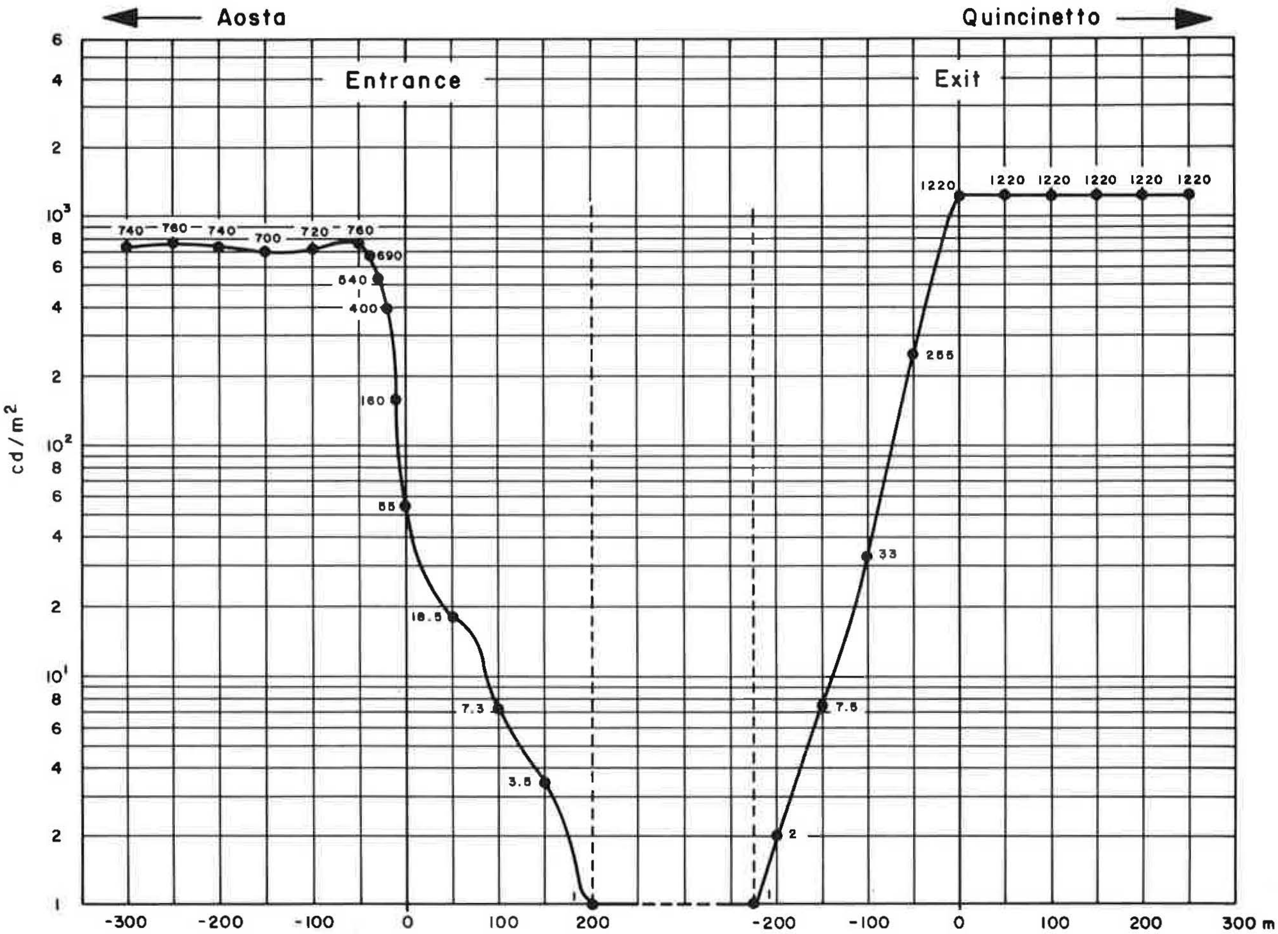

Figure 15. Luminance readings, Hone tunnel, Italy (by Dr. M. Bonomo).

Some of these tunnels employed the sun screen method to solve the visual adaptation problem, resulting in a substantial addition to the length of structure and increase in cost. Others simplified the visibility requirements to such an extent that a single fluorescent tube is provided on each side of the tunnel, with little or no additional lighting at the portal. Again, other authorities recognized the seriousness of the visibility problem at the tunnel entrance and designed tunnels using multiple rows of fluorescent tubes or a combination of fluorescent and mercury or fluorescent and sodium sources.

The arrangement suggested in this paper to use the luminous gallery method, with short louvres at the portal, perhaps offers solutions to many aspects of this complicated problem. The possibility of using higher intensity sources by diffusing the concentrated beams, co-ordination of overall visual field components, pleasing architectural appearance, flexibility in switching, ease of maintenance - these are only a few of the advantages offered by this system.