Tunnel Lighting Systems

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ABSTRACT
The significant light contrast between daylight and tunnel luminance causes motorists to slow down as they approach the tunnel entrance. This phenomenon, known as the “black hole” effect, can be minimized by providing enough light at the immediate tunnel entrance, or the threshold zone to allow time for eye adaptation. The goal is to create a lighting system that facilitates constant traffic volume and speed throughout the road and into the tunnel entrance during daylight hours.

KEYWORDS: tunnel lighting system, safety, economical design

INTRODUCTION
There are benefits for using both asymmetrical and symmetrical lighting systems depending on distribution factors including ambient luminance, geographic location, structure of the tunnel, and traffic speed and volume. All factors must be analyzed to develop the appropriate tunnel luminance level criteria. In design practice, tunnels are divided into three zones: threshold, transition(s), and interior.

LIGHTING SYSTEMS
The linear symmetrical lighting using fluorescent luminaires distributes similar patterns in all directions to create a uniform luminescence throughout the tunnel. Figure 1 shows the shape of distribution with low contrast values.

Figure 1 Symmetrical Lighting Distribution [1]
Asymmetrical (directional) lighting such as counterbeam and probeam lighting distributes patterns only in one direction, either with or against traffic. Counterbeam lighting (Figure 2) directs the maximum candlepower against traffic at the driver’s line of vision, creating a high negative contrast. By minimizing glare, drivers can clearly see the contours of the vehicle ahead. Probeam lighting (Figure 3) directs the maximum candlelight with the traffic away from the driver providing high object luminance and low road luminance, creating a positive contrast. This system operates by minimizing luminaire glare and increasing distance visibility.

Figure 2 Asymmetrical Counterbeam Lighting Distribution [1]

Figure 3 Asymmetrical Probeam Lighting Distribution [1]
LUMINAIRE AND LIGHT SOURCES
According to the USDOT Federal Highway Administration, fluorescent lights produce a more uniform lighting distribution than point source lighting. Benefits of fluorescent lamps are quick startup and high color rendering. However, their large size makes it hard to maintain; and lamps with longer life require special and expensive ballasts. Traditional fluorescent lamps have a low efficacy (lumens/watt); more lights are required to create the same light levels as other lamp sources. In addition, it’s large size and vulnerability causes maintenance to be difficult and expensive.
Since current U.S. standards require high luminance levels at the threshold zone, point source lighting is preferred over linear lighting. Point source lighting can easily be controlled and redirected, and more efficacious lamps are available. Common types of point source lighting are high pressure sodium lamps and metal halide lamps. High pressure sodium lamps have many advantages such as longer lamp life, minimum lumen depreciation, and small lamp size. Their use though, is limited by lamp cycling and poor color rendering. Metal halide lamps provide white light with good color rendering and cool appearance, high efficacy, and long lamp life. These lamps are suitable for recessed downlights and low mounting heights.
Although point source is the preferred system for tunnel lighting, its discontinuity creates the “flicker effect” caused by periodic luminance changes and the spacing of luminaires. This can be reduced by adjusting the luminaire spacing outside of the annoyance range (Figure 4).

![Figure 4 Annoyance zone for Flicker](image)

FACTORS AFFECTING THE PERFORMANCE OF THE LIGHTING SYSTEM
The design luminance is based on the length of time for the driver’s eye to adapt from ambient light to light at the threshold zone. Sufficient illumination must be provided to mitigate the “black hole” effect which obstructs a driver’s view at the threshold during daylight hours. Factors must be taken into account when designing an ideal lighting system. Varying road surfaces influences luminance values and the speed of traffic affects lighting levels. The amount and angle at which the sunlight enters the tunnel in accordance to the roadway’s compass direction must also be taken into consideration. The quality, type, maintenance requirements and average annual daily traffic volume are critical in the selection of the lighting system.

TUNNEL ZONES

![Figure 5 Recommended Luminance Reduction for Threshold and Transition Zones](image)

Schematic representation of lighting level in the various zones

\[ L_{E} = L_{B} \cdot (1.9 + t)^{-1.4} \]

with \( L_{B} = 100\% \)

\( t = \) time in second
Lighting levels are gradually reduced in sequential zones within the tunnel comprising of the threshold, transition, interior, and exit zones. The calculated curve in Figure 5 (adapted from CIE 88 2004, Figure 6.6) demonstrates the appropriate step down lighting levels for each zone. Steps must never fall below this curve. Point source lighting is used to appropriately reduce luminance levels to save energy and assist in eye adaptation for motorists.

Areas to be considered in tunnel lighting design are shown in Figure 6.

**Lighting Level Criteria**

RP-22-10 presents two methods of obtaining threshold zone luminance values either from Table 1 or by using the $L_{\text{seq}}$ equation:

1) **Table 1 Threshold Zone Luminance**

<table>
<thead>
<tr>
<th>Approach/Method</th>
<th>Speed</th>
<th>Left</th>
<th>Right</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Road</td>
<td>100</td>
<td>120</td>
<td>300</td>
<td>370</td>
</tr>
<tr>
<td>Zone 5.2.3</td>
<td>50</td>
<td>120</td>
<td>180</td>
<td>300</td>
</tr>
<tr>
<td>Urban Tunnel</td>
<td>100</td>
<td>120</td>
<td>180</td>
<td>300</td>
</tr>
<tr>
<td>Zone 9.2.6</td>
<td>50</td>
<td>120</td>
<td>180</td>
<td>300</td>
</tr>
<tr>
<td>Highway</td>
<td>100</td>
<td>120</td>
<td>180</td>
<td>300</td>
</tr>
<tr>
<td>Zone 7</td>
<td>50</td>
<td>120</td>
<td>180</td>
<td>300</td>
</tr>
</tbody>
</table>

2) **$L_{\text{seq}}$ Method**

   \[
   L_{\text{seq}} = 9.2 \sum_{i=1}^{n} \frac{E_i}{\theta_i^2}
   \]

   where:
   - $L_{\text{seq}}$ = equivalent veiling luminance in cd/m²
   - $E_i$ = illumination at the eye produced by glare source $i$ in lux
   - $\theta_i$ = angle between fixation line and glare source $i$ in degrees

   This formula serves as the basis for the development of a polar diagram with 10 rings divided by 12 sections. This diagram is superimposed on a tunnel portal in Figure 7.

**Pavement luminance for threshold zones of tunnels can be mathematically determined using the tunnel portal luminance and the formula above.**

**Table 2 Daytime Interior Zone Levels**

<table>
<thead>
<tr>
<th>Traffic Speed</th>
<th>Traffic Flow</th>
<th>Low ≤ 2,400 AADT</th>
<th>Medium &gt;2,400 AADT ≤24,000 AADT</th>
<th>Heavy &gt; 24,000 AADT</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 km/h (60 mph)</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>80 km/h (50 mph)</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>60 km/h (40 mph)</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

*AADT = Annual Average Daily Traffic

**Transition zone** luminance is calculated by gradually stepping down the luminance levels in Figure 5. Recommended average luminance for interior zone is shown in Table 2. Values are dependent on traffic speed and average annual daily traffic (taken from RP-22 [1]).

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Figure 6 Vehicular Tunnel Topology

Figure 7 Polar Diagram Superimposed on a Tunnel (Letters represent measured luminance levels)
Exit zone lighting is used where additional hazards are expected near the exit of the tunnel and in tunnels where the interior zone is long. CIE-88 recommends that daytime luminance increase linearly over a distance equal to 1 SSSD before the exit portal. Over this interval, lighting levels are to be gradually increased to five times of the interior zone 20 meters from the exit portal. RP-22 requires the designer to review and determine the necessity of the exit zone with the tunnel operator. The recommended nighttime lighting luminance throughout the tunnel is a minimum of 2.5cd/m² by a consensus of experts. Emergency lighting is used in the event of failure in the normal lighting power supply. It is recommended that an emergency non interruptible power supply be installed to maintain the normal nighttime luminance level throughout the tunnel.

TUNNEL LIGHTING DESIGN SOFTWARE
Commonly used 3-D lighting software packages, such as AGI32, perform computations and analyses of luminaire values for lighting designs. Formulas used are the Major Threshold Lighting Calculation and the $L_{seq}$ Method. Luminance at a particular location is calculated by a sum of contributions from all luminaires and test points (Figure 8) on road surfaces.

![Figure 8 Luminance measurements on tunnel road surfaces – test points](image)

CURRENT LAMP TECHNOLOGIES, DAYLIGHTING ANALYSIS AND MODELING
LEDs and electrodeless lamps are newer technologies on their way to be potential future tunnel lighting systems. LEDs are semi-conductor diodes that convert electrical energy to visible light and are able to produce many colors without color filters. They operate on low voltage, have high efficacy, and instantly turn on. However, LEDs are not yet suitable for tunnel lighting because of their complex setup, and inconsistencies in color, lamp lives, and efficacy. Electrodeless lamps run on a combination of induction and gas discharge with a high color rendering white light. These lamps have a longer lamp life due to the lack of filaments and the use of magnetic induction. Two types of electrodeless lamps in the United States are the Icetron™ and QL™ Induction Lamp. Instead of the use of electrodes, the Icetron™ produces light with the excitation by a radio frequency magnetic field. In a QL™ Induction Lamp, the core and coil power coupler produces a magnetic field which is then used to activate a secondary electrical current in a mercury vapor contained inside a bulb. Daylighting is the use of natural sunlight. In tunnels, luminaire use would be reduced by opening up the tunnel roof to allow sunlight in. The issues involved with the use of daylighting would be shadows, insufficient lighting and difficulty in guiding the sunlight.

SUMMARY AND CONCLUSION
Tunnel lighting systems are constantly being improved with new technologies, techniques, and breakthroughs to ensure a safe and comfortable driving environment. The design for the ideal tunnel lighting system should include understanding symmetrical and asymmetrical lighting; the various luminaires and light sources; factors affecting the performance of the lighting system; the different tunnel lighting zones; 3-dimensional modeling; and current lamp and ballast technologies.

REFERENCES