DESIGN CRITERIA FOR TUNNEL LIGHTING

Huo-Yen Liu

1. INTRODUCTION

There are many mountains in the longitudinal center of Taiwan, which slow down transportation between the west and east in Taiwan. In order to solve this problem, Taiwan's government decided to build a highway and an expressway between these two areas, which would include tunnels as part of the project because tunnels are more dangerous than the open road, how to safely enter, pass and leave tunnels is very important when tunnel projects are issued. Therefore, tunnel lighting is the first step towards providing safety.

The most dangerous part of a tunnel is the access zone, because the driver's pupils can't immediately adapt to the darker area when the driver enters the tunnel.When this happens, the driver can't see any obstacles in front of him. So proper lighting must be installed in the access zone to help the driver adapt to the darker zone. The method for determining the brightness in an access zone was issued by the CIE (International Commission on Illuminance) [2]. In addition, the CIE also issued recommendations on uniformity, glare control and flicker to enhance lighting quality in tunnel interiors[3],[4].

The brightness of a tunnel is its luminance. The calculation of a tunnel's luminance is not only dependent upon the intensity of it's lighting, but also on the road type and the observer's location. This is unlike the calculation of illuminance, which is just calculated by measurements at certain points and lighting fixture positions. On the other hand, the source of light illuminating a road is called illuminance. When it is reflected into an observer's eyes, the observer's eyes feel the intensity of the light as luminance. Even though the formula for calculating luminance is simple, it has to be calculated many times in order to verify it's accuracy. In order to get a speedy design result, we have developed a program to calculate luminance according to the CIE technical report [3].

2. TYPES OF LIGHTING SOURCE

There are four types of light sources used in tunnels: fluorescent, high pressure sodium, low pressure sodium and high pressure mercury. The characteristics of each type are different. Some have high color rendering but low luminous efficacy and others have high luminous efficacy and low color rendering, but none have high color rendering and high luminous efficacy. Also, the higher the luminous efficacy, the greater the impact on cost.

Before we decide on how to design tunnel lighting, we should understand all types of tunnel lighting sources and they are described as follows:

2.1 Fluorescent Lamps

A fluorescent Lamp is a low-pressure mercury discharge lamp in which light is produced predominantly by fluorescent powders activated by the ultraviolet energy of the discharge. It provides for a good colour rendering index which is between 80% and 90% and a good luminous efficacy of up to 90 lm/W.

2.2 Low-pressure Sodium Lamps

The principle of how low-pressure sodium lamps work is similar to that of fluorescent lamps. However, the light of low-pressure sodium is produced by directly converting ultraviolet radiation from the sodium discharge

Table 2-1 Performance Comparison of Tunnel Lighting Sources

Feature / Type	Luminous Efficacy (Lm/W)	Lumen Range (Lumen)	Watt Range (W)	Life (hr)	Colour Rendering (Ra %)
Fluorescent	50~90	1,100~ 15,500	20~200	25000	80~90
Low-pressure Sodium	130~200	4,550~ 32,500	35~180	16,000~ 20,000	Non-existent
High-pressure Sodium	80~125	1200~ 125,000	150~ 1,000	20,000~ 24,000	23~60
High-pressure Mercury	40~60	1,800~ 58,000	50~ 1,000	7,500~ 20,000	65~85

into visible radiation, not from mercury discharge. Because low-pressure sodium lamps just produce the characteristic monochromatic yellow light with a wavelength of 589 nm, their colour rendering is not so good. The color of the light is between yellow and red, but they do provide for a high luminous efficacy of up to 200 lm/W.

2.3 High-Pressure Sodium Lamps

These are composed of air-tight inner and outer tubes. The inner tube is a transparent tube with sodium, and the outer tube can be of two types: ovoid and tubular. The ovoid has an internal coating with a diffusing layer of white powder. The tubular type is always made of clear glass. The colour rendering is up to 85% which is better than low-pressure sodium lamps. The luminous efficacy is 130 lm/W and above.

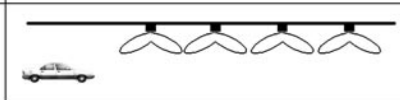
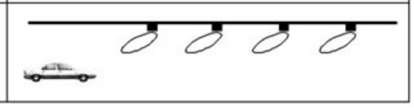
2.4 High-Pressure Mercury Lamps

These work similar to high-pressure sodium lamps. The main difference is that the sodium discharge is replaced by a mercury discharge or a halogen metal. The vaporized metal produces light. These provide for a fair colour rendering, but have a poor luminous efficacy of about 60 lm/W.

Some features of the abovementioned light sources are shown in table 2-1. From this table, you can see that the best luminous efficacy is from a low-pressure sodium lamp although it has poor colour rendering, and the best colour rendering is from a fluorescent lamp but it has poor luminous efficacy. The luminous efficacy and colour rendering of high-pressure sodium and mercury lamps are between that of both types of lamps. Generally, the life of a fluorescent lamp is 4,000~8,000 hours. However, table 2-1 shows a life of 25,000 hours for a fluorescent lamp.. This longer life is due to the lower switching frequency. Fluorescent powder is lost as a result of switching the lamp on so decreasing the frequency of switching the lamp on and off will extend the life of the fluorescent lamp. Therefore, when a fluorescent lamp is applied to the interior of a tunnel and the switching frequency is only once per day or less, the life of a fluorescent lamp will not be less than an HID lamp.

3. TUNNEL LIGHTING SYSTEMS

Table 3-1 Tunnel Lighting System

Typical light distribution of the luminance	
Transverse	
Longitudinal	
Counter-beam	

The lighting systems employed in tunnels are characterized by three types of light distribution: transverse, longitudinal, and counter-beam as shown in Table 3-1. The transverse and longitudinal light distributions are often referred to as symmetrical, while the counter-beam system is a clear example of asymmetrical lighting.

3.1 Transverse System

The light is radiated mostly perpendicular to the axis of the tunnel. The most familiar example of transverse lighting is the continuous line of tubular fluorescents as shown in Figure 3-1. The advantages of this system are the good visual guidance, minimal glare, light penetration between vehicles, and simple switching. Its disadvantages are the close luminaire spacing and that it has the highest power consumption of all the different types of light sources with the same average luminance requirement. It is suited for central placement, because its light can be distributed to both sides of the road and it provides for good visual guidance to clearly separate the two lanes of the road.

Figure 3-1 Transverse Lighting System

Figure 3-1 Longitudinal Lighting System

3.2 Longitudinal System

The light is radiated more parallel to the tunnel axis as shown in Figure 3-2. This type can use high-pressure sodium or mercury lamps. The advantages of this system are the high luminous efficacy and the bigger luminaire spacing that results in a power consumption savings. Disadvantages are the poor uniformity which could possibly result in shadowing and uneven wall luminance, and the fact that night-time switching involves twin-lamp luminaries. It is suited for opposite and staggered arrangements which have two parallel lines of lighting fixtures that can mutually cast light on the center of the road, so it can focus light on the axis of the tunnel to improve uniformity.

3.3 Counter-beam System

The light is radiated parallel to the tunnel axis against the direction of traffic flow as shown in Figure 3-3. Objects on the road are seen in negative contrast. It produces a high L/Ev value and gives relatively high contrast values for most objects on the road. This system demands a lower threshold zone luminance than does the symmetrical lighting system which will be described in Section 5.2. and this is the main advantage of counter-beam lighting. Disadvantages are that the tunnel entrance is darker and that can lead to a feeling of insecurity for approaching drivers, the risk of larger vehicles shadowing smaller vehicles, and dark and uneven wall luminance.

Figure 3-3 Counter-beam Lighting System

4. ZONES FOR TUNNEL

In order to avoid encountering the black-hole effect when approaching the portal of a tunnel and to help drivers adapt to the lighting environment in a tunnel, there are six lighting zones distributed throughout a tunnel. In this section we will discuss each zone's characteristics and particular type of vision problems.

4.1 Access Zone

This is located in the front of the tunnel portal. The brightness around this portal will affect the driver's eyes in adapting to the level of lighting in the tunnel and his recognition of an obstacle when approaching the tunnel portal. The length of this zone is usually within stopping distance of maximum speed, and the luminance is represented by L20.

4.2 Threshold Zone

This zone is from the portal to a proper distance inside the tunnel and still for detecting obstacles in the threshold zone. The length of this zone is dependent upon the speed of the traffic and should be equal to the corresponding stopping distance. This is because the driver must have enough time to react and stop his vehicle when he sees an obstacle in the road in front of him. The luminance is represented by Lth.

4.3 Transition Zone

This zone extends from the threshold zone. The purpose of this zone is to transition from a higher lighting level to a lower lighting level in the interior zone which makes drivers gradually adapt to the lighting environment in the tunnel following pupil changes in the driver's eyes. The length of this zone is a function of time, and begins from Lth and ends at the luminance of the interior zone. The luminance is represented by Ltr.

4.4 Interior Zone

Basically, this zone is the farthest from the tunnel portal influenced by daylight. Here the driver's vision is controlled by the artificial lighting in the tunnel. This zone provides a fixed luminance throughout because adaptation is not necessary. The requirement for luminance is dependent upon the traffic speed and density, and it is represented by Lin.

4.5 Exit Zone

This zone is the zone at the end of the tunnel, and will be influenced by the brightness outside of the tunnel which results in changing the driver's visual adaptability when he approaches the exit area. The problem is that a larger car will block sunlight coming from the outside to the inside which will affect the driver's ability to detect a car in front of him when seen against the dark silhouette of the larger vehicle farther ahead. The luminance is represented by Lex.

4.6 Conjunction Zone

This zone extends outwards from the exit zone. It provides road lighting for connecting the tunnel to the open road at night. The problem is that when the drivers leave the tunnel at night, they could encounter another black-hole effect upon entering this zone without any road lighting system installed and operational. The luminance is represented by Lco.

The zones for unidirectional tunnels and the luminance curve are shown as Figure 4-1. In the next section we will discuss how to decide on a proper luminance and length for each zone.

5. DETERMINATION OF LUMINANCE AND LENGTH

The purpose of having enough lighting in a tunnel is to ensure a driver's safety and his ability to comfortably pass through the tunnel during daytime or nighttime. The first requirement is to let drivers recognize obstacles in front of them when they enter a tunnel. The second requirement is to maintain the driver's field of vision. This will allow the driver to not have to slow down his vehicle due to the sudden change in light when entering the tunnel and to prevent accidents from happening.

5.1 Access Zone

The determination of the luminance to which a driver's eyes are adapted to as he approaches a tunnel is fundamental to the calculation of the correct luminance in the threshold zone. The luminance is decided by the brightness detected in the environment of the tunnel portal which is influenced by the portal direction, the percentage of sky in a conical view of 20 degrees from the stopping distance ahead and at a height of 1.5m, seasonal changes and reflectional factors against the background of the portal. L20 can be determined from Table 5-1 and the detailed descriptions are

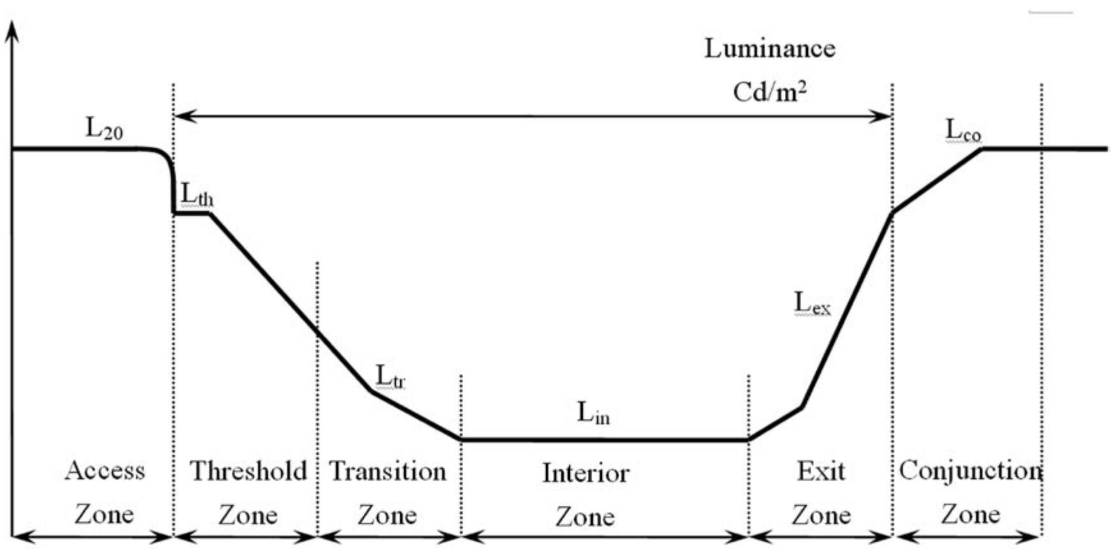


Figure 4-1 The tunnel zones defined for the purpose of lighting design.

Table 5-1 Access Zone Luminance

Percentage of Sky in 20 Degree Cone of View(kcd/m²)								
Stopping Distance (m)	35%		25%		10%		0%	
	normal	snow	normal	snow	normal	snow	normal	snow
60	-	-	4~5	4~5	2.5~3.5	3~3.5	1.5~3	1.5~4
100~160	4~6	4~6	4~6	4~6	3~4.5	3~5	2.5~5	2.2~5

referenced from [2].

5.2 Threshold Zone

This luminance is determined by L20 described above and calculated from the Lth/L20 ratios K which are shown in Table 5-2 according to the lighting systems. The stopping distances in Table 5-2 are dependent upon traffic speed and road gradient plus the driver's reaction time. We can find a stopping distance by using the formula SD=(V/10)2+3*(V/10) on a dry road and SD=(V/10)2+6*(V/10) for a wet road, or refer to Table 5-3 [5] to find a proper stopping distance from the corresponding designated traffic speed and gradient on a wet road. If the stopping distance is different from that in Table 5-2, we can use linear interpolation to find the exact value K for a corresponding stopping distance. For example, when the stopping distance is 130m, the ratio K is equal to 0.06.

The length of the threshold zone must be at least equal to the stopping distance. In the first half of this distance, the luminance must be equal to Lth. After the first half of the distance, it can be gradually decreased to 0.4 Lth. From the design view, it has to be above the curve shown in Figure 5-1. That means we usually set this vale at 60~80% of Lth, in order that real change in luminance can follow the curve tracing shown in Figure 5-1. The following procedures will show step by step how each zone will decrease its luminance in order to gradually match the interior lighting level, and each step in luminance ratios should not be more than 3:1.

5.3 Transition Zone

The end of the threshold zone is the beginning of the transition zone. That means the luminance at the first transition zone is 0.4 Lth, which will be decreased to the luminance of the interior zone. This curve of reduced luminance is expressed by an exponential function Ltr=Lth(1.9+t)-1.4 along the tunnel axis as shown in Figure 5-1.

The variable of this function is time (t), so the length of the transition zone is dependent upon the traffic speed and the level of luminance that needs to be reduced to the luminance of the interior zone. This zone can be divided into however many zones are necessary depending on how many steps are needed to reach the luminance of the interior zone under the condition that they can't exceed the ratio of 3:1. The following examples show how to divide the transition zone.

Ex. 5-1:

The luminance of the interior zone is 0.06 $L_{th.}$

The luminance of the first step of the transition zone is 0.4 $L_{th.}$

The luminance of the second step of the transition zone is 0.4/3=0.133 L_{th}.

The reduced luminance to interior zone is only 0.133/0.06= 2.2:1, which isn't more than 3:1. Therefore, only two steps in the transition zone are necessary for this example.

Ex. 5-2:

The luminance of the interior zone is 0.03 L_{th}.

The luminance of the first step of the transition zone is

Table 5-2 Recommended Threshold/Access Luminance Ratios K

Stopping Distance (m)	Symmetrical Lighting System L_{th}/L_{20}	Counter-beamLighting system L_{th}/L_{20}
60	0.05	0.04
100	0.06	0.05
160	0.10	0.07

Table 5-3 Safe Stopping Distances on Wet Roads (m)

Speed (km/hr) / Gradient	50	60	70	80	90	100	110	120
12%	30	45	60	75	100	125	145	175
8%	35	48	65	78	110	130	165	185
4%	40	50	70	80	115	145	175	210
0%	42	55	75	95	125	160	195	230
-4%	45	60	80	110	140	180	220	260
-8%	48	65	85	125	160	205	250	295
-12%	52	75	105	145	180	250	290	340

0.4 L_{th}.

The luminance of the second step of the transition zone is 0.4/3=0.133 L_{th}.

The reduction in luminance to the interior zone is only 0.133/0.03= 4.4:1, which is more than 3:1. Therefore, this example would need an extra step . However, there are many different combinations of how to adjust the luminance for each step . One way to divide the zones is to divide the time periods evenly. We may adjust the above values of luminance as follows:

The luminance in the second step of the transition zone is 0.14 L_{th} at 2 seconds.

The luminance in the third step of the transition zone is 0.05 L_{th} at 6 seconds.

The luminance in the interior zone is 0.03 Lth at 10 seconds.

The length of each zone can be calculated according to the traffic speed. For example, when the designated speed is 80km/hr, the length of the first transition zone from example 5-2 above is 80(1000m)/(3600s)*2=44.4m 45m. And the length of the other zones is 90m.

5.4 Interior Zone

In this zone, drivers have completely adapted to the lighting environment inside the tunnel. Actually, the lighting requirement is similar to that of the open road at night but must be somewhat higher due to escape difficulty and vision restriction. The luminance requirements of the interior zone are shown in Table 5-4 and are given in terms of traffic speed and stopping distance.

5.5 Exit Zone

In order to help drivers adapt to the brightness outside of the tunnel, luminaries can be added in the exit zone. However, the human eye adapts from darkness to light faster than from light to darkness. Whether there is a need to add extra luminaries or have the same amount as the interior zone is dependent upon the orientation of the tunnel

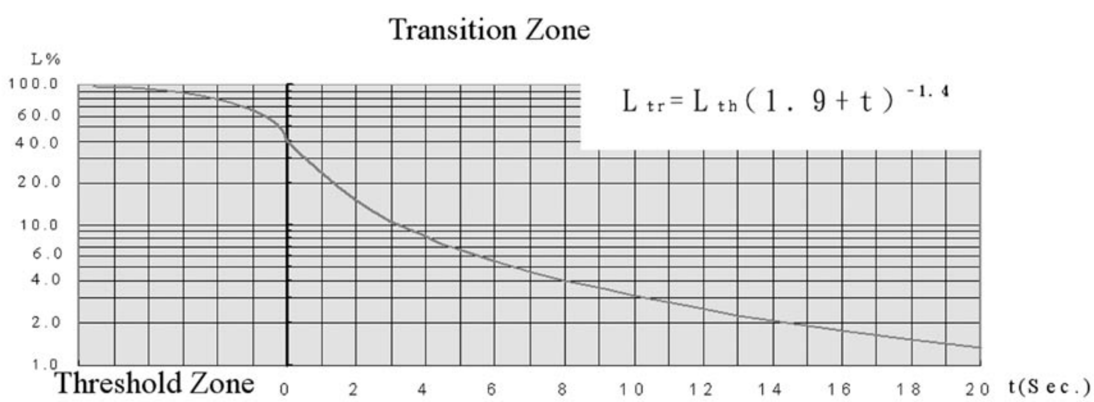


Figure 5-1 The Luminance Reduction in a Tunnel as Specified by the CIE.

Table 5-4 Recommended Interior Zone Luminance (cd/m^2)

Stopping Distance (m)	Traffic Density (Veh/hr)		
	<100	100 < veh/h < 1000	>1000
60	1	2	3
100	2	4	6
160	5	10	15

portal in the exit zone. If the orientation is western or eastern, luminaries should be added over the last 60m of the tunnel at a level 5 times the luminance of the interior zone.

5.6 Conjunction Zone

In order to avoid the black-hole effect when vehicles exit the tunnel at night, the road luminaries have to be installed along the open road beyond the tunnel exit. The luminance of this zone should not be less than one third of the luminance of the interior zone and the length of this zone should be equivalent to the distance traffic travels in 5 seconds.

6. EMERGENCY LIGHTING

In the event of a power failure, it is necessary to provide basic power to maintain a minimum luminance in the tunnel. This is necessary both for autos to avoid braking suddenly which could possibly result in multiple collisions and also to aid in the work of emergency crews should an accident nevertheless occur.

The emergency lighting should be combined with LED signs installed 100~150 m before the portal to alert drivers who are approaching the tunnel that they should slow down. The lighting level is usually 10~25% of the interior lighting level, and they are connected to UPS power with backup by diesel generator.

7. LIGHTING QUALITY

The above descriptions focus on quantity design, such as how to decide luminance or how to calculate the length of each zone. How to maintain good vision and provide a comfortable environment will be described in the next section. This description will include the discussions of uniformity, glare restriction and flicker effect avoidance.

7.1 Uniformity

Good uniformity is not only necessary on the road surface, but also on the tunnel wall. Both of these serve as a background for the detection of obstacles.

There are two types of uniformity employed in tunnel lighting for quality control. The overall uniformity (μO)is a ratio of the minimum to the average value of luminance (Lmin/Lav) on the road surface and on the walls up to 2m in height, and the longitudinal uniformity (μL) is a ratio of the minimum to the maximum value of luminance (Lmin/Lmax) along the centre of each lane. μO and μL should be greater than 0.4 and 0.6 respectively.

7.2 Glare Restrictions

When light is incident to the retina, glare forms a veil of luminance which reduces the contrast and thus decreases the visibility of an object.. We cannot see intensity differences efficiently in the presence of a high intensity background light. In a long tunnel, the glare will affect the driver's eyes and result in driver fatigue and traffic safety hazards.

According to the CIE's suggestions, glare restriction is calculated by threshold increment (TI.) which must be less than 15%. The definition of TI is as follows:

(1) $TI=65LV/Lav^{0.8}$ for Lav 5 cd/m^2

(2) $TI=95LV/Lav^{1.05}$ for Lav > 5 cd/m^2

Lav : Average Luminance

LV : Veiling Luminance

The veiling luminance is calculated from the following formula [1]:

$$LV=C^{*}\sum(EG/\Theta^{2})$$

C: Constant 10 when is expressed in degrees.

EG: illuminance from the glare source at eyes in lx.

Θ: Angle between the primary object and the glare source in degree.

Table 5-4 Recommended Interior Zone Luminance (cd/m²)

Traffic Speed (km/hr)	40	50	60	80	100	110
Avoidance Space (m)	0.7~4.4	0.9~5.6	1.1~6.7	1.5~8.9	1.9~11.1	2.0~12.2

7.3 Avoidance of Flicker

The flicker effect is produced by the luminance difference over a single cycle caused by the luminaries themselves and reflection off the shiny surface of vehicles. This cycle is related to the spacing of luminaries and traffic speed. According to the CIE's suggestions, the frequency of flicker is avoided at 2.5~15 Hz. Table 7-1 shows the forbidden spacing via traffic speed.

However, if the length of the tunnel is less than 1000m, the upper limitation of the flicker cycle can be modified from a lower frequency of 2.5Hz to a higher frequency of up to 5.8Hz to 3.2Hz for the length of the tunnel at 125m to 500m respectively [5]. In addition, if the length of luminance of luminaries is longer than the length of the dark area between two luminaries, the flicker effect can be negligible. This feature can be applied to fluorescent lighting fixtures used as luminaries in the interior zone.

8 LIGHTING CONTROL

8.1 Lighting Control

Tunnel lighting is controlled by computer calculation according to a luminance meter 150m away from the tunnel portal at a height of 1.5m. Generally, most tunnel lighting is controlled in several steps, and not in a continuous linear adjustment. Tunnel luminaries are grouped together by different circuit breakers, and they are switched on/off by luminance values gathered from the luminance meter.

How many steps there are in threshold and transition zones is determined by how quickly it is necessary to reduce the luminance to the level of the interior zone. First, the luminance of the first threshold zone is proportional to the access/threshold luminance ratio K as described in Section 5.2. For example, if the luminance of the access zone is 3,000cd/m2 with a symmetrical lighting system and K=0.06, then the luminance of the first threshold zone is 180cd/m2 and the luminance of the second threshold zone is 70% of Lth, i.e. 126cd/m2. We assume that the luminance of the interior zone is 10cd/m2, and the stages (n) at the first threshold zone can be determined by the formula (180-10)/n (180-126). Because n is integer, the luminance of each stage at the first threshold zone is 42.5cd/m2 for n=4. From this example, we can get control stages at each zone as shown in Table 8-1.

In night mode, the luminance of the conjunction zone is usually 1 cd/m2, so the luminance of the interior zone at stage 2 in Table 8-1 is 2.5cd/m2 and that is in accordance with the rule of not being more than a 3:1 ratio.

The luminance value in the column "Switch off" shows how to switch to a lower stage, but the reverse procedure cannot employ this value for switching to a higher stage. It must have a delay control like hystereses with two luminance values in parentheses in the first column in Table 8-1.This can ensure that the high pressure sodium or mercury lamp is not frequently switched on/off because of just one luminance value.

Table 8-1 The Luminance of Each Stage at Each Zone (cd/m²)

Stage \ Zone	Switch Off	The First Threshold Zone	The Second Threshold Zone	The First Transition Zone	The Second Transition Zone	The Third Transition Zone
7(3000 above)	2290	180	126	72	24	10
6(2000~3000)	1580	137.5	126	72	24	10
5(1000~2000)	875	95	87.3	72	24	10
4(100~1000)	167	52.5	48.6	41	24	10
3(20~100)	40	10	10	10	10	10
2(Night)	Timer	2.5	2.5	2.5	2.5	2.5
1(Emergency)	-	1	1	1	1	1

8.2 Wire Material

In order to prevent drivers from having to escape from the tunnel in the case of a fire that produces toxic smoke, all exposed wire material used in the tunnel has to be Low-Small Free-Halogen (LSFH) cable. Because all the tunnel lighting cable is placed on a cable tray or mounted beneath the ceiling, all cable for tunnel lighting should be LSFH. In addition, the cable for emergency tunnel lighting should additionally be fire-resistant in order to continuously work in case of fire.

9. CONCLUSION

Good tunnel lighting design not only reduces accidents from happening, but also can induce a higher usage rate for a road, reduce criminal activity and provide definitive vision guidance and a comfortable driving environment. Hence, the design of tunnel lighting must have a correct concept to follow. Fortunately, The CIE provides many good suggestions and calculations in order to promote the quality of tunnel lighting. These qualities are presented as luminance requirements, uniformities, glare restrictions, color renderings and luminary arrangements. All these factors directly affect traffic safety, and are related to good or bad tunnel lighting design.

The above qualities of luminance, uniformity and glare control can be represented by real values yielded from simple formulae, but need numerous calculations. They are not suited for hand calculation, and they require the assistance of a computer. Not only can the time for the design schedule be reduced, but also different types of lamps can be compared in order to get a proper lighting system and reduce the cost of the luminaries and save on power consumption.

BIBLIOGRAPHY:

* IESNA 1993, Lighting Handbook, Reference & Application.
* CIE 88- 1990, Guide for the Lighting of Road Tunnels an Underpasses.
* CIE No. 30 (TC-4.6) 1976, Calculation and Measurement of Luminance and Illuminance in Road Lighting.
* CIE No. 31 (TC-4.6) 1976, Glare and Uniformity in Road Lighting Installations.
* Philips Lighting, 5th Edition 1993, Lighting Manual.