Effects of Luminaire Angle on Illumination Performance in Tunnel Lighting

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Abstract— **In this study, the effect of luminaire angle on the path parameters of tunnel lighting was investigated. Tunnel illumination was performed with a simulation program adapted to CIE 88-2004 standards. The lighting performance parameters were compared while the angle of the luminaire was 0°, 5°, 10° and 15°. According to the simulation results, the luminaire angle is 0°and the highest efficiency is reached. As the luminaire angle increased, the yield decreased in direct proportion to the angle. The highest lighting efficiency was observed at 0° and the lowest illumination efficiency was observed at 15°. This problem can be overcome by using a higher power lamp in angled lighting. As a result, it is revealed that angled lighting should be avoided in highway and tunnel lighting.**

Index Terms—**Illumination, luminance, road lighting, tunnel lighting.**

I. INTRODUCTION

TUNNELS ARE underground road structures which are alternative to highways and railways. They are used to facilitate traffic flow. Tunnels, should ensure the visibility comfort, speed and safe traffic flow. If the tunnel lighting does not illuminate as much as necessary, a driver approaching the tunnel experiences a black hole effect. Therefore, intense lighting should be done at the entrance of the tunnel. Intensive lighting is not required in the interior of the tunnel [1-3].

In long tunnels, the tunnel interior area is an important part of tunnel lighting cost. Therefore, for the most appropriate tunnel illumination that provides economic but necessary vision conditions, the brightness level in the tunnel interior should be determined correctly. The driver using any vehicle on highways should have detailed visual information about the way in which he is driving. Especially at high speeds, the driver should be able to see the route easily, the driver should be able to perceive the position and movements of the vehicle he is driving, be able to monitor the movements of other vehicles, and easily be able to see the obstacles on the road [4-6].

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CIE reports the results of 30 different studies, covering road lighting studies that improve vision conditions. In this report, according to the standards of road lighting: pedestrian accidents from 57% to 45%, fatal accidents from 65% to 48%, severe injuries from 30% to 24%, and the total number of accidents it decreased from 53% to 14% [7, 8]. Even if there is little traffic at night, the number of accidents that occur in roads or tunnels without illumination is about three times higher than in daylight hours. The reason for this is the lack of road lighting in accordance with the standards. Figure 1 shows traffic accidents in the tunnel.

Fig.1. Traffic accidents in the tunnel

Tunnel lighting design calculations performed in this study are based on the recommendations involved in the technical report "Guide for The Lighting of Road Tunnels and Underpasses" CIE-1990 dated 2004 No-88. Conducting appropriate road lighting to the CIE reduces the rate of crime committed in city roads. According to the studies in the literature, the number of forensic cases has decreased by 20% in urban roads thanks to the proper lighting. The severity of offenses has decreased by 40%. In the severity of crimes committed, it was seen that there was a 40% decrease [8-10].

II. TUNNEL VEHICLE TRANSITION ZONES

Tunnel lighting is examined by classifying different luminance zones in order to ensure adaptation and provide economic solutions. Figure 2 shows zones of the tunnel.

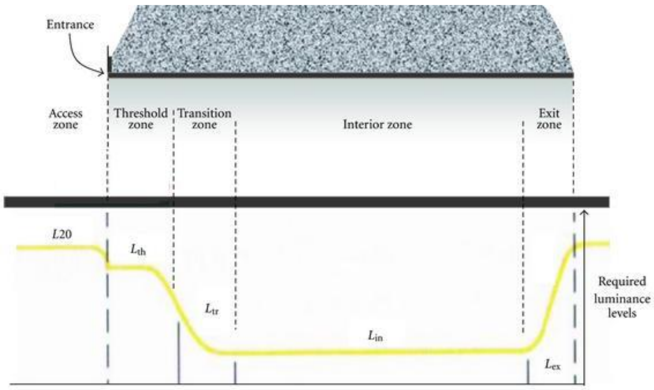


Fig.2. Zones of the tunnel

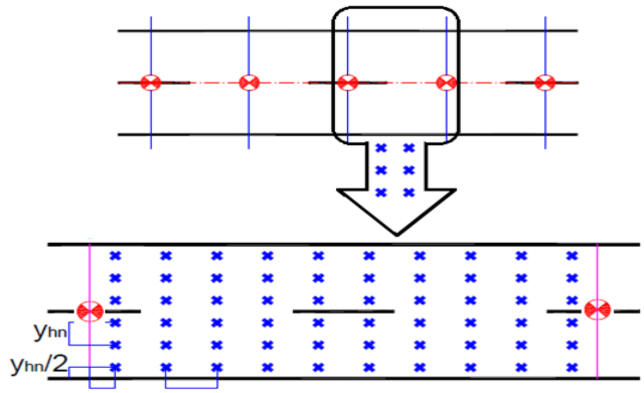


Fig.3. A sketch of a point lighting calculations

The access zone is the area starting before the tunnel entrance (100–200) m and ending at the tunnel entrance. There are two factors affecting the adaptation luminance:

• Around the tunnel entrance, "equivalent veiling luminance" (L_{seq}) formed by different luminance values;

• Luminance at the centre of the driver's field of view. Equivalent veiling luminance is one of the most important factors in determining adaptation of the driver [1-2, 11-13].

Entrance zone is the place where adaptation accurately starts from the tunnel entrance and continues to the interior zone of the tunnel. It is examined in two different zones:

– **Threshold zone:** limits of the zone starting from the tunnel entrance are determined on the basis that a critical object that may be dangerous in that zone can be seen by the driver in the approach at least from a distance equal to the stopping distance;

– **Transition zone:** after the threshold zone, the transition zone is where the luminance in the threshold zone is reduced to a luminance level in the interior zone. The length of the zone varies by the initial and final luminance value and the allowed speed limit.

– **Interior Zone:** the constant luminance zone between entrance and exit zones of the tunnel.

– **Exit Zone:** the zone from the end of interior zone to the exit that makes the adaptation easier to the zone with high luminance at the exit [1-2, 11-13].

III. Determination of the Account Area for Tunnel Lighting

In this study, Point Lighting Account Method is used on road surface. In this method, firstly the area to calculate the spot lighting is selected. The area between the two pole is determined as the account area. Starting from the first armature in the calculation area, point calculation is made according to the observer which is positioned 60 m backward and in the middle of each strip. The luminance level of a point on the road surface is equal to the sum of the light levels that come to a point [6, 14, 15]. Figure 3 shows a sketch of a point lighting calculations.

Calculations are based on a period for periodic and linear paths. If you have more than one periodic and linear path pieces on the road, you need to make a separate calculation for each part of the road. Radius greater than 300 m radius can be considered as linear path. The area between the two light sources on the single roads is considered the account area. On double roads (refugee), the area between two light sources is considered as the area of account, considering only one of the routes of departure or arrival. Only one side calculation is sufficient [16-23].

In this study, lighting calculations are made for tunnel inner zone. Tunnel inner region is the place where energy consumption is the highest in long tunnels.

The horizontal illuminance of a point P on an illuminated path; This is the sum of the horizontal light levels that all the luminaires affecting the account area in the lighting installation formed at this point. Figure 4 shows the horizontal illumination level vector state [14, 15]. Equation 1 shows the correlation between horizontal illumination levels.

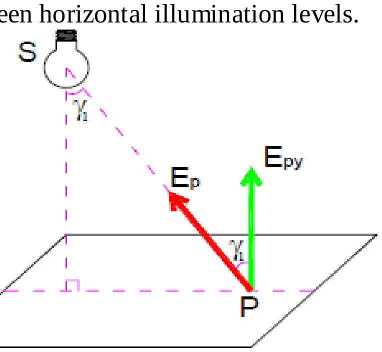


Fig.4. Horizontal illumination level vector state

$$E_{p\gamma} = \sum_{i=1}^{a} \frac{\Phi_L .MF.\mathrm{I}(C,\gamma_2)}{1000.h^2} \qquad (1)$$

I (C,γ): is value of light intensity reaching from luminaire i to point P (cd),

γ: is angle of gleam falling within point P by the vertical line,

a: is amount of luminaires contributing to point P,

h: is ground clearance of luminaire photometric center (m)

C: is plane angle,

MF: Maintenance factor.

IV. TUNNEL LUMINANCE

The most important objective to design lighting systems is to obtain sufficient light without supplying excessive lighting and increasing energy cost [1, 2, 6]. Luminance is the most important dimension in terms of light effect on a road. Luminance is indicated by L and the unit is cd/m^2. A smooth luminance distribution as much as possible on the road surface should be ensured for the good visibility of the objects and the driver's visual comfort. Today, road lighting is based on Luminance Method which is based on road surface glow. The horizontal illuminance of a point P on an illuminated road; It is the sum of the horizontal illuminance levels that all the light sources acting at point P have at this point [1, 2, 6, 14, 15]. In Equation 2, the relation between the variables to be used in the calculation of P point luminance is seen.

$$E_{p\gamma} = \sum_{i=1}^{a} \frac{\Phi_L . MF . \mathrm{I}\left(C, \gamma_2\right)}{1000 . h^2} \tag{2}$$

A fluorescent lamp has a glow of 5000-15000 cd/m^2, a full moon has a glow of 2500 cd/m^2 and a road surface under 30 lux of lighting has a glow of 2 cd/m^2. Since the glitter concept involves a specific point of the surface and observation direction, it is necessary to identify these conditions when glitter is mentioned. The glow of ideal reflective surfaces can be calculated by benefiting from the illumination level [1, 2]. When ρ is the reflection factor of the surface, the relation between glitter and illumination level is determined by Equation 3.

$$L = \rho \frac{E}{\pi} \tag{3}$$

The mean road level luminance (L_{th}) in any point of the threshold zone (it is the first extension at the tunnel entrance in Figure 5) is called the threshold zone luminance [3-5].

The rate of the threshold zone and access zone luminance's is $k = L_{th} / L_{20}$, where (L_{th}) is the mean road surface luminance at the beginning of the threshold zone and (L_{20}) is the luminance distance equal to the stopping distance in front of the tunnel. The mean value of the road surface luminance at any point of the transition zone is called the transition luminance (L_{tr}). The value of the mean road surface luminance in the interior zone is called the interior zone luminance (L_{in}) [1, 2, 6, 14, 15].

IV.1 Average road surface luminance

In the road lighting, the fund of objects is the road surface that forms the driver's field of vision. Therefore, a higher $L_{average}$ makes it easier to see by providing a higher background glow. The increase in $L_{average}$ increases the sensitivity of the driver's eye by increasing the luminosity of the objects in the road. Therefore, the most important parameter for detection is $L_{average}$. $L_{average}$ is calculated using the glitter values on the selected mxn pieces on the road. For $L_{average}$, the luminance values of all the light sources affecting the account area are calculated and collected as vector. In this way, the glare value at each point is calculated. The average surface road luminance is calculated separately for each observer [1, 2, 6, 14, 15].

IV.2 Uniformity

Even though lighting systems provide a good mean road surface luminance, there may be zones with low luminance where contrast is weak and small obstacles cannot be detected. The difference between minimum and mean road surface luminance's into the field of view is expected to be lower than a certain value in order to obtain enough illumination at all points on the road. This obligation brings us to the overall uniformity and longitudinal uniformity values that are important secondary parameters.

There should be an equal distribution of luminance in the road (on the road surface) in order to provide a clear view for the driver. Two kinds of uniformity are considered important in tunnel lighting [7-10]:

1) Mean (resultant) uniformity (U_o): When traffic is on the right side, it is the rate of minimum luminance (L_{min}) to mean luminance of the road ($L_{average}$), which is determined by an observer at ¼ distance of the road width on the right side of the road. The lower sections of the walls should be considered as well as road surface [1, 2, 6, 14, 15]. Equation 4 presents the ratio suitable for the road surface and mean luminance uniformity of the walls up to 1.5 m from the ground according to CIE 140-2000 and CIE 88-2004 [24, 25].

$$U_o = \frac{L_{\min}}{L_{average}} \geq 0.4 \tag{4}$$

Longitudinal uniformity (U_ι): According to an observer on the center line of road lane, it is the rate of minimum luminance applied through the center line to maximum luminance. Equation 3 presents the rate suitable for longitudinal uniformity through the road. Equation 5 shows change of longitudinal uniformity factor.

$$U_I = \frac{L_{\min}}{L_{\max}} \geq 0.7 \tag{5}$$

IV.3 Surround rate

Light sources illuminate the emergency lane or pavement at a certain rate when illuminating the road surface. The parameter defined for this is the surround rate (SR).

IV.4 Light sources

High-pressure sodium vapor (HPS) lamps are preferred under conditions of higher luminance level, including under water tunnels, as HPS lamps have higher light flux and smaller dimensions than low-pressure lamps. As a result, less luminaries and area are required for lighting. The luminance efficiency is defined as the luminance level from the power required for the road (for 1 m^2). In this study, 50 W HPS lamp was used. The lamp is luminous flux 4000.

V. Determination of the Account Area for Tunnel Lighting

Road types are defined in international technical reports and an optimal solution range is presented technically for these road types. The required design calculations should be made through luminaries with known photometric values, and the number and type of the luminaries should be determined according to these calculations [8, 20, 26-31].

Related road, road lighting class is determined by the table in the CIE 115-2010 [8, 20, 27]. According to Table 1, road lighting class M2 was found. Road lighting class selection parameters are shown in Table 1. Road lighting quality parameters are shown in Table 2.

TABLE I
ROAD LIGHTING CLASS SELECTION PARAMETERS

Parameter	Options	Weight factor
Speed	High	0.5
Traffic jam	High	0.5
Traffic layout	Only motor vehicles	0
Middle median strip on the road	Yes	1
Intensity of intersection	High	1
Parked vehicle	No	0
Environmental lighting	High	1
Traffic control	Medium or good	0
	Total of weight factors:	4

Road lighting class was found with equality 6, 7 and 8. Road lighting quality parameters are shown in table 4 [8, 20, 27].

$$MX = 6 - Total\ weight\ factors \quad (6)$$

$$MX = 6 - 4 = 2 \quad (7)$$

$$MX = M2 \quad (8)$$

TABLE II
ROAD LIGHTING QUALITY PARAMETERS

Lighting class	$L_{average}$	U_O	U_I	$TI\%$	SR
M2	>1,5	>0,4	>0,7	<10	>0,5

V.1 Features of the tunnel lighting

The road pavement is asphalt, class R4. Additionally, Q_o=0.08, the wall coating is concrete, the reflectivity is 0.4, and the height of the luminary is 11 m. The maintenance factor of the luminary is 0.83 and all calculated luminance values are corrected. The ratio of the smallest luminance value to mean luminance value is greater than 0.4 in the calculations for road lighting, ensuring that the rate of the smallest luminance value to the largest at the latitude coordinate of the observer is greater than 0.7 $(U_I \geq 0.7)$.

The luminance levels and uniformities of the tunnel walls are in accordance with relevant standards and thay are very important for driving safety. All lighting luminaries were established in single line 2 m from the tunnel walkways to the axis of the road and at a height of 6 m. The lighting in the tunnel will be supplied by the luminaries with symmetric light distribution. The contrast revealing coefficient, which is the most important criterion in the application of symmetric light distribution, is less than 0.2. Table 3 illustrates the road and lighting parameters [20-22, 29, 30].

TABLE III
TUNNEL AND LIGHTING PARAMETERS

Tunnel lighting parameters			
Lighting pole type	Galvanized	Lighting class	M2
Number of road lanes	1	Console length (m)	-
Strip Width (m)	4	Console Angle	-
Road Width (m)	4	Armature Angle	0°/5°/10°/15°
Road Class	R4	Lamp type	HPS
Q_o	0.08	Lamp power(Watt)	50
Distance to illumination	0	Lamp luminous flux	4000
Illumination height from ground (m)	6	Maintenance factor (every 3 years)	0.83

V.2 Simulation study

A non-commercial simulation program was used for lighting in this study [1, 29, 30]. The main purpose of the new studies is to reach the most economical results that provide adequate conditions. In the new study's made about road lighting, classifications are taken into consideration in the various scenarios conditions. The most accurate reference to road-tunnel lighting are international standards. For this reason, simulation is adapted to CIE standards. According to CIE 140 - CIE 88, the luminance values, averaged luminance level, averaged and longitudinal uniformity values of all points were calculated for the observers [24, 25].

Luminaires to be used in road-tunnel lighting should be chosen by taking into account glare level, luminance level of the road, lighting uniformity and economy, and they should be determined in consequence of computer calculations according to the luminance method [30-37].

Various choices are available for the road parameters in the simulation program. For the road-tunnel parameters, the lighting system (mutual, cross, divided road, road with single luminary, road with two luminaries, etc.), road class (R1, R2, R3, R4, N1, N2, N3, N4, etc.), number of lanes, lane width, refuge width, and road lighting class (M1, M2, M3, M4, M5, M6, etc.) can be chosen. For the lighting parameters, features such as distance between the luminaries, height of the luminary, distance of the luminary from the road, console angle, IP protection class, pollution rate, cleaning period, and maintenance factor are chosen for post or hanger system lighting. For the luminary parameters, the name, angle of the luminary (angle relative to the road), power of the lamp used, lifetime, light flux, ballast power, and new lamps can be added into this simulation under the Database process at any time. As a result, it is possible to add any kind of lamp into the simulation [1, 2, 29, 30]. An easy and accurate calculation is achieved in the simulation results for the lighting system in which data is entered.

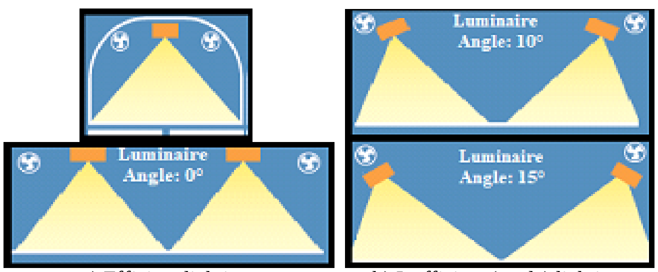
VI. Applications of Tunnel Lighting

In this study, a problem encountered in tunnel lighting were investigated. These problem are about angled lighting. For this purpose, it has been proven with a simulation program that the angled lighting encountered almost everywhere in the road lighting is inaccurate [30-37]. It is proved that it is necessary to perform (0º) illumination parallel to the road surface instead of angled lighting. New solutions can be found in the simulation environment for roads with different strengths and lamps with different strengths, as in this example.

VI.1 Angle effect in lighting

Various design tools or physical measurements are used in order to determine illumination level of certain points selected in lighting systems. These are physical measurements carried out by models, numerical equations and computer programs or by luxmeter in real environment. In this study, HPS 50W lamp luminaires inserted dually 6 m high are used in the road. Determination of luminaire angle (0°, 5°, 10° and 15°) for a 50W HPS lamp luminaire with protection class IP65 is calculated simulation.

Today, the most important problem in energy is efficiency [33-42]. It causes loss efficiency of angled lighting. Efficiency loss was calculated on the basis of simulation. As the angle increased, the luminance efficiency in the road decreased. Fig. 5 shows efficient and inefficient (angle) lighting.



a) Efficient lighting b) Inefficient (angle) lighting

Fig.5. Efficient and Inefficient (angle) lighting

In this study, a single-lane road which is suitable for CIE 88-2004 The Lighting of Road Tunnels and Underpasses has been investigated in the simulated environment. Calculations were made at 0°, 5°, 10° and 15° angles for 50 W HPS lamp. With the exception of 0°, 5°, 10° and 15° angles illumination has been found to cause loss of efficiency. For example, luminaire angle=0° while $L_{average}$=1.51 cd/m². This corresponds to CIE 88-2004 standard The Lighting of Road Tunnels and Underpasses for M2 (While the distance between the poles is 11 m) [10]. Luminaire angle is 5°, 10° and 15° $L_{average}$ is less than 1.50 cd/m² (While the distance between the poles is 11 m). If $L_{average}$=1.50 cd/m² less than the lighting is not suitable for CIE 88-2004 standard. Table 2 shows the requirements for lighting class:M2. Table 4 shows tunnel lighting results for 0°, 5°, 10° and 15° angles.

TABLE IV
TUNNEL LİGHTİNG RESULTS FOR 0°, 5°, 10° AND 15° ANGLES

Angle of illumination (Degree)	0°	5°	10°	15°
Observer location (m)	2	2	2	2
$L_{average}$	1,51	~~1,36~~	~~1,16~~	~~0,95~~
U_o	0,59	0,55	0,53	0,52
U_l	0,77	0,83	0,78	0,81
TI%	3,2	3,0	3,0	3,1
E_{min}	15,94	13,23	10,98	9,67
E_{max}	41,4	41,11	36,85	29,36
$E_{average}$	29,08	26,37	22,52	18,45
U_{oa}	0,55	0,51	0,5	0,54
U_{la}	0,38	0,32	0,3	0,33
SR	0,53	0,64	0,78	0,94
Lamp power (W)	50			
Luminous flux	4000			
Distance between illuminations(m)	11			

For Table 4; if the $L_{average}$ for 0° is accepted 100%;

- The loss rate for luminaire angle=5° is approximate 10%.
- The loss rate for the luminaire angle=10° is approximate 23%.
- The loss rate for the luminaire angle=15° is approximate 37%.

Table 5 shows illuminance level for tunnel lighting (luminaire angle: 0°). Table 6 shows luminance (luminaire angle: 0°) for tunnel lighting. Tables 7, 8 and 9 show the luminance (luminaire angle: 5°, 10°, and 15° respectively) for tunnel lighting. The change of the lighting parameters according to the luminaire angles is shown in Figure 6.

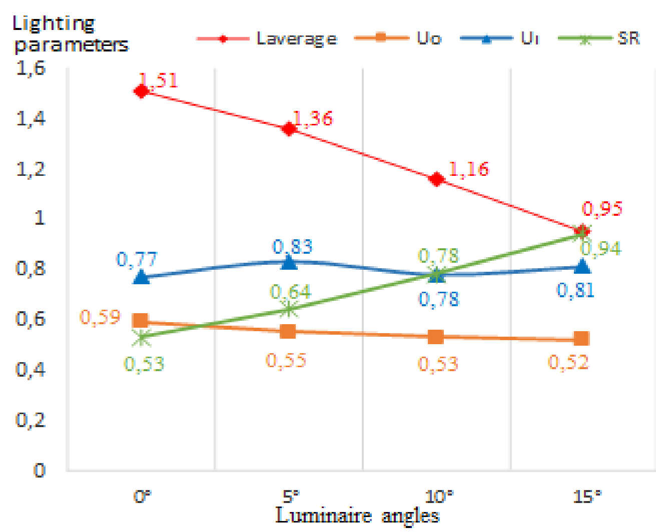


Fig.6. The change of the lighting parameters according to the luminaire angles

TABLE V
ILLUMINANCE LEVEL FOR TUNNEL LIGHTING (LUMINAIRE ANGLE: 0°)

Emin=15,94 Lx Emax=41,40 Lx $E_{average}$=29,08 Lx Uoa=0,55 Ula=0,38 SR=0,53										Angle:0°
Observer location (m)	0,550	1,650	2,750	3,850	4,950	6,050	7,150	8,250	9,350	10,450
0,667	25,897	19,360	23,902	20,434	15,937	15,937	20,435	23,905	19,365	25,902
2,000	34,774	31,556	33,584	28,075	22,387	23,583	29,504	37,240	33,709	36,287
3,333	36,951	34,211	41,400	33,165	29,603	29,604	33,167	41,404	34,216	36,958

TABLE VI
LUMINANCE (LUMINAIRE ANGLE: 0°) FOR TUNNEL LIGHTING

$L_{average}$ **= 1,51 cd/m²** Uo = 0,59 Ul = 0,77 TI = %3,2										Angle:0°
Observer location (m)	0,550	1,650	2,750	3,850	4,950	6,050	7,150	8,250	9,350	10,450
0,667	1,068	0,987	1,117	1,026	0,912	0,954	1,149	1,177	0,894	1,050
2,000	1,667	1,698	1,781	1,669	1,584	1,737	1,930	2,055	1,718	1,700
3,333	1,641	1,659	1,895	1,679	1,631	1,797	1,907	2,084	1,624	1,623

TABLE VII
LUMINANCE (LUMINAIRE ANGLE: 5°) FOR TUNNEL LIGHTING

$L_{average}$ **= 1,36 cd/m²** Uo = 0,55 Ul = 0,83 TI = %3,0										Angle:5°
Observer location (m)	0,550	1,650	2,750	3,850	4,950	6,050	7,150	8,250	9,350	10,450
0,667	0,896	0,839	0,928	0,873	0,758	0,781	0,944	0,946	0,749	0,879
2,000	1,466	1,475	1,579	1,499	1,396	1,483	1,664	1,683	1,414	1,441
3,333	1,584	1,582	1,843	1,637	1,634	1,787	1,844	2,037	1,546	1,555

TABLE VIII
LUMINANCE (LUMINAIRE ANGLE: 10°) FOR TUNNEL LIGHTING

$L_{average}$ **= 1,16 cd/m²** Uo = 0,53 Ul = 0,78 TI = %3,0										Angle:10°
Observer location (m)	0,550	1,650	2,750	3,850	4,950	6,050	7,150	8,250	9,350	10,450
0,667	0,714	0,696	0,734	0,708	0,627	0,642	0,723	0,702	0,614	0,695
2,000	1,293	1,180	1,320	1,258	1,160	1,224	1,360	1,381	1,081	1,260
3,333	1,447	1,432	1,643	1,470	1,463	1,595	1,643	1,799	1,410	1,411

TABLE IX
LUMINANCE (LUMINAIRE ANGLE: 15°) FOR TUNNEL LIGHTING

$L_{average}$ **= 0,95 cd/m²** Uo = 0,52 Ul = 0,81 TI = %3,1										Angle:15°
Observer location (m)	0,550	1,650	2,750	3,850	4,950	6,050	7,150	8,250	9,350	10,450
0,667	0,577	0,567	0,597	0,602	0,544	0,554	0,603	0,554	0,499	0,558
2,000	1,083	0,982	1,080	1,040	0,942	0,976	1,093	1,102	0,894	1,051
3,333	1,243	1,172	1,345	1,247	1,198	1,319	1,372	1,433	1,131	1,195

VII. Discussions

In this study, the effects of angled lighting in tunnel lighting were investigated. For this purpose, the parameters of a road used for single-lane military purposes (for underground arsenals) were processed into a lighting simulation. Firstly, the optimum distance was determined as 11 m when the angle of the luminaire was 0°. When the angle of the luminaire is 0° and the distance between the luminaires is 11 m, all values are suitable for CIE 88-2004 standard. If the luminaire angle is 5°, 10° and 15°, the distance between the poles falls below the average value of $L_{average}$=1.50 cd/m^2. Luminaire angle 5° $L_{average}$=1.36 cd/m^2; luminaire angle 10° $L_{average}$=1.16 cd/m^2; luminaire angle 15° $L_{average}$=0.95 cd/m^2; value falls. $L_{average}$=1.50 cd/m^2 falling below does not comply with CIE standards. Accordingly, when the luminaire angle is 0°, the highest lighting efficiency is reached and the luminous efficiency decreases as the angle increases.

This work for the tunnel can be applied on all roads. Angled lighting is used in about 90% of the currently roads. As stated in this example, angled lighting (5°, 10° and 15°) with 70 W HPS lamp corresponds to tunnel lighting with 50 W HPS lamp (not angled, 0°). Using higher power lighting increases energy consumption. Increased energy consumption is undesirable in terms of efficiency.

VIII. Conclusion

The most accurate reference to road-tunnel lighting and lamp selection is the international standards. For this reason, simulation road lighting is adapted to CIE standards. According to CIE 88-2004 standard, luminance values, average luminance level, average and longitudinal uniformity values of all scores were calculated for the observers. The data of the lamp used were processed in the simulation database and the results were analyzed.

The 50 W HPS lamp complies with the standards specified in the CIE 88-2004 The Lighting of Road Tunnels and Underpasses at the luminaire angle=0° optimum pole pitch (11m).

If the angle of the luminaire is 5°, 10° and 15°, the $L_{average}$ is less than 1.50 cd/m^2. This doesn't fit the CIE standards. Inefficient and inadequate lighting was observed under the standards.

Such special solutions can be improved by lighting simulations. Therefore, as in this example, special solutions should be analyzed in road lighting in simulation environments.

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