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SIMULATION AND DESIGN STUDY FOR INTERIOR ZONE LUMINANCE IN TUNNEL LIGHTING

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ABSTRACT

An optimal solution for tunnel lighting designs was determined using a computer software. The road tunnel under construction 14481 m in length was selected in order to get an optimal design solution for tunnel lighting.The lighting, luminaries, and road parameters were changed and the resulting scenarios were examined in a simulation environment. The proposed approach can be applied for the illumination of interior zones in tunnels of 10 km or longer with significant reduction in energy consumption. The optimal luminance values that affect vision comfort in the tunnel were calculated in a simulation environment. As a result, the most economic lighting system and luminaries were chosen among solutions conforming to technical standards for luminance values.

Keywords: tunnel lighting, luminance, glare, HPS lamp

1. INTRODUCTION

Tunnels are underground road constructions that are alternatives to over ground pedestrian ways, railways, highways, and channels, and they are used to enable urban or rural traffic flow. Vision comfort, speed, and safe traffic flow should be ensured in the tunnel just as in typical roads. When tunnels are not sufficiently lit, an approaching driver will experience a black hole effect during the daytime. A gradual lighting level decrease should be provided into the tunnel considering the time required for eyes to adapt to the dark to avoid vision loss during the daytime. The ideal condition is to light the tunnel to a typical road luminance level. However, such a solution cannot be applied in practice as both the installation and operating cost will be high. The main purpose of this study is to find a sufficient, economic, and optimal solution. When considering the adaptation of eyes to darkness, intense lighting in the first section of the tunnel and a gradual decrease in lighting will aid driver vision.

In this study, luminance levels from the technical report for tunnel lighting published by the International Commission on Illumination (CIE) in 1990 and 2004 were used [1,2].

2. LUMINANCE

Luminance is represented by L and has a unit of cd/m^2. L is the luminous intensity emitted in a certain direction from unit surface area. The luminance of the unit area at point M of a luminous surface at a normal direction and α angle of this surface is the limit of the ratio of the ΔI_α luminous intensity

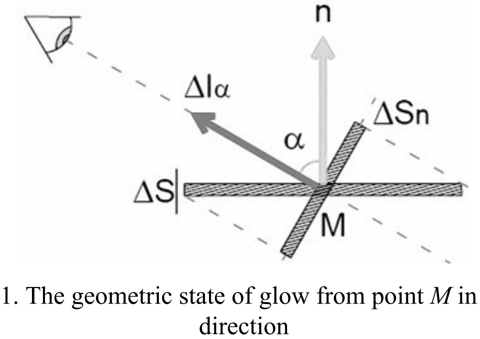


Fig. 1. The geometric state of glow from point *M* in the *α* direction

of the ΔS surface element involving point M in the ΔS_n apparent area of ΔS at a plane perpendicular to this direction [3]. The geometric state of the glow from point M of a surface in the α direction is illustrated in Fig. 1. The relative luminance calculation is presented in Equation 1.

$$L_\alpha = \lim_{\Delta S_n \to 0} \frac{\Delta I_\alpha}{\Delta S_n} = \frac{dI_\alpha}{dS_n}. \quad (1)$$

The surface can produce light itself or can reflect the light emitted from other sources. The levels of surfaces brightness with equal illumination but different reflection properties are different. For example, dull asphalt and bright asphalt have different glitter levels because of their reflection properties [3, 4–6].

3. TUNNEL ZONES AND CLASSIFICATION

When a driver travelling safely on an open road enters a tunnel, he/she continues to move on without experiencing a visual loss. Intense lighting is required in the first zone of the tunnel, so visual conditions do not go wrong for the driver entering the tunnel from daylight into darkness [7–9].

In tunnel lighting, there are differences between night time lighting that need to be established regardless of tunnel length and daytime lighting for tunnels longer than a critical length [10–12]. A tunnel can be illuminated at night similar to a typical road. However, the illumination level of the tunnel should be greater than open roads to make the tunnel safer and consider the noise in the tunnel. Previous studies demonstrate that a luminance level equal to 3cd/m^2 is sufficient throughout a tunnel in night time lighting even in long tunnels that have low traffic and a specific speed limit.

3.1. Tunnel Zones

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

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:

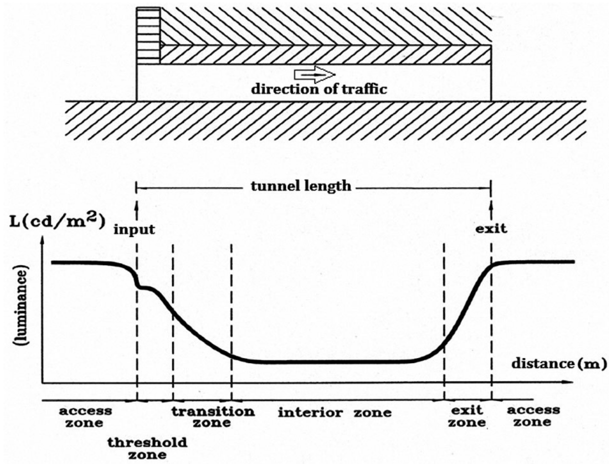


Fig. 2. Zones of the tunnel

• 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, 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:

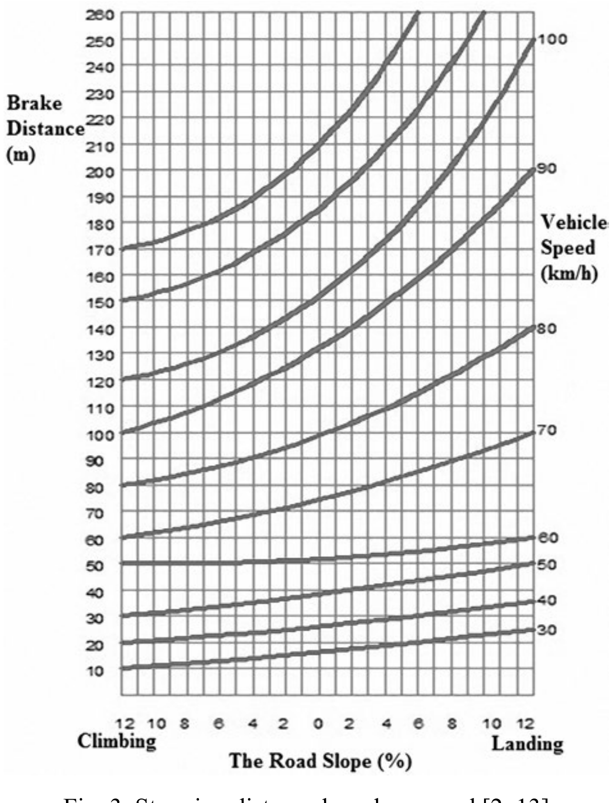


Fig. 3. Stooping distance based on speed [2, 13]

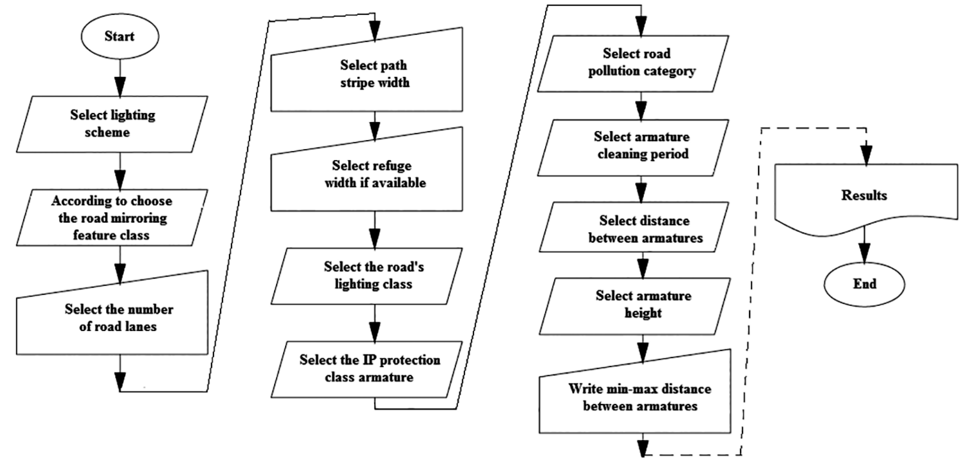


Fig. 4. The algorithm of the simulation program and data entered

– **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.

3.2. Stopping (Brake) Distance

The stopping distance or safe driving distance is the distance, from which the driver observes a dangerous object and can stop the vehicle safely. This distance depends on reaction time of the driver, stopping distance of the vehicle, allowed speed limit, inclination of the road, road pavement, and brake jamming ability of the vehicle. Fig. 3 presents a graphic for the stopping distance based on the speed considering the inclination of the road for the vehicle with moderately worn tires on a wet, clear road [2, 13].

4. LIGHT SOURCES

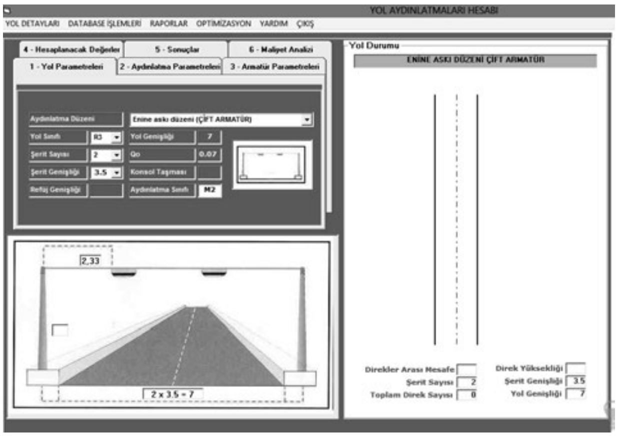
High-pressure sodium vapour (HPS) lamps are preferred under conditions of higher luminance level including under water tunnels, as HPS lamps have higher luminous flux and smaller dimensions than low-pressure lamps. As a result, less luminaries and area are required for lighting. Lighting efficiency (in terms of electricity consumption) of a similar lighting system increases up to 90 % with HPS lamps compared to fluorescent lamps based on results obtained from various tunnels with different structures that are open to vehicular traffic. The luminous efficiency is defined as the luminance level from the power required for the tunnel (for 1 m^2).

Previous studies on the photometric properties of HPS lamp armatures used in road lighting with LED light sources were performed. In the study designs, M3, M4, and M5 road lighting classes with 100 W and 150 W LED armatures could be achieved. M1 and M2 road lighting classes did not produce acceptable lighting magnitudes [14]. Since the road lighting class in this study is M2, LED lamps were not used as HPS lamps are widely used in road lighting [15–18]. Additionally, in Turkey, regulation studies, which were concluding in 2006, are requiring HPS lamps. As a result, this study simulation was performed accordingly with HPS lamps.

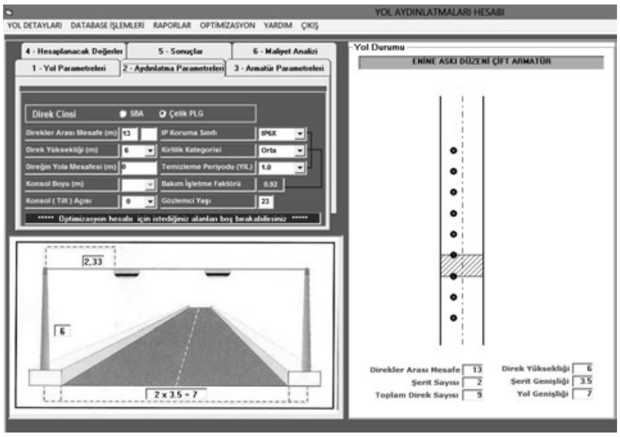
Since HPS lamps have more luminous flux than fluorescent lamps, glare can be prevented using reflection suitable for the direction of the driver. Sufficient luminance can be achieved by placing HPS lamps with proper power in a band-like order (correct line) at the entrance and transition zones. Since the lighting system is always band-like, problems concerning flickers and luminance uniformity are automatically addressed.

5. TUNNEL LIGHTING SYSTEM

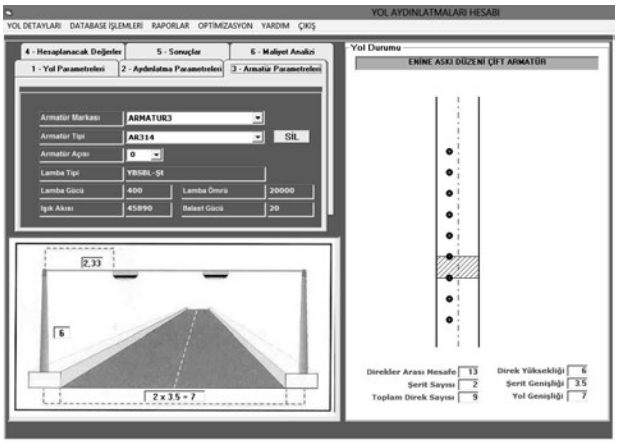
Tunnel lighting is supposed to allow the driver travelling on a clear road with a certain comfort and



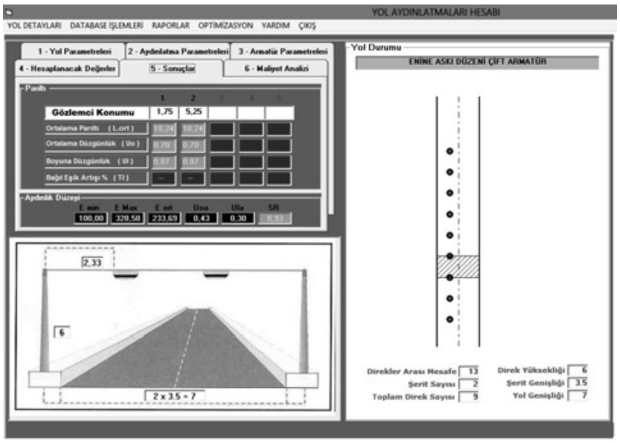
a) Road parameters



b) Illumination parameters



c) Luminary parameters



d) Results

Fig. 5. Simulation program: a) road parameters, b) illumination parameters, c) luminary parameters, and d) results

safety without visual loss when moving into a tunnel. A tunnel entrance that is not illuminated sufficiently creates a “black hole” effect for a driver moving on a clear road, especially on a sunny day. The threshold zone constituting an important part of the tunnel lighting cost (the first entrance zone) depends on the luminance level of the access zone encountered while approaching the tunnel. For that reason, the first starting point of the most proper tunnel lighting, which is economic but provides the required conditions of view, is the accurate determination of the luminance level of the access zone in the tunnel approach zone.

There is an adverse condition for night time lighting compared to daytime lighting in terms of the technique of tunnel lighting. While outside the tunnel is brighter in daytime hours, the interior sections of the tunnel are brighter in night time hours. This condition eliminates the adaptation problems and the black hole effect from occurring in daytime. Since adaptation of eyes to low luminance takes more time than adaptation to high luminance, a luminance level of 3cd/m^2 should be ensured throughout the tunnel in night time lighting even in longer tunnels with low traffic and a certain speed limitation.

In tunnel lighting design, the vehicle speed limitation on a clear road approaching the tunnel should be considered. The tunnel design speed is the 90 km/h. The “stopping distance” of 130 m for a driver travelling with speed 90 km/h is to see a risky object and stops their car safely.

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.

5.1. Design and Planning Processes

Luminaries to be used in tunnel lighting should be chosen by taking into account glare level, luminance level of the road and walls, lighting uniformity and economy, and they should be determined

Table 1. Tunnel Road and Lighting Parameters

Tunnel road parameters	
Double armature, transverse arrangement	
Road class	R3
Number of lanes	2
Strip width	3.5 m
Road width	7 m
Q_o	0.07
Road lighting class	M2

(M2: *Speed of 90 km per hour can be* done the way)

Tunnel parameters of illumination	
Armature height	6 m
Fence distance	0 m
Console angle	0
IP protection	IP65
Pollution category	Middle
Annual clear period	1
Distance between armatures	13 m (400 W)
	17 m (250 W)
	15 m (150 W)
	17 m (100 W)
	15 m (70 W)

Table 2. Tunnel Lighting Parameters for HPS Lamps at Various Powers

Lamp type	Lamp power, W	Distance between armatures, m	$L_{average}$, cd/m^2	U_o	U_l	Number of luminaires (binary)	Current consumption, kW	Consumption situation
HPS	400	13	10.24	0.70	0.87	2208	883200	Over consumption
HPS	250	17	7.91	0.65	0.73	1688	422000	Over consumption
HPS	150	15	3.78	0.60	0.71	1912	286800	Over consumption
HPS	100	17	5.14	0.82	0.85	1688	168800	Suitable
HPS	70	15	2.46	0.65	0.75	1912	133840	Does not fit

in consequence of computer calculations according to the luminance method.

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 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 (U_o) and longitudinal uniformity (U_l) values that are important secondary parameters.

Road types are defined in international technical reports and an optimal solution range is presented technically for these road types [19]. The required design calculations should be made through luminaries with known photometric characteristics, and the number and type of the luminaries should be determined according to these calculations.

Various choices are available for the road parameters in the simulation program. For the road parameters, the lighting system (bilateral, displaced, divided road, tunnel road with single luminary, tunnel road with two luminaries, etc.), road classes (R1, R2, R3, R4, N1, N2, N3, N4, etc.), number of lanes, lane width, refuge width, and road lighting classes (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, luminous 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 [20–24]. An easy and accurate calculation is achieved in the

Table 3. Luminance Values According to the 1st and 2nd Observers under the 400 W HPS Lamps

$L_{average}$ = 10.24 cd/m² *Uo* = 0.70 *Uι* = 0.87									HPS-400 W	
1st observer, metre	**0.65 m**	**1.95 m**	**3.25 m**	**4.55 m**	**5.85 m**	**7.15 m**	**8.45 m**	**9.75 m**	**11.05 m**	**12.35 m**
0.583 m	8.70	10.82	13.08	14.82	15.84	16.08	15.09	14.93	12.90	9.17
1.750 m	8.86	9.00	9.02	9.49	9.78	9.63	9.03	9.54	10.24	9.26
2.917 m	8.01	8.11	7.40	7.61	7.88	7.90	7.18	7.52	9.08	8.39
4.083 m	8.12	8.23	7.64	7.86	8.08	8.03	7.32	7.71	9.20	8.47
5.250 m	9.07	9.31	9.58	10.12	10.46	10.14	9.33	9.82	10.52	9.44
6.417 m	8.57	10.72	12.99	14.82	15.83	16.21	15.08	14.85	12.92	9.10

2nd observer. metre	**0.65 m**	**1.95 m**	**3.25 m**	**4.55 m**	**5.85 m**	**7.15 m**	**8.45 m**	**9.75 m**	**11.05 m**	**12.35 m**
0.583 m	8.57	10.72	12.99	14.82	15.83	16.21	15.08	14.85	12.92	9.10
1.750 m	9.07	9.31	9.58	10.12	10.46	10.14	9.33	9.82	10.52	9.44
2.917 m	8.12	8.23	7.64	7.86	8.08	8.03	7.32	7.71	9.20	8.47
4.083 m	8.01	8.11	7.40	7.61	7.88	7.90	7.18	7.52	9.08	8.39
5.250 m	8.86	9.00	9.02	9.49	9.78	9.63	9.03	9.54	10.24	9.26
6.417 m	8.70	10.82	13.08	14.82	15.84	16.08	15.09	14.93	12.90	9.17

Table 4. Luminance Values According to the 1st and 2nd Observers under the 250 W HPS Lamps

$L_{average}$ = 7.91 cd/m² *Uo* = 0.65 *Uι* = 0.73									HPS-250 W	
1st observer, metre	**0.85 m**	**2.55 m**	**4.25 m**	**5.95 m**	**7.65 m**	**9.35 m**	**11.05 m**	**12.75 m**	**14.45 m**	**16.15 m**
0.583 m	7.49	8.81	7.97	8.77	9.29	10.75	11.31	11.18	11.20	7.87
1.750 m	7.40	7.28	6.43	7.09	7.48	8.15	8.16	8.38	8.82	7.71
2.917 m	7.05	6.11	5.13	5.67	6.01	6.24	6.21	5.83	6.98	7.38
4.083 m	7.27	6.30	5.34	5.99	6.29	6.44	6.37	6.04	7.15	7.58
5.250 m	7.77	7.69	6.98	7.81	8.13	8.85	8.74	8.79	9.22	8.06
6.417 m	7.24	8.61	7.74	8.58	9.22	10.66	11.34	11.10	11.10	7.71

2nd observer, metre	**0.85 m**	**2.55 m**	**4.25 m**	**5.95 m**	**7.65 m**	**9.35 m**	**11.05 m**	**12.75 m**	**14.45 m**	**16.15 m**
0.583 m	7.49	8.81	7.97	8.77	9.29	10.75	11.31	11.18	11.20	7.87
1.750 m	7.40	7.28	6.43	7.09	7.48	8.15	8.16	8.38	8.82	7.71
2.917 m	7.05	6.11	5.13	5.67	6.01	6.24	6.21	5.83	6.98	7.38
4.083 m	7.27	6.30	5.34	5.99	6.29	6.44	6.37	6.04	7.15	7.58
5.250 m	7.77	7.69	6.98	7.81	8.13	8.85	8.74	8.79	9.22	8.06
6.417 m	7.24	8.61	7.74	8.58	9.22	10.66	11.34	11.10	11.10	7.71

simulation results for the lighting system in which data is entered. Fig.4 shows the algorithm of the simulation program and the data entered.

The simulation and design study was performed for the New Zigana Mountain Tunnel (14481 m). As a result, the most economic and accurately calculated lighting data was achieved for a tunnel in which the lighting will be supplied. In the simulation, it was easier to calculate the most suitable luminance values, which is one of the most important problems in tunnels that need to be optimized.

Luminance values were first chosen. Luminaries were then chosen to provide the illumination level and they were placed to provide proper adaptation and safety conditions. This tunnel example requires daytime lighting because of its length and

Table 5. Luminance Values According to the 1st and 2nd Observers under the 150 W HPS Lamps

$L_{average}$ = 3.78 cd/m² *Uo* = 0.60 *Ul* = 0.71									HPS-150 W	
1st observer, metre	0.75 m	2.25 m	3.75 m	5.25 m	6.75 m	8.25 m	9.75 m	11.25 m	12.75 m	14.25 m
0.583 m	5.05	3.93	3.99	5.12	5.83	6.19	5.52	4.67	4.64	5.40
1.750 m	3.73	3.00	2.77	3.47	3.85	3.74	3.24	3.23	3.42	3.90
2.917 m	2.94	2.51	2.26	2.74	2.97	2.86	2.64	2.60	2.76	3.07
4.083 m	3.01	2.57	2.36	2.87	3.07	2.96	2.69	2.70	2.82	3.12
5.250 m	3.88	3.16	3.00	3.77	4.13	4.03	3.41	3.37	3.56	4.02
6.417 m	4.98	3.87	3.92	5.09	5.82	6.18	5.51	4.64	4.63	5.36

2nd observer, metre	0.75 m	2.25 m	3.75 m	5.25 m	6.75 m	8.25 m	9.75 m	11.25 m	12.75 m	14.25 m
0.583 m	4.98	3.87	3.92	5.09	5.82	6.18	5.51	4.64	4.63	5.36
1.750 m	3.88	3.16	3.00	3.77	4.13	4.03	3.41	3.37	3.56	4.02
2.917 m	3.01	2.57	2.36	2.87	3.07	2.96	2.69	2.70	2.82	3.12
4.083 m	2.94	2.51	2.26	2.74	2.97	2.86	2.64	2.60	2.76	3.07
5.250 m	3.73	3.00	2.77	3.47	3.85	3.74	3.24	3.23	3.42	3.90
6.417 m	5.05	3.93	3.97	5.12	5.83	6.19	5.52	4.67	4.64	5.40

Table 6. Luminance Values According to the 1st and 2nd Observers under the 100 W HPS Lamps

$L_{average}$ = 5.14 cd/m² *Uo* = 0.82 *Ul* = 0.85									HPS-100 W	
1st observer, metre	0.85 m	2.55 m	4.25 m	5.95 m	7.65 m	9.35 m	11.05 m	12.75 m	14.45 m	16.15 m
0.583 m	5.14	5.18	5.14	5.00	4.75	4.54	4.43	4.68	4.91	5.04
1.750 m	5.35	5.46	5.32	5.37	5.42	5.00	4.62	4.98	5.24	5.19
2.917 m	4.66	4.97	5.06	5.42	5.86	5.46	4.68	4.63	4.75	4.50
4.083 m	5.01	5.27	5.29	5.74	6.10	5.61	4.84	4.88	5.03	4.80
5.250 m	6.04	6.16	6.05	6.07	6.00	5.56	5.17	5.55	5.87	5.78
6.417 m	4.87	4.96	4.91	4.79	4.58	4.32	4.23	4.46	4.73	4.89

2nd observer, metre	0.85 m	2.55 m	4.25 m	5.95 m	7.65 m	9.35 m	11.05 m	12.75 m	14.45 m	16.15 m
0.583 m	4.87	4.96	4.91	4.79	4.58	4.32	4.23	4.46	4.73	4.89
1.750 m	6.04	6.16	6.05	6.07	6.00	5.56	5.17	5.55	5.87	5.78
2.917 m	5.01	5.27	5.29	5.74	6.10	5.61	4.84	4.88	5.03	4.80
4.083 m	4.66	4.97	5.06	5.42	5.86	5.46	4.68	4.63	4.75	4.50
5.250 m	5.35	5.46	5.32	5.37	5.42	5.00	4.62	4.98	5.24	5.19
6.417 m	5.14	5.18	5.14	5.00	4.75	4.54	4.43	4.68	4.91	5.04

a 90 km/h vehicle speed limitation in the clear road approaching the tunnel. The stopping distance of approximately 130 m for a driver travelling with speed 90 km/h is to see a risky object and stops their car safely. A symmetrical lighting system was preferred at night time lighting, which would continue through the threshold, transition, interior zones, and throughout the tunnel.

5.2. Features of the Tunnel Lighting System

The road pavement is asphalt, class R3. Additionally, Q_o = 0.07, the wall coating is concrete, the reflectivity is the 0.4, and the height of the luminary is the 6 m. The maintenance factor of the luminary is 0.92 and all calculated luminance values are corrected. The ratio of the smallest luminance

Table 7. Luminance Values According to the 1st and 2nd Observers under the 70 W HPS Lamps

$L_{average}$ = 2.46 cd/m² *Uo* = 0.65 *Uι* = 0.75									HPS-70 W	
1st observer, metre	**0.75 m**	**2.25 m**	**3.75 m**	**5.25 m**	**6.75 m**	**8.25 m**	**9.75 m**	**11.25 m**	**12.75 m**	**14.25 m**
0.583 m	2.72	3.06	2.73	2.64	2.49	2.58	3.06	3.36	3.49	2.77
1.750 m	2.59	2.65	2.37	2.28	2.17	2.15	2.48	2.85	2.87	2.61
2.917 m	2.11	1.96	1.80	1.68	1.66	1.59	1.72	1.96	2.01	2.14
4.083 m	2.18	2.02	1.89	1.77	1.73	1.66	1.78	2.05	2.07	2.20
5.250 m	2.77	2.85	2.59	2.50	2.36	2.35	2.64	3.00	3.02	2.74
6.417 m	2.68	3.02	2.69	2.61	2.48	2.56	3.05	3.35	3.49	2.75

2nd observer, metre	**0.75 m**	**2.25 m**	**3.75 m**	**5.25 m**	**6.75 m**	**8.25 m**	**9.75 m**	**11.25 m**	**12.75 m**	**14.25 m**
0.583 m	2.68	3.02	2.69	2.61	2.48	2.56	3.05	3.35	3.49	2.75
1.750 m	2.77	2.85	2.59	2.50	2.36	2.35	2.64	3.00	3.02	2.74
2.917 m	2.18	2.02	1.89	1.77	1.73	1.66	1.78	2.05	2.07	2.20
4.083 m	2.11	1.96	1.80	1.68	1.66	1.59	1.72	1.96	2.01	2.14
5.250 m	2.59	2.65	2.37	2.28	2.17	2.15	2.48	2.85	2.87	2.61
6.417 m	2.72	3.06	2.73	2.64	2.49	2.58	3.06	3.36	3.49	2.77

value to mean luminance value is greater than 0.4 in the calculations for tunnel 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 ($U_l \geq 0.7$). The luminance levels and uniformities of the tunnel walls are in accordance with relevant standards and that is very important for driving safety. All lighting luminaries were established in two lines 2.33 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 and the flicker frequency of the interior zone is out of the 2.5–15 Hz range as mentioned in CIE-2004.

5.3. Simulation Study

The tunnel entrance lighting is approximately 130 m for a 90 km/h speed because of the stopping distance. The New Zigana Mountain Tunnel is 14481 m long, and the threshold zone has a length of 130 m, equal to the stopping distance. If 130 m of the road length is deducted from the whole road distance, 14351 m of the remaining road is the length of the transition, interior, and exit zones. There will be continuous lighting through 14481 m, all day. While the large part of the total power is consumed by the threshold zone in relatively short tunnels, consumption in the threshold zone is very low in a 14351 m long tunnel compared to the entire tunnel. In this study, lighting was established in a simulated environment with HPS luminaries for 400 W, 250 W and 150 W, 100 W and 70 W through the entire tunnel, excluding the threshold zone (130 m). Table 1 illustrates the tunnel road and lighting parameters.

Acceptable luminance values that do not disturb the vision comfort into the tunnel were calculated in the simulation performed with the values in the table. According to CIE-88 on 3.5 m wide road with two lanes, 1st observer stands at 1.75 m (transversal) and a 2nd observer stands at 5.25 m (transversal). Fig. 5 illustrates the simulation program and data entered for a 400 W HPS lamp. These processes are repeated at 250 W, 150 W, 100 W, and 70 W.

The simulation program written with Visual Basic is illustrating the optimum spacing between the two fittings, shown in Table 1 and with use of 400 W HPS lamps, is 13 m. 2x1104=2208 luminaries at 400 W were required for 14351 m of the remaining length of the tunnel, excluding the threshold zone. For the M2-type road lighting class, the desired criterions are, $L_{average} \geq 1.5\,\text{cd/m}^2$, $U_0 \geq 0.4$, $U_1 \geq 0.7$ and $TI \leq 10\%$, and all results obtained from this study are available for the CIE31 standards. As a result of the simulation, the mean luminance of the road is the $L_{average} = 10.24\,\text{cd/m}^2$, the mean luminance uniformity is the U_0=0.7 and the longitudinal luminance uniformity is the U_1=0.87. This process is performed for 17 m with 250 W luminaries, 15 m with 150 W luminaries, 17 m with 100 W luminaries, and 15 m with 70 W luminaries. The chosen distances are optimal for luminance values based on the simulation. Table 2 illustrates the tunnel lighting parameters for HPS lamps at various powers (3 cd/m^2 or higher for highway tunnel lighting in Turkey).

According to simulation results, the 100 W HPS lamp is preferred as the most economic and optimal solution meeting the conditions. The M2-type road lighting class is available since *TI* is lower than 10 % in all regions in the tunnel.

5.4. Luminance Values

Table 3 presents the luminance values for the 1st and 2nd observers under 400 W HPS lamps in the tunnel according to simulation results.

Table 4 presents the luminance values for the 1st and 2nd observers under 250 W HPS lamps in the tunnel according to simulation results.

Table 5 presents the luminance values for the 1st and 2nd observers under 150 W HPS lamps in the tunnel according to simulation results.

Table 6 presents the luminance values for the 1st and 2nd observers under 100 W HPS lamps in the tunnel according to simulation results.

Table 7 presents the luminance values for the 1st and 2nd observers under 70 W HPS lamps in the tunnel according to simulation results.

5. RESULTS

The most accurate reference concerning tunnel road lighting and the selection of lamps to be used is international standards. The simulation tunnel road lighting was therefore adapted to the standards.

This simulation provided easier calculation of luminance values, which is very important in tunnel lighting.

The data of the desired lamp can be processed on the simulation compared to the Database option and the application results were observed.

This program is suitable for many tunnel lighting systems, such as single-sided from left, one-sided from right, displaced, bilateral, and double-sided from the refuge. According to CIE140, the luminance values for all points, mean luminance level, mean and longitudinal uniformity values were calculated for the observers.

Scenarios for HPS lamps meeting the desired conditions at various powers were examined by changing the luminary distance, height, and lamp power of the current tunnel lighting. Calculations were performed on simulations for 400 W, 250 W, 150 W, 100 W, and 70 W HPS lamps, and the 100 W HPS lamp was the most economic that met the minimum conditions conforming to the standards.

As shown in Table 2, the mean luminance value was greater than the 3 cd /m^2 value specified in the standards for the 100 W HPS lamp, which reached 5.14 cd /m^2 mean luminance. The 100 W HPS lamp provides sufficient luminance conditions. The 70 W HPS lamp luminance is equal to 2.46 cd /m^2 and that is less than the standard requirements.

When examining the instantaneous consumption values presented in Table 2, the 150 W HPS lamp consumed 1.7 times more energy than the 100 W HPS lamp, the 250 W HPS lamp 2.5 times, and the 400 W HPS lamp 5.23 times.

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