Research Article

Artificial Intelligence-Assisted Control of Light Pipe & LED Luminaire Hybrid Tunnel Lighting System

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Abstract

Tunnels are designed as infrastructure elements that facilitate smoother traffic movement, enhance operational safety, and minimize environmental effects. However, when adequate lighting is not provided in tunnels, sudden transitions from bright outdoor environments to dim indoor spaces cause temporary vision loss while the eyes adapt to the new environment. Sudden changes in light at tunnel entrances and exits can disorient drivers and increase accident risks. Daylight offers a mix of wavelengths and color temperatures that provide optimal visual conditions for humans. In this study, an energy-efficient hybrid tunnel lighting system combining light tubes with artificial lighting was designed, and an artificial intelligence–based control system dependent on daylight was developed for this setup. To make tunnel conditions more efficient and comfortable for drivers, a control system incorporating an artificial neural network (ANN) algorithm was designed to apply the instantaneous outdoor illuminance level at the tunnel entrance. The control system results were analyzed, indicating that approximately 25.30% energy savings can be achieved *compared to conventional lighting control methods, along with an expected improvement in drivers' visual comfort.*

Keywords: Tunnel lighting, Artificial intelligence, Light pipe (light tube), Artificial neural networks, Illuminance control

1. Introduction

Tunnels, an essential part of urban and intercity transportation today, play a crucial role in driver comfort and safety. However, glare at tunnel entrances can pose a potential accident risk for drivers. To address this issue and improve driver safety, AI-powered tunnel lighting systems are being developed.

Tunnels significantly simplify road travel in mountainous regions, shortening roads and reducing road gradients. However, these tunnels can be potentially dangerous in terms of traffic accidents. Inadequate safety measures can increase the risk of fire accidents, particularly those involving vehicles carrying flammable, combustible, explosive, and hazardous materials. Therefore, effective safety measures must be implemented to prevent accidents. [1]

A critical factor in tunnel lighting is a vehicle's ability to see an object ahead and stop safely within a given speed limit. [2] Therefore, determining speed limits and lighting levels in tunnels is of critical importance. Therefore, various professional computer software programs have been developed to perform these calculations. This software allow the optimal lighting level and/or maximum speed limit to be determined by considering many factors, including tunnel dimensions and the light reflectance of tunnel surfaces. [3]

Tunnel lighting systems are extremely difficult to install successfully due to the inherent risks of road traffic and the limitations of the tunnel's enclosed, isolated environment. Effectively managing tunnel lighting involves time-consuming and labor-intensive challenges, such as maintaining illuminance tolerances, determining the economic life of electrical components, and predicting and addressing performance losses.[4] Because traditional tunnel lighting fails to account for external ambient light levels, potential differences in illuminance across transition zones can lead to eye fatigue and glare. Furthermore, the older-style fixtures used in traditional tunnel lighting are inefficient and require high maintenance costs. Consequently, operating costs, and therefore energy costs, are higher compared to LED fixtures.

Artificial neural networks are complex networks of interconnected "neurons" that process information and learn from experience. Inspired by the brain, these systems demonstrate superior performance in pattern recognition, solving complex tasks, and processing incomplete data. With artificial neural networks, it is possible to design a variety of control systems, from simple single-layer sensors to powerful multi-layered giants, each specialized in different tasks. [5]

During training, an artificial neural network fine-tunes its performance by adjusting the connections between neurons, much as humans learn. Just like memories stored in the brain, the information within these networks resides in the complex dance of these connections. The seeds of modern neural networks were planted in 1943 by McCulloch and Pitts. They demonstrated that, in theory, any computable function could be mimicked by these artificial brains. This groundbreaking work opened the door to a vast range of possibilities, paving the way for the diverse applications of neural networks we see today. [6] So, in essence, neural networks are intelligent mimics of the brain, allowing machines to learn, recognize patterns, and solve complex problems in ways eerily similar to humans. The future holds enormous potential for these artificial neurons, promising to revolutionize countless fields and redefine our understanding of intelligence. [7]

Artificial intelligence-powered lighting systems aim to optimize the operating environment based on daylight and occupancy rates. These systems provide high-performance lighting management by collecting ambient data and implementing the best-case scenario without requiring any additional work. This data allows for optimal equipment maintenance. By reducing glare at tunnel entrances, they reduce the risk of accidents and improve visibility, ensuring safer tunnel travel for drivers. They also increase energy efficiency, reduce costs, and offer more environmentally friendly lighting solutions [8].

The study developed a hybrid tunnel lighting system that combines light pipes and artificial lighting with an AI-supported control system. The tunnel lighting was adjusted based on the annual and daily average illumination data obtained. This ensures optimal use of artificial lighting within the tunnel.

2. Materials and Methods

The aim of AI-based tunnel lighting is to eliminate the problem of sudden light changes at tunnel entrances and exits by dynamically adjusting tunnel illumination based on external environmental conditions. In this way, issues related to driver glare are mitigated, contributing to a driving environment that is significantly safer.
According to the International Commission on Illumination (CIE), tunnels are divided into 5 zones based on luminance levels, and lighting calculations are performed separately for each zone [9, 10, 11]. These zones and their relative luminance values are shown in Figure 1.

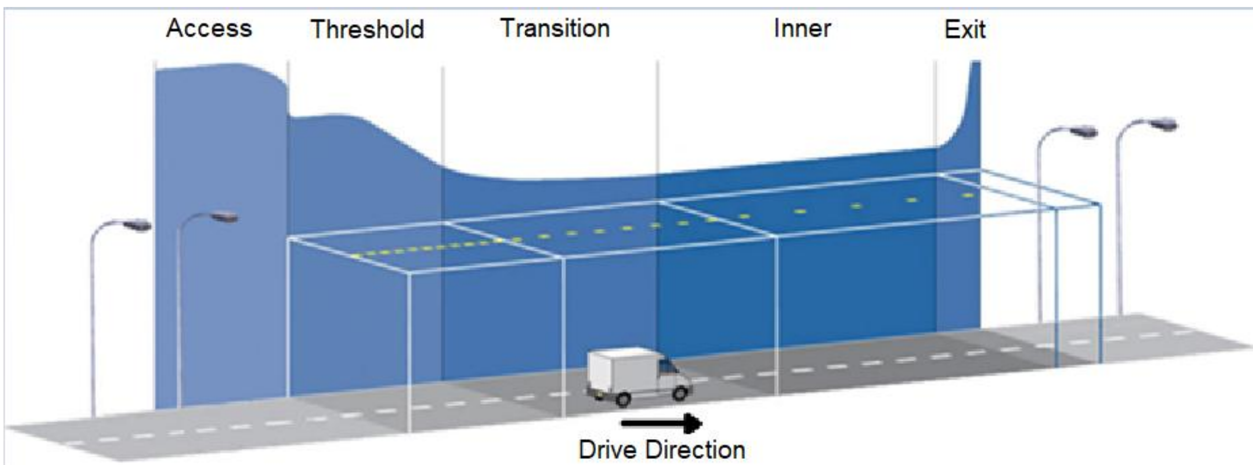

Figure 1: Tunnel zones according to luminance levels [15]

Access zone: This is the length of the road leading to the tunnel entrance. Drivers must be able to look into the tunnel from this zone to detect potential obstacles and enter the tunnel without reducing speed. Drivers' adaptability in the access zone determines the level of lighting in the subsequent section of the tunnel.

Threshold zone: This zone is equal in length to the vehicle's stopping distance for the given speed limit. During the initial portion of this zone, the required illumination level should remain constant, depending on the exterior lighting and traffic conditions. At the end of the zone, the provided illumination level can be rapidly reduced to 40% of the initial value.

The luminance value of the threshold zone is expressed as Lth. Drivers entering a low-light environment from a high-light environment are subject to the "dark hole effect." The dark hole effect occurs when a high-light environment appears like a black hole when viewed from a low-light environment, and when the eye transitions to this environment, it causes temporary blindness during the dark adaptation process. Illumination of the threshold zone is crucial for drivers to avoid this dark hole effect and to continue driving safely [9, 12]. Figure 2 illustrates the dark hole effect that occurs when lighting is insufficient.

Figure 2: The "Dark hole effect" that occurs when there is insufficient lighting [16]

The threshold zone luminance varies depending on the approach zone luminance, the selected contrast parameter, and the braking distance data. For different braking distances and L/EV ratios, the average road surface luminance that should be achieved at the beginning of the threshold zone can be calculated using the data in Table 1 [13].

Table 1: Ratio values for braking distances recommended by CIE [9]

Maximum Braking Distance (m)	Lth / L20 depending on the lighting system used	
	When using the Opposite Directional Lighting System (L/Ev≥0,6)	When using a Symmetrical Lighting System (L/Ev≤0,2)
60	0,04	0,05
100	0,05	0,06
160	0,07	0,1

A series of experiments was conducted using a tunnel entrance simulator to determine the illumination luminance in the tunnel threshold zone. The experiments determined the minimum ground luminances required to detect an object with a 7-degree visual angle in 0.1 seconds with a 75% probability of being seen at various adaptation luminances of 81%, 53%, and 26%. However, since the experiments were conducted for a stationary observer and a known object location, the values obtained by the simulator were multiplied by a factor of 2.78 to reflect real traffic conditions. The study results are given in Table 2. [14]

Table 2: Lth values corresponding to L20 value [14]

L20 (cd/m2)	C (%)		
	81	53	26
	Lth (cd/m2)		
7500	24	45	206
5000	23	40	142
3000	21	33	100
1000	20	28	53
500	20	24	42
100	19	22	31

Transition zone: Throughout the transition zone, the illumination level is gradually reduced to reach the required level in the interior. Because these reductions depend on the human eye's ability to adapt to the environment and therefore on time, the ratio should not exceed 1:3. At the end of the transition zone, the illumination level is reduced until it is three times the interior level.

The luminance value of the transition zone is expressed as Ltr. 75% of studies show that a 15-second transition from a luminance level of 6500 cd/m² to a luminance environment of 15 cd/m² is sufficient.

Approximately 75% of the studies indicate that a 15-second period is sufficient for the visual adaptation from a luminance level of 6500 cd/m² to 15 cd/m². [9]

Inner zone: This zone corresponds to the rest of the tunnel. The illumination level is maintained at a constant level. If full compliance with the inner zone can be achieved, nighttime road lighting regulations can be applied in this zone. As is known, a luminance level of 2 cd/m^2 is recommended for roads with heavy traffic at night. The International Commission on Illumination (CIE) recommends a luminance level of 1-15 cd/m^2 for the tunnel interior, depending on traffic density and braking distance. Table 3 can be used for glare levels in the interior zone, depending on the tunnel's location and speed restrictions [17, 18].

Table 3: Le value according to Lc, Lr Values [9]

Driving Direction	Lr [kcd/m^2] Road luminance value	Lc [kcd/m^2] Sky luminosity value	Le [kcd/m^2] Luminance value of the environment			
West-East Direction	4	12	2	6	15[H] 10[V]	2
North Direction	3	8	3	8	15 [V] 15 [H]	2
South Direction	5	16	1	4	15 [H] 5[V]	2

Exit zone: This is the area extending from the end of the tunnel's interior to the tunnel's exit point. Drivers entering a low-light environment into a high-light environment are subject to the "bright hole effect." The bright hole effect occurs when a low-light environment appears like a bright hole when viewed from a high-light environment. Upon entering, the eye experiences temporary blindness as it adapts to darkness. The human eye can quickly adapt from seeing in the dark to seeing in daylight (light adaptation). Therefore, lighting conditions are less critical at the tunnel exit than at the tunnel entrance. In fact, some one-way tunnels do not even have lighting at the exit. The lighting level is gradually increased until it matches outdoor lighting.

Although lighting at the tunnel exit is not critical, providing good lighting in this section will provide several advantages, such as eliminating the bright hole effect that occurs at the tunnel exit, allowing the tunnel to be used in both directions during maintenance or troubleshooting, and allowing vehicles exiting the tunnel to clearly see the vehicles behind them in the rearview mirror [14]. Figure 3 shows the bright hole effect that occurs under insufficient lighting.

Figure 3: The "bright hole effect" that occurs when there is insufficient lighting [19]

Tunnel lighting is summarized in its simplest form in Figure 4. The number of lighting elements, and therefore the luminance level, is highest in the entrance area. The number of fixtures gradually decreases in the transition area. The number of fixtures is lowest in the interior area. The exit area, like the entrance area, has a high number of lighting elements.

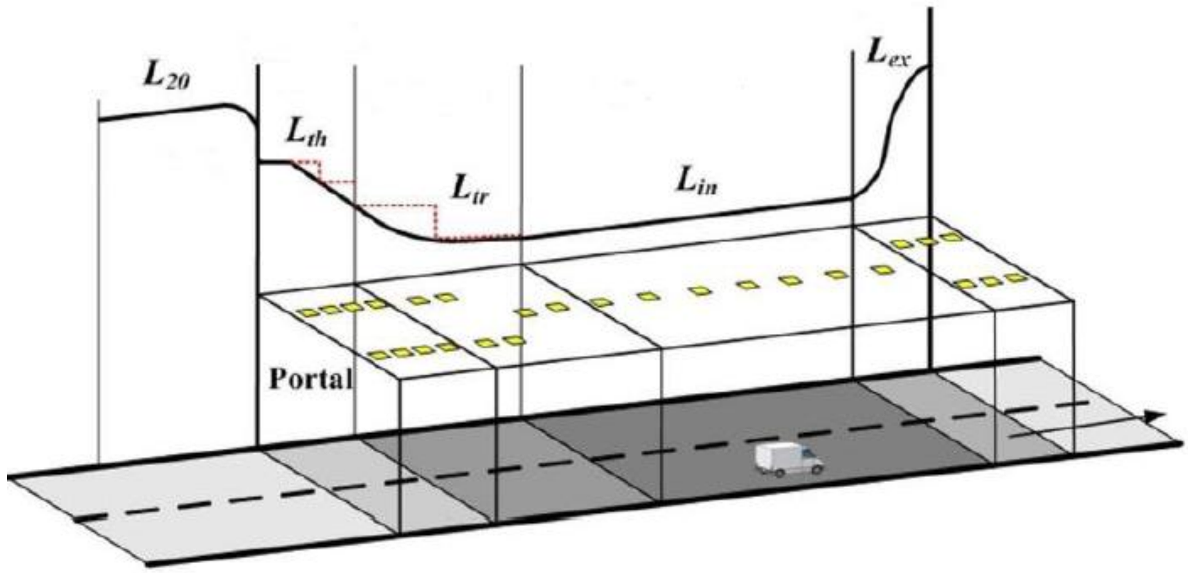

Figure 4: Illuminance levels by region [11]

2.1. Project Components

With the system we will develop, the lighting level at the tunnel's threshold will be optimized for the outdoor environment. This will allow drivers entering the tunnel to enter an environment with the same level of illumination, resulting in minimal ambient light. The light pipes will bring sunlight from outside the tunnel to the tunnel's threshold. This will bring the lighting level at the tunnel entrance very close to the outdoor environment.

Since the required illumination level in the threshold area cannot be met by light pipes alone, the remaining illumination needs will be provided by LED luminaires.

2.1.1. Artificial Light Sources

LED luminaires were chosen as the artificial light source for the project due to their high energy efficiency, long lifespan, and low maintenance costs. Designed for tunnel lighting, the luminaires feature DALI-based dimming and can be integrated into AI-controlled automation. The LED luminaire used in the project is shown in Figure 5.

Figure 5: GOLEDO-T 128 LED tunnel lighting fixture [22]

Calculations were made assuming the tunnel entrance is south. The specifications of the fixtures used in this system are given in Table 4.

Table 4: GOLEDO-T 128 LED tunnel lighting fixture technical specifications [22]

Brand / Model	HEPER GOLEDO-T 128 LED (LT2037.888-EN)
Luminous Flux	18 774 – 41 445 lm
Power Consumption	138 – 272 W
Efficiency	129 – 165 lm/W
Color Temperature (CCT)	3000 K / 4000 K
CRI (Color Rendering)	≥ 70
Supply Voltage	220–240 V AC, 50/60 Hz
Protection Class	IP66
Impact Resistance	IK08
Body Material	Marine grade aluminum, electrostatically painted
Optical Element	Tempered glass + PMMA lens
Control Options	On/Off, 0-10 V, DALI, AutoDIM, StepDIM
Operating Temperature	–40 °C … +25 °C

Lifespan (L90B10)	> 102 000 hour
Insulation Class	Class I (Optional Class II)
Certifications	CE, ENEC, ENEC+, UKCA
Weight	18,75 kg

2.1.2. Light Pipes

A light pipe structure is a system designed to collect, transmit, and distribute sunlight homogeneously over the desired area. The core components of this structure are assembled through detailed engineering to optimize each function. Light pipes essentially consist of three basic parts: the light collector, the light transmission channel, and the diffuser. In addition to these basic components, additional components such as structural support elements, cladding, and protection systems are also included. Figure 6 shows the main components of a light pipe.

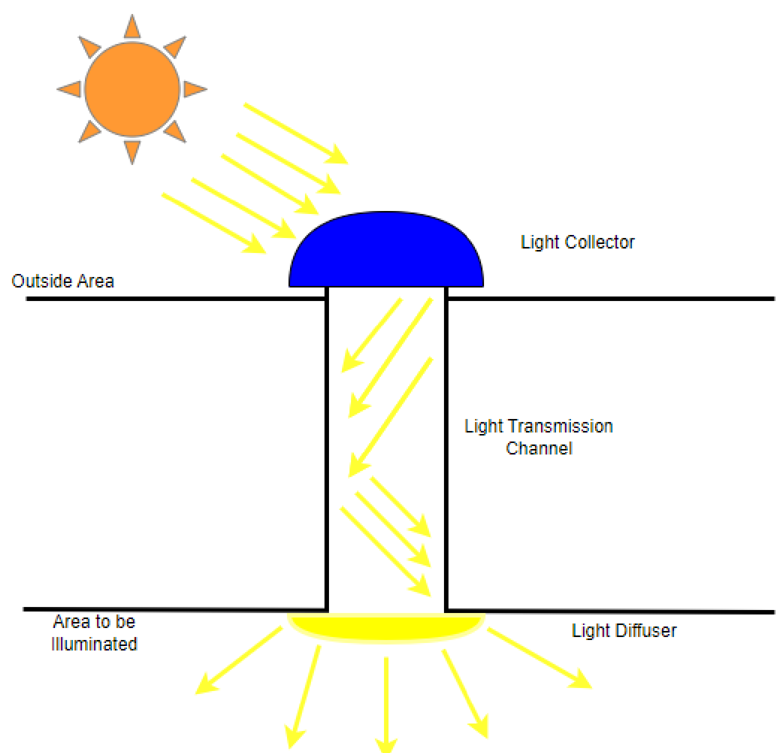

Figure 6: Structure of the light pipe

In the simulation phase of our project, Solatube SkyVault M74 DS series light pipes, featuring a high reflectance coefficient and modular structure, were used. This system transmits sunlight to the interior with minimal loss, enhancing natural lighting performance and supporting the energy efficiency of the hybrid lighting system.

The Solatube SkyVault M74 DS series is an advanced light pipe system designed to deliver natural daylight into large indoor spaces (e.g. industrial facilities, sports halls, airports or tunnels) with high efficiency.

This system minimizes light loss even at long distances thanks to its highly reflective interior surface, and its modular structure allows for easy adaptation to different roof and ceiling heights. The technical specifications of this light pipe system are listed in Table 5.

Table 5: Solatube SkyVault M74 DS light pipe specifications [20, 21]

Tube Diameter	≈ 29 inch (~740 mm) (Solatube)
Maximum duct length	≈ 100 ft. (~30 m) (Solatube)
Inner surface reflectivity	Spectralight® Infinity — ≈ %99,7 efficiency (Solatube)
Dome thickness/material	~ 3,2 mm polycarbonate outer dome (DP tipi) (Powerdaylight)
Wind uplift resistance	195 psf (~9,3 kPa) (Powerdaylight)
Fire spread class	Class A (Powerdaylight)
Hail resistance	Resistant to 2 inch (≈ 50 mm) diameter hail (Powerdaylight)
Diffuser/light distribution	Homogeneous light distribution with prismatic diffuser (Solatube)
Thermal control technology	InfraReduction™ feature to limit IR rays (Solatube)

In the designed system, a total of nine light pipes were placed in the threshold area. Twenty LED fixtures were used to support the light pipes. The LED fixture groups are dimmed to the required level when the illumination provided by the light pipes is insufficient. Figure 7 shows a tunnel lighting simulation created in the DiaLux Evo program.

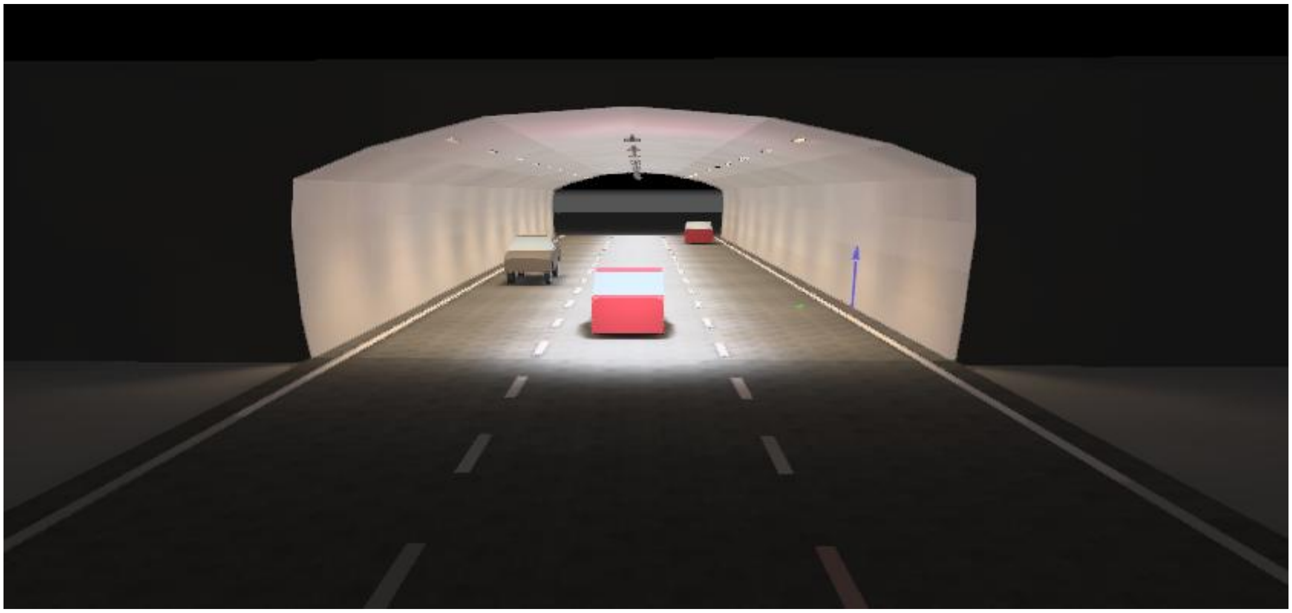

Figure 7: Tunnel lighting simulation created in the DiaLux Evo

The literature indicates that the fundamental parameters used in the design of tunnel lighting systems are critical for driver comfort, safety, and energy efficiency [9]. In this context, it is emphasized that the boundary conditions for the lighting system should be determined by considering tunnel geometry, road slope, surface reflectance properties, luminance levels, and speed limits. Factors such as tunnel exterior luminance conditions, threshold zone adaptation, and driver braking distance are stated to be influential in determining lighting levels. In this regard, the tunnel design parameters and their corresponding values used in the reviewed study are presented in Table 6 [9].

Table 6: Tunnel design parameters and values [9]

Permissible speed value in the tunnel	70 km/hour
Tunnel design speed	80 km/ hour
Road slope	%4
Tunnel outer zone luminosity	3000 cd / m2
Tunnel threshold zone luminosity	150 cd / m2
Braking distance	100 meter
Tunnel wall lining	Concrete (reflection coefficient 0.4)
Road pavement	Asphalt quality class R3, q0 = 0,07 (cd/m2) / lx

Maintenance factor	0,7

2.1.3. Tunnel Lighting Control Design with ANN

The average daily illuminance values collected throughout the year, which form the basis of this study, and some of the artificial lighting dim output levels used to achieve the required illuminance level are shown in Table 7. As can be seen in the table, the collected data were grouped according to three different light intensities: overcast, cloudy, and clear days. These data were collected in 5-minute time intervals.

Table 7: Artificial lighting output values calculated according to light pipe illuminance values

	Kapalı gün ort. Ayd. Değeri(cd/m2)						Bulutlu gün ort. Ayd. Değeri(cd/m2)						Açık gün ort. Ayd. Değeri(cd/m2)					
Zaman	Işık Borusu1	Işık Borusu2	Işık Borusu3	Çıkış 1	Çıkış 2	Çıkış 3	Işık Borusu	Işık Borusu	Işık Borusu	Çıkış 1	Çıkış 2	Çıkış 3	Işık Borusu	Işık Borusu	Işık Borusu	Çıkış 1	Çıkış 2	Çıkış 3
00:00	0,00	0,00	0,00	10,00	10,00	10,00	0,00	0,00	0,00	10,00	10,00	7,00	0,00	0,00	0,00	10,00	10,00	4,50
00:05	0,00	0,00	0,00	10,00	10,00	10,00	0,00	0,00	0,00	10,00	9,75	7,25	0,00	0,00	0,00	10,00	9,75	4,75
06:35	0,00	0,00	0,00	10,00	9,75	10,00	18,34	15,00	11,98	9,00	9,00	6,25	55,00	43,05	32,83	6,50	7,00	2,75
06:40	0,30	0,24	0,19	9,75	9,75	10,00	19,29	15,79	12,60	9,00	9,00	6,25	56,17	43,96	33,52	6,50	7,25	2,75
06:45	0,68	0,56	0,45	10,00	10,00	9,75	20,50	16,78	13,39	8,75	8,75	6,25	57,12	44,70	34,09	6,25	7,00	2,50
06:50	1,03	0,85	0,68	10,00	9,75	9,75	21,53	17,61	14,06	8,75	8,75	6,25	58,10	45,47	34,67	6,25	6,75	2,50
06:55	1,29	1,05	0,84	10,00	10,00	9,75	22,54	18,44	14,72	8,50	9,00	6,25	59,08	46,23	35,26	6,25	7,00	2,50
07:00	1,63	1,33	1,06	9,75	9,75	10,00	23,61	19,31	15,42	8,50	8,50	6,00	60,89	47,66	36,34	6,25	6,75	2,25
07:05	2,10	1,72	1,37	10,00	9,75	10,00	24,83	20,31	16,21	8,25	8,75	6,25	61,49	48,12	36,70	6,00	6,50	2,50
07:10	2,57	2,11	1,68	9,75	10,00	9,75	26,04	21,30	17,00	8,50	8,75	6,00	62,81	49,16	37,49	6,00	6,75	2,25
07:15	3,07	2,51	2,00	9,75	9,75	9,75	27,10	22,18	17,70	8,25	8,75	6,00	63,81	49,94	38,09	6,00	6,75	2,50
07:20	3,75	3,07	2,45	9,75	9,75	9,75	28,11	23,00	18,35	8,25	8,50	6,00	65,07	50,92	38,83	5,75	6,75	2,50
07:25	4,21	3,45	2,75	9,75	9,75	9,50	29,00	23,72	18,94	8,25	8,25	6,00	65,83	51,52	39,29	6,00	6,50	2,25
07:30	4,69	3,83	3,06	9,50	9,75	9,75	29,55	24,17	19,30	8,25	8,50	6,00	67,03	52,46	40,01	5,75	6,50	2,25
07:35	5,21	4,27	3,41	9,50	9,50	9,75	30,07	24,61	19,64	8,00	8,50	6,00	68,85	53,88	41,09	5,50	6,25	2,00
07:40	5,87	4,81	3,84	9,75	9,75	9,75	30,51	24,97	19,93	8,00	8,50	6,00	69,33	54,26	41,38	5,50	6,25	2,25
07:45	6,39	5,23	4,17	9,50	9,50	9,75	31,15	25,49	20,34	8,25	8,25	6,00	71,13	55,67	42,45	5,75	6,50	2,00
07:50	7,07	5,79	4,62	9,50	9,50	9,75	31,64	25,88	20,66	8,00	8,25	5,75	72,15	56,47	43,06	5,25	6,25	2,00
07:55	7,54	6,17	4,92	9,50	9,50	9,75	32,35	26,47	21,13	8,00	8,25	5,75	72,90	57,05	43,51	5,25	6,25	2,00
08:00	8,12	6,64	5,30	9,50	9,50	9,50	32,64	26,70	21,31	8,00	8,25	6,00	74,28	58,13	44,33	5,25	6,00	2,00
08:05	8,57	7,01	5,60	9,50	9,50	9,75	33,35	27,29	21,78	7,75	8,25	5,75	75,39	59,00	45,00	5,25	6,00	1,75

The hybrid system aims to bring daylight to the tunnel threshold area using light pipes and supplement the remaining lighting with dimming LED fixtures. To this end, the threshold area was divided into three zones, with a total of nine light pipes installed, three in each zone, and three separate LED lighting groups were integrated into these zones, totaling 20. The lighting design for the tunnel threshold area, created in Dialux Evo, is shown in Figure 8.

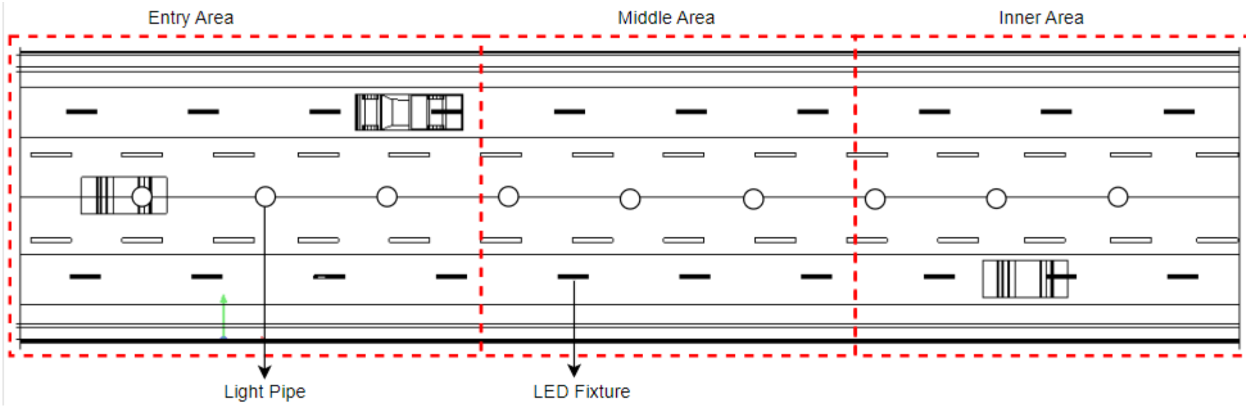

Figure 8: Tunnel threshold area lighting system

The artificial neural network-based control system automatically adjusts LED brightness based on outdoor light levels and traffic density. The system was tested under various weather conditions in simulations using MATLAB 2025b. Figure 9 shows a diagram of the neural network fitting block used.

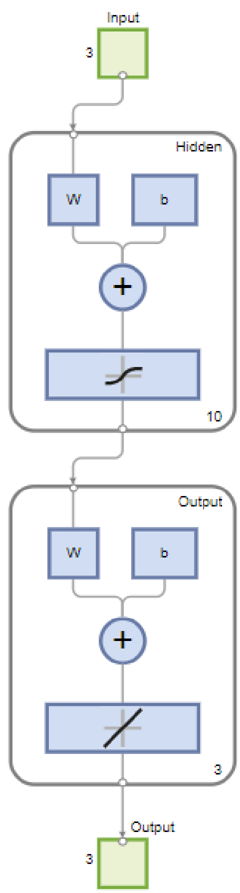

Figure 9: MATLAB neural network diagram

In the neural network fitting application, the learning results and error rates that occur when the input and output data sets are entered and the learning is run are shown in Figure 10.

Training Progress

Unit	Initial Value	Stopped Value	Target Value
Epoch	0	9	1000
Elapsed Time	-	00:00:05	-
Performance	3.41	0.0104	0
Gradient	4.8	0.00301	1e-07
Mu	0.001	1e-05	1e+10
Validation Checks	0	6	6

Figure 10: MATLAB neural network dim level training results

The graphs generated when the regression plots of the learning results are run are shown in Figure 11.

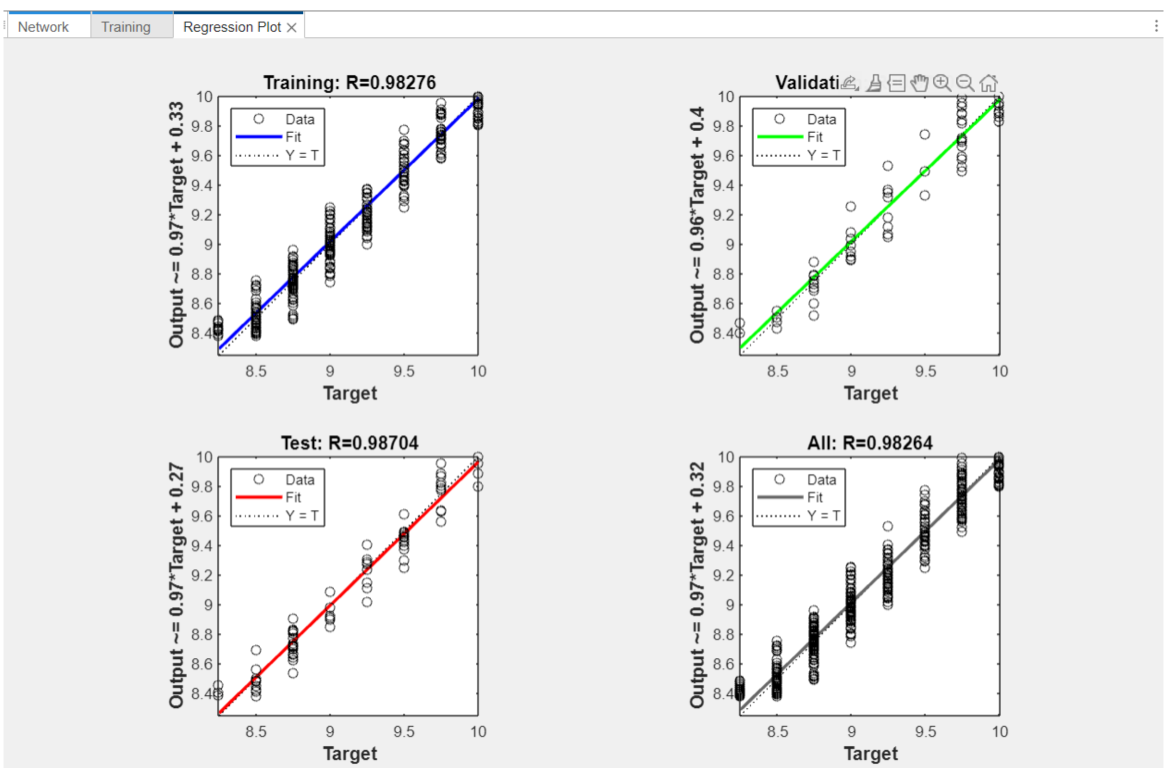

Figure 11: MATLAB neural network regression graphs

Using a neural network fitting block, ANN blocks were created by learning separately for each of the three sections of the tunnel threshold area. The threshold area of the tunnel was created as "ANN Tunnel Area 1" for the entrance section, "ANN Tunnel Area 2" for the middle section, and "ANN Tunnel Area 3" for the interior section, and was added to the ANN control circuit shown in Figure 12.

The control system is implemented with an artificial neural network (ANN) in MATLAB 2025b. The ANN blocks generate the LED dimming percentage for each zone using natural illuminance (lux) inputs from the light pipe on a per-zone basis. Figure 12 shows the ANN control flow.

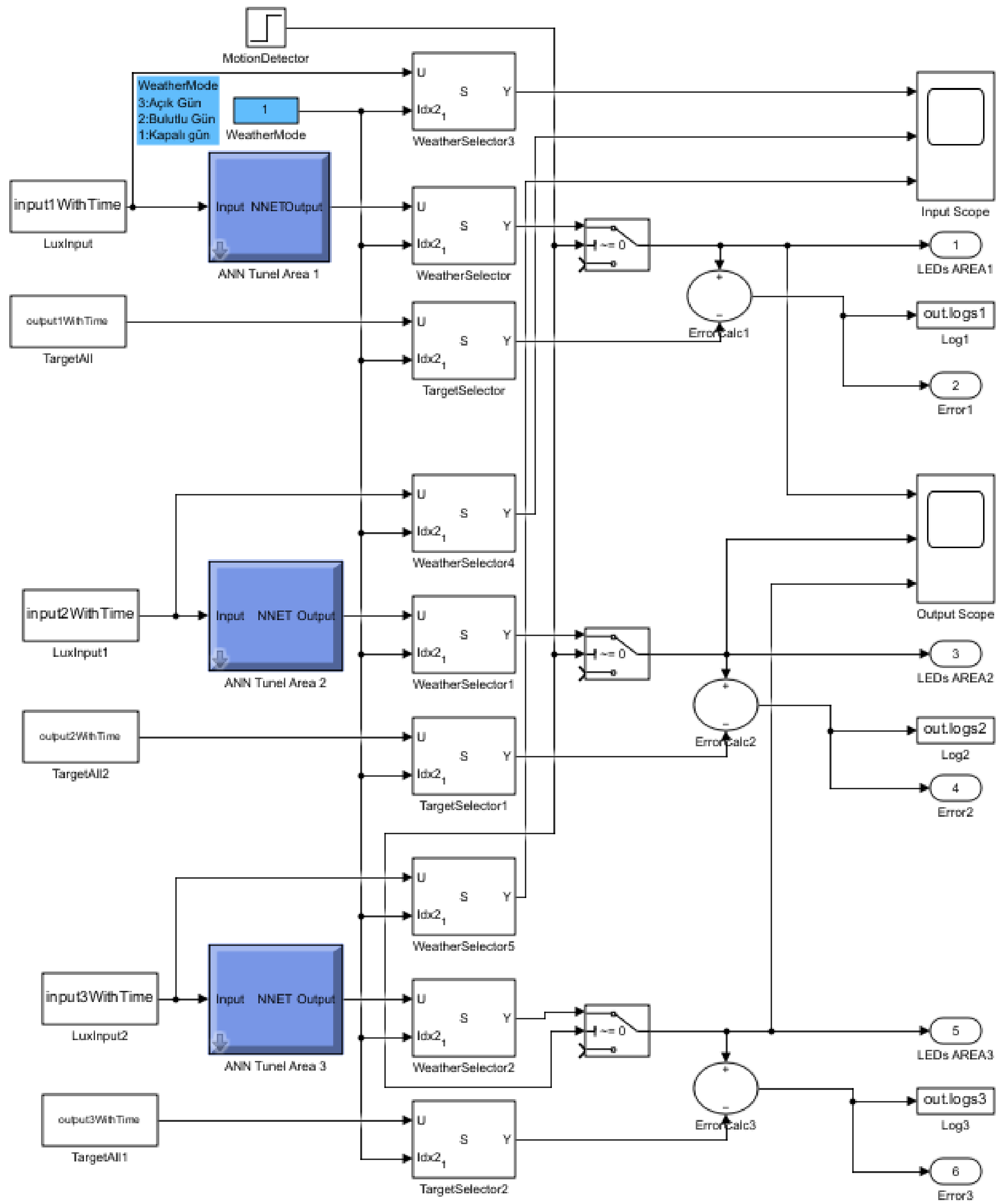

Figure 12: Light Pipe and artificial lighting ANN simulink control circuit

The Motion Detector (MotionDetector) operates artificial lighting only when there are vehicles in the tunnel. The "WeatherMode" block is set using weather information, and the ANN block adjusts the artificial lighting dim level accordingly.

3. Results

Three different meteorological scenarios were examined in the simulation: overcast, cloudy, and clear weather conditions. These scenarios were created to increase the accuracy of the artificial neural network (ANN). Significant differences in light pipe performance were observed between the scenarios depending on the outdoor conditions. Figure 13 graphically illustrates the changes in illuminance data collected during an overcast day for three different sections of the tunnel threshold (entrance, middle, and inner region).

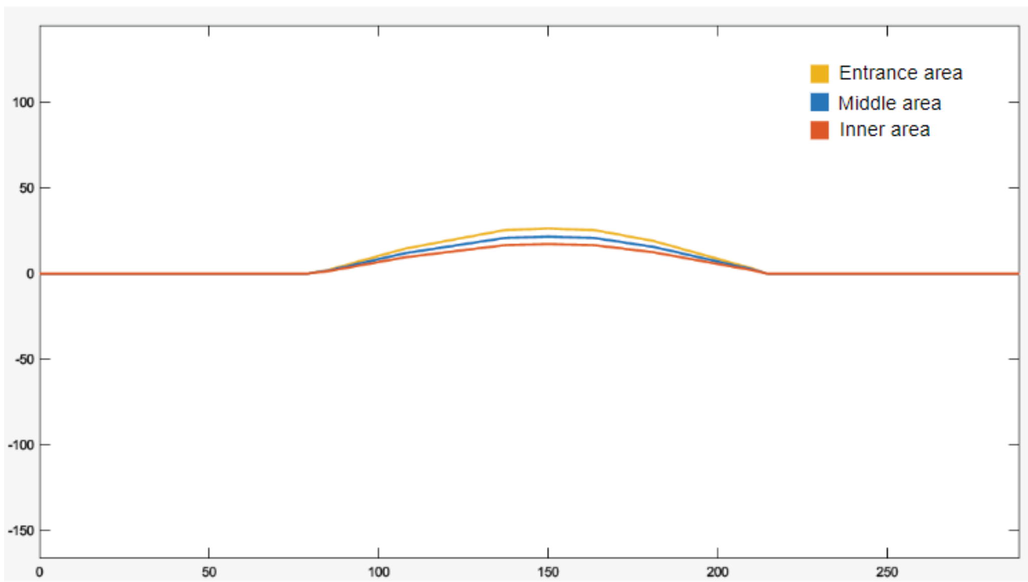

Figure 13: Overcast daylight data

The graph of illuminance data collected for a cloudy day is shown in Figure 14 for three separate sections of the tunnel threshold region (entrance, middle, and inner region).

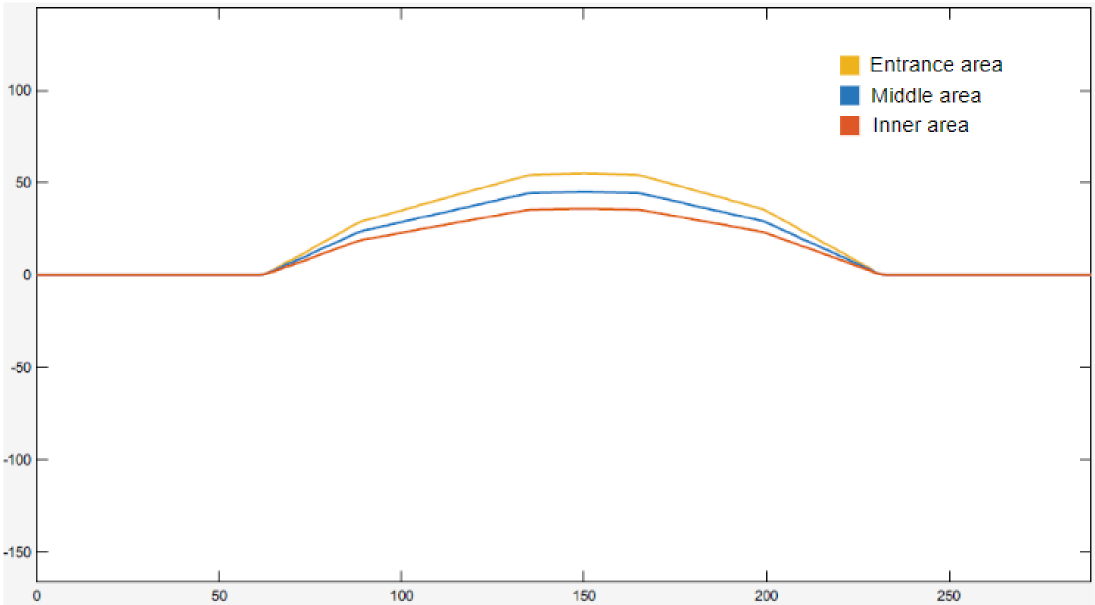

Figure 14: Cloudy daylight data

The graph of the illuminance data collected under clear day conditions is shown in Figure 15 for three different parts of the tunnel threshold region (entrance, middle, and inner region).

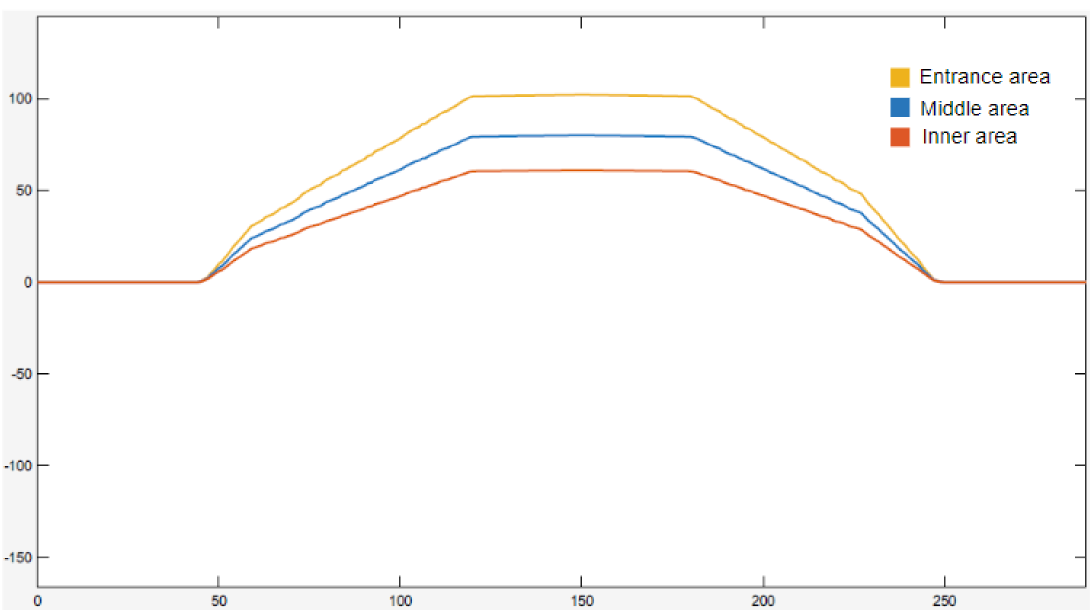

Figure 15: Clear daylight data

An examination of the illuminance data graphs revealed a distinct decrease in illuminance from the tunnel entrance toward the interior. This decrease is due to the gradual weakening of natural daylight as one progresses through the tunnel.

To achieve the targeted luminance level at the entrance section of the threshold zone, the artificial lighting dimming levels required in addition to the light pipes were calculated by an artificial neural network (ANN) algorithm. The ANN processes input data obtained under different meteorological conditions and dynamically determines the optimal dimming rates for each zone.

The time-dependent change of artificial lighting dim levels determined by ANN in order to achieve the targeted indoor luminance level under overcast day conditions is presented as oscilloscope output obtained in the MATLAB environment in Figure 16.

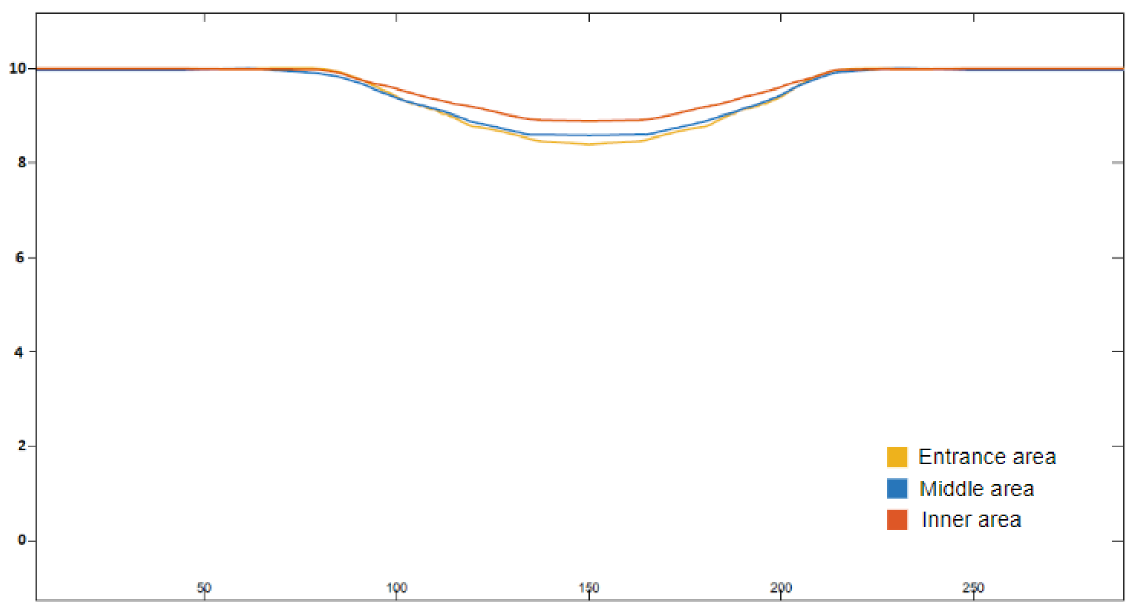

Figure 16: Dim levels of artificial lighting during the day

The time-dependent change of artificial lighting dim levels determined by the artificial neural network (ANN) to achieve the targeted indoor luminance level on a cloudy day is presented as an oscilloscope image in Figure 17.

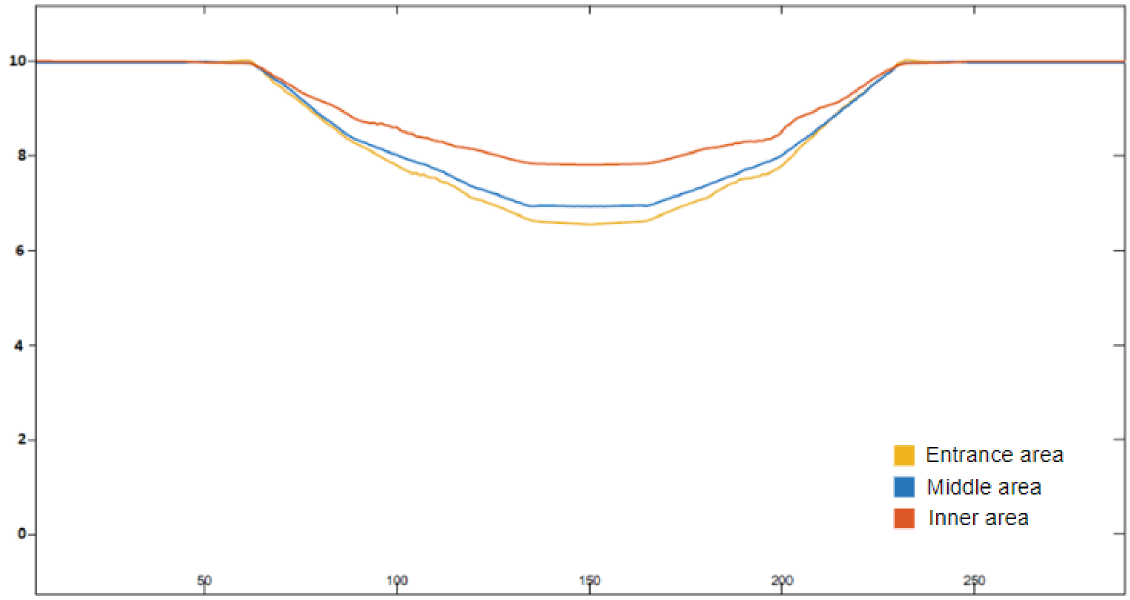

Figure 17: Dim levels of artificial lighting on a cloudy day

The time-dependent change of artificial lighting dim levels determined by the artificial neural network (ANN) to achieve the targeted indoor luminance level on a sunny day is presented as an oscilloscope image in Figure 18.

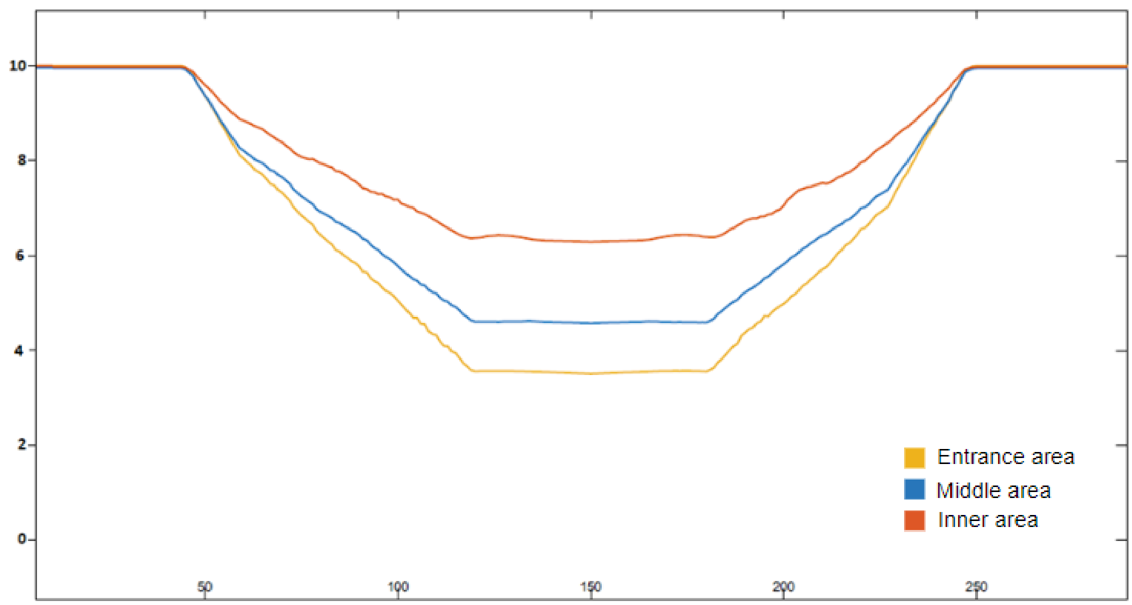

Figure 18: Dim levels of artificial lighting on a sunny day

An evaluation of the artificial lighting control results of the system designed using artificial neural networks demonstrates that a successful lighting system is designed by supplementing daylight with artificial lighting. While artificial lighting remains constantly active in the traditional system, this value drops significantly in our artificial neural network control design supported by light pipes, as seen in Figures 16, 17, and 18.

4. Discussion and Conclusion

In this study, a lighting simulation was performed for the tunnel threshold area using an artificial neural network application. The tunnel threshold area was divided into three sections, with three separate light pipe sets for each section. Furthermore, the artificial lighting used in these sections was also dimmed separately.

The designed system adapts brightness to the outside environment, eliminating the dark hole and bright hole effect at tunnel entrances, thus preventing glare for drivers. The lighting inside the tunnel is significantly more efficient than traditional methods. The savings achieved in each zone are shown in Table 8.

Table 8: Saving percentages of regions compared to traditional lighting

Savings percentages				
	Threshold zone 1	Threshold zone 2	Threshold zone 3	Average Value
Overcast Day	4,62	4,64	3,49	4,25
Cloudy Day	13,00	12,20	8,78	11,32
Clear (Sunny) Day	31,40	26,70	18,22	25,30

When the savings percentages are examined;

On overcast days, an average energy saving of 4.25% is observed. On these days, when sunlight is very low, the light pipe transmits very little light, so the savings are lower than on other days.

On cloudy days, savings of 11.32% are achieved on average. On cloudy days, sunlight is more diffused, but because it's not directly incident, savings are limited. Because there's more light on cloudy days, savings are higher than on overcast days.

On clear (sunny) days, savings of an average of 25-30% are observed. On such days, the savings are even higher because the sunlight is direct. Light pipes direct sunlight into the tunnel, significantly reducing energy costs. Therefore, this is when the savings are highest.

These data demonstrate the success of the designed system. This system will be widely used in the future to improve driver safety and reduce the risk of accidents.

Currently, the relatively high investment costs may be cited as a handicap. However, this handicap will be overcome over time. Countries and companies that invest in this technology will profit.

Tunnel lighting systems are a dynamic field constantly evolving to meet the demands of modern transportation. By embracing energy-efficient technologies, human-centered designs, and intelligent control systems, tunnel lighting not only illuminates the road but also, as in this study, improves driver safety, comfort, and even health. As research delves deeper into personalization and biofeedback, the future of tunnel lighting promises to be as adaptable and responsive as the drivers navigating it.

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