International Journal on Advanced Science Engineering Information Technology

Vol.14 (2024) No. 3
ISSN: 2088-5334

Modeling Night and Daylighting Toll Road Tunnel Using Dialux to Compare the Performance of HPS and LED Lamp

Endah Setyaningsih [a,*], Jeanny Pragantha [b], Henry Candra [c]

[a] Department of Electrical Engineering, Universitas Tarumanagara, Jl. S. Parman, Jakarta, Indonesia
[b] Informatics Engineering, Universitas Tarumanagara, Jl. S. Parman, Jakarta, Indonesia
[c] Department of Electrical Engineering, Universitas Trisakti, Jl. Kyai Tapa, Jakarta, Indonesia

*Corresponding author: *endahs@ft.untar.ac.id*

***Abstract*—In toll road tunnels, the lighting at the threshold zone must balance the brightness of the access zone with natural light. Therefore, artificial lighting is strategically placed in that area to match the brightness to the intensity of natural light. This balance shifts during nighttime to ensure uniform brightness throughout the tunnel, equivalent to street lighting. Additionally, a significant amount of power is required to realize this artificial lighting. Two lamp technologies are used for tunnel lighting: HPS lamps with low energy efficiency and LED lamps with better energy efficiency. The challenge is determining artificial lighting in the threshold zone using energy-efficient lamps. To address this issue, simulations were conducted to compare the two lamp types applied in tunnels to achieve the most significant power savings. This research creates a model of toll road tunnel lighting using DIALux software better to understand the characteristics of toll road tunnel lighting using HPS and LED lamps. The SNI and ANSI/IES are the standards used. The Cisumdawu tunnel is used as the case study. The simulation results show that the luminance in the interior zone using LED or HPS lamps meets the SNI standard. Using LED lamps results in higher luminance with less power than using HPS. This discovery can improve energy efficiency in tunnel environments and contribute to lighting solutions for transportation infrastructure.**

***Keywords*—Tunnel lighting; Cisumdawu tunnel; daylighting; night lighting; lighting simulation.**

Manuscript received 8 Mar. 2024; revised 25 Apr. 2024; accepted 19 May. 2024. Date of publication 30 Jun. 2024.

I. INTRODUCTION

Based on research in tunnel lighting that the authors conducted (decentralization research that the Higher Education Department funded), it was found that the lighting in the Pasar Rebo tunnel and the Cibubur tunnel did not meet the lighting standards for both nighttime lighting and daylight lighting [1]. The research conducted to enhance energy efficiency in tunnel lighting applies three methodological approaches: implementing smart lighting technology in the tunnel [2]–[7]; organizing the environment by planting trees and plants at the tunnel entrance [8], [9]; and by replacing HPS lamps with LED lamps. The average lighting during the day is either very excessive, that is, the illumination and luminance exceed the SNI standards and international standards, or much less than standard, especially at mid-day [10], [11]. As a result, the face of the tunnel looks very dark compared to sunlight, which causes the driver's eyes to lose sight temporarily (or black hole effect) [12]–[16]. By designing a tunnel lighting system that prioritizes both driver safety and minimizes the disruptive effects of light transitions, we can significantly improve overall safety and reduce negative impacts on drivers' vision within the tunnel [17].

The Cileunyi-Sumedang-Dawuan Tunnel (Cisumdawu Tunnel) is used to overcome congestion and shorten vehicle tracks which is implemented massively in developed countries such as China [18]. This tunnel is part of the Cisumdawu toll road in Cilengser Village. It is located in section II of the toll road, which connects Ranca Kalong and Sumedang, Subang, West Java. The Cisumdawu toll road is expected to shorten the distance from Bandung to Sumedang and West Java International Airport in Kertajati via the Cikampek-Palimanan toll road. The Cisumdawu tunnel consists of two tunnels: the right tunnel with the initials R (Right) and the left tunnel L (Left). Fig. 1 is the Cisumdawu tunnel, the twin tunnel. The inside view of the Cisumdawu tunnel can be seen in Fig. 2. Fig. 3 shows the location of the Cisumdawu toll road in the West Java area. The Cisumdawu Tunnel is the longest in Indonesia, with a length of 472 m and a diameter of 14 m for each tunnel [19].

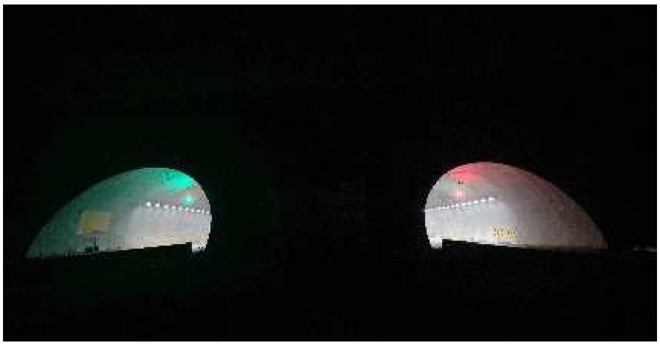

Fig. 1 Cisumdawu Tunnel, the Twin Tunnel

A tunnel is a road whose surroundings are covered by structures. Generally, this road is below ground level [8]. Tunnel can be divided into "long tunnel" and "short tunnel" based on the clarity of view [20]. In the tunnel road, drivers usually have a short visual blind zone and visual shock when entering and exiting the tunnels [21], [22]. In a short tunnel, the exit is visible from a point directly in front of the tunnel entrance when no vehicles are passing. Usually, the short tunnel length is limited to 75 meters [9]. During the day, the short tunnel generally does not require a lighting system because the inclusion of daylight from both sides of the short tunnel, plus the silhouetted effect of the bright light at the other end of the tunnel, generally guarantees satisfactory visibility. In contrast to long tunnels, the driver cannot see the exit end of the tunnel. Tunnels that are less than 75 m long but whose paths are not straight so drivers cannot see the exit end of the tunnel are defined as long tunnels [9], [23].

The essential purpose of tunnel lighting is to provide sufficient and comfortable visibility for tunnel users to pass through the tunnel safely day and night [24], [17], [5]. Several things must be considered To achieve this goal, which are as follows [16], [12]:

- Lighting must provide a sufficient and even level of illuminance to the driver throughout the tunnel in dry and wet conditions.
- The angle of incidence of the lamp light relative to the driver's vision should provide a high level of sight of the road markings in all weather conditions.
- Lighting should not cause glare.
- Lighting should not flicker [25].

Fig. 2 Inside Cisumdawu Tunnel

Fig. 3 Map of Cisumdawu Tunnel in Rancakalong Sumedang

In the long tunnel, acknowledging the difference in human visual adaptation speeds for light and dark transitions, five distinct lighting zones are implemented (refer to Fig. 4 below the paper) [17], [23], [26]:

Access Zone: The driver's approach to the tunnel is illuminated by the same ambient light level as outside, allowing them to see the tunnel entrance.

Threshold Zone: Upon entering, the tunnel reveals its interior gradually over a distance equal to the stopping distance. The luminance within the first part is maintained constant, matching the outside level and adapting to traffic conditions. As the zone progresses, the luminance is smoothly reduced to 40% of its initial value.

Transition Zone: A gentle transition bridges the gap between the threshold's dimmed lighting and the interior's deeper darkness. The luminance level is progressively lowered, mimicking the natural light changes of a sunset. The length and stages of this transition are carefully designed to match the human eye's adaptation capabilities, ensuring a comfortable shift.

Interior Zone: Within the tunnel's depths, sunlight is replaced by a consistent artificial lighting level. This unwavering luminance provides a stable visual environment for drivers, akin to navigating a starlit cavern bathed in a constant glow.

Exit Zone: As the tunnel's end approaches, the gradual increase in light level creates a sense of emergence. The luminance rises smoothly, replicating the dawn experience until it matches the natural outside environment.

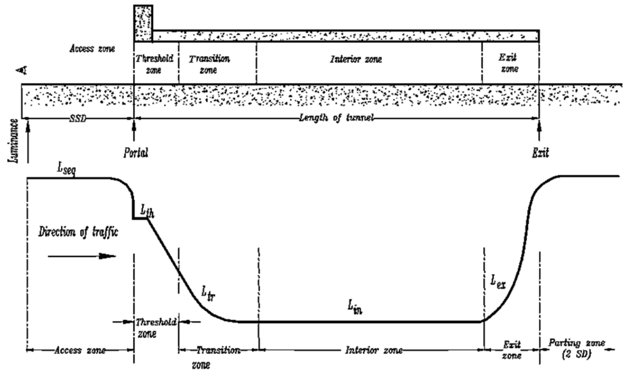

Fig. 4 Five Tunnel Zone [17], [23], [26]

Air characteristics in the tunnel differ from those of ordinary roads. In the tunnel, the concentration of vehicle exhaust gas will be higher than on regular roads because the air exchange is slower than on ordinary roads. Thus, the lighting must also be more resistant to dangerous substances in vehicle exhaust gases such as sulfuric acid, nitric acid, carbon monoxide, etc. Several types of lamps recommended for tunnel lighting are High-Pressure Sodium (HPS) lamps and Light Emitting Diode (LED) lamps [24], [27], [28], [29].

In this paper, to address the challenge of determining energy-efficient artificial lighting in the threshold zone, simulations are conducted to compare tunnel lamp types, aiming for maximum power savings. This research involves modeling toll road tunnel lighting using Dialux software, examining characteristics with both HPS and LED lamps using the Indonesian National Standard (SNI) and ANSI/IES Rp-22-11 as reference [1], [23]. The Dialux software is commonly used for tunnel lighting planning [30], [31]. Using the Cisumdawu tunnel as a case study, a dynamic lighting system capable of adapting to night and daylighting is demonstrated. The investigation into night and daylighting simulation for the Cisumdawu double tunnel in Indonesia reveals that Simulation results indicate that LED or HPS lamps can meet SNI standards for luminance in the interior zone. Furthermore, the double-mounted LED lamps surpass their HPS counterparts, offering increased luminance while consuming less power [32].

This manuscript's research problem is how to enhance energy efficiency and safety in toll road tunnel lighting by investigating the comparative effectiveness of HPS lamps and LED lamps across the tunnel's threshold, transition, and interior zones. Therefore, the research will utilize DIALux software to simulate and model toll road tunnel lighting and compare HPS and LED lamps. The objective is to identify the most energy-efficient lighting solution for the tunnel's threshold zone, promoting sustainable lighting for transportation infrastructure. It further evaluates luminance levels, power consumption, and uniformity of both lamp types in this zone. Additionally, the goal is to optimize tunnel lighting systems to enhance traffic safety and minimize energy usage.

The significance of the research lies in its potential to contribute to energy efficiency, safety, and sustainability in tunnel lighting for transportation infrastructure. This finding suggests potential improvements in energy efficiency within tunnel environments, contributing to sustainable lighting solutions for transportation infrastructure [27], [10].

II. Materials and Methods

In this study, a simulation was carried out to determine the luminance in the five tunnel zones mentioned above, using data from the Cisumdawu tunnel, such as tunnel length and geometry. Lamp data and others are determined according to lighting requirements. The simulation was carried out using DIALux 4.12 software. The simulation using DIAlux software has been commonly used and implemented in the study for evaluating lighting efficiency for indoor and outdoor lighting, which has become a de facto standard [33], [34]. The simulation process for tunnel lighting using DIALux software and data collected from the Cisumdawu tunnel involves:

1) Data Collection: Gathering relevant data from the tunnel to serve as input parameters for the simulation.

2) Software setup: Installing and configuring DIALux software with necessary parameters for accurate simulation.

3) Model Creation: Creating a 3D model of the tunnel within DIALux, accurately representing its geometry and layout.

4) Light Source Selection: Choosing HPS lamps and LED lamps as the primary light sources for simulation.

5) Placement Configuration: Arranging selected lamps in single and double rows along the tunnel's interior.

6) Simulation Execution: Initiating the simulation process within DIALux to replicate real-world conditions.

7) Luminance Analysis: Analyzing simulation results to assess luminance levels across tunnel zones.

8) Comparison and Evaluation: This compares the performance of HPS and LED lamps in terms of luminance distribution. The two lamps are also compared in the SNI 7391:2008 and ANSI/IES Rp-22-11 standards.

9) Optimization Strategies: Identifying potential areas for improvement based on simulation outcomes.

10) Documentation and Reporting: Documenting simulation parameters, results, and findings comprehensively for further analysis.

The parameters used for the simulation were implemented according to the parameters in Fig. 4, which include the luminance of threshold, transition, and interior zones. The DIALUX simulations were carried out using two light sources commonly used for tunnel lighting: HPS lamps and LED lamps. In addition, simulations were carried out by placing the lights in one row (single-mounted lamps) and two rows (double-mounted lamps). The results of this simulation can be used to provide input to the Ministry of Public Works and Public Housing (Kementrian PUPR), the agency responsible for constructing the Cisumdawu tunnel.

This research uses data from the Cisumdawu tunnel, a semicircular tunnel with a length of 472 m and a diameter of 14 m. Other data is determined according to tunnel conditions in Indonesia, which includes road surface material in the form of concrete paving, with a reflux value of 30%, and tunnel walls in the form of concrete, with a reflectance value of 24% (Source: data available from the Dialux software). The lamps used in the simulations for the tunnels are High-Pressure

Sodium (HPS) and light-emitting diode (LED) lamps of various types from the Philips brand lamp manufacturer [35], [36]. The choice of this brand was based entirely on the ease of obtaining the photometric data of the lamp and the light polar diagram required for the simulation, and there was no sponsorship message in this regard. The types of HPS lamps used are HNF901 C 1xSON-T250W WB_220 and HNF901 C 1xSON-T400W WB_220. This simulation still uses HPS lamps because some roads and tunnels in DKI Jakarta and Indonesia still use HPS lamps, although some have been replaced with LED lamps. The types of LED lamps used are:

- Philips BVP161 LED26 30W
- Philips BVP381 LED60 50W
- Philips BVP382 LED180 150W
- Philips BVP383 LED270 240W

For this study, there are two variations of the simulation were carried out, namely:

- Simulation using HPS and LED lamps
- Simulations with single and double-mounted lamps.

A. Tunnel Lighting Simulation for Cisumdawu Tunnel with Single and Double Mounted LED Lamps

The simulation is carried out using the Cisumdawu tunnel dimension equipped with the following data:

- Tunnel: Cisumdawu
- Direction: East-West
- Length of tunnel: 472m
- Simulation time: 21 Juli 2018
- Road reflectance: 30%
- Wall reflectance: 24%
- Threshold zone: 100 m
- Transition zone: 110 m
- Lamp mounted: at the tunnel's ceiling
- Type of Lamp:
  a) Threshold zone: Philips BVP382 LED180 150W or Philips BVP383 LED270 240W.
  b) transition and interior zones: Philips BVP161 LED26 30W or Philips BVP381 LED60 50W

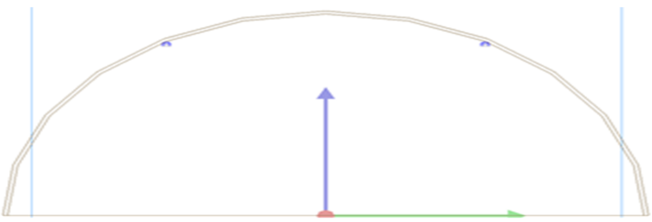

Fig. 5 Dimensions of Cisumdawu tunnel with a diameter of 14 m and a height of 7m

III. Result and Discussion

The simulation results are presented below. First, Fig. 6 shows the luminance color reference for the simulation results.

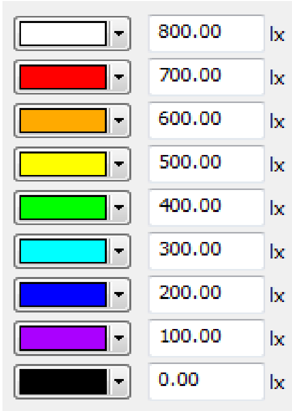

Fig. 6 The luminance color reference for the simulation results

Second, we present the simulation results for the semicircle tunnel with LED lights with single mounting in Fig. 7, followed by the simulation results for the semicircle tunnel with LED lights using double mounting in Fig. 8. To achieve a high level of luminance in the access zone and threshold (12 to 30 cd lm/m2), it used:

- 50 Philips BVP382 LED180 150W for double-mounted lamps.
- 25 Philips BVP383 LED270 240W for single-mounted lamps.
- For transition, interior, and exit zones, types and number of lamps are used:
- 94 Philips BVP161 LED26 30W for double-mounted lamps.
- 47 Philips BVP381 LED60 50W for single-mounted lamps.

Fig. 9 shows the simulated luminance level using LED with double-mounted lamps. The total power needed is 50 x 150W + 94 x 30W =10320W. Fig. 10 shows the simulated luminance level using LED with single-mounted lamps. The total power needed is 25x240W + 47x50=8350W.

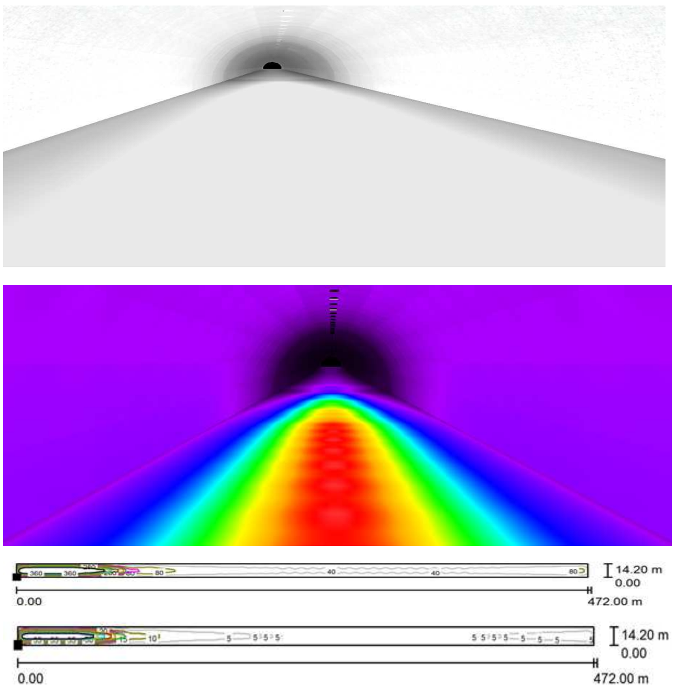

Fig. 7 Simulation results of semicircle tunnel with LED lights with a single mounting

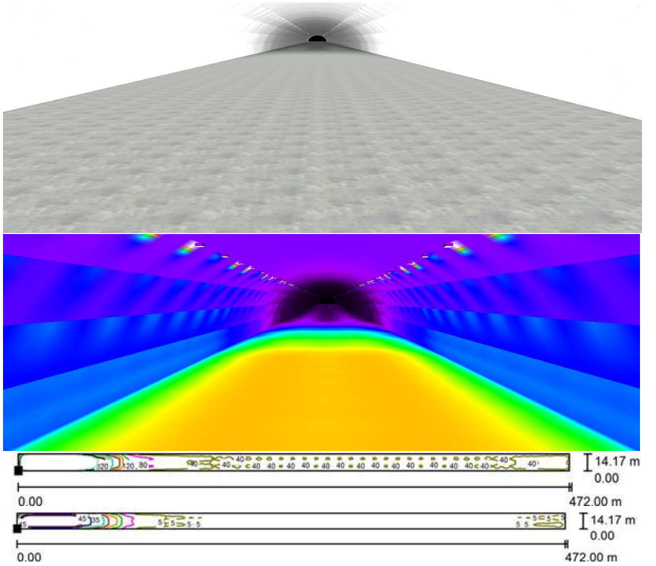

Fig. 8 Simulation results of semicircle tunnel with LED lights with double mounting

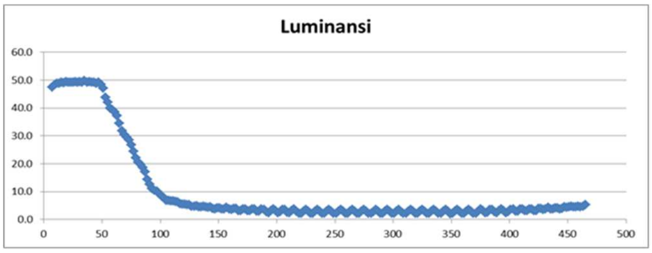

Fig. 9 Simulated luminance level using double-mounted LED lamps

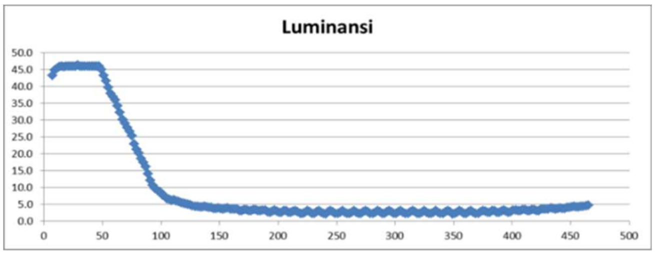

Fig. 10 Simulated luminance level using single-mounted LED lamps

In summary, the luminance level in the tunnel with the installation of single and double-mounted lights can be seen in Table 1 below this paper.

TABLE I
THE SIMULATION RESULTS OF THE SEMICIRCLE TUNNEL USING DOUBLE AND SINGLE-MOUNTED LED LAMPS

A	Mounted	Double mounted	Single mounted
B	Luminaires	50x BVP382 150W 94 x BVP161 30W	25x BVP383 240W 47x BVP381 50W
C	Total power	10320 Watt	8350 Watt
D	Average luminance in the zone:		
	1. Threshold 1	49.9 cd/ m^2	33.6 cd/m^2
	2. Threshold 2	26.4 cd/m^2	18.3 cd/m^2
	3. Transition	4.5 cd/m^2	4.9 cd/m^2
	4. Interior	3.1 cd/m^2	3.5 cd/m^2
E	Uniformity (Uo)	0.67	0.76

Referring to the SNI for the Interior zone, the recommended luminance is 2.00 cd/m^2 with 0.70 uniformity. Based on the simulated results in Table I, all types of mounts fulfill the recommendations for luminance levels in the interior zone (D.4); for the double mounted, the average luminance in the interior zone is 3.1 cd/m2, and for the single mounted is 3.5 cd/m^2. Therefore, the average luminance selected is double as it has less average luminance than single mounted, which means less luminaire LED is used.

For uniformity, the installation of both double-mounted and single-mounted LED lamps slightly does not meet the standard because it has less (0.67) or more (0.76) uniformity compared to the SNI standard (0.70). For the threshold 1 zone, the luminance level of a double-mounted structure is much greater than that of a single installation. Based on Table I and the ANSI/IES RP-22-11 standard, if the access zone is 200 cd/m^2, it is necessary to install double-mounted lamps to produce average luminance in Threshold 1 zone in the amount of 49.9 cd/m^2 (D.1) to compensate for the high luminance value in the access zone and at the start of the threshold zone, especially during the day.

A. Tunnel Lighting Simulation with HPS Lights installed in Single and Double Mounted

To achieve a high level of luminance in the access zone and threshold, we used:

- 50 HNF901 276W lamps for double-mounted installation
- 25 HNF901 433W lamps for single-mounted installation.

For the transition zone, interior, and exit, we used:

- 94 BVP116 35W lamps for double-mounted installation
- 47 BVP117 54W lamps for single-mounted installations

The simulation results for the semicircle tunnel with HPS lights with single mounting are presented in Fig. 11, and the simulation of the double mounting in Fig. 12.

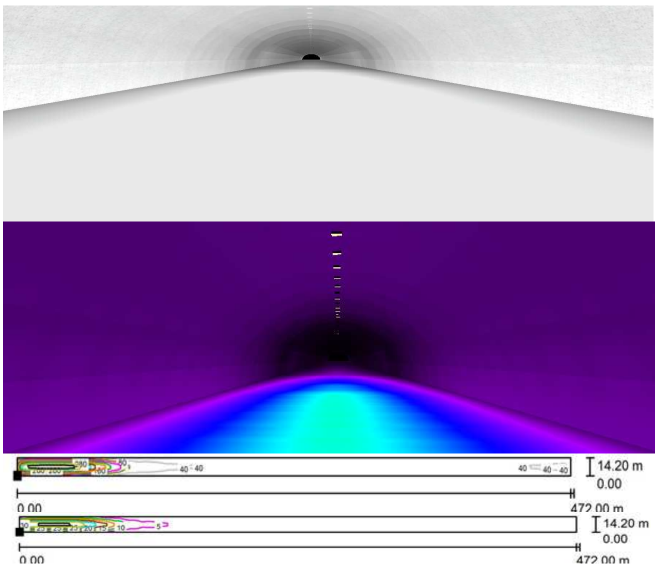

Fig. 11 Simulation results of semicircle tunnel with HPS light using single mounting

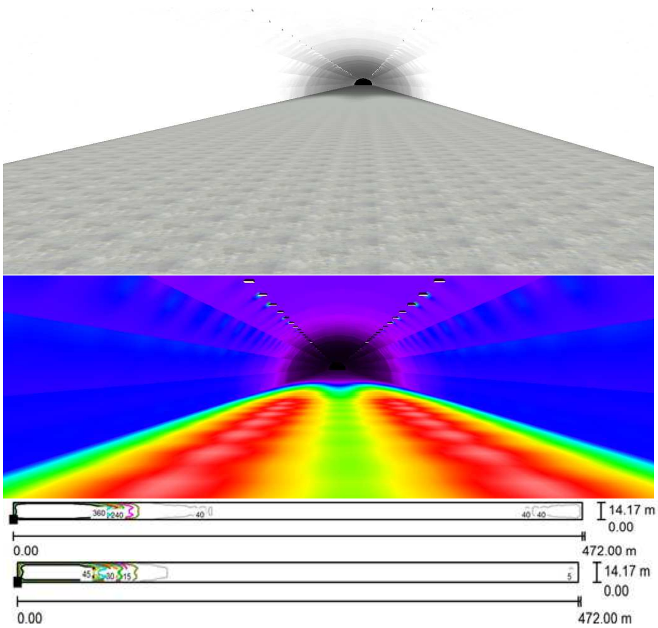

Fig. 12 Simulation results of semicircle tunnel with HPS light using a double mounting

The simulated luminance level for the single-mounted HPS lamps can be seen in Fig. 13. Total power needed = 25 × 240W + 47 × 50 = 13363W. Followed by the simulated luminance level using double-mounted HPS lamps is shown in Fig. 14. The total power needed = 50 × 150W + 94 × 30W = 17090W.

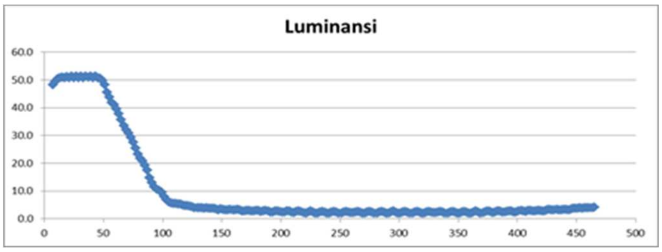

Fig. 13 Simulated luminance curve using single-mounted HPS lamps

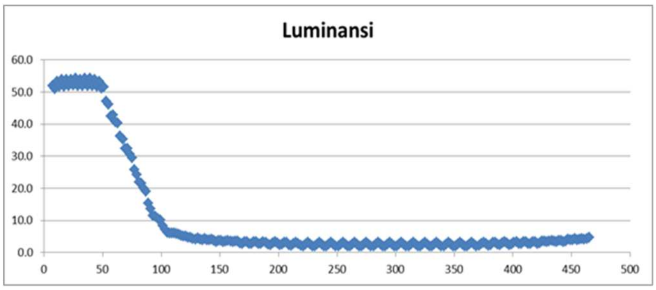

Fig. 14 Simulated luminance curve using double-mounted HPS

In summary, the simulation results of luminance level in the tunnel with the installation of conventional (HPS) lamps in single and double mounted can be seen in Table II below.

TABLE II
THE SIMULATION RESULT OF THE SEMICIRCLE TUNNEL USING DOUBLE AND SINGLE-MOUNTED HPS LAMPS

A	Mounted	Double mounted	Single Mounted
B	Luminaire	50x HNF901 276W 94x BVP116 35W	25x HNF901 433W 47x BVP117 54W
C	Total power	17090 Watt	13363 Watt
D	Average luminance in the zone:		
	1. Threshold 1	52.7 cd/ m²	23.3 cd/m²
	2. Threshold 2	28.5 cd/m²	12.6 cd/m²
	3. Transition	4.1 cd/m²	3.0 cd/m²
	4. Interior	2.8 cd/m²	2.2 cd/m²
E	Uniformity (Uo)	0.70	0.79

Based on Table II, the average luminance of double-mounted HPS in the Interior zone and uniformity meet the SNI standard. For the single-mounted HPS, the average luminance in the Interior zone meets the SNI standard, but the uniformity does not. However, both double-mounted and single-mounted HPS need much greater total power than double-mounted and single-mounted LED lamps.

B. Discussion

For the threshold 1 zone, using either LED or HPS lights, the luminance value of a double-mounted installation is much greater than that of a single-mounted structure. The comparison is shown in Fig. 15 for the LED and Fig. 16 for the HPS lights. ANSI/IES Rp-22-11 luminance standard in the access zone is 200 cd/ m2, so double-mounted installation is recommended to compensate for the luminance value at Threshold 1 zone (49.9 cd/m^2) at the entrance of the threshold zone during the day. The compensation of average luminance at the Threshold 1 zone increases safety by temporarily preventing the driver's eyes from losing sight (or the black hole effect).

In threshold 2 and transition zones, the lamp's position has been designed to follow the curve from the CIE standard graph. The distance between the lights can be adjusted, or with the addition of a controller, the output level of the lamps (dim) can be adjusted to obtain a more significant decrease. Referring to the SNI for the Interior zone, the recommended luminance is 2.00 cd /m2 with a uniformity of 0.70.

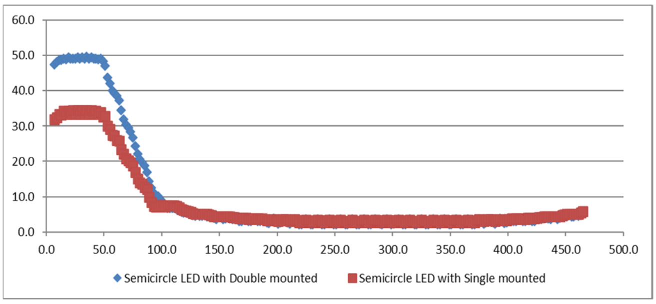

Fig. 15 Luminance Comparison of Double-mounted vs. Single-mounted LED

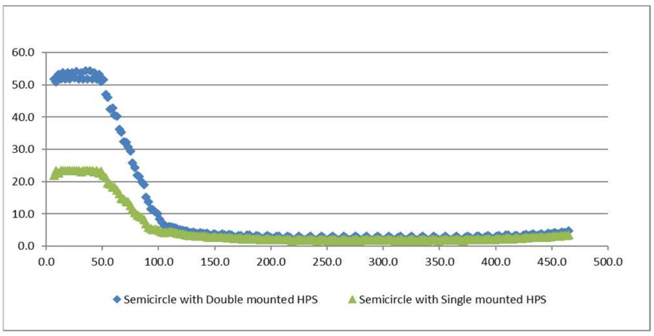

Fig. 16 Luminance Comparison of Double-mounted vs. Single-mounted HPS

Based on the simulated conditions, all lamps and installations meet the recommended luminance level. For uniformity, the structure of double-mounted LED lamps does not meet the standard. There is no significant difference in luminance level in the interior zone for a single or double-mounted installation. When comparing the use of LED and HPS lamps in terms of power, LED lamps produce higher luminance with less power. Similar results have been reported in [37]Fig. 17 compares LED and HPS using double and single mounting. Therefore, to achieve energy efficiency, it is better to use LED lamps instead of HPS lamps in the future.

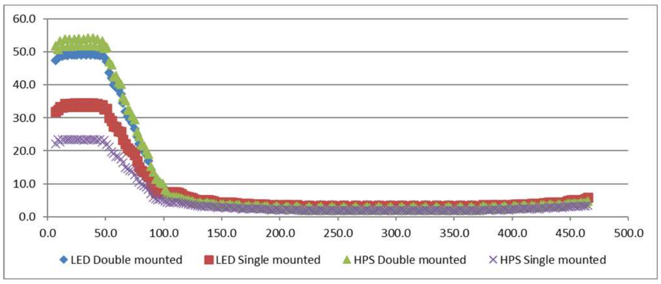

Fig. 17 Comparison of Luminance using LED and HPS with Double-mounted and Single-mounted.

The simulation findings demonstrate that the luminance levels in the interior zone comply with the SNI standard when employing LED or HPS lamps. LED lamps yield greater luminance levels and lower power consumption than HPS lamps. This revelation holds promise for enhancing energy efficiency within tunnel environments and fostering sustainable lighting solutions for transportation infrastructure.

Finally, implementing proposed lighting solutions in real-world tunnel environments may face high initial costs, maintenance requirements, compatibility issues, regulatory compliance, environmental factors, energy efficiency optimization, and emergency preparedness.

IV. Conclusion

The conclusion was obtained from the simulation results with DIALux 12.4 software for the Cisumdawu tunnel with two types of lamps and two installation methods. To compensate for the luminance value of the threshold zone during the day, double-row lights are recommended rather than single-row lamps in the Cisumdawu tunnel. In the threshold zone, the luminance value of the double lamp installation is much greater than that of the single lamp installation, using either an LED lamp or an HPS lamp.

Based on the ANSI / IES standard Rp-22-11, the luminance in the initial zone is 200 cd/m2. For this reason, the installation of double lights in the Cisumdawu tunnel is recommended to offset the luminance value at the beginning of the threshold zone during the day. The luminance in the interior zone, using either LED lights or HPS lamps, can meet the SNI standard, which is 2 cd / m2. For uniformity of 0.7, installing a dual LED lamp does not meet the standard. The use of LED lamps results in higher luminance with less power than using HPS lamps.

Future directions include integrating lighting control systems that automatically adjust illumination levels in response to real-time factors like traffic flow, time of day, and weather conditions to ensure optimal visibility while conserving energy during off-peak periods.

Acknowledgment

The authors thank the Universitas Tarumangara and DRPM, Ministry of Research, Technology, and Higher Education of the Republic of Indonesia for the research funding granted to us to conduct this research.

References

[1] E. Setyaningsih and J. Pragantha, "Lighting Simulation of Flat and Slightly Arched Type Tunnel Based on Pasar Rebo Tunnel Data," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 508, no. 1, p. 12077, Apr. 2019, doi:10.1088/1757-899X/508/1/012077.

[2] R. Xu *et al.*, "Intelligent dimming control and energy consumption monitoring system of tunnel lighting," *Light. Res. Technol.*, vol. 56, no. 1, pp. 72–86, Mar. 2023, doi: 10.1177/14771535231158078.

[3] W. Wang and J. Ma, "Exploration of Smart Tunnel Solutions," in *2023 35th Chinese Control and Decision Conference (CCDC)*, 2023, pp. 697–702. doi: 10.1109/CCDC58219.2023.10327189.

[4] S. Yu, C. Zhao, L. Song, Y. Li, and Y. Du, "Understanding traffic bottlenecks of long freeway tunnels based on a novel location-dependent lighting-related car-following model," *Tunn. Undergr. Sp. Technol.*, vol. 136, p. 105098, 2023, doi: 10.1016/j.tust.2023.105098.

[5] Y. Song, H. Zhu, Y. Shen, and S. Feng, "Green tunnel lighting environment: A systematic review on energy saving, visual comfort and low carbon," *Tunn. Undergr. Sp. Technol.*, vol. 144, p. 105535, 2024, doi: 10.1016/j.tust.2023.105535.

[6] F. Xu, Z. Du, J. Mei, and L. Han, "Transmittance optimization of tunnel shading shed for maximum energy savings and traffic safety: When replacing tunnel lighting in threshold zone," *Tunn. Undergr. Sp. Technol.*, vol. 143, p. 105493, 2024, doi: 10.1016/j.tust.2023.105493.

[7] P. Chiradeja and S. Yoomak, "Development of public lighting system with smart lighting control systems and internet of thing (IoT) technologies for smart city," *Energy Reports*, vol. 10, pp. 3355–3372, 2023, doi: 10.1016/j.egyr.2023.10.027.

[8] Ming, Liu, Zhiqiang, Liu, and Rongrong, Qiang, "Discussion on Landscape and Greening Technology of Highway Structural Tunnel Entrance," *E3S Web Conf.*, vol. 261, p. 3035, 2021, doi:10.1051/e3sconf/202126103035.

[9] Y. Que, H. Tang, Z. Zhang, and H. Zhao, "A brief analysis method in plant landscape design of motorway," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 702, no. 1, p. 12048, Mar. 2021, doi: 10.1088/1755-1315/702/1/012048.

[10] P. Chiradeja and S. Yoomak, "Optimal tunnel lighting design in aspect of lighting quality and energy performance," *Tunn. Undergr. Sp. Technol.*, vol. 131, p. 104837, 2023, doi: 10.1016/j.tust.2022.104837.

[11] J. Chen, L. You, M. Yang, and X. Wang, "Traffic safety assessment and prediction under different lighting service states in road tunnels," *Tunn. Undergr. Sp. Technol.*, vol. 134, p. 105001, 2023, doi:10.1016/j.tust.2023.105001.

[12] J. Niu, B. Liang, S. He, C. Qin, and J. Xiao, "Assessment and optimization of tunnel lighting quality based on drivers' visual comfort: From methodology to application," *Tunn. Undergr. Sp. Technol.*, vol. 143, p. 105487, 2024, doi: 10.1016/j.tust.2023.105487.

[13] X. Wang, R. Wen, K. Cheng, and M. Yang, "Evaluation and analysis of tunnel lighting service status based on driving safety," *Traffic Inj. Prev.*, vol. 24, no. 5, pp. 436–444, 2023, doi:10.1080/15389588.2023.2204986.

[14] X. Wang, L. You, J. Chen, and S. Han, "The impact of different service states of tunnel lighting on traffic safety," *Accid. Anal. Prev.*, vol. 192, p. 107237, 2023, doi: 10.1016/j.aap.2023.107237.

[15] J. Niu, B. Liang, S. He, J. Xiao, and C. Qin, "Long tunnel lighting environment improvement method based on multiple-parameter intelligent control: Considering dynamic changes in luminance difference," *Tunn. Undergr. Sp. Technol.*, vol. 128, p. 104637, 2022, doi: 10.1016/j.tust.2022.104637.

[16] A. Peña-García, "Sustainable tunnel lighting: One decade of proposals, advances and open points," *Tunn. Undergr. Sp. Technol.*, vol. 119, p. 104227, 2022, doi: 10.1016/j.tust.2021.104227.

[17] A. Mehri, M. Aliabadi, R. Golmohammadi, and S. A. Zakerian, "An empirical investigation of disability glare and visibility level during driving inside very long road tunnels: A case study," *Tunn. Undergr. Sp. Technol.*, vol. 125, p. 104496, 2022, doi:10.1016/j.tust.2022.104496.

[18] B. Su, J. Hu, J. Zeng, and R. Wang, "Traffic Safety Improvement via Optimizing Light Environment in Highway Tunnels.," *Int. J. Environ.*

Res. Public Health, vol. 19, no. 14, Jul. 2022, doi:10.3390/ijerph19148517.

[19] A. L. W. Wijaya, P. P. Rahardjo, "Investigation of Twin Tunnel Deformation with Umbrella Grouting Protection & NATM Tunneling using 3D Finite Element: Case Study," *U Karst*, vol. 5, no. 2, pp. 252–267, 2021, doi: 10.30737/ukarst.v5i2.1977.

[20] S. Ma, J. Hu, E. Ma, W. Li, and R. Wang, "Cluster Analysis of Freeway Tunnel Length Based on Naturalistic Driving Safety and Comfort," *Sustainability*, vol. 15, p. 11914, 2023, doi:10.3390/su151511914.

[21] S. Wang, Z. Du, G. Chen, H. Zheng, Z. Tang, and F. Jiao, "Drivers' visual characteristics in small-radius optically long tunnels on rural roads," *Tunn. Undergr. Sp. Technol.*, vol. 113, p. 103969, 2021, doi:10.1016/j.tust.2021.103969.

[22] Y. Zhou, S. He, X. Li, Y. Li, and G. Du, "Study on Drivers' Visual Load Features in Lighting Environments of Interior Zones of Extra-Long Tunnels over 10 km," *Adv. Civ. Eng.*, vol. 2022, p. 4840334, 2022, doi: 10.1155/2022/4840334.

[23] S. Feng, W. Gao, L. Zhou, J. Li, W. Mao, and X. Liu, "Experimental study on obstacle visibility and driving safety in lighting environment of road tunnel interior zone," *Tunn. Undergr. Sp. Technol.*, vol. 146, p. 105641, 2024, doi: 10.1016/j.tust.2024.105641.

[24] S. G. Li, G. Tu, and Q. Zhou, "An optimal design model for tunnel lighting systems," *Optik (Stuttg).*, vol. 226, p. 165660, 2021, doi:10.1016/j.ijleo.2020.165660.

[25] S. Chen, Y. Lin, and H. Zhao, "Effects of flicker with various brightness contrasts on visual fatigue in road lighting using fixed low-mounting-height luminaires," *Tunn. Undergr. Sp. Technol.*, vol. 136, p. 105091, 2023, doi: 10.1016/j.tust.2023.105091.

[26] M. Cengiz, "Simulation and Design Study for Interior Zone Luminance in Tunnel Lighting," *Light Eng.*, vol. 27, pp. 42–51, 2019, doi: 10.33383/2018-043.

[27] H.-Y. Liao *et al.*, "Design and Prototyping of Efficient LED Counter Beam Light with Free-Formed Surface for Meeting International Tunnel Lighting Standards," *Energies*, vol. 14, no. 2, 2021, doi:10.3390/en14020488.

[28] L. Qin, A. Peña-García, A. S. Leon, and J.-C. Yu, "Comparative Study of Energy Savings for Various Control Strategies in the Tunnel Lighting System," *Appl. Sci.*, vol. 11, no. 14, 2021, doi:10.3390/app11146372.

[29] M.-J. Chen *et al.*, "Design of Counter Beam Tunnel Lights for CIE 88 : 2004 Regulation in Threshold Zone," *Int. J. Opt.*, vol. 2020, p. 6145638, 2020, doi: 10.1155/2020/6145638.

[30] Y. Su, H. Chen, Y. Gao, and R. Wei, "Calculation model for tunnel lighting based on DIALux," in *International Conference on Smart Transportation and City Engineering (STCE 2023)*, M. Mikusova, Ed., SPIE, 2024, p. 130185N. doi: 10.1117/12.3024160.

[31] C.-C. Hsieh, C.-L. Tsai, and T.-C. Li, "The research for designing the LED tunnel light for highway tunnels.," *Heliyon*, vol. 10, no. 4, p. e26305, Feb. 2024, doi: 10.1016/j.heliyon.2024.e26305.

[32] D. Katzin, L. F. M. Marcelis, and S. van Mourik, "Energy savings in greenhouses by transition from high-pressure sodium to LED lighting," *Appl. Energy*, vol. 281, p. 116019, 2021, doi:10.1016/j.apenergy.2020.116019.

[33] A. Hangga *et al.*, "Modelling of lighting system utilizing natural and artificial lighting using DIALux," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 969, no. 1, p. 12024, Jan. 2022, doi: 10.1088/1755-1315/969/1/012024.

[34] M. L. Nurrohman, P. Feros, Wahyuning, R. F. Madina, and N. Pratiwi, "Efficient Lighting Design for Multiuse Architecture Studio Classroom using Dialux Evo 9," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 738, no. 1, p. 12034, Apr. 2021, doi: 10.1088/1755-1315/738/1/012034.

[35] E. Setyaningsih, Y. Calvinus, and B. A. Pramudia, "CSL19 design excellence analysis for street lights with previous products," *AIP Conf. Proc.*, vol. 2680, no. 1, p. 20077, 2023, doi: 10.1063/5.0128005.

[36] J. Fat, E. Setyaningsih, Y. Calvinus, V. Reinard, and A. Hendisutio, "Temperature, humidity, voltage and current data logger for LED street light luminaire," in *AIP Conference Proceedings*, 2023, p. 20053. doi: 10.1063/5.0127315.

[37] A. Nauta, J. Han, S. H. Tasnim, and W. D. Lubitz, "Performance Evaluation of a Commercial Greenhouse in Canada Using Dehumidification Technologies and LED Lighting: A Modeling Study," *Energies*, vol. 16, no. 3, 2023, doi: 10.3390/en16031015.