Statistical Analysis of the Influence of Lighting Parameters on Photometric Performance in Outdoor Lighting Design

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Abstract – *This study examines the effects of several physical design elements on important photometric measurements used in street lighting design, particularly pole height, pole spacing, and luminaire wattage. Indicators including threshold increment, uniformity index, illuminance uniformity, and average luminance were the focus of the analysis. Descriptive statistics, a one-way ANOVA, and visual inspection of data patterns were used to examine these effects across various configurations. The findings demonstrate that a variety of lighting performance indicators significantly impacted by changes in pole height. Additionally significant is the luminaire's wattage, which has a special impact on* average luminance, threshold increment, average illuminance, *minimum illuminance, and maximum illuminance. The variation of these indicators also showed that the distance between poles influenced lighting quality, particularly when uniformity and overall illumination were considered. In conclusion, these findings provide evidence on how to modify physical factors to satisfy photometric criteria while maintaining good visibility and economical energy use, which aids in guiding practical street lighting design decisions*.

Keywords*:* ANOVA, illuminance, lighting design optimization, photometric performance, street lighting

Article History
Received 15 Jun 2025
Received in revised form 30 August 2025
Accepted 18 September 2025

I. Introduction

These Street lighting plays a vital role in urban and peri-urban environments, including villages and roadside areas, by providing nighttime illumination that enhances safety, security, and visibility for both pedestrians and drivers. A well-designed and efficiently managed street lighting system is therefore integral to the overall functionality and livability of a city. Among available technologies, LED-based luminaires are often prioritized in modernization and upgrading projects due to their superior cost-effectiveness and energy efficiency. According to the IEA Net Zero by 2050: A Roadmap for the Global Energy Sector report, the full implementation of LED lighting by 2025 is a critical milestone for achieving net-zero carbon emissions by 2050, reflecting the technology's growing dominance in the global lighting market and its recognition as a cornerstone of sustainable energy transitions [1].

The quality of road lighting is defined by a series of standardized photometric parameters established in EN 13201 [2] and CIE 115:2010 [3]. These parameters include threshold increment T_i, which evaluates disability glare; average illuminance E_{av}, representing mean light levels; minimum E_{min} and maximum illuminance E_{max}, which describe the variation of light distribution; the uniformity index U_i, expressed as the ratio of minimum to average illuminance; overall uniformity U_o, defined as the ratio of minimum to maximum values across the evaluation grid; and average luminance L_{av}, which directly influences road visibility. Collectively, these indicators provide an objective framework for performance evaluation and compliance with international standards. In Malaysia, roadway lighting design criteria are guided by the MS 825 standard as in Table I, which specifies minimum requirements for luminance, uniformity, and glare control to ensure effective illumination.

Simulation-based approaches have become a cornerstone of street lighting performance evaluation, with DIALux being one of the most widely adopted tools in both research and practice. Numerous studies have demonstrated its effectiveness in assessing standardized photometric parameters. For example, [4] showed that DIALux simulations can evaluate not only photometric compliance but also energy performance indicators, enabling comparative analysis between high-pressure sodium (HPS) and LED systems. Similarly, in [5] reported that metrics such as average illuminance, uniformity, and glare effectively demonstrated the superior performance of LED retrofits in terms of visual comfort and long-term energy efficiency. In addition, in [6] evaluated eight proposed lighting designs for UniMAP's main campus using DIALux evo, ensuring compliance with MS 825 and JKR standards, and highlighting the importance of standardized parameters in advancing sustainable energy management strategies.

While conventional Excel-based tabulation offers useful summaries on descriptive analysis of the data, it lacks in advanced statistical analysis that can confirm whether the significant differences are exist or not. In regard to this, analysis of variance (ANOVA) was selected to provides a robust inferential framework to determine the significance parameters on the photometric performance. By distinguishing genuine effects of structural and electrical variations from random fluctuations, ANOVA strengthens the reliability of lighting system optimization [7]-[8].

Analysis of Variance (ANOVA) is a suitable statistical technique for evaluating street lighting performance, as it enables comparison across multiple design alternatives, lamp technologies, and mounting configurations to determine whether variations in illuminance, luminance, and uniformity are statistically significant. Previous studies have highlighted the importance of key photometric indicators such as average luminance, uniformity, and glare in assessing lighting quality across different installation settings, including variations in luminaire types and pole spacing [9]. Comparative research examining LED and high-pressure sodium vapor (HPSV) technologies has also reported measurable differences in photometric distribution, where ANOVA proved effective for validating statistical significance [10]. Moreover, simulation-driven analysis of pedestrian road lighting confirm that design parameter adjustments influence both uniformity and energy performance, reinforcing the capability of ANOVA to capture main and interaction effects among categorical factors [11].

However, existing research has primarily focused on simulation environments and comparative technology assessments, with limited emphasis on summarizing which categorical factors most significantly affect photometric performance in real-world settings, particularly in relation to MS 825 compliance. Addressing this gap, the present study applies ANOVA to evaluate the statistical significance of photometric indicators in an operational street lighting installation at Bukit Rambai, Melaka, thereby offering empirical insight into performance relative to national lighting standards.

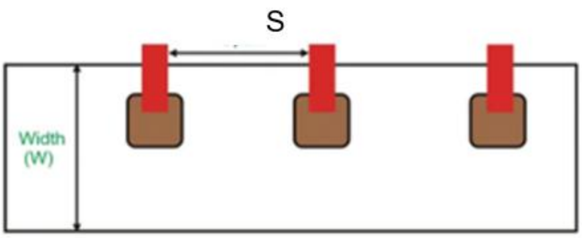
TABLE I
MS 825 STANDARD FOR ME3 LIGHTING TYPE

Average Luminare L_{ave} (cd/m^2)	Overall Uniformity, U_0	Logitudinal Uniformity, Ui	Threshold increment (Ti),
<2.0	<0.4	<0.7	>10

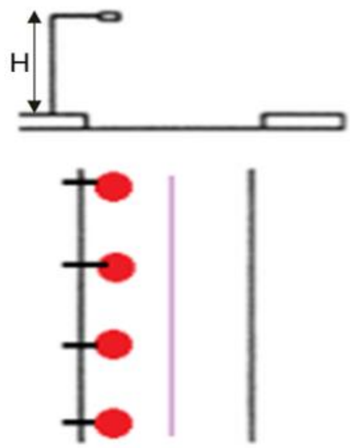
II. Single sided street lighting configuration

In the case study, a single sided arrangement and pole installation at Bukit Rambai Road is shown in Fig. 1(a) and (b). Single-sided street lighting configuration, where all lamps are positioned on one side of the road, is recommended when the road width *W* is less than or equal to the installation height *H* as defined in (1), typically around 6 meters. According to street lighting standards such as BS 5489 and MS 825, this arrangement is ideal for narrower streets.

$$Road\ Width\ (W) \leq Pole\ Height\ (H) \tag{1}$$



(a)



(b)

Fig. 1. (a) Arrangement of pole distance *S*, (b) pole height *H*, of single-sided arrangement and pole installation at Bukit Rambai road

To measure the luminance-based quality criteria, a rectangular grid of the relevant area is defined. There are usually three transversal points and a minimum of ten longitudinal points per traffic lane (3x10 points)/lane), i.e. typically 60 points for two lanes, as shown in Fig. 2. The distance of transversal point d and distance of longitudinal points D is estimated in (2) and (3).

$$d = \frac{road\ width\ (W)}{3} \tag{2}$$

$$D = \frac{pole\ distance\ (S)}{10} \tag{3}$$

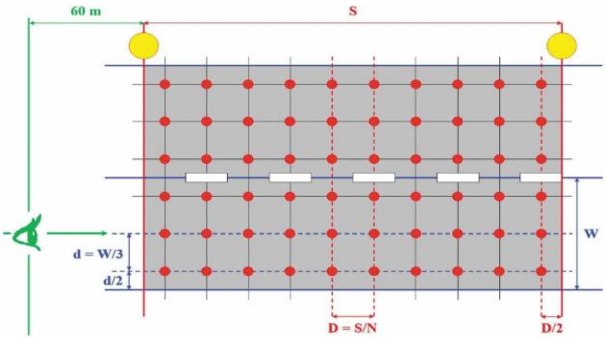


Fig. 2. Location of photometric measurement

In the DIALux configuration, Philips LED luminaires with capacities between 70 W to 180 W were selected. The simulated road has a width of 7 meters, representing a two-lane layout with width smaller than pole height. Pole heights were set between 8 and 12 meters, while spacing was varied from 25 to 40 meters to assess lighting performance as detailed in Table II.

TABLE II
SPECIFICATION OF PHOTOMETRIC MEASUREMENT

Parameter	Unit
Philip LED	70 – 180 Watt
Road Width (W)	7 m
Lane type	2
Pole Height (H)	8 m – 12 m
Pole Distance (S)	25 m – 40 m

A. Simulation of Street Lighting Systems

The evaluation of street lighting performance was carried out using DIALux evo, a professional lighting design software. The software allows precise modelling of road geometry, luminaire characteristics, and environmental conditions in compliance with international standards (EN 13201-2:2015, CIE 115:2010) and MS 825 national standard. Each design was assessed using standardized photometric indicators, namely uniformity index U_i, overall uniformity U_o and average luminance L_{av}, which collectively form the basis for determining compliance and visual performance.

B. Data Extraction and Processing

The photometric data generated from DIALux evo simulations were exported into tabular form for further analysis. Microsoft Excel was used for data organization, preliminary calculations, and comparative evaluation of the photometric indicators for the proposed lighting designs. The data are to be validated with local standards, specifically MS825 requirements.

C. Statistical Analysis

To investigate the influence of photometric indicators such as overall uniformity U_o, luminance L_{av}, uniformity index U_i, threshold increment T_i, average illuminance E_{av}, minimum illuminance E_{min}, and maximum illuminance E_{max} across multiple groups that are pole height, pole distance and lamp wattage, a statistical approach was adopted. Descriptive statistics analysis was performed to summarize and describe the central tendency and the dispersion of the collected data. For this purpose, the mean and standard deviation of the data were calculated and examined for each photometric indicator. In this work, a one-way Analysis of Variance (ANOVA) was carried out to check whether the mean values of three or more independent lighting groups differed across the selected photometric indicators. This method is commonly used to assess the influence of categorical factors by comparing the average response at each level. The analysis was conducted using the MINITAB software. In applying ANOVA, the study begins with a null hypothesis H_0 that assumes no significant difference between group means for all factor level, versus an alternative hypothesis H_1 that suggests at least one group mean is significantly influence and is difference than the others. The H_0 is statement on the equality of all means while the H_1 is the existence of different means in at least one of the sampling locations. The rejection or acceptance of the hypothesis depends on the p-value gained from the ANOVA analysis. The H_0 is rejected if the p-value is less than the significant value, α of 0.05. The significant value, α indicates a five percent deviation of the confidence level, and it is considered reliable to be used in the statistical analysis. The coefficient of determination, R^2 is an indicator used to describe how much variation is explained in by the water quality parameters and sampling locations. Equation (4) is the formula for R^2 in the ANOVA analysis.

$$R^2 = 1 - \frac{unexplained\ variation}{total\ variation} \tag{4}$$

One of the main objective of this study is to assess the influence of overall uniformity U_o, luminance L_{av}, uniformity index U_i, threshold increment T_i, average illuminance E_{av}, minimum illuminance E_{min} and maximum illuminance E_{max} on pole height, pole distance and lamp wattage. Therefore, the graphical analysis was applied on the collected data to justify the results gain from ANOVA analysis. Therefore, the associate graphical analysis that are box plot and interval plot are display together with the p −values and R^2 from ANOVA .

D. Validation of Standards Compliance

The results from statistical and simulation analysis were benchmarked against the photometric performance requirements outlined in EN 13201-2:2015 and MS825, ensuring that the proposed designs achieved both international and national compliance. This dual validation approach reinforced the reliability of the study outcomes, while also ensuring practical applicability within the Malaysian context.

III. Results and Discussion

In this study, pole height, pole spacing, and LED wattage were analyzed using the DIALux software tool. These parameters were selected as they directly affect photometric indicators such as average illuminance, uniformity, and glare, which are critical in meeting the MS825 standard. Simulations were carried out with pole heights ranging from 8 m to 12 m, pole spacing from 25 m to 40 m, and LED wattages between 70 W to 180 W. The results provide insight into how variations in these parameters influence street lighting performance and their compliance with MS825 requirements. Several simulation results are shown in Fig. 3 and Fig. 4.

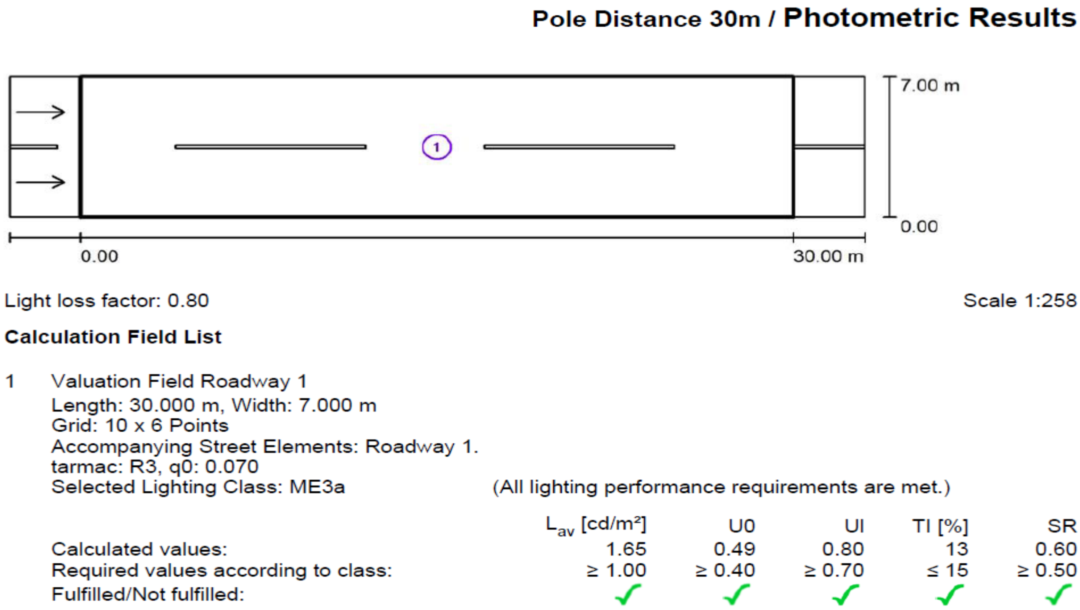


Fig. 3. LED Philips 90-Watt, 8 m pole height and 30 m pole distance

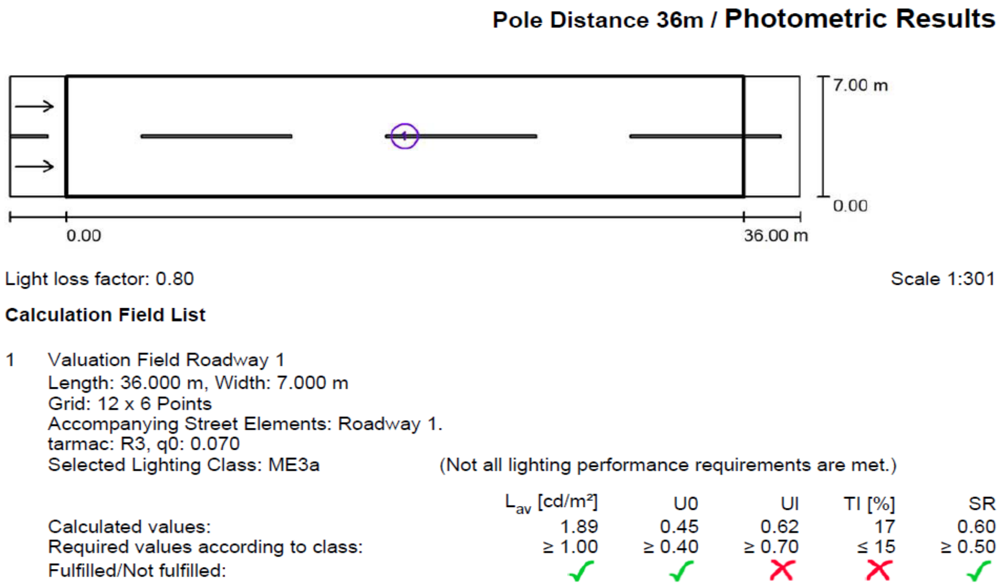


Fig. 4. LED Philips 120-Watt, 8 m pole height and 36 m pole distance

Based on the results obtained from DIALux simulations, the photometric performance parameters were further evaluated using descriptive statistics, graphical analysis and one-way ANOVA. This statistical approach was applied to determine the influence of structural factors on illuminance levels and lighting uniformity. The assessment emphasized the extent to which variations in pole height, pole spacing, and lamp wattage contributed to significant differences in lighting performance across the tested configurations. Table III shows the descriptive analysis of overall uniformity U_o, luminance L_{av}, uniformity index U_i, threshold increment T_i, average illuminance E_{av}, minimum illuminance E_{min}, and maximum illuminance E_{max} on pole height. Based on the values of mean in Table III, it can be said that the photometric indicators have significant impact on pole height. Increasing the height of the pole for a lamp will increase the U_o and U_i. On the contrary, the L_{av}, T_i, E_{av}, and E_{max} tend to decrease as the height of the pole is increased. The value of E_{min} is fluctuated within 15 to 16 although the pole height varies.

TABLE III
THE MEAN OF PHOTOMETRIC INDICATORS ON POLE HEIGHT

Pole Height (m)	U_o	L_{av}	U_i	T_i (%)	E_{av}	E_{min}	E_{max}
8	0.53	2.06	0.72	15.02	30.27	15.95	59.59
10	0.63	1.79	0.85	9.76	25.52	16.33	41.24
12	0.71	1.57	0.91	7.11	21.83	15.70	30.80

Table IV shows the mean of photometric indicator for each lamp wattage tested in this study. Based on the tabulated values in Table IV, it can be concluded that the wattage somehow affects the L_{av}, T_i, E_{av}, E_{min} and E_{max}. Whereas the change of lamp wattage does not have significant effect on U_o and U_i.

TABLE IV
THE MEAN OF PHOTOMETRIC INDICATORS ON LAMP WATTAGE

Lamp Wattage	U_o	L_{av}	U_i	T_i (%)	E_{av}	E_{min}	E_{max}
70	0.62	1.10	0.82	9.71	15.83	9.75	26.77
90	0.62	1.36	0.82	10.10	19.52	12.06	33.13
100	0.62	1.54	0.82	10.35	22.17	13.72	37.46
120	0.62	1.87	0.82	10.77	26.77	16.52	45.44
150	0.64	2.23	0.82	11.21	31.98	19.77	54.21
180	0.62	2.72	0.82	11.65	38.98	24.12	66.27

The descriptive statistics of pole distance and photometric indicators is shown in Table V. In this study, the increment of pole distance is set to 1 meter increase per testing. Observing Table V, the mean values for each photometric indicators proven that the pole distance has significant effect on U_o, L_{av}, U_i, T_i, E_{av}, E_{min} and E_{max}.

TABLE V
THE MEAN OF PHOTOMETRIC INDICATORS ON POLE DISTANCE

Pole Distance (m)	U_o	L_{av}	U_i	T_i (%)	E_{av}	E_{min}	E_{max}
25	0.73	2.29	0.92	8.89	33.06	23.61	47.78
26	0.72	2.21	0.91	9.06	31.72	22.39	47.06
27	0.71	2.13	0.90	9.28	30.56	21.22	46.17
28	0.69	2.05	0.88	9.50	29.50	20.06	45.44
29	0.67	1.98	0.88	9.67	28.33	18.83	44.83
30	0.66	1.91	0.87	9.94	27.39	17.72	44.39
31	0.64	1.86	0.85	10.33	26.56	16.49	44.00
32	0.62	1.80	0.84	10.56	25.67	15.77	43.67

33	0.61	1.74	0.83	10.78	24.94	14.96	43.17
34	0.65	1.69	0.81	11.00	24.11	14.29	43.00
35	0.58	1.64	0.79	11.17	23.67	13.54	42.56
36	0.57	1.60	0.78	11.50	22.94	12.80	42.33
37	0.55	1.55	0.76	11.61	22.17	11.94	42.33
38	0.53	1.51	0.74	12.06	21.67	11.35	42.06
39	0.52	1.47	0.71	12.28	21.17	10.60	41.67
40	0.51	1.44	0.69	12.50	20.56	10.30	41.61

The descriptive analysis that is based on the values of mean provide an insight on the impact of pole height, lamp wattage and pole distance on photometrics performance of outdoor lighting design. The mean values for each photometric indicators presented the central tendency of the data. Further analysis was conducted to enhance and improve the findings of this project. Following this, the ANOVA was carried out for each lighting parameters and photometric indicators. The ANOVA provided clear evidence on the influence of structural and electrical parameters on photometric performance. The hypothesis statement for the ANOVA of pole height is:

H_o:All means of photometric indicators at each level of lighting parameters are equal.

H_1: At least one of the means of photometric indicators are different.

Table VI presents the p-value and R^2 for each photometric indicators of pole height from the ANOVA analysis. The p-value for U_o, L_{av}, U_i, T_i, E_{av} and E_{max} are 0.000, (that is less than 0.05) which lead to the rejection of H_o statement. The low p-value for these indicators suggest a highly significant relationship of U_o, L_{av}, U_i, T_i, E_{av} and E_{max} with the pole height. However, the p-value of 0.796 for E_{min} shows that adjusting the pole height does not significantly affect the minimum illuminance. The threshold increment, T_i has the highest R^2 of 84.30%. Hence, 84.30% of the variation in the threshold increment can be explained by the changes in pole height. The highest value of R^2 implies that extending the pole distance is highly impact the threshold increment of lighting.

TABLE VI
THE p-VALUE AND R^2 OF PHOTOMETRIC INDICATORS ON POLE HEIGHT

Indicator	p −value	R^2 (%)
U_o	0.000	39.25
L_{av}	0.000	9.72
U_i	0.000	46.38
T_i (%)	0.000	84.30
E_{av}	0.000	13.29
E_{min}	0.796	0.16
E_{max}	0.000	42.27

Fig. 5 shows the interval plot of pole height and threshold increment T_i. The interval plot graphically displays the mean of T_i for each pole height and its corresponding 95% confidence interval. The highest pole height of 12 meters, has the lowest T_i, that is approximately 7.2%. Fig. 5 clearly exhibits that an increment in the pole height will decrease the threshold increment for lighting mechanism. The interval plot justify the results gain from ANOVA.

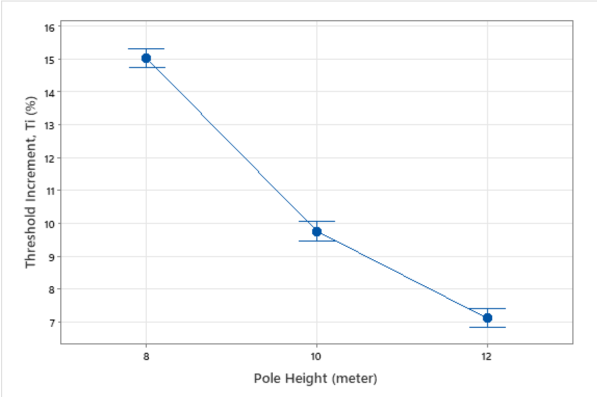


Fig. 5. Interval plot of pole height versus threshold increment T_i

Table VII shows the results from ANOVA analysis on the p-value and R^2 for each photometric indicators with respect to the lamp wattage. The lamp wattage is set from 70W to 180W. The p-value for U_o, U_i and T_i are greater than 0.05, which lead to acceptance of H_o. Therefore, the U_o, U_i and T_i are not statistically significant to the lamp wattage. The R^2 values are also extremely low for U_o (0.44%) and U_i (0.01%), confirming that these indicators are poor predictors of lamp wattage. Results from Table VII prove that L_{av}, E_{av}, E_{min} and E_{max} are significant photometric indicators of lamp wattage. The luminance, L_{av} are highly affected by the lamp wattage as the R^2 value is the highest (71.40%).

Following this, the box plot of luminance, L_{av} together with the lamp wattage is shown in Fig. 6. The median and mean luminance values consistently rise as the lamp wattage increase from 70W lamp to the 180W lamp. This indicates a strong positive correlation between lamp wattage and average luminance. As the wattage increases, particularly at 150W and 180W, the boxes and whiskers become taller. This indicates a greater spread in the measured luminance values, meaning the data is more variable at higher wattages.

TABLE VII
THE p-VALUE AND R^2 OF PHOTOMETRIC INDICATORS ON LAMP WATTAGE

Indicator	p −value	R^2 (%)
U_o	0.941	0.44
L_{av}	0.000	71.40
U_i	1.000	0.01
T_i (%)	0.084	3.37
E_{av}	0.000	67.75
E_{min}	0.000	55.40
E_{max}	0.000	52.73

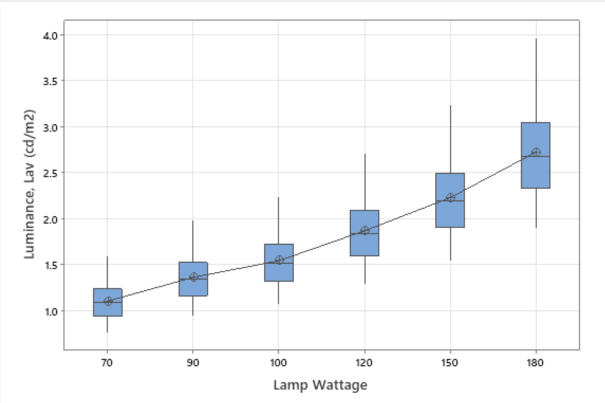


Fig. 6. Box plot of wattage versus luminance L_{av}

Results from ANOVA analysis for pole distance and photometric indicators is presented in Table VIII. The measurement of photometric indicators is measured from the pole distance of 25 meters up until 40 meters. The p-values in Table VIII proved that the pole distance has significant effect in all photometric indicators, except the maximum illuminance E_{max}.

TABLE VIII
THE p-VALUE AND R^2 OF PHOTOMETRIC INDICATORS ON POLE DISTANCE

Indicator	p −value	R^2 (%)
U_o	0.000	36.17
L_{av}	0.000	16.29
U_i	0.000	35.94
T_i (%)	0.014	10.01
E_{av}	0.000	15.95
E_{min}	0.000	40.56
E_{max}	1.000	1.03

The p-value (1.00) and R^2(1.03%) shows that the maximum illuminance is not affected by adjusting the pole distance. On the other hand, the highest value of R^2 is on E_{min} (40.56%) and U_o (36.17%) indicates that both indicators are statistically significant on the pole distance.

The interval plot of pole distance versus minimum illuminance E_{min} is presented in Fig. 7. The plot shows a clear negative correlation exist between pole distance and minimum illuminance. As the distance between poles increases, the minimum illuminance decreases consistently. As the pole distance increases, the minimum illuminance steadily drops. The trend of the plot in Fig. 7 suggests that the farther the poles are spaced, the less light reaches the areas between them, resulting in a lower minimum illuminance. The interval plot also shows that the variability in the minimum illuminance measurements are relatively consistent across the different pole distances. Hence, increasing the pole distance will decrease the minimum illuminance of lighting system.

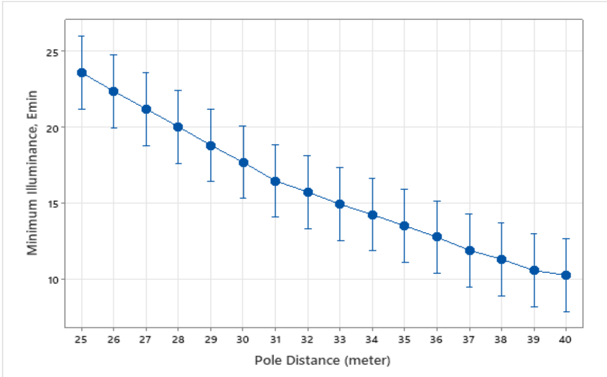


Fig. 7. Interval plot of pole distance versus minimum luminance E_{min}

Fig. 8 displays the box-plot of pole distance versus overall uniformity U_o. The trend of the box-plot indicates a negative correlation between pole distance and overall uniformity U_o. As the distance between poles increases, the overall uniformity of the light distribution decreases. The vertical bars at each pole distance represent the range of the overall uniformity measurements. The height of these bars generally decreases as the pole distance increases, suggesting that the variability or spread in the uniformity measurements becomes slightly smaller at larger pole distances.

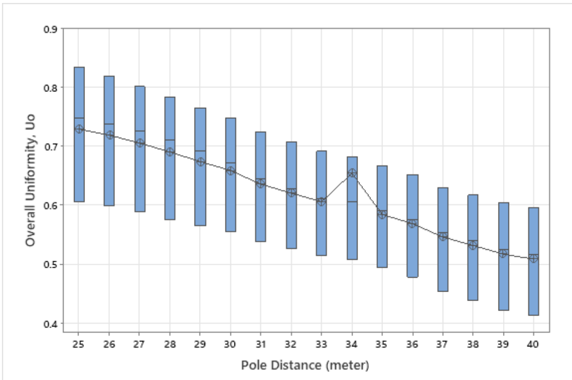


Fig. 8. Box plot of pole distance versus overall uniformity U_o

This trend suggests that placing light poles farther apart leads to less even lighting, with a greater difference between the brightest and darkest spots within the illuminated area. The decrease in uniformity is a key trade-off to consider when designing a lighting system, as wider spacing can be more cost-effective but results in lower-quality illumination.

Overall, the findings emphasize that pole height and pole distance are the most critical variables for achieving compliance with MS825 lighting standards. Pole height was found to have a significant effect on the overall uniformity U_o, uniformity index U_i, threshold increment T_i as well as average luminance L_{av}, indicating that increasing pole height directly impacts both the distribution and intensity of light on the road surface. In contrast, wattage did not show a significant effect on overall uniformity U_o or uniformity index U_i, although it was strongly associated with changes in luminance L_{av}, confirming that lamp power primarily influences brightness rather than distribution. While wattage contributes to overall luminance levels, it is the physical configuration of poles that predominantly determines uniformity and visual comfort in street lighting installations. Pole distance demonstrated a significant effect on overall uniformity U_o, luminance L_{av}, uniformity index U_i and threshold increment T_i. These results highlight that the spacing of poles strongly governs the balance between lighting uniformity and glare control. Conversely, wattage exhibited no significant influence on U_i or T_i, reinforcing that geometric factors outweigh electrical rating in determining these parameters.

IV. Conclusion

The study confirms that pole height, wattage, and pole distance each play distinct roles in influencing outdoor lighting performance. Designers should prioritize pole distance for uniformity and comfort, and wattage for achieving target brightness levels. These insights can guide future lighting designs for better energy efficiency and compliance with illumination standards.

Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Author Contributions

All authors contributed meaningfully to the completion of this research. The study was conceptualized and designed by Author 1, while Author 2 developed the methodology and supervised data collection. Author 3 carried out the analysis and investigation to ensure accurate interpretation of findings. The initial draft of the manuscript was prepared by Author 4, and Author 5 undertook a thorough review and editing process to refine the final version for clarity and coherence.

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