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Transport and Telecommunication, 2024, volume 25, no. 4, 427-438
Transport and Telecommunication Institute, Lauvas 2, Riga, LV-1019, Latvia
DOI 10.2478/ttj-2024-0031

THE APPLICATION OF 2^K FACTORIAL DESIGN TO DETERMINE THE LUMINANCE IN TRUCK PARKING LOTS

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Road freight is a main mode of transportation in the logistics system, and its operation substantially depends on the heavy goods vehicle (HGV) trucks. One of the places, where trucks drivers spend hours in the long-haul route, is the parking lot. As a result, the safety matter in truck parking lots is important to the efficient performance of trucks in the system, especially during the night time. The enough amount of light significantly contributes to the safety of both drivers and pedestrians in the parking lots. This research focused on the optimal design of lighting installation in the target truck parking lot. The first stage of this study was the survey of the available truck parking lots, and the layout of the selected lot was used as the input of the simulation program. Afterwards, DIALux software was used to simulate the luminance for the chosen layout. To carry out the empirical study, a statistical design method, 2^k full factorial design, was utilised to determine the relationship between design parameters and two responses, average luminance (L_{av}) and overall uniformity ratio (Uo). The design parameters were categorized into three groups, luminaire (LED wattage), the placement of pole (spacing, height, boom angle, and overhang), and pavement reflectance (average luminance factor or Q_0). The analysis results showed that all designed parameters had a significant effect on L_{av}. There were also effects from two interactions, height*Q_0 and boom angle*Q_0. Moreover, Uo was considerably influenced by all parameters except wattage. Another important finding was that the following setting, spacing (low) and Q_0 (high), should lead to the maximization of L_{av} and Uo. Finally, the validation stage was carried out by applying the optimal setting with the lighting design on a different truck parking layout. The empirical and validation results signified that the setting of design parameters for the highest L_{av} also led to the acceptable level of Uo as well. In practice, the research results can assist lighting designers to improve the design of a lighting system, so it would provide the adequate amount of light for truck parking lots.

Keywords: Full factorial design, luminance, parking lot, simulation, truck, uniformity

1. Introduction

Road freight transport is considered as one of the backbone modes of transportation, since it can efficiently move the finished goods to the final destination in the supply chain. According to the Office of the National Economic and Social Development (NESDC), the logistics cost of the road freight transport in Thailand was 519 billion baht in 2021, and the economic value added from road activities was 146.1 billion baht. A vehicle type dominating the road transport in Thailand is heavy goods vehicle (HGV) trucks, which transport a variety of products, e.g., industrial products, machinery, construction materials, containers, and consumer products. A major disruption in this mode of transportation is the road accident, which causes the significant losses of lives and income. Based on the data provided by the department of land transportation (2022), there were 591 truck accidents in Thailand, and 213 accidents were related to semi-trailer and trailer trucks. The statistics also show that the majority of accidents (62.77 percent) occurred during the evening and night time (4 p.m. to 8 a.m.). Thirty-nine of the total number of accidents were linked to the parking issue (illegal park). The analysis conducted by Texas Department of Transportation (2022) pointed out that the illegally parked trucks in an unsafe location was highly likely to cause the severe collision. Moreover, the fatality rate due to crashes with parked trucks in the unlit conditions was twice than those in the well-lit one. Another potential cause of accidents was the continuous driving period, which can be extended for more than four hours. As a result, the light level in truck parking lots or service areas for trucks played an important role on improving the safety condition on the road, since the adequate amount of lighting crucially contributed to the improvement of the safety condition in the lots. These included the property protection and the reduction of accidents, crimes, and vandalism.

However, the construction of truck parking lots is an ongoing process, so there is a limited amount of information regarding the accidents as well as the assessment of lighting system in the truck parking lots. Therefore, the objective of this research is the application of empirical study to analyse and recommend the appropriate setting of design parameters regarding the outdoor street light in truck parking lots. The results could be used as the proactive approach to appropriately design the lighting installation for newly built parking lots or improve the condition of the existing ones.

1.1. Literature Review

Koszalka and Olejnik (2012) clearly indicated that the scenario of insufficient amount of light around semi-trailer trucks was highly likely to cause accidents and collisions. The light from headlights only illuminated the road ahead, but it did not support the backwards and surrounding areas invisible to drivers. Therefore, the additional luminance was required to provide the adequate amount of light.

Narendran, Freyssinier and Zhu (2016) performed a study on the illumination assessment in a parking lot. The objective was the improvement of illuminance uniformity, so the glare and light pollution were also minimized. The types of light sources under the consideration were LED, metal halide, and high-pressure sodium. Another objective was the evaluation of safety perception among people. Rea, Bullough and Brons (2017) determined a provisional model to predict the brightness and security level in parking lots. The different levels of light sources were considered in this study, and the results signified that there was a relationship between the brightness and security level.

Fotios and Gibbons (2018) discussed the existing standard regarding the road lighting. The relationship between the illuminance and night/day crash ratio was determined for four and six-lane roads. The night/day accident ratio and average road surface luminance were calculated in this study as well. Islam and Ozkul (2019) identified the risk factors of fatal crash among commercial and large trucks. These risks were associated with the following characteristics of drivers, spatial and temporary, vehicle, vehicle maneuvering, and environmental conditions. The results showed that the possibility of involving in the accident (odd ratio) was between 0.203 and 0.25.

Bullough, Snyder, and Kiefer (2019) studied the brightness and safety perceptions regarding the parking lot, and they had conducted laboratory experiments by measuring the average luminance and illumination uniformity in the lot. The scaled model parking lot and LED system were utilised as the main tools of this experiment. The result of this research was the determination of mathematical models for predicting the overall brightness and safety perceptions.

Bhagavathula and Gibbons (2020) carried out an empirical study on the appropriate light levels of parking facilities. The outputs of the study were the visual performance, safety perceptions, and comfort, where the inputs were three types of light sources (high-pressure sodium, 3000 K LED, and 5000 K LED) and the different types of pavements (asphalt and concrete). The result indicated that the higher level of K in LEDs led to the higher level of comfort, safety, and visibility. However, there was no indication due to the different types of light sources on the visual performance.

Pracki and Skarzynski (2020) utilised the multiple criteria decision to assess the procedure of designing a lighting system. The case study used in this study was a parking lot, and the selected standard criteria were lighting conditions (average maintained illuminance, uniformity, and glare rating), light pollution (the upward light ratio (ULR) of luminaires and the upward flux ratio (UFR) of lighting), and energy efficiency (light power installed density).

Svechkina, Trop and Portnov (2020) studied the amount of light that made people feel safe, whilst they were on the street during the night time. The index was the feeling of safety (FoS), and the tool used was the questionnaire done through smartphone application. The relationship between the illumination and the FoS level was also determined.

Zhang *et al*. (2022) applied the monocular visual simultaneous localization and mapping (vSLAM) and local interpretable model-agnostic explanation (LIME) method to improve the quality of the environmental mapping and camera pose.

Bertkier and Macioszek (2022) studied the characteristics of parking lots for HGV trucks in Poland. This study focused on the security-related elements, i.e., lighting, fencing, physical protection, and monitoring. Other factors were traffic volume, technical quality and population density, whilst the presence of lighting was interpreted as the sense of safety perception. According to the study, the majority of truck drivers believed that only 22 percent of parking lots were lit enough.

Skarżyński and Ruthowska (2023) assessed the light pollution and energy efficiency of a lighting system. The design parameters in this study were ULR and UFR, and normalized power density (NPD). The multi-variant computer simulations of the exemplary large-area parking lot lighting system were conducted, and the analysis was based on the available data of more than four hundred cases. The differences among each case were the shape of the task area, luminaire arrangements, mounting height, luminous intensity distribution, aiming, and maintenance factor.

1.2. Research Gap

Since the literature review pointed out that the amount of luminance and its uniformity on parking lot surface played an important role on the safety driving, the effects of significant design parameters of lighting system on these responses need to be fully understood. Accordingly, the proposed design parameters to be analysed were LED wattage, spacing (between pole-to-pole), pole height, boom angle, pole overhang, and pavement reflectance. Moreover, an empirical study based on a design of experiment method, 2^k full factorial design, was likewise applied to quantify the elaborated effects from these design parameters.

2. Method

Three folds of methodologies utilised in this research were the simulation of luminance, the computation of luminance and uniformity, and the application of 2^k full factorial design to analyse the data.

2.1. Luminance and Uniformity

The adequate amount of light in the parking lots is important for all types of vehicles, especially, trucks, and it significantly depends on the optimal design of lighting system. Basically, the performance index is in the form of luminance, which is the proportion between luminous intensity and the area as shown in (1). The graphical representation of luminance is also illustrated in Figure 1,

$$L = I/A, \tag{1}$$

where L is the luminance (cd/m^2), I is the luminous intensity (cd), and A is the focused area (m^2).

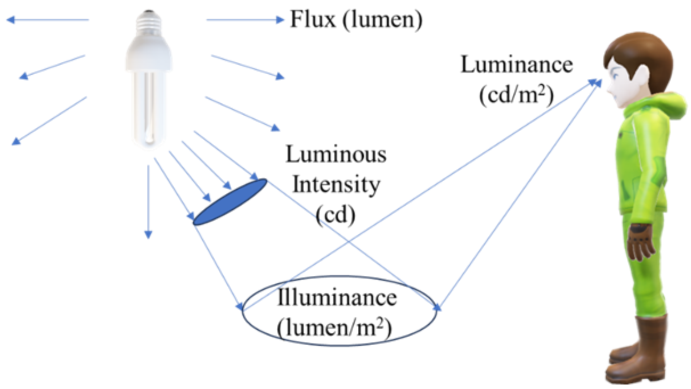


Figure 1. Graphical representation of luminance

The luminance on an area can be measured as the average luminance (L_{av}), which is the mean of luminance from all calculated points in the measurement area as demonstrated in (2),

$$L_{av} = \sum L_i/n, \tag{2}$$

where L_i = luminance at each calculated point and n = number of points.

Another performance index of the lighting amount in the parking lot is the overall luminance uniformity indicating, whether the luminance is equally distributed throughout a lot. It is represented in the form of overall uniformity ratio (Uo), which is the ratio between the minimum luminance in the measurement area (L_{min}) and the average illuminance (L_{av}) as indicated in (3).

$$Uo = L_{min}/L_{av}. \tag{3}$$

There are many design parameters affecting the luminance and uniformity in the parking lots. These parameters are categorized into three groups, luminaire, pole placement, and parking lot surface. The type of luminaires used was LED, and the amount of illumination depended on wattage indicating how much energy the luminaire used. Other parameters regarding the pole placement were pole spacing, pole height, boom angle, and pole overhang (Figure 2). The last parameter to be considered was the reflective characteristic of lot surface, and this was characterized by its surface properties. This characteristic was represented in the form of average luminance factor (Q_0), which was the overall reflectance of the pavement. The reflective characteristics of roadways are defined by its physical surface properties, and they are listed in Table 1 according to the International Commission on Illumination (CIE).

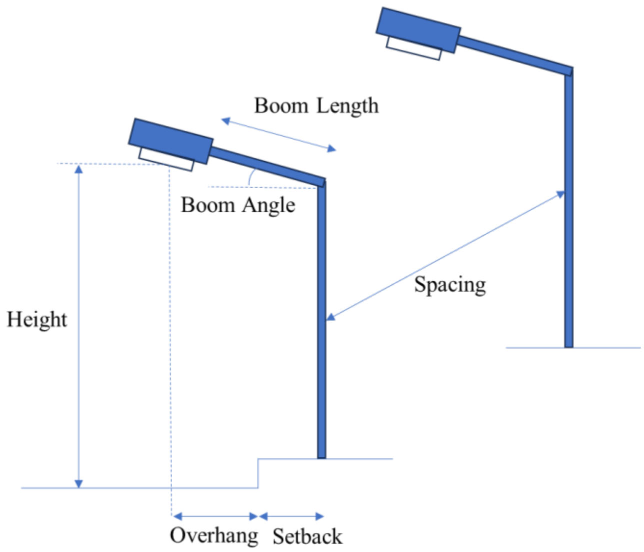


Figure 2. The characteristics of pole placement

Table 1. List of pavement reflectance

Class Standard	Q_0	Description
R1	0.1	-Mostly diffuse reflectance properties characteristic of asphalt surface or Portland cement. -A minimum of 15% of the aggregates is artificial brightener aggregates.
R2	0.07	-Diffuse + specular reflectance characteristic of asphalt surfaces. -Aggregate composition of a minimum of 60% gravel of size > 10 mm.
R3	0.07	-Slightly specular reflectance typical of asphalt surfaces. -Dark aggregates.

2.2. Simulation

Two responses, average luminance (L_{av}) and overall uniformity ratio (Uo), corresponding to each treatment of design parameters, were simulated by using a lighting design software, DIALux evo version 12.1. Afterwards, the study results were analysed by using a design of experiment (DOE) method, and a DOE software, Design Expert version 12, was utilised to carry out the statistical analysis of both responses.

3. Research Procedure

There were two stages of research procedure. The first stage was the survey of the available parking lot for trucks in Thailand. The objective was the characteristics understanding of the available parking lot layouts. When the target parking lot was selected, its layout was recreated by using DIALux software. Afterwards, L_{av} and Uo were simulated under the different scenarios by varying the values of all design parameters, namely, wattage, spacing, height, boom angle, overhang, and average luminance factor (Q_0).

3.1. The layout of parking lot

A number of truck parking lots were surveyed, and the results showed that many truck parking lots shared a common layout as shown in Figure 3. The shape pattern of these parking lot layouts was herringbone drive-through (HDT) with the tilted degree of 30°. There were eight parking slots between the strips, where the lighting poles were installed. For the in-depth analysis, the focused area of parking lot was selected for the study, and its dimension was 100 m*50 m. The vertical length of each slot was 18 m, whilst the clear path between each row of slots was 7 m. The layout, its dimension (Figure 3), and the lighting poles (x-position) were installed on the median strips at each corner of the target area.

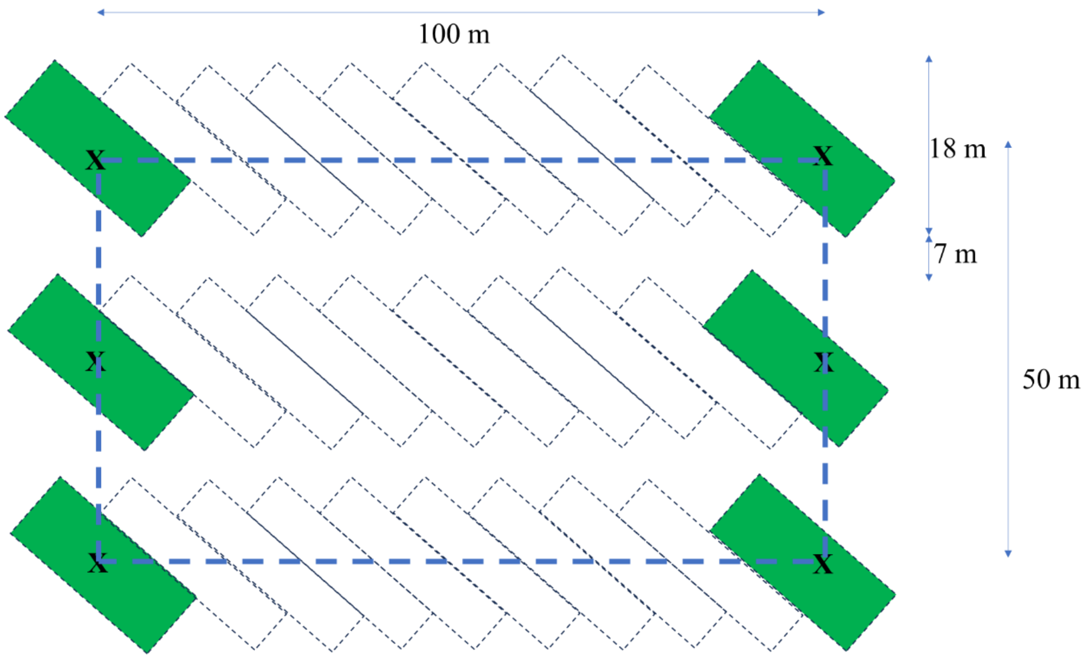


Figure 3. Truck parking lot layout

3.2. Luminaire Configuration

The selected type of luminaire was LED with the high-pressure, die-cast aluminium, and polyester power coated. There were 48 LED lamps in each luminaire. The number of luminaires per a lighting pole was four, so there were 24 luminaires used in the selected area. The layout of a lighting pole and luminaires is shown in Figure 4. The power consumption of the selected luminaires was 130 W and 150 W. The LED layout of the luminaire is illustrated in Figure 5. The total luminous fluxes were 17,384 (130 W) and 19,785 lumens (150 W).

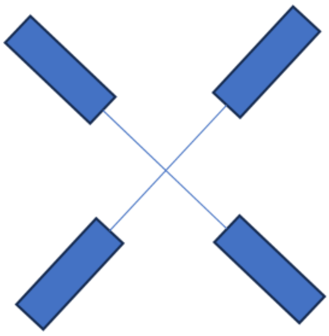


Figure 4. Luminaires on each lighting pole

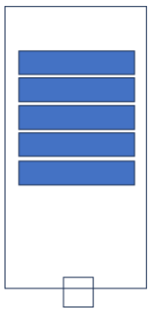


Figure 5. LED layout

3.3. Empirical Study

To carry out the empirical study, an experimental design method, 2^k full factorial design, was applied to determine the relationship between two responses, L_{av} and Uo, and the focused six inputs, i.e., LED wattage (unit: W), spacing (unit: m), height (unit: m), boom angle (unit: degree), overhang (unit: m), and average luminance factor or Q_0. Since it was a 2^k full factorial design, the input levels were categorized into two levels, low and high. Table 2 shows the input factors and their levels. The wattage of luminaires was 130 W and 150 W, whilst the spacing was 90 m and 100 m. The pole height was between 10 m and 12 m, and the boom angles was 45° and 60°. The light overhang was 0.5 m and 1.5 m. Finally, the value of Q_0 for the different types of parking surface was set at 0.07 (CIE R3) and 0.1 (CIE R1). The levels of each input as well as its coded variable are portrayed in Table 2.

Table 2. Design parameters and their design levels

Coded variable	Factor	Level	
		Low (-)	**High (+)**
A	Wattage (W)	130	150
B	Spacing (m)	90	100
C	Height (m)	10	12
D	Boom Angle (Degree)	45	60
E	Light Overhang (m)	0.5	1.5
F	Q_0	0.07	0.1

4. Results

Because the 2^k full factorial design of experiment was used in this study, the total number of experimental runs were 2^6 = 64 runs. Based on the empirical results, the highest L_{av} (2.26 cd/m^2) was achieved when wattage = 150 W (high), spacing = 90 m (low), height = 10 m (low), angle = 45° (low), overhang = 0.5 m (low), and Q_0 = 0.1 (high). On the other hand, when the setting was as follows: wattage = 130 W (low), spacing = 90 m (low), height = 12 m (high), angle = 60°(high), overhang = 0.5 m (low), and Q_0 = 0.1 (high), this scenario led to the highest Uo (0.79). However, it is interesting to note that the second highest uniformity (0.78) was obtained under the similar setting except overhang = 1.5 m (high). To visualize the luminance in a parking lot, the same setting of parameters leading to the highest L_{av} was used as the inputs of the simulation. The parking lot was divided into two lanes as the observations were at the centre of each lane, and it was illustrated as the arrows (Figure 6). In Figure 6, the luminance on the parking lot is illustrated in the form of the iso-luminance curve, and the curve shows that the contour of luminance ranged from 1.8 to 5.2 cd/m^2. The curve indicates that the area of the highest luminance locates near the lighting source. When the measurement area moves towards the centre, the luminance gradually decreases and reaches the lowest point near the centre area at 1.8 cd/m^2. These setting also leads to the value of Uo at 0.48, which is at the acceptable level, since it is still greater than the minimum Uo at 0.4.

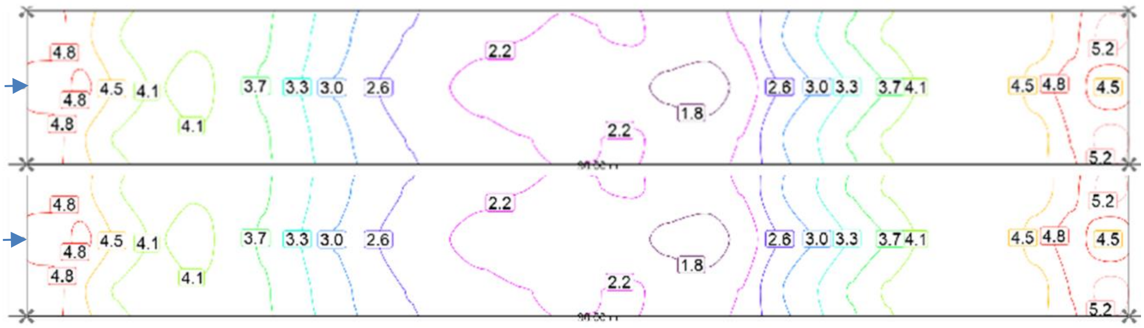


Figure 6. Iso-luminance curve of the parking lot

5. Analysis

The analysis on the simulation results was performed and visualized in the form of pareto charts, main effect plots, contour plots, and interaction plots. They were categorized into two groups according to their responses, L_{av} and Uo.

5.1. Average Luminance

The analysis of the relationship between input factors and L_{av} is elaborated in the form of a pareto chart (Figure 7). The L_{av} was transformed by using logarithm function to ensure the satisfaction of the residual conditions. Due to Figure 7, the effects of design parameters and their interactions are ranked in the pareto chart. If the effects are above the Bonferroni Limit, they should be included in the model. Therefore, the selected effects on L_{av} (from the highest to the lowest) are listed as follows, angle (D), wattage (A), height (C), spacing (B), the interaction D*F, Q_0 (F), overhang (E), and C*F.

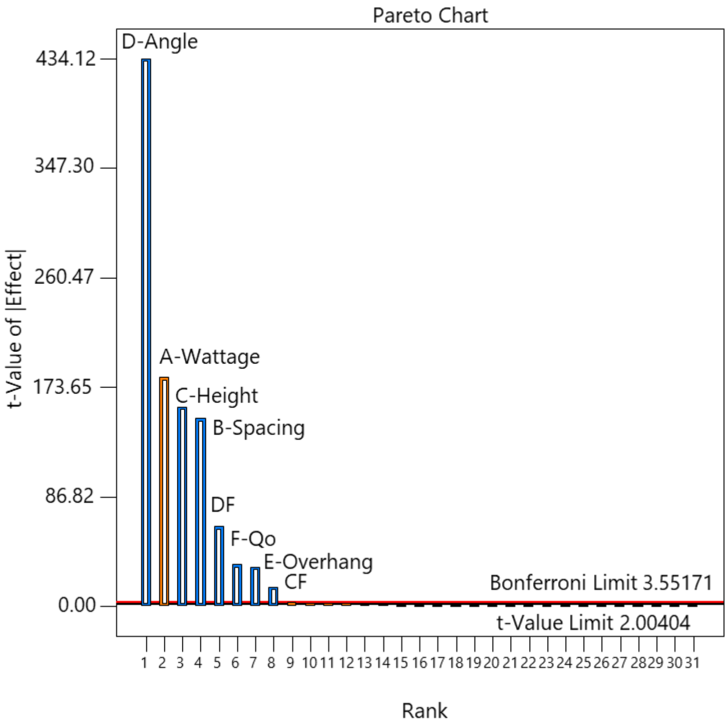
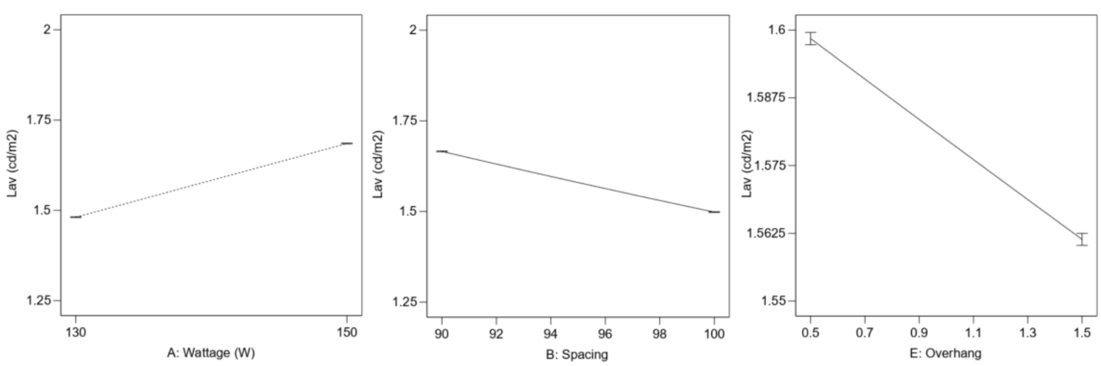


Figure 7. Pareto chart of selected effects on L_{av}

Three main effects from these design parameters, wattage (A), spacing (B), and overhang (E), and their effects are quantified and shown in the main effect plots (Figure 8). The adjustment of these design parameters alone had a direct effect on the average luminance. Elaborately, the increment in the wattage would also result in the increasing luminance. On the other hand, the increment in spacing and overhang leads to the decreasing luminance. Moreover, there are two interactions, height (C) * Q_0 (F) and angle (D)* Q_0 (F), and these interactions are illustrated in the contour plots (Figure 9). If the pole height or the boom angle are set at the low levels (height = 10 m and boom angle = 45°) with the high level of Q_0, L_{av} will be maximized.



(a) (b) (c)

Figure 8. Main effect plots for (a) Wattage (b) Spacing (c) Overhang

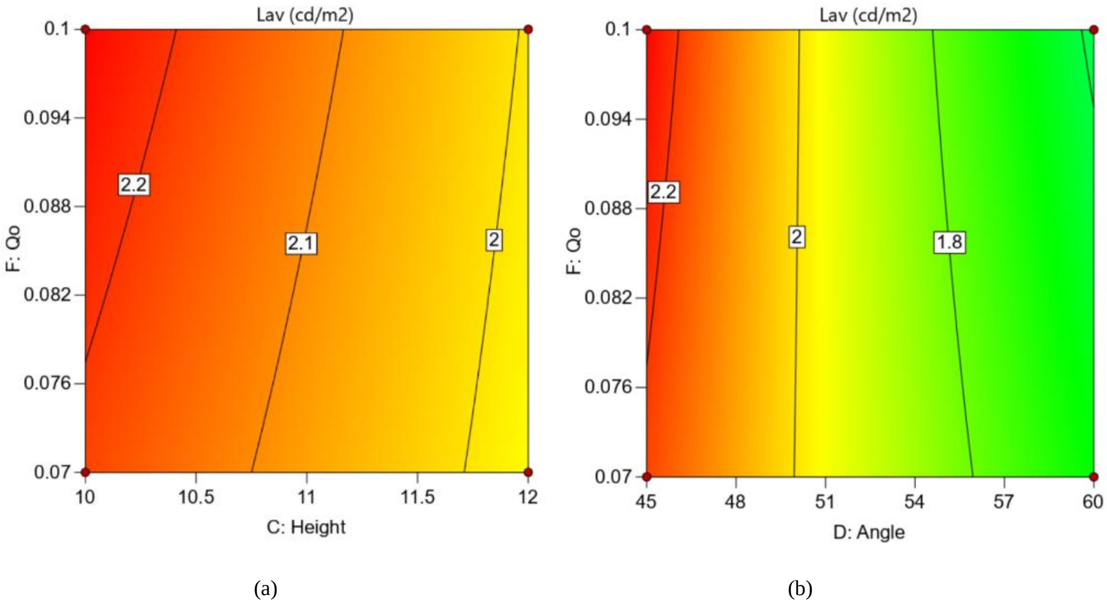


Figure 9. Contour plots for (a) C*F (b) D*F

5.2. Overall Uniformity Ratio

According to the analysis of uniformity, the transform function of 1 / (sqrt/(Uo + 0.35)) was applied to the original data, and the list of significant effects is shown in the pareto chart (Figure 10). The rank of selected effects from the highest to lowest was height (C), C*F, angle (D), spacing (B), B*F, D*F, E (Overhang), C*D, B*D, Q_0 (F), B*C, B*C*D*F, C*E, B*C*F, B*D*F, C*D*F, and B*C*D. These effects are above the Bonferroni limit, but some insignificant terms are also included because of the hierarchy principle. The important finding was that LED wattage (A) did not seem to have a significant effect on Uo. Another finding was that there was an interaction among B*C*D*F, and their effects are depicted in the cube plots (Figure 11). It indicates that the luminance is maximized at 0.785052 cd/m^2, when the design parameters were set as follows: spacing = 90 m (low), height = 12 m (high), angle = 60° (high), and Q_0 = 0.1 (high). Another interaction was between C and E (Figure 12). When the pole height is high (12 m), the values of overhang do not have a significant impact on Uo (overlapped whisker).

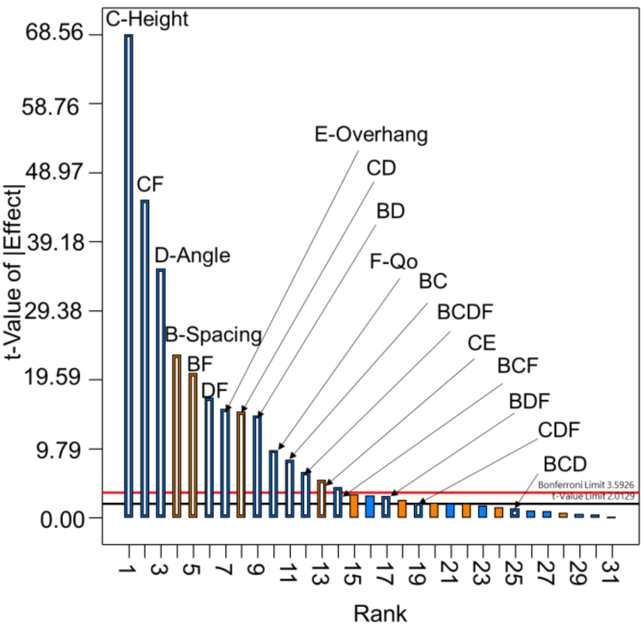
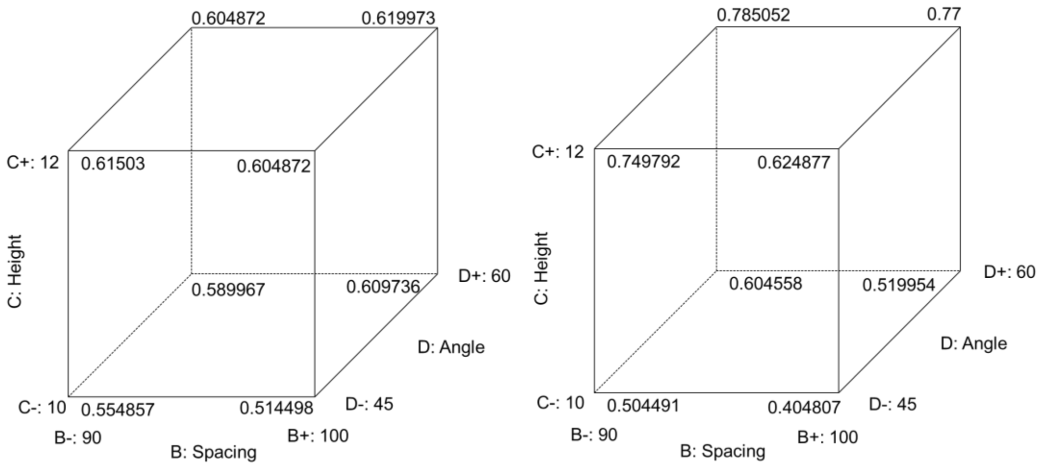


Figure 10. Pareto chart of selected effects on Uo



(a) (b)

Figure 11. Cube plots of B*C*D*F for (a) $Q_0 = 0.07$ (b) $Q_0 = 0.1$

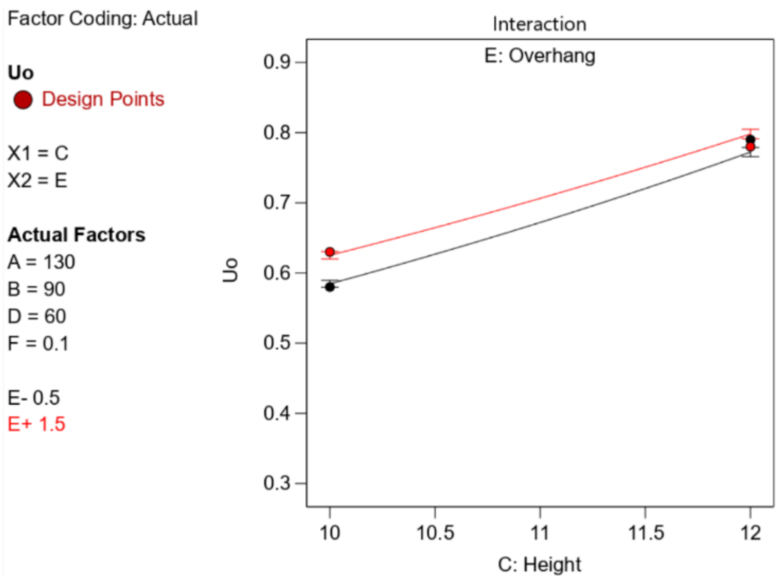


Figure 12. Interaction plot of C*E

In conclusion, the recommended setting of design parameters to maximize each response is listed in Table 3. The low and high settings are listed as the sign – and +, respectively. Due to Table 3, the optimal settings of parameters depend on the response that will be maximized.

Table 3. Recommended setting of design parameters

Response	Wattage	Spacing	Height	Boom angle	Overhang	Q_0
Luminance	+	-	-	-	-	+
Uniformity	Not significant	-	+	+	- or +	+

6. Validation

The optimal results from the analysis were used for the design of lighting system for a different parking layout to ensure the validity of the proposed design parameters. The layout adopted for the validation purpose was the herringbone drive-through (HDT) pattern for WB-67 trucks with slot depth = 74 ft, slot width = 20 ft, and herringbone angle = 45° as recommended by the Federal Highway Administration (Figure 13). Due to Figure 13, the focused areas are chosen to assess the luminance and uniformity and listed as A (clear path), B (herringbone slot), and C (clear path).

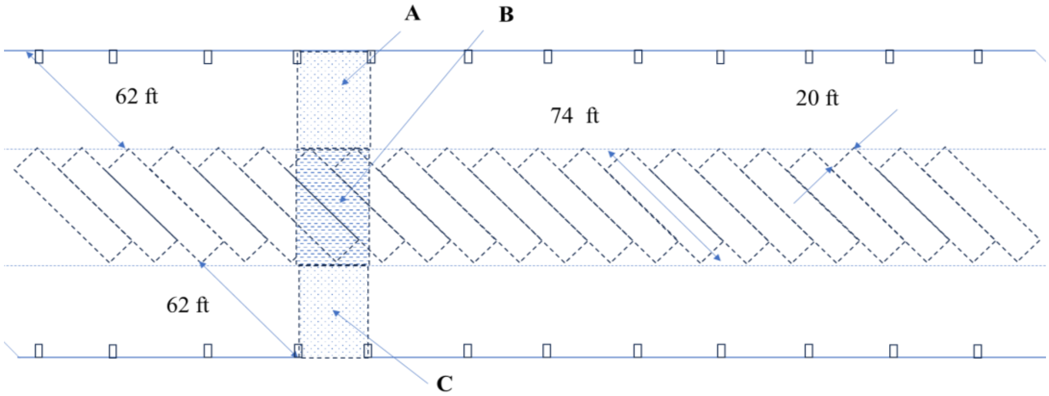


Figure 13. Parking layout for the validation

To start the validation process, the simulation and calculation of L_{av} on the target area were carried out, and the parameter setting to achieve the highest luminance, spacing (low, 9 m), height (low, 10 m), angle (low, 45°), overhang (low, 0.5 m), and Q_0, (high, 0.1), was used for the validation. The selected luminaire used was LED 36 W with the total luminous flux of 4,600 lumens. The simulated luminance of the focused area is shown in the form of iso-luminance curve in Figure 14. The luminance on the herringbone slot (B) is between 0.77 and 0.83 cd/m^2, whilst those on both clear path areas (A and C) are between 0.42 and 1.0 cd/m^2. According to Table 4, the L_{av} of area A, B, and C are 0.83, 0.81, and 0.83 cd/m^2, respectively, and these values are greater than the minimum L_{av} at 0.75 cd/m^2. Moreover, the results on uniformity shows that the Uo of area A, B, and C are 0.48, 0.94, and 0.47, and these values exceed the minimum value of Uo (0.4). As a result, this result explicitly indicates that the analysis results from the empirical study were also valid for the alternative parking layout.

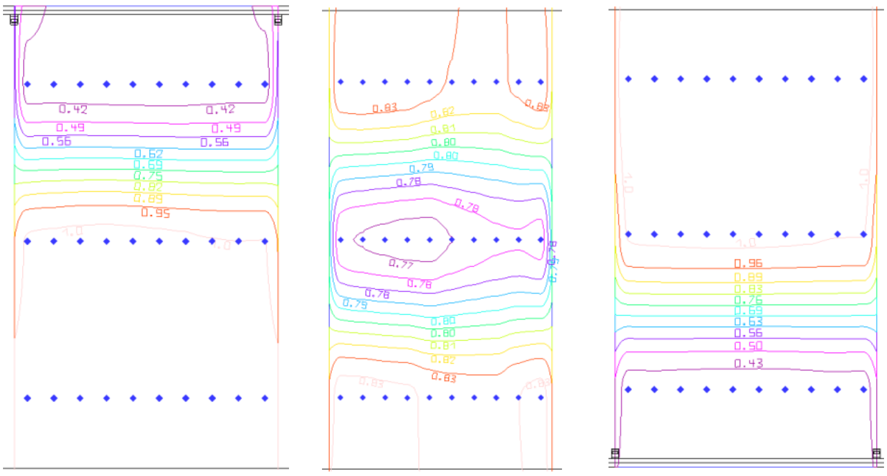


Figure 14. Iso-luminance curve of area (a) A (b) B (c) C

Table 4. The L_{av} and Uo of focused area

Area	L_{av} (cd/m^2)	Uo
A	0.83	0.48
B	0.81	0.94
C	0.83	0.47

7. Conclusions

The optimal design of lighting system is critical to ensure that there is enough light in the parking lot, especially for trucks, and the safety level in the lot can be greatly enhanced with the appropriate lighting level. In this study, two responses, L_{av} and Uo, were simulated and calculated for the corresponding layout, adopted from the survey on the available parking lots for trucks. The effects from the selected design parameters, wattage, pole spacing, pole height, boom angle, overhang, and Q_0, on L_{av} and Uo were assessed by performing an empirical study based on the 2^k full factorial design of experiment method. The statistical analysis was conducted to specify the recommended setting for the maximization of each response. Although the settings of design factors to optimise L_{av} and Uo were different, both results agree that the spacing between poles should be kept at the low level, whilst Q_0 should be high. Afterwards, the validation testing was performed by using the layout of a standard design for a truck parking lot, and the optimal setting of parameters to maximize L_{av} was applied. The validation results also pointed out that the setting for maximizing L_{av} led to the acceptable level of Uo. Therefore, this setting was proved to be valid for the different truck parking layout, so it could be used as a guideline to efficiently design the lighting system for other newly built truck parking lots. In addition, the extended utilisation of these results can also be applied to improve the lighting quality of the existing systems.

Acknowledgements

This work is supported by Phranakhon Rajabhat University. The author also gratefully acknowledges the helpful comments and suggestions of the reviewers.

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