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Lighting Analysis at Access Zone of Tunnel Entrance of Hong Kong-Zuhai-Macao Bridge (HZMB)

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ABSTRACT

The study aimed to evaluate several shading schemes at access zone of the tunnel entrance of HZMB in order to find the best scenario to increase the user lighting comfort. The study analysed the luminance at the tunnel entrance (L_{20}) and energy saving in the thereshold zone. For these analyses, four shading schemes have been simulated. The schemes were the Original Scheme (Zebra, 50% solid & 50% transparent), Option 1 (Gradation Glass), Option 2 (Perforated Material), and Option 3 (No Shading). The results shows that the Original scheme has the lowest L_{20} luminance and consequently the highest lighting energy saving. While the Option 3 (No Shading) has the highest L_{20} luminance and consequently the lowest lighting energy saving.

Keywords: luminance, tunnel lighting, tunnel entrance, Hong Kong, Zuhai, Macao

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1. INTRODUCTION

In 2003, the Government of Hong Kong Special Administrative Region (HKSAR) carried out a study entitled “Transport Linkage between Hong Kong and Pearl River West.” The study was completed in July 2003. The study reported that the transport linkage between Hong Kong and Pearl River West is weak, and land transport between them requires longer transport time result in high cost. In order to shortening the travelling time and reduce the travel cost, the Governmnet of HKSAR proposed the Hong Kong-Zhuhai-Macao Bridge (HZMB). This project is expected to have the following macro socio-economic benefits [1]:

- promoting the socio-economic development of the Pearl River West;
- reinforcing Hong Kong 's status as an international shipping and aviation center;
- promoting the development of regional tourism industries; and
- perfecting the regional transport network.

Based on the 2003 study some following governmental meetings between Hong Kong, Zuhai and Macao have been held. They agreed to inititate the project in 2009. The project includes a 29.6 km dual 3-lane carriageway in the form of bridge-cum-tunnel structure comprising a tunnel of about 6.7 km; two artificial islands for the tunnel landings west of the HKSAR boundary; and associated works including civil and structural works, environmental mitigation, drainage, electrical and mechanical, traffic control and surveillance system, etc. [2].

Fig. 1. Hong Kong-Zuhai-Macao Bridge (HZMB) location

The Department of Architecture of the University of Hong Kong has been participated in the project in the area of the study of lighting analyses in the tunnel access zone. The work includes the field measurement at the sea, validation of RADIANCE lighting simulation and the simulation study of the tunnel entrance.

The following part will explain the simulation study of access zone. The simulation study aimed to find the best scenario of tunnel entrance based on the luminance at access zone *(L20).*

2. LITERATURE REVIEW

Tunnel design involved several different aspects, including the structure and construction of the tunnel, ventilation as well as tunnel lighting design. The major difference between tunnel lighting and conventional road lighting is in the need for lighting by day. A driver needs to be able to see a certain distance ahead such that if an unexpected hazard appears, the driver can react and stop within that distance (stopping distance or *SD*). When this distance extends into a tunnel there should be a sufficiently high lighting level inside to maintain visibility. If the lighting level is not high enough, the driver will be unable to see into the tunnel, the so-called "black hole effect" [3]. The *SD* is determined by vehicle speed allow to pass the tunnel. Britsh Standard (BS) provides a table to determine the *SD* based on the vehicle speed as listed in Table 1.

Table 1. Stopping Distance determination for various design speed [3]

Design speed (km/h)	Stopping Distance (*SD*) m
120	215
100	160
85	120
70	90
60	70
50	50

In Chinese, the determination of *SD* is based on the Chinese Standard (CS) [4]. For flat road, the determination of SD is similar to BS, but for slope road they are different. For this situation, the *SD* in CS is longer than the BS.

During approach and entry to a tunnel, drivers' eyes become adapted to the darker surroundings. This adaptation is a continuous process with the result that further into the tunnel, providing it is of sufficient length, the lighting level may be steadily reduced until it reaches the constant level in the tunnel interior zone. On emerging from a tunnel into daylight the eye adapts far more quickly to the higher luminance level [3]. Similarly, according to Liu [5], the most dangerous part of a tunnel is the access zone, because the driver's pupils can't immediately adapt to the darker area when the driver enters the tunnel. When this happens, the driver can't see any obstacles in front of him. So proper lighting must be installed in the access zone to help the driver adapt to the darker zone.

According to BS [3], the lighting of a tunnel should be sufficient to:

a) avoid the "black hole effect" when a driver is unable to see into the tunnel;
b) reduce the likelihood of a collision with another vehicle (or bicycle or pedestrian);
c) enable a driver to react and stop within the stopping distance *SD* (Table 1) if an unexpected hazard appears;
d) provide visual guidance.

When planning the lighting of a tunnel, there are five key areas to consider as follows [6]:

1. Access zone. This area is outside the tunnel. From this zone, drivers must be able to see into the tunnel in order to detect possible obstacles and to drive into the tunnel without reducing speed. The driver's capacity to adapt in the access zone governs the lighting level in the next part of the tunnel. One of the methods used by CIE [7] to calculate visual adaptation is the L_{20} method, which considers the average luminance from environment, sky and road in a visual cone of 20°, centred on the line of sight of the driver from the beginning of the access zone.
2. Threshold zone. This zone is equal in length to the 'stopping distance'. In the first part of this zone, the required luminance must remain constant and is linked to the outside luminance (L_{20}) and traffic conditions. At the end of the zone, the luminance level provided can be quickly reduced to 40% of the initial value.

3. Transition zone. Over the distance of the transition zone, luminance is reduced progressively to reach the level required in the interior zone. The reduction stages must not exceed a ratio of 1:3 as they are linked to the capacity of the human eye to adapt to the environment and, thus, timerelated. The end of the transition zone is reached when the luminance is equal to 3 times the interior level.
4. Interior zone. This is the area between transition and exit zones, often the longest stretch of tunnel. Lighting levels are linked to the speed and density of traffic.
5. Exit zone. This part of the tunnel located between interior zone and portal. In this zone, during the day time, the vision of a driver approaching the exit is influenced by brightness outside the tunnel. The human eye can adapt itself almost instantly from low to high light levels, thus the processes mentioned when entering the tunnel are not reversed.

The calculation of Luminance of access zone (L_{20}) from the photograph, drawing or computer model should be carried out as follows [3]:

a) The limit of the field of view should be added by superimposing a circle of 20º subtense centred on the tunnel portal from a viewing point height of 1.5 m from the road surface as shown in Figure 2.
b) The 20º field of view should be divided into segments (see Figure 3) and each segment identified with a reference number or letter. A luminance value L should be assigned to each segment using a measured value taken at the site or a typical value from Table 2.
c) A schedule of the segments should be made up showing the area A of each segment, its assigned luminance L and the product of the two, $A \times L$. The average luminance L_{20} should then be calculated using equation (1).

$$L_{20} = (A \times L)/A \quad (1)$$

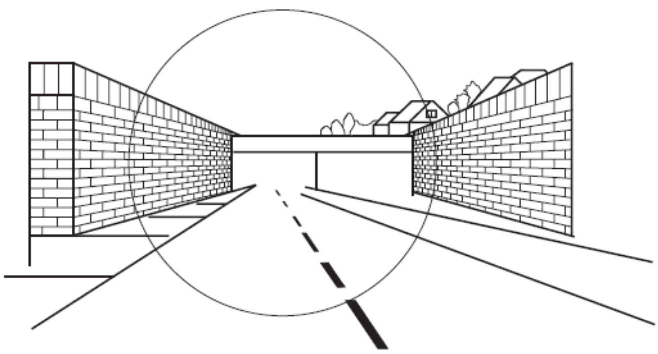

Fig. 2. Perspective view of a tunnel entrance with superimposed 20o subtense circle.

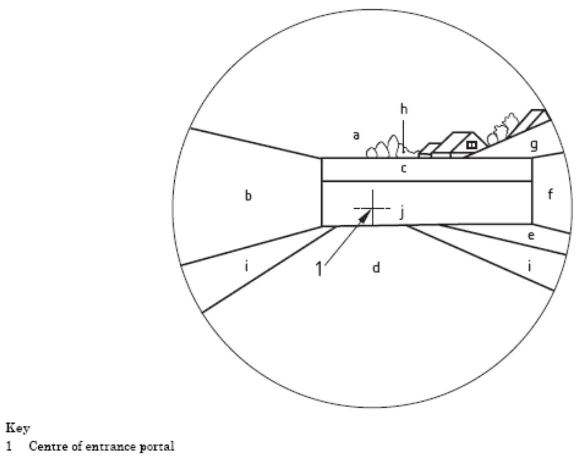

Fig. 3. 20º field of view divided into assessment areas.

Table 2. Typical value of ground reflectance (ρg) and building reflectance (ρb).

Material	ρg, ρb (%)
Aluminium	70-85
Asphalt	10
Concrete	0-50
Stone	5-50
Wood	5-40
Paints, white	70-90
light tones	50-75
dark tones	20-40
black	5
Brick, red	25-45
Snow, fresh	60-75
Glass, ordinary	7
reflex	20-40
Grass	10-30

Source: Medved and Arkar [8]

After determining the L_{20}, the next crucial lighting design is to determine the luminance at threshold zone (L_{th}). The road surface luminance of the threshold zone should be derived from the luminance of the access zone during daytime. The length of the threshold zone is equal to the stopping distance *SD*. The L_{th} should be provided during daytime from the beginning of the threshold zone for a length of 0.5*SD*. The appropriate value of *k* should be selected from Table 3, and the threshold zone luminance L_{th} should be calculated using equation (2).

$$L_{th} = k \times L_{20} \quad (2)$$

From half the stopping distance *SD* onwards, the lighting level should gradually and linearly decrease to a value, at the end of the threshold zone, equal to $0.4L_{th}$. The gradual reduction over the last half of the threshold zone may also be in steps. However, the luminance level should not fall below the values corresponding to a gradual linear decrease [3].

The tunnel lighting class is selected based on the Figure 4.

3. METHODE

As mentioned before, the analysis of L20 in this study includes four schemes i.e. the Original scheme (Zebra with 50% solid and 50% transparent), Option 1 (Gradation Glass), Option 2 (perforated material), and Option 3 (No Shading). The simulation settings using similar technique with Mardaljevic [9] which follows the static daylight simulation at certain date and time using CIE Clear sky model. The simulations using RADIANCE software have been carried out with the following procedures:

Table 3. Values of k for different speed limits and tunnel lighting classes [3]

Tunnel lighting class	*k* value		
	Speed limit 30 to 40 mph	Speed limit 50 to 60 mph	Speed limit 70 mph
4	0.05	0.06	0.10
3	0.04	0.05	0.07
2	0.03	0.04	0.05
1	-	-	

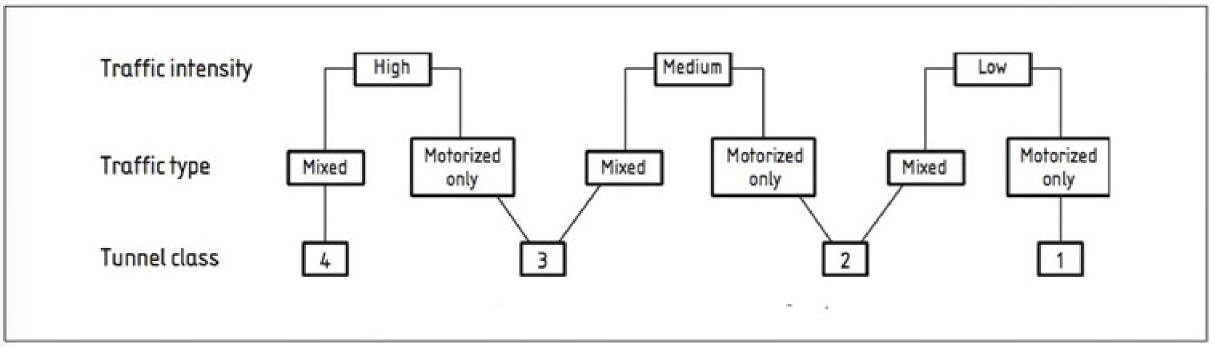

Fig. 4. Tunnel lighting class [3]

- The simulation has been carried out only for the summer soltice, as at this day the highest luminance of L_{20} will occur.
- The Stopping Distance (*SD*) at 173m to the tunnel entrance (0m). The *SD* is longer than the one that is specifying in the BS (160m). This is because the road is sloping.
- The simulation was carried out at 12:00 noon, as at this time the highest luminance L_{20} will occur.
- The sky condition was CIE Clear sky model (Default sky).

The material setting was based on the Table 1. For the shading parts, the material setting as follows:

a. Original scheme

- Shading structure (metal) reflectance 0.20
- Shading transparent material, transmittance 0.80

b. Option 1 (Gradation Glass)

- Shading structure (metal) reflectance 0.20
- Shading transparent material, the transmittance reduced gradually from 0.80 to 0.50

c. Option 2 (Perforated Material)

- Shading structure (metal) reflectance 0.20
- Shading perforated material, the perforated density reduced gradually from 0.80 to 0.50

d. Option 3 (No Shading)

Based on the validation study, the simulation result underestimated the measurement value by 36%. Therefore, the L_{20} resulted by RADIANCE simulation should be multiplied by 1.36. The shading part of the tunnel is presented in the Figure 5.

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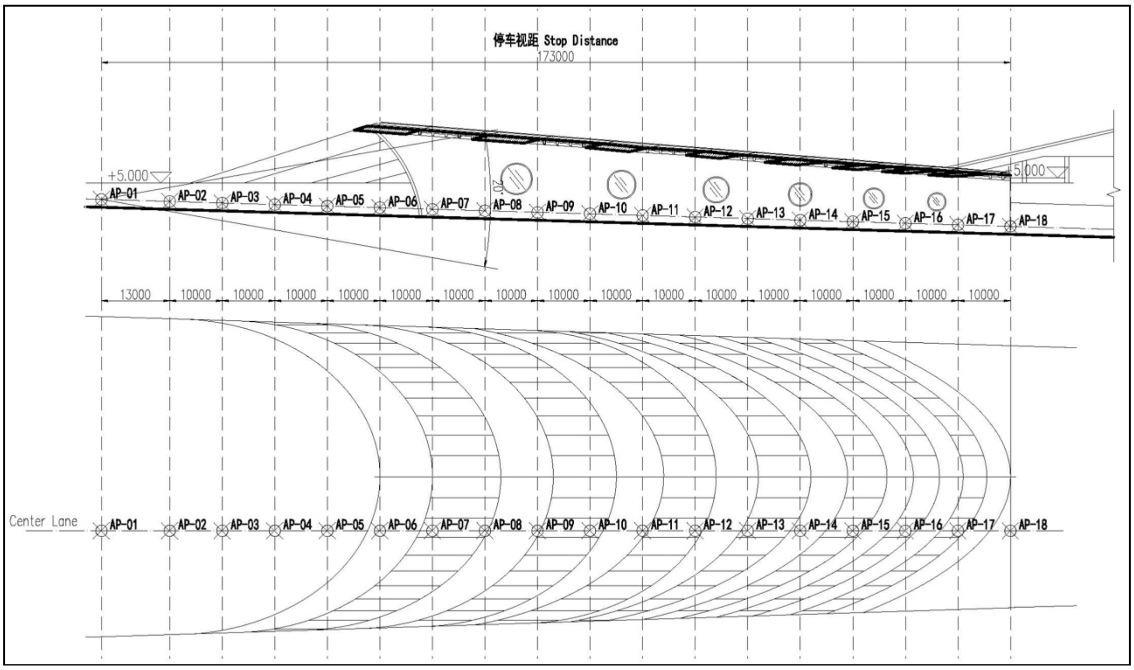

Fig. 5. The location of assessed points (AP-01 to AP-18)

4. RESULT AND DISCUSSION

A. Original Scheme (Zebra 50% solid & 50% transparent)

The following figures and tables show the calculation of L_{20} on the summer solstice (21 June) at 12:00 noon for the Original scheme. The L_{20} luminance for the Original scheme is 2779.60cd/m2. The highest luminance is contributed from the direct luminance received by the road surface in front of the shading parts. The low luminance seen in the *SD* is mainly due to the inclusion of sub-structure underneath the transparent material, which is block some of light penetrates under the shading parts.

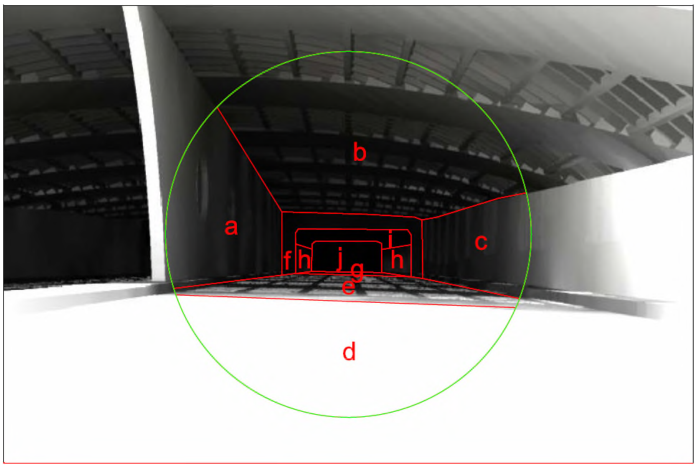

Fig. 6. The area within 20° field of view seen at SD on summer solstice at 12:00 for the Original Scheme.

Table 4. The calculation of L_{20} at SD (173m) on summer solstice at 12:00 for the Original Scheme

Division by surfaces and luminance	Nominal Area (*A*)	Luminance cd/m2 (*L*)	*A x L*
a	44.22	130.00	5748.60
b	111.4	75.00	8355.00
c	26.45	110.50	2922.73
d	85.59	7,185.00	614,964.15
e	20.88	440.60	9,199.73
f	9.82	40.33	396.07
g	0.82	102.00	83.64
h	3.68	84.50	310.96
i	4.96	2.80	13.89
j	6.33	11.60	73.43
Total	314.15		642,068.19
		Calculated L_{20}	2,043.83
		Corrected L_{20} x 1.36	**2,779.60**

B. Option 1 (Gradation Glass)

Table 5 shows the L_{20} luminance for the Option 1 (Gradation Glass). The L_{20} luminance for the Option 1 is 3041.87cd/m2. The highest luminance is also contributed from the direct luminance received by the road surface in front of the shading parts. If we compared to the Original Scheme, there is an increase of L_{20} of 262.27cd/m2 (2,779.6cd/m2 to 3,041.87cd/m2). This increase is mainly due to the amount of light penetrated under the shading parts.

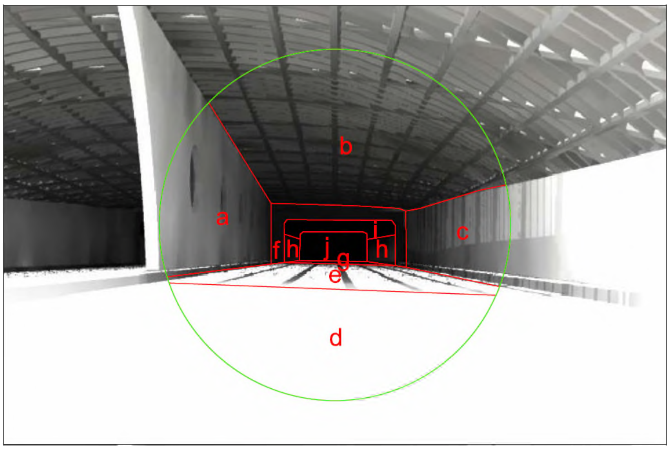

Fig. 7. The area within 20º field of view seen at SD on summer solstice at 12:00 for Option 1.

Table 5. The calculation of L_{20} at SD (173m) on summer solstice at 12:00 for Option 1.

Division by surfaces and luminance	Nominal Area (A)	Luminance cd/m2 (L)	A x L
a	44.22	427.00	18 881.94
b	111.40	199.00	22 168.60
c	26.45	308.00	8 146.60
d	85.59	7,185.00	614,964.15
e	20.88	1,783.00	37,229.04
f	9.82	74.00	726.68
g	0.82	102.00	83.64
h	3.68	98.00	360.64
i	4.96	2.80	13.89
j	6.33	11.60	73.43
Total	314.15		702,648.61
		L_{20}	2,236.67
		Corrected (L_{20} x 1.36)	3,041.87

C. Option 2 (Perforated Material)

Table 6 shows the L_{20} luminance for the Option 2 (Perforated Material). The L_{20} luminance for the Option 2 is 3594.23cd/m2. The highest luminance is also contributed from the direct luminance received by the road surface in front of the shading parts. If we compared to the Original Scheme, there is an increase of L_{20} of 814.63cd/m2 (2779.6cd/m2 to 3594.23cd/m2). This increase is also mainly due to the amount of light penetrated under the shading parts.

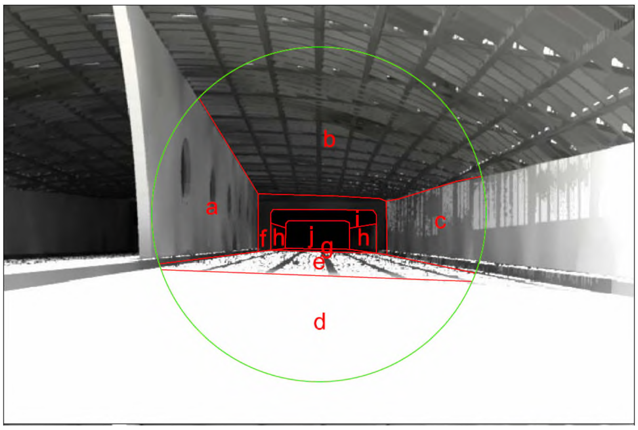

Fig. 8. The area within 20° field of view seen at SD on summer solstice at 12:00 for Option 2.

Table 6. The calculation of L_{20} at SD (173m) on summer solstice at 12:00 for Option 2.

Division by surfaces and luminance	Nominal Area (A)	Luminance cd/m2 (L)	A x L
a	44.22	919.50	40,660.29
b	111.40	518.00	57,705.20
c	26.45	1,016.00	26,873.20
d	85.59	7,259.50	621,340.61
e	20.88	3,856.80	80,529.98
f	9.82	262.67	2,579.39
g	0.82	102.00	83.64
h	3.68	103.20	379.78
i	4.96	3.00	14.88
j	6.33	11.60	73.43
Total	314.15		830,240.39
		L_{20}	2,642.82
		Corrected (L_{20} x 1.36)	3,594.23

D. Option 3 (No Shading)

In order to study the impact of shading parts on the energy saving. We have carried out the simulation with no shading part. Table 7 shows the L_{20} luminance at Stopping Distance (*SD*) for the Option 3 (No Shading). As seen in the Table 7, the L_{20} could reach 6,424.02cd/m2 at 12:00 on summer solstice. This very high luminance is contributed by the high luminance reflected by road surfaces, the building above the tunnel and the visible sky.

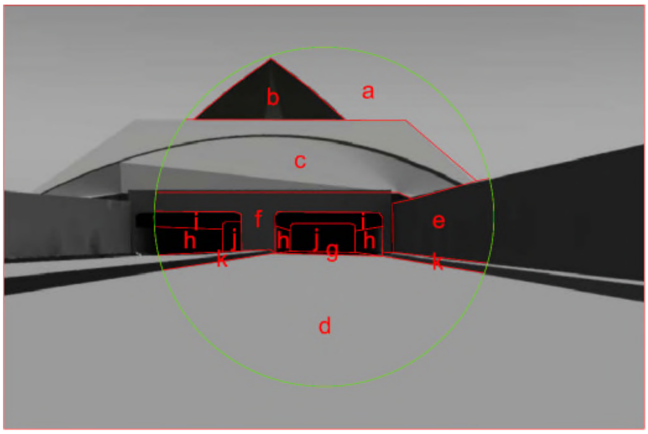

Fig. 9. The area within 20^{o} field of view seen at *SD* on summer solstice at 12:00 for Option 4

E. Energy Analysis

Table 8 shows the summary of L20 luminance for four different shading schemes. As seen from the Table 8, the lowest L20 luminance is occurred when using the Original Scheme and the highest one occurred when no shading used. The L20 of Option 1 and Option 2 lay in between the two extremes.

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Table 7. The calculation of L_{20} at *SD* (173m) on summer solstice at 12:00 for Option 4.

Division by surfaces and luminance	Nominal Area (A)	Luminance cd/m2 (L)	A x L
a	40.5	6,715.00	271,957.50
b	16.74	1,560.00	26,114.40
c	69.83	6,028.00	420,935.24
d	106.43	6,311.00	671,679.73
e	23.2	1,248.00	28,953.60
f	22.6	1,659.00	37,493.40
g	0.8	102.00	81.60
h	9.47	120.00	1,136.40
i	9.51	2.80	26.63
j	8.23	11.60	95.47
k	6.7	3,696.50	24,766.55
Total	314.01		1,483,240.52
		L20	4,723.55
		Corrected (*L20* x 1.36)	6,424.02

In order to estimate the energy saving, the required luminance for the inside the tunnel (threshold, transition and interior zones) should be determined. The L_{th} (Luminance at threshold) is determined by the L_{20} at the Stopping Distance (*SD*).

Because the tunnel was designed to accommodate high traffic intensity and motorized only, so the tunnel lighting is classify as tunnel class 3. Based on Table 3 and tunnel class 3, then the k should be taken for the Lth calculation is 0.05. The corresponding threshold luminance values at road surface are listed in table 9.

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Because the tunnel was designed to accommodate high traffic intensity and

Table 8. The summary of L_{20}

	L_{20} Luminance (cd/m^2)			
Local time	Original Scheme	Option 1	Option 2	Option 3
12:00	2,779.60	3,041.87	3,594.23	6,424.02

motorized only, so the tunnel lighting is classify as tunnel class 3. Based on Table 3 and tunnel class 3, then the k should be taken for the Lth calculation is 0.05. The corresponding threshold luminance values at road surface are listed in table 9.

As seen from the Table 9, the Original Scheme with sub-structure will have a very good impact on the reduction of artificial lighting by providing the smallest road surface luminance required at threshold zone (L_{th}), while the Option 3 (no shading) required the highest energy use for providing highest Lth at threshold zone. This analysis shows that the best option for energy saving is the Original Scheme, while the worst is the Option 3 (no shading). This analysis also shows that the existence of shading parts in front of tunnel entrance will reduce the lighting energy used inside the tunnel by reducing the L_{20} luminance which has direct impact on the calculation of L_{th} (luminance at threshold zone).

5. CONCLUSION

The results of simulation show that the highest L20 luminance of more than 6400cd/m2 will occur at 12:00 noon on summer solstice when there is no shading used in front of the tunnel entrance. If the shading parts are used, the L20 luminance reduced according to the type of shading used. The highest L20 will be observed by drivers if there is no shading installed (Option 3), while the lowest one will be perceived by drivers if used the Original Scheme. In terms of energy saving, it is clear from the analysis that the no-shading will increase the L20 luminance by 97.66% from 3250 to 6424.02cd/m2. The Original scheme is expected to use less energy in comparison to other schemes.

6. ACKNOWLEDGEMENTS

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Table 9. The road surface luminance at threshold zone (L_{th}) for four different schemes of shading

Shading Schemes	Corresponding luminance, L_{20} (cd/m2)	Corresponding threshold luminance, L_{th} (cd/m2)
Original Scheme	2779.60	138.98
Option 1 (Gradation Glass)	3041.87	152.09
Option 2 (Perforated Material)	3594.23	179.71
Option 3 (No Shading)	6424.02	321.20

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