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A Scheme for the Evaluation of Tunnel Lighting Alternatives

– Life Cycle Cost Comparison by Simulation Approach –

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Life Cycle Cost 비교에 의한 터널조명 대안분석 연구

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The number of tunnel has fast increased with the rapid expansion of highway network. Tunnel should be designed to provide for drivers both safety and pleasant driving conditions. In this perspective, the design for tunnel lightning is very important in order to provide its safety, pleasantness, and cost-efficiency of maintenance, all of which should be considered and analyzed for a better tunnel lighting. This paper attempts to compare the low-pressure sodium lamp, which has usually been used for tunnel lighting, with the fluorescent lamp, which we consider as an alternative for the former. In an effort to determine the number of lamps to meet the required illuminance in the tunnel, this research employs a simulation technique which would allow us to conjecture, with the aid of basic model, the life cycle cost for illumination per each tunnel. This analysis is expected to provide a basic method and related information for tunnel development and design.

1. Introduction

With the steady increase of cars thanks to the economic development, the demand for better conditions and illumination on the roads has been growing. The same is true of tunnels. The illumination system inside tunnels must put the priority on the safety and pleasantness of drivers, because tunnels are, unlike other roads, narrow and dark. A tunnel needs to provide an environment in which drivers could adapt gradually and comfortably to the abrupt change of brightness and illumination, from the bright outside to the dark inside. When we consider the lighting system of tunnel that should moderate the abrupt change of brightness and illumination that the drivers may experience between the inside and the outside of a tunnel, it is very important that we consider the cost and energy efficiency of the system, and thus any possible alternatives. Based upon the method of a life cycle cost comparison, this paper compares the cost of low-pressure sodium lamp with that of fluorescent lamp. For this study, we represent a sample tunnel through computer simulation and thereby estimate the number of light bulbs needed for a certain degree of roadway illumination. Then we project the cost for initial installment and its maintenance cost needed for tunnel lighting and thus suggest a method of calculating the life cycle cost of the alternative lighting systems.

2. Tunnel Lighting and Simulation

2.1 The Structure of Tunnel Lighting

Tunnel lighting is a main factor to determine the conditions of safe-driving in that drivers must be quickly able to adapt to the difference of illumination and brightness between the inside and the outside of tunnel, according to which we divide and categorize the standard of illumination and brightness. Tunnel lighting is divided into parts of approach, entrance, interior, exit, and emergency zone. The inside lighting of tunnel applies to the zones of entrance, interior,

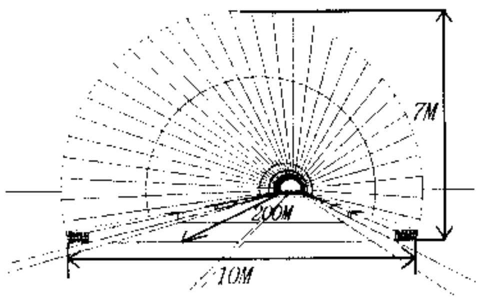


Figure 1. Tunnel Structure in the Research.

Table 1. Tunnel Zones in the Research

Zone	Distance (m)	Required Illuminance (lx)	
		Day	Night
Threshold	69	1550	220
Transition2	30	1250	
Transition2	30	1250	
Transition3	30	1100	
Transition4	41	770	

and exit. For daytime drivers, it is not easy to adapt to the darkness of tunnel and recognize the inside tunnel when they approach to a dark tunnel, due to the contrasting brightness of the outside. The entrance lighting is designed to help drivers adapt with the darkness of tunnel inside. According to the degree of brightness at tunnel entrance, the entrance lighting is divided into the parts of threshold, transition. The gradual change of brightness leads drivers to adapt to the interior zone, which is the part of tunnel just after drivers have adapted their eyesight with the entrance lighting. The exit lighting is to give drivers appropriate lighting by illuminating the preceding vehicles and objects, with a view to reducing the phenomenon of silhouette, which happens because the eyes of drivers are slow to adjust themselves to the brightness of outside while vehicles moving quickly out of tunnel. The structure of tunnel used for this study is as in <Figure 1>.

2.2 The Design of Tunnel Lighting

The brightness of entrance lighting, which is designed to eliminate the blackhole phenomena and the late adjustment of drivers to brightness when they approach to a tunnel. The degree of drivers' adaptation to brightness when they approach to a tunnel is determined by the brightness required for the entrance lighting. The design of entrance lighting is based on the concept of outside brightness, the designed speed in the tunnel, the length of tunnel, and the kind of road surface. We posit the outside day-brightness as 5000 cd/m^2. According to the road illumination per each section, we come up the road brightness in need for each section. With the road illumination divided by the maintenance rate, we determine the initial road illumination. Here we simulate it on the basis of required road brightness. <Table 1> shows an example tunnel in which dimensions(distance, required illuminance) are roughly taken from a real tunnel in Korea. It shows the required road illuminance for each zone. Since the tunnel for the research is only 200 m long, it is composed of the zones of threshold and transition without interior zone, while the 4th transition part takes place of the exit part. It has the even illuminance at night as the tunnel is not divided into zones.

2.3 The Simulation of Lighting

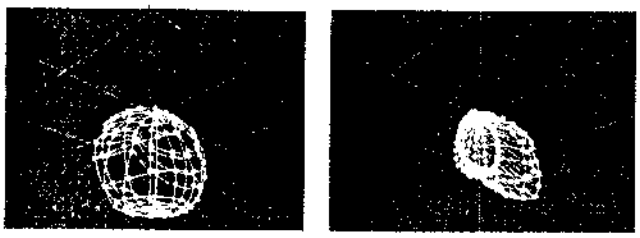
The simulation of lighting can be used to analyze and appraise the distribution plan of illumination and brightness before the lighting system is actually installed. It can also become a foundational information for decision making process on any new investments for lighting system. By having the simulation test before the lighting system is actually installed, we can calculate and optimize the efficiency of the lighting system. It is desirable to examine the effectiveness of system through the simulation test, since the lighting system in a large tunnel might be very difficult and very costly to change once installment is done.

2.3.1 Luminous Intensity Distribution (LID)

Every lighting appliance has its own genuine LID. The adjustment of LID is needed in accordance with the purpose of light use. A big room needs proper LID for such a big space while museums for art exhibition needs a different kind of LID for lighting works. LID should be carefully chosen based upon its specific purpose. LID is represented by LID curves. <Figure 2> shows the lighting appliance and LID curves used in this research.

2.3.2 The Definition of Surface Reflectance

Whether inside or outside of building, the attributes of surfaces could affect effectiveness of lighting and psychological comfortableness. The reflecting rate varies according to the materials used. When light falls on the reflecting surface, there will be reflection, penetration and absorption in accordance with the



Low-pressure Sodium Lamp
- SOX-E 36W(5900 lm)
- SOX-E 91W(17000 lm)

Fluorescent Lamp
- FL32W/2(6100 lm)
- FL32W/3(8400 lm)

Figure 2. LID Curves Used.

characteristics of the surface and the materials used. Also will there be specular reflection and diffused reflection according to the materials. For this study, we apply 25% reflection rate for the concrete surface inside the tunnel and 60% for white tiles on the side-wall.

2.3.3 The Location of Lighting Appliance

The lighting appliance is usually installed along the upper part of side-wall. Installing lights on high place is very desirable to keep the illumination and brightness in an excellent condition. The glaring effect could be produced due to the height of its installment and background light. If the lighting appliance is installed too low, glaring effects from the sides may increase substantially. Among the ways of arranging lights such as zigzag, symmetry or central arrangement, we must choose the optimal way of arrangement, depending upon the LID of lighting appliance, the distribution of road brightness and the convenience of maintenance.

In the tunnel for this research, the lamps are installed at 4.5m up from the road. For the angles of pole(lighting direction), the low-pressure sodium lamp is installed around 62° from the road surface while 50° is applied for the fluorescence lamp as in <Figure 3>.

2.4 The Result of Simulation

The required numbers of lamps which meet the required road illumination for low-pressure sodium

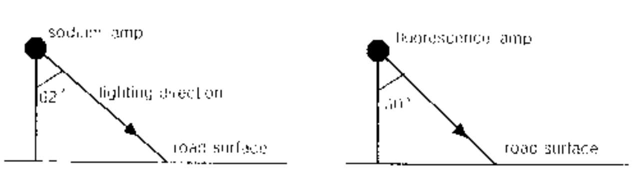


Figure 3. Lamp Installation.

Sodium Lamp

Fluorescent Lamp

Figure 4. Tunnels Simulated.

lamp and fluorescent lamp are derived through the trial-and-error approach in simulation. Finally, this research found that 524(day) and 60(night) low-pressure sodium lamps were needed whereas 1084 (day) and 198(night) were for fluorescent lamps. Though the fluorescent lamp uses more electricity than the sodium lamp does, the former is superior to the latter in providing the uniformity of illuminance and the color rendition inside the tunnel. The fluorescent lamp used in this research is not so energy-efficient, which causes more fluorescence lamps in use. So if a new fluorescent lamp for tunnel lighting is developed, the number of fluorescence lamps is expected to decline. If a new lighting appliance is invented for tunnel lighting itself, the number of needed lighting would also be decreased.

3. The Analysis of LCC(Life Cycle Cost)

This study suggests the method of using simulation to estimate the cost, Life Cycle Cost, for keeping each lighting lamp during a certain period. LCC consists of the initial installation cost and maintenance cost in a certain period. The followings are the simple algorithm for the main cost items with which to estimate the costs by using arithmetic counting. We discard such a cost as disposal cost because it is common for each alternative.

LCC = initial installation cost + maintenance cost
initial installation cost = appliance + lamp + ballast
maintenance cost = electricity + exchange + cleaning
electricity cost = Watt/lamp × number of lamps × $/Watt
exchange = cost of lamps exchanged + labor cost

In order to estimate LCC, we need a basic data to determine each items and a presupposition for the general issues related to the system. For example, we need to know the operating period of the tunnel, the life expectancy of light bulbs, the policy of exchange

Table 2. Simulation Results

[Low-pressure Sodium Lamp]

Zone	Model	Day		Night	
		# of Appliances	# of Lamps	# of Appliances	# of Lamps
Threshold	SOX-E 91W	94	94	The tunnel is not divided into zones during the night.	
	SOX-E 36W	94	94		
Transition1	SOX-E 91W	40	40		
	SOX-E 36W	40	40		
Transition2	SOX-E 91W	36	36		
	SOX-E 36W	36	36		
Transition3	SOX-E 91W	34	34		
	SOX-E 36W	34	34		
Transition4	SOX-E 36W	116	116		
Total	SOX-E 91W	204	**204**	60	60
	SOX-E 36W	320	**320**	0	0

[Fluorescent Lamp-FL32W]

Zone	Model	Day		Night	
		# of Appliances	# of Lamps	# of Appliances	# of Lamps
Threshold	3 Lamps	130	442	The tunnel is not divided into zones during the night.	
	2 Lamps	26			
Transition1	3 Lamps	38	190		
	2 Lamps	38			
Transition2	3 Lamps	60	180		
	2 Lamps	0			
Transition3	3 Lamps	46	154		
	2 Lamps	8			
Transition4	3 Lamps	30	118		
	2 Lamps	14			
Total	3 Lamps	304	1084	66	198
	2 Lamps	86		0	

(the cycle and method of replacement periodical or instance replacement), and the cleaning policy (the number of cleaning per year). The degree of veracity of the data will affect the estimation and thus the cost in general. We need to analyze and compare the estimation of the whole LCC for each alternative lighting. With the aid of sensitivity analysis of each cost element, we could arrive at the more concrete, objective analysis about the cost efficiency.

4. Conclusions

For this research we used the method of comparing the cost of low-pressure sodium lamp and that of fluorescent lamp in terms of cost efficiency. The number of needed light bulbs is determined through simulation for each lighting system to embody the same road illumination inside the tunnel. Based upon the result, we suggest the whole process of computing LCC through the basic model for each tunnel lighting system. Before we can apply the result of this research to any actual installment of lighting system, however, we need to be equipped with the general data that are thoroughly examined. A study of mixed installation of low-pressure sodium lamps with fluorescent lamps might be very useful and illuminating. For the future development of tunnel industry we need to carry a more variety of studies on this issue and related matters. It should include various situations of tunnels including tunnel shape, length, appliance installation, side-wall, etc..

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