The Choosing of Control Mode in Tunnel Lighting Intelligent Control System

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Abstract. Nowadays, more and more tunnel lighting intelligent control systems are applied into reality. For most control systems, there are five control modes. In this paper, the workings of the five control modes are expounded, and the conditions of adjusting the luminance level are obtained. Further, the luminance level and the power consumption of those control modes are compared. In order to choose the more suitable control mode, equipment cost, tunnel length and traffic volume are all considered for meeting equipment-lifetime and energy-saving. Combined lighting mode and automatic lighting mode are more suitable for most tunnels. Furthermore, the formula to forecast the lighting time using the minimum level and the difference of power-saving between combined lighting mode and automatic lighting mode are acquired. In the end, the options of the controls mode are listed for choosing.

1. Introduction
With the development of the intelligent control, more and more tunnel lighting intelligent control system are used into highway tunnels for energy-saving and comfortable lighting. According to the tunnels of HeDa highway, the cost of lighting is over 70% of the total energy cost for a tunnel. Profiting from tunnel lighting intelligent control system, the cost of lighting is declined by about 40% and it can provide the environment with comfortable lighting [1]. So, tunnel lighting intelligent control system is worthy for practical application.

In recent years, there are many studies in tunnel lighting energy-saving. In 2004, Clipsal of Australia studied tunnel lighting intelligent control technology, and developed a highway tunnel intelligent lighting control and management system [2]. In 2005, Beka and others proposed the influence of black hole effect and white hole on driving into and off a tunnel, and stated the importance of tunnel lighting [3]. In 2005, S. Nagai and others proposed an energy-saving tunnel lighting system for reducing energy waste, ensuring safety and providing a comfortable visual environment [4]. In 2010, L.M. Gil-Martín and others used a semi-transparent tension structure of polyester set just before the entrance to the tunnel, and realized the purpose of using sunlight for lighting in a tunnel [5]. In 2012, Sonjia H M Leung reviewed the LED lighting technology and stresses on its application to address the long tunnel lighting design requirements, proposing the adjustment of tunnel lighting to reality [6]. In 2013, Dandan Li designed a safe and comfortable tunnel lighting system considering the design of tunnel lighting energy-saving system [7]. In 2014, Qiang Yang and others compared the simulation from the software DIALUX and the actual measurement in a repetitive region, acknowledging the measured points in tunnel lighting [8]. In 2015, Li Shuguang presented a tunnel lighting optimal control model in considering traffic safety and energy-saving problems [9]. In 2017, Li Qin et al. propose an energy-saving control system including 3 control modes [1].
According to the above studies, most of them concerned on system design and control mode. Although many intelligent control methods have applied to tunnels, there are no specific theory to guide how to choose control mode for suit the different length of tunnels and traffic volume. In this paper, control modes, length of tunnels and traffic volume are discussed and analysed, basing on the operating experiences of 18 tunnels in HeDa expressway in Jilin Province, China.

2. Tunnel Lighting Control Mode
For the most tunnel lighting intelligent control systems, the system has 5 different control modes. There are high lighting mode, time lighting mode, adaptation luminance lighting mode, automatic lighting mode and combined lighting mode. Each control mode uses one or more conditions to control the luminance level (from 20% to 100%) of the LED lamps in tunnel for saving energy.

High lighting mode, the lighting lamps are adjusted to their highest luminance (the luminance level is 100%) all the day, regardless of all the conditions. This mode is an outdate mode, because it causes superfluous energy consumption. But it needs no extra equipment when it works.

Time lighting mode, the tunnel lighting luminance only depends on the different permutations in one day, the lighting luminance is determined by permutation, and the luminance level can be seen in table 1. It needs no extra equipment either, and it consumes the less energy than high lighting mode. But the LED lamps in tunnel are works in their higher power all the day. The comparison of high lighting mode with time lighting mode is shown in Figure 1. According to Figure 1, the luminance levels of time lighting mode are changed in one day, but the high lighting mode is changeless.

| Permutation | Time          | Luminance level |
|-------------|---------------|-----------------|
| Morning     | 2:00am-6:00am | 60%             |
| Forenoon    | 6:00am-10:00am| 80%             |
| Noon        | 10:00am-14:00pm| 100%           |
| Afternoon   | 14:00pm-18:00pm| 80%            |
| Dusk        | 18:00pm-22:00pm| 60%            |
| Night       | 22:00pm-2:00am  | 40%             |

Figure 1. The comparison of high lighting mode with time lighting mode

Adaptation luminance lighting mode, regardless of the existence of vehicles, the tunnel lighting luminance depends on the adaptation luminance only. It needs extra equipment like the luminance meter to measure adaptation luminance when it works. Adaptation luminance lighting mode can provide a comfortable lighting and save energy better than time lighting mode. The comparison of time lighting mode with adaptation luminance lighting mode at the condition of the same adaptation luminance is shown in Figure 2. According to Figure 2, the luminance levels of adaptation luminance mode are changed with the real-time adaptation luminance. And the luminance level of adaptation luminance mode is less than time lighting mode.
Automatic lighting mode is “vehicle in, light brightens; vehicle out, light darkens”, the tunnel lighting luminance depends on the existence of vehicles and the adaptation luminance. When vehicles are about to enter the tunnel, the system control the LEDs to their demand luminance level calculated by the adaptation luminance and the speed of vehicle. When no vehicles are about to enter the tunnel and there are no vehicles in the tunnel, LED lamps are adjusted to their minimum luminance level. It needs extra equipment like the luminance meter to measure adaptation luminance and the microwave traffic detectors to measure the speed of vehicle when it works. Automatic lighting mode can provide a comfortable lighting and save energy obviously.

Combined lighting mode, it is automatic lighting mode at night (from 18:00pm to 8:00am morrow) and it is adaptation luminance lighting mode in the daytime (8:00am to 18:00pm). It also needs extra equipment to measure adaptation luminance and the speed of vehicle when it works. It is same as automatic lighting mode that combined lighting mode can provide a comfortable lighting and save energy at night. Combined lighting mode can avoid adjusting LED lamps frequently to use adaptation luminance lighting mode in the daytime for the increasing lifetime of the equipment and the burthen of the system. But combined lighting mode saves the less energy than automatic lighting mode. The comparison of automatic lighting mode with combined lighting mode at the condition of the same adaptation luminance and traffic volume is shown in Figure 3. According to Figure 3, the luminance levels of the two control modes are changed with the real-time adaptation luminance and the existence of vehicles at night. But in the daytime, the two control modes are different. The luminance level of combined lighting mode could not be adjusted to 20% because it is same as adaptation luminance mode.

![Figure 2. The comparison of time lighting mode with adaptation luminance lighting mode](image)

![Figure 3. The comparison of automatic lighting mode with combined lighting mode](image)
For tunnel lighting intelligent control system, the energy-saving depends on the luminance level of LED lamps. The numbers of LED lamps are different in the different length of tunnels. For the length of tunnel is 1500m, when the weather is clear and the traffic volume is about 1000 vehicles per day. The power consumption (only right hole of tunnel) under 5 control modes can be seen in table 2. The power consumption is calculated by the power rating of LED lamp. The power and electricity saving of each tunnel is compared with high lighting mode. The price of electricity is 1.0 Chinese Yuan (CNY for short) per kilowatt-hour in China.

| Control mode                        | Power consumption per day (kWh) | Power saving | Electricity saving per month (CNY) |
|-------------------------------------|---------------------------------|--------------|-----------------------------------|
| High lighting mode                  | 650                             | 0%           | 0                                 |
| Time lighting mode                  | 454                             | 30.2%        | 5,880                             |
| Adaptation luminance lighting mode  | 393                             | 39.5%        | 7,710                             |
| Combined lighting mode              | 341                             | 47.5%        | 9,270                             |
| Automatic lighting mode             | 332                             | 48.9%        | 9,540                             |

According to table 2, the effect of energy-saving in combined lighting mode and automatic lighting mode is better than time lighting mode and adaptation luminance lighting mode. The high lighting mode saves no energy.

3. The Choosing of Tunnel Lighting Control Mode

3.1. The effect of equipment cost

For tunnel lighting intelligent control system, some extra equipment is used to realize intelligent control. The different control mode uses the different equipment. Although combined lighting mode and automatic lighting mode save energy obviously, they need more cost for extra equipment. Because of the type of equipment and the length of tunnel, there are some differences in the cost and number in equipment. The equipment about control system used in Xiaogou Tunnel (length is 1150m) are listed in table 3.

| Equipment                      | Server | Local optical transceiver | Remote optical transceiver | LED dimming controller | Luminance meter | Infrared sensor | Microwave traffic detector |
|--------------------------------|--------|---------------------------|---------------------------|------------------------|-----------------|-----------------|---------------------------|
| Number (CNY)                   | 1      | 1                         | 14                        | 14                     | 2               | 2               | 6                         |
| Unit-price (CNY)               | 26,000 | 8,000                     | 2,500                     | 4,500                  | 12,000          | 800             | 900                       |

According to table 3, the equipment cost of time lighting mode and high lighting mode is same, but the electricity saving of time lighting mode is more about 70,000 CNY per year. The equipment cost of time lighting mode is less about 24,000 CNY than adaptation luminance lighting mode, and the lifetime of LED is about 5 years under normal utilization, the electricity saving of adaptation luminance lighting mode is more about 22,000 CNY than time lighting mode per year. The equipment cost of automatic lighting mode and combined lighting mode is more about 7,000 CNY than adaptation luminance lighting mode, and the lifetime of LED is more than 2.5 years under the utilization of frequent adjusting. The electricity saving of automatic lighting mode and combined lighting mode is more about 20,000 CNY than adaptation luminance lighting mode per year.
Combined lighting mode and automatic lighting mode are preponderant than other control modes in energy-saving, and they can repay the equipment costs in lifetime of LED. So, tunnel lighting intelligent control system use combined lighting mode or automatic lighting mode is worthy.

3.2. The effect of length of tunnel

For tunnel lighting intelligent control system, the energy-saving depends on the luminance level of LED lamps. So, the result of energy-saving is upon the lighting time using the minimum level directly. In order to display the lighting time using the minimum level intuitionistic, the formula to forecast the time is inferred. The lighting time using the minimum level is the time that there are no vehicles in the tunnel. So the lighting time using the minimum level in one hour (called \( t \)) is equal to 60 minutes minus the time that there are vehicles in the tunnel. For a vehicle, the lighting time using the minimum level is the length of tunnel (called \( L_{\text{tunnel}} \)) divided by the speed of vehicle (called \( v \)). In order to insure the lighting luminance level is high when the vehicle is in, the sensors are situated in 500m front of the entrance of the tunnel. So, the length of tunnel should be added 500m (called \( L_{eq} \)). For real situation in highway tunnel, there are more than one vehicles in the tunnel. So, the time that there are vehicles in the tunnel is not only the time that there is vehicle in the tunnel for one vehicle multiplied by the number of vehicles. It should be multiplied by a coefficient of traffic volume (called \( k \)) again. Above all, the lighting time using the minimum level in an hour is forecasted in (1).

\[
t = 60 - k_i \times N \times \frac{L_{eq}}{v_d}
\]  

(1)

In (1): \( t \) is the lighting time using the minimum level an hour, its unit is minute; \( k_i \) is the coefficient of traffic volume in each period of time, it depends on the length of tunnel and the traffic volume. The value of \( k_i \) are got from the change of (1), \( k_i = \frac{(60 - t) \times v_d}{N \times L_{eq}} \). Other variables can be got from each tunnel. In a whole year, 50 days are chosen randomly in each season. For a certain tunnel, the average value of \( N \) and \( t \) in each hour of the daytime are got. The \( v_d \) and \( L_{eq} \) is certain for a tunnel. So, the value of \( k_i \) can be calculated; \( N \) is the traffic volume in the period of time, its unit is vehicles/hour; \( L_{eq} \) is the equivalent length of the tunnel, its unit is meter, \( L_{eq} = L_{\text{tunnel}} + 500m \); \( v_d \) is the speed of design, its value is 80km/h in HeDa expressway. In this formula, the unit of \( v_d \) should be meters/minute, its value should be 1333m/min in the formula.

According to (1), the lighting time using the minimum level in an hour from 18pm to 18pm morrow is shown in Figure 4. In Figure 4, each figure indicates the different traffic volume. The 5 curves in each figure indicate the different length of tunnel and each curve from top to bottom indicate the increase of length.

(a) Traffic volume is less than 500 vehicles per day

(b) Traffic volume is about 800 vehicles per day
Figure 4. The lighting time using the minimum level in an hour

According to Figure 4, the lighting time using the minimum level is less with the increase of the tunnel length. The lighting time using the minimum level is much more in the daytime (from 18pm to 8am morrow) than at night (from 8am to 18pm) obviously. Especially from 13pm to 14pm, the lighting time using the minimum level is close to 0 minute in the situation of the traffic volume is heavy and the tunnel length is long. So, combined lighting mode and automatic lighting mode used at night is worthy. Combined lighting mode or automatic lighting mode used at the daytime will be discussed.

3.3. The effect of traffic volume

Baishuitan Tunnel, located in Baishan City, China, its length is 2370m. In 9 May, 2017, the traffic volume of Baishuitan Tunnel is 1041 vehicles, and the lighting time using the minimum luminance level under automatic lighting mode in the daytime and night is listed in table 4.

Table 4. The lighting time using the minimum luminance level in Baishuitan Tunnel

| Permutation Time | Daytime 8am -18pm | Night 18pm - 8am morrow |
|------------------|-------------------|-------------------------|
| The traffic volume | 602 vehicles | 439 vehicles |
| The average lighting time using the minimum luminance level per hour | 3 minutes/hour | 16 minutes/hour |
| The average number of times in the minimum luminance level per hour | 6 times/hour | 7 times/hour |
| The shortest time using the minimum luminance level in one time | 3 seconds | 11 seconds |
| The longest time using the minimum luminance level in one time | 35 seconds | 964 seconds |

According to table 4, it is necessary to use automatic lighting mode at night for energy-saving. But it is difficult to save energy by using automatic lighting mode in the daytime. In addition, the frequent adjusting increases lifetime of the equipment and the burthen of the system.

For a tunnel, its length is certain. The traffic volume of the tunnel affects the energy-saving. In order to expound the effect of traffic volume on mode choosing of tunnel lighting control system, the difference of power-saving between automatic lighting mode and combined lighting mode in the daytime is shown in Figure 5. In Figure 5, each figure indicates the different length of tunnel, the areas in each figure indicate the different traffic volume and each area from outside to inside indicates the increase of traffic volume, the x-axis means the lighting time using the minimum level of automatic
lighting mode, the y-axis means the difference of power-saving between the two control mode. With the increase of the traffic volume, the lighting time using the minimum level of automatic lighting mode is less. For each area, the intercepts on y-axis means the maximum and the minimum difference of power-saving in the certain traffic volume, the intercepts on x-axis means the maximum and the minimum lighting time using the minimum level in the certain traffic volume.

(a) Length: < 1000m                                  (b) Length: 1000m-1500m                          (c) Length: 1500m-2000m  
(d) Length: 2000m-2500m                         (e) Length: > 2500m

Figure 5. The difference of power-saving between the two control modes in the daytime

According to Figure 5, the effect of traffic volume is got. The difference of power-saving gets more with the decrease of traffic volume for a tunnel. The lighting time using the minimum level of automatic lighting mode reaches the peak earlier with the increase of traffic volume for a tunnel. On average, the difference of power-saving is 5% between the two control modes, when the lighting time using the minimum level is 1 hour.

When the lighting time using the minimum level is 1 hour, the electricity saving for the different length of tunnel is shown in table 5. According to table 5, the lighting time using the minimum level about 1 hour can save 9,000 CNY per year.

| Tunnel      | Erdaoling Tunnel | Shidaoyan Tunnel | Dongnan Tunnel | Dapuchaihe Tunnel | Zuomutai Tunnel |
|-------------|------------------|------------------|----------------|------------------|-----------------|
| Length (m)  | 810              | 1270             | 1770           | 2250             | 2970            |
| Power saving (kWh/day) | 21.6          | 22.0             | 23.2           | 24.5             | 26.4            |
| Electricity saving (CNY/year) | 7,884         | 8,030            | 8,468          | 8,943            | 13,286          |

So, when the difference of power-saving is more than 5% between automatic lighting mode and combined lighting mode in the daytime, choosing automatic lighting mode is worthy because it has obvious economic effect. When the difference of power-saving is less than 5% between the two control modes, choosing combined lighting mode can increase lifetime of LED lamps and the burden of the system obviously.
The effect of traffic volume, length of tunnel and the extra equipment are all considered, the choosing of tunnel lighting control mode is shown in Table 6.

| Traffic volume per day (veh) | Length range of tunnel (m) | <1000 | 1000-1500 | 1500-2000 | 2000-2500 | >2500 |
|-----------------------------|---------------------------|-------|-----------|-----------|-----------|-------|
| Less than 500               | Automatic                 |       |           |           |           |       |
| About 800                   | Automatic                 |       |           |           |           |       |
| About 1000                  | Automatic                 |       | Automatic  |           |           |       |
| More than 1300              | Combined                  |       | Combined  |           |           |       |

*The “Automatic” means automatic lighting mode, the “Combined” means combined lighting mode.*

4. Conclusions
In this paper, 5 control modes in tunnel lighting intelligent control system are explained based on the existing tunnel lighting intelligent control system. The 5 control modes are high lighting mode, time lighting mode, adaptation luminance lighting mode, automatic lighting mode and combined lighting mode.

Basing on the effect of traffic volume, length of tunnel and the extra equipment, the choosing of control mode is proposed. The difference of power-saving and the formula for forecasting the lighting time using the minimum level are given to choose control mode. When the tunnel is shorter and the traffic volume is less, automatic lighting mode can save more energy and have no influence in lifetime of the equipment. When the tunnel is long and the traffic volume is many, combined lighting mode can ensure the lifetime of the equipment and the burden of the system, on this base to save energy. When the tunnel is longer and the traffic volume is more, adaptation luminance lighting mode can decrease the extra equipment to save cost of system.

Acknowledgments
This paper was supported in part by the National Natural Science Foundation of China under Grant 61701069. This paper was supported in part by the Fundamental Research Funds for the Central Universities of China under Grant 3132016351 and 3132018189.

References
[1] Qin Li, Lili Dong, Wenhai Xu and Lidong Zhang 2017 A “vehicle in, light brightens; vehicle out, light darkens” energy-saving control system of highway tunnel lighting *Tunnelling and Underground Space Technology* **66** (2017) 147–156
[2] Guide for the lighting of road tunnels and underpasses CIE No.88,1990,ISBN3-90-743-259
[3] Beka, M.C. 2005 A study on tunnel lighting *J. Light. Des* **6** (2005) 10–16
[4] S Nagai, S Ishida, M Shinji and K Nakagawa 2005 Energy-saving lighting system for road tunnel *Underground Space Use: Analysis of the Past and Lessons for the Future – Erdem & Solak* 04 1537459
[5] L.M. Gil-Martín, A. Peña-García, E. Hernández-Montes and A. Espín-Estrella 2010 Tension structures: A way towards sustainable lighting in road tunnels *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research* **26** (2010) 223-227
[6] Sonjia H M Leung 2012 LED Lighting Application in Long Railway Tunnels *HKIE Transactions* **10** (2012) 42-46
[7] Dandan Li 2013 Research and Implementation of Tunnel Lighting Intelligent Control System *Value Engineering* **32** (2013) 102-103
[8] Qiang Yang, Bo Liang, Guo Bing Pan, Shi Yong He, Wei Chen, Xiao Yu Dang and Zhi Wei Wu 2014 Research on Layout of Measurement Points in Tunnel Lighting *Experiment Applied Mechanics and Materials* **580** (2014) 1024-1028
[9] Li Shuguang 2015 An optimal model for tunnel lighting control systems *Tunnelling and*
Underground Space Technology incorporating Trenchless Technology Research 05 (2015) 328-335