A “vehicle in, light brightens; vehicle out, light darkens” energy-saving control system of highway tunnel lighting

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ABSTRACT

In order to meet the requirements of traffic safety and energy-saving in tunnel, a “vehicle in, light brightens; vehicle out, light darkens” energy-saving control system is proposed. The tunnel lighting control system is designed based on “Guidelines for Design of Lighting of Highway Tunnels (China)” (JTG/T D70/2-01-2014). Firstly, when the approach of a vehicle is detected by the vehicle detectors, the demand luminance of tunnel interior is calculated based on changes of tunnel exterior environmental luminance, traffic volume and vehicle speeds. Then the actual luminance is calculated based on road surveillance images, the incremental PID (Proportional-Integral-Derivative) method was adopted to ensure the actual luminance meet the requirements of tunnel lighting. Further, when there are no vehicles in tunnel, the LEDs will be adjusted to their minimum electric energy consumption. The operation results show the tunnel lighting control system contributes to reduce electric energy consumption.

1. Introduction

Tunnels are the important sections of highways, and they have the special lighting circumstance. When the drivers arrive from the external environment to the tunnel, an alternate changing process of “bright-dark-bright” can be caused, and the “black hole effect” (Beka, 2005) and “white hole effect” (during the day, when drivers are close to tunnel exit, the tunnel exit appears to be a bright hole because of the high luminance of the tunnel exterior (Qin et al., 2015; Li, 2015), we call this phenomenon “white hole effect”) phenomenon can be generated. These changing process and phenomenon may directly affect driving safety (Roberts et al., 2016; Yeung and Wong, 2014). Tunnel lighting is essential for the normal operation of road tunnels, and its main objective is to create a favorable visual environment for drivers and to ensure visibility for the sight stopping distance.

In the special environments of tunnels, tunnel luminaries must be lit in order to ensure the driving safety. And in the central and western regions of China, most tunnel lighting systems have a low traffic flow, especially at night till midnight. However, the lighting in tunnels operates continuously (24 h a day and 365 days a year) (Gil-Martín et al., 2014) regardless of the existence of vehicles in the tunnel, which can cause the high lighting energy consumption. How to balance operating costs and the tunnel lighting is a highlight issue that the transportation department has to be concerned with.

In this paper, we propose a “vehicle in, light brightens; vehicle out, light darkens” energy-saving control system that ensures traffic safety and saves the energy of tunnel lighting significantly.

2. Lighting literature review

In order to reduce energy consumption and related costs in road tunnels, various technologies and methods are proposed by many researchers around the world. Methods can be divided into several categories as listed below.

The first category means using sunlight via shift of the threshold zone out of the tunnel. Peña-García and Gil-Martín (2013) set a pergola just before the portal gate of the road tunnel. Gil-Martín et al. (2011) placed a semi-transparent tension structure just before the entrance of the tunnel allowing natural light to pass. Peña-García et al. (2010 and 2011) provided an optimization model of tension structure in terms of light distribution. Gil-Martín et al. (2015) proposed a new method introducing a diffuser material in the space between beams of the pergola to save energy in the electrical lighting. Abdul Salam and Mezher (2014) introduced a construction method to reduce the sunlight levels at tunnel portals using shading structures. Drakou et al. (2015) placed a daylight “filter” structure before the tunnel’s portal to reduce...
the energy consumption.

The second category means decreasing the lighting level requests. Peña-García et al. (2015) presented the method to decrease the $L_{20}$ (which determines the lighting requirements in tunnel) by means of planting the climb plants on the surroundings of the tunnel portal gate, achieve the lowest consumption from the lighting installation. Salata et al. (2015) used a new type of special asphalt (with a higher reflection coefficient) for road paving than other ordinary asphalts. The higher reflection coefficients ensures the same lighting results on the usable surfaces while using lower luminous flux systems, consuming less electric energy.

The third category is introducing sunlight as light source inside tunnel. Qin et al. (2015) introduced sunlight inside the tunnels. The system used the optical fiber lighting for enhanced lighting in highway tunnel, which can significantly reduce the energy consumption of tunnel lighting, environmental pollution and the maintenance costs of lighting facilities. Besides, Lu et al. (2015) used solar LED lighting for tunnel basic lighting and emergency lighting. However, the solar tracking device and optical fiber lighting system were relatively expensive, which were the major reasons affecting the application and popularization of the solar energy lighting system.

Another category is using the latest highly efficient light sources and adjusting the luminance of tunnel luminaries with intelligent control system. The method can provide tunnel interior luminance as needed and avoid wasting energy. Since the intelligent dimming system has been used in tunnel lighting, tunnel lighting control methods can be divided into two categories: one is the logic switch control method (in which the different combinations and permutations of tunnel luminaries are used to achieve required lighting luminance and its merits are flexible luminaries selection, easy maintenance and simple circuitry design, but its uniformity of luminance is not good enough and tunnel interior luminance can’t adjust along with exterior luminance), which is adopted in most current tunnel lighting control systems (Guo and Lang, 2009); another control method of tunnel lighting is stepless control method (which can realize continuous adjustment of tunnel lighting luminance based on dimming controllers and is an ideal control model with the consideration of energy saving. So the luminance of tunnel interior can achieve dynamic change along with the exterior luminance, traffic volume and vehicle speed). Tunnel lighting aims to ensure drivers’ safety and comfort during both daylight and nighttime conditions, it is also the largest energy consumption unit in the tunnel’s engineering; various technologies and methods are employed to reduce energy consumption in road tunnels.

Nagai et al. (2005) and Huang and Luo (2006) used manual and sequential control methods to control road tunnel lighting system to minimize electric power consumption amounts. However, the previous studies turned on the tunnel luminaries in a 100% luminance level when there were vehicles passing through the tunnel.

Carni et al. (2013) proposed an intelligent control to operate and tune automatically the luminous flux emitted by the lighting system according to the input signals of the external luminance, the climate condition and the traffic intensity. However, this method was not implemented in a real tunnel to analyze the effect of energy-saving. Yang and Wang (2010) presented the tunnel energy-saving technology from tunnel luminaries’ layout, tunnel luminaries’ selection, lighting control methods and lighting system maintenance, and introduced several intelligent control methods for saving energy in tunnel lighting system. However, the method hadn’t been deployed in the real tunnel to show any practical limits.

Li (2015) presented a nonlinear tunnel lighting optimal control model in considering traffic safety and energy-saving problems, and meeting the demand luminance, total average luminance and minimum dimming ratio constraints. Zeng et al. (2011) designed a fuzzy control algorithm for tunnel lighting energy control systems, the results showed that energy conservation system provided sufficient lighting levels for traffic safety. Yang et al. (2011) adopted a fuzzy method to design the tunnel lighting control system, which was established with tunnel exterior environment luminance, traffic volume and vehicle speed information as inputs, the results showed that the fuzzy system had a notable energy-saving effect and nice adaptability. However, previous studies could not consider to dim tunnel luminaires when there are no vehicles in tunnels, which can effectively eliminates excessive lighting to reduce energy use, especially for low traffic tunnel.

Recently, a big interest in LED lamps has given rise to a new lighting system in the tunnel. LED is a new, green lighting source, and it requires less maintenance, provides high brightness to drivers, has high color rendering index, starts up faster, provides better safety perception to drivers, uses less energy and the LED current can be adjusted continuously (He et al., 2010; Mao et al., 2008). However, the persistent controversy about the use of LED in the threshold zone is existence, because of the number of luminaires in threshold zone (its required luminance value is directly related to exterior environmental luminance) needed would be huge. In order to avoid an excessive number of LEDs used in threshold zone, many researchers used a mixture of High Pressure Sodium Lamps and LED (Salata et al., 2015), which caused the problem of strange color of the lighting. Although the LED devices are expensive than High Pressure Sodium Lamps, which will increase the installation costs, they will produce financial savings for their lower management costs. Furthermore, the use of LED luminaries in tunnels will give the drivers a visualization of the alignment of the tunnel, thus giving the driver more comfort. Besides, LED luminaries will increase the safety distance between oncoming vehicles (Flø and Jensen, 2007). In the present situation, although the mixture use of High Pressure Sodium Lamps and LEDs and only LEDs used in threshold zone of road tunnel are existed. Many road tunnels in China adopt LED as the tunnel lighting source because of its many advantages.

3. Materials and methods

3.1. Structure of tunnel lighting control system

The structure block diagram of tunnel lighting control system is shown in Fig. 1. The control system is divided into three layers: data process and display layer, data communication layer and data acquisition layer. The first layer is data process and display layer, including lighting control software, which is used to calculate the demand luminance of each section of the tunnel, send dimming command to LED dimming controller to adjust the LED luminaries’ output power, implement lighting electricity statistics, show the lighting conditions of each section of the tunnel, and implement the maintenance management of luminaries. The second layer is data communication layer that consists of local and remote optical transceiver and passes the data collected from the detectors to the lighting control software, and then sends the control commands to LED dimming controller through the RS-485 bus. The third layer is data acquisition layer, realizing the data acquisition, directly collecting traffic speed, traffic volume, exterior luminance and surveillance images information by vehicle detectors, luminance meter and surveillance cameras disposed in the tunnel entrance or interior. LED luminaries’ power is adjusted through the LED dimming controller.

3.2. Structure of tunnel hardware system

The proposed “vehicle in, light brightens; vehicle out, light darkens” energy-saving tunnel lighting control system employs the Chibai Tunnel (right hole) in Tonghua City, Jilin Province of China as an example. Fig. 2 gives the hardware layout diagram of tunnel lighting control system. The hardware system mainly consists of vehicle detectors, luminance meter, surveillance cameras (C1, C2, ..., CN), LED dimming controller (DC1, DC2, ..., DCN), the optical fiber network, lighting control software and the control server operated in the tunnel opera-
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