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An optimal model for tunnel lighting control systems

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ABSTRACT

We present a tunnel lighting optimal control model in considering traffic safety and energy-saving problems. Firstly, the demand brightness function with relation to tunnel exterior brightness, traffic flow and speed is described. Then an actual tunnel brightness curve is derived according to lamp equipment layouts and lamp properties in tunnels. Further, a simple method is used to determine an average brightness indicator in tunnels. We present a nonlinear optimal control tunnel lighting model in meeting the demand brightness, total average brightness and minimum dimming ratio constraints and so on. Finally, the simulation results at the JiangBeiLing tunnel of Wenzhou city in China show the optimal control system can meet the demand brightness and total average brightness constraints, and have a notable energy-saving effect.

1. Background

A tunnel as a special section of highways, which can cause the brightness differences between a tunnel interior and exterior, can reduce road capacity and influence traffic safety. A tunnel lighting system can create a better vision environment and reduce the "black hole" and "white hole" phenomenon as much as possible, and then can improve traffic safety and smooth tunnel traffic (Mashimo, 2002). According to the tunnel lighting design standards in China, a tunnel lighting system can be divided into several parts such as entrance zones, transitional zones, basic zones and exit zones and so on, Furthermore, according to the maximum environmental luminance of tunnel exteriors, the maximum expected traffic volume and maximum driving speed, lamp power and number for each zone in a tunnel can be designed. However, the tunnel lighting system can lead to a serious waste of energy.

In China, a simple logic switch control method is usually adopted in a tunnel lighting system for energy-saving purposes, however, can result in poor continuity and uniformity of luminance in a tunnel, and then may influence the driving safety. In this paper, we present an optimization algorithm for tunnel lighting control systems that ensures traffic safety in tunnels and saves the energy of tunnel lighting greatly.

2. Literature review

Cunningham and White (1970) proposed an operational vehicular tunnel traffic flow control system. In order to avoid accidents in a single lane tunnels, Patnaik et al. (2014) used an automatic traffic control system to control the traffic density on a single lane tunnel. However, the method given by Cunningham and White (1970) and Patnaik et al. (2014) did not consider the effect of the tunnel lighting system.

Hagras et al. (2008) presented used intelligent real time control to minimize building energy use. Cziker et al. (2007) used a fuzzy control for illumination control considering the impact of various parameters on the illumination level. Mitsunori et al. (2013) presented a Linear Programming method for intelligent lighting systems. However, the previous studies given some illumination control methods which do not fully consider the case of the tunnel.

In order to reduce the operating costs of tunnel lighting systems, Yang and Wang (2010) introduced the energy-saving technologies of tunnel lighting from tunnel lighting luminaire selection, lighting luminaire layout, lighting control technologies and system maintenance, and emphasized to improve lamp control performances and use new control methods for saving energy in tunnel lighting systems. Carni et al. (2013) presented a smart control method based on switching mode to operate the tunnel interior luminance according to the input signals of the external luminance, the climatic condition and the traffic flow. Currently, control methods of tunnel lighting systems can be divided into two categories: one is a logic-switch control method to turn on or off lamps in a tunnel. Although the method can reduce energy consumption, the continuity and uniformity of luminance in tunnels can become poor, and the tunnel lighting specifications cannot be satisfied.

Another is a stepless control method that uses electronic ballasts to control lamps in a tunnel. Huang et al. (2006) used a fuzzy

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logic control method to make actual luminance close to the demand luminance in a tunnel. Zeng et al. (2011) presented a LED-based tunnel lighting control system. Yang et al. (2011) adopted a fuzzy control method to design the tunnel lighting control system, the simulation results showed a notable energy-saving effect and nice adaptability. However, previous studies ignored the relationships among actual lamp layout, lamp power regulation and tunnel luminance. That is to say, the methods could not really achieve the energy-saving targets in considering traffic safety.

3. Tunnel lighting optimal control method

3.1. Structure of tunnel lighting control system

Fig. 1 gives a tunnel lighting control system architecture. The system includes three layers; the lower layer is a lamp control layer, directly controlling lamps in a tunnel by electronic ballasts. The middle layer is a PLC-based control layer that can collect traffic volume, vehicle speeds and environmental luminance information by traffic and light detectors, receive the control commands of the upper-layer computers, and then send control commands to electronic ballasts through the RS-485 bus. Furthermore, according to the data of the middle layer, tunnel lighting control system software on the upper layer can use an algorithm to calculate an optimal strategy, and implement the maintenance management of lamps in tunnels and so on.

3.2. Tunnel lighting optimal control algorithm

Fig. 2 gives a tunnel lighting optimal control algorithm procedure. Firstly, environmental luminance, traffic volume, and vehicle speed can be collected by PLC controllers. Secondly, according to the data and "Specifications for the Design of Ventilation and Lighting of Highway Tunnels (China)" (JTJ, 2000), a tunnel interior demand brightness curve can be calculated. Thirdly, an optimal control algorithm is presented to determine optimal lamp control strategy in a tunnel in considering some constraints such as actual tunnel interior brightness constraints, tunnel interior total average brightness constraints and tunnel interior centerline brightness constraints. Finally, the optimal lamp control strategy in a tunnel is outputted.

3.2.1. Tunnel interior demand brightness

According to the CIE (Commission International d'Eclairage) technical report, Ishimura (2004), Beka (2005) described variety vision problems in tunnels. Leitao et al. (2009) used a Genetic Algorithms for the design of road tunnels lighting systems, which guarantee minimal luminance values within tunnels in order to ensure a easy driving problem. Martirano and Parise (2010) presented a structured architecture of tunnel lighting system complying with electrical loads extensively distributed and with installation requirements proper to external stresses. Parise et al. (2013, 2015) proposed a fit distribution system and an adaptive criterion for the tunnel lighting system in order to minimize costs and energy impact. Due to different lamp equipment layouts in tunnels and tunnel lengths in China, many methods can be used to calculate a demand brightness curve in tunnels. In this paper, for simplicity we use the method presented by Fan and Li (2011) to calculate an interior demand brightness curve under a two-row tunnel lamp equipment layout mode in long tunnels. Fig. 3 gives a longitudinal section of a long unidirectional tunnel, enhanced the longitudes and levels of brightness in different zones. From Fig. 3, a tunnel lighting system can include threshold zones, transitional zones, interior zones, exit zones in a long tunnel. From Fig. 3, step light level formed by threshold and transitional zones at the beginning of tunnels during the daytime can compensate for the "Black Hole Effect" that occurs by the tunnel structure

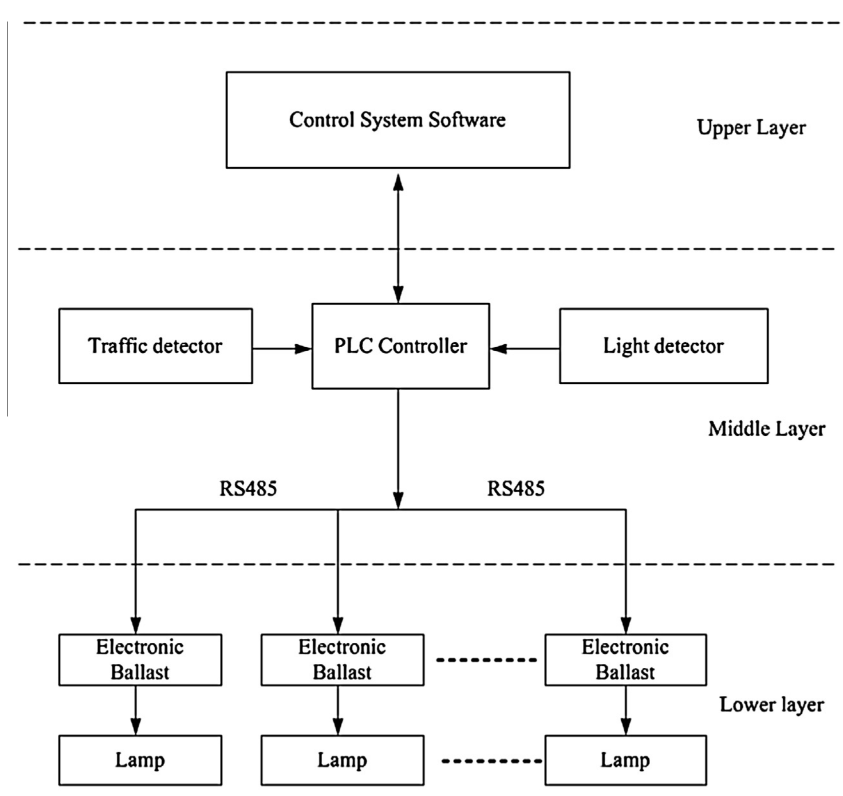

Fig. 1. Tunnel lighting control system architecture.