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The SLT equation: A tool to predict and evaluate energy savings in road tunnels with sunlight systems

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ABSTRACT

The high economical and environmental impact of tunnel lighting has led to the proposal of a wide variety of strategies to use sunlight in these infrastructures. However, the choice of the most accurate strategy for each tunnel requires reliable tools to evaluate its efficacy and estimate the potential savings before real implementation in order to decide whether it is really interesting and profitable. In spite of the increasing number of ways to complement electrical lighting with sunlight during daytime, the only way up to date to really foresee which one is better for one given tunnel is the use of mockups or simulations that cost time and money. In this work, a general equation based on physical considerations and covering a vast variety of situations is presented. The deduction of the equation departs from the two main philosophies proposed or implemented up to date and converges in one general expression which is applied to some examples.

1. Introduction

The high consumption of the lighting installations in road tunnels, mainly during daytime, is a major problem with difficult solution. This consumption is especially critical in the first part of the tunnel, the threshold zone. The energy consumption in this zone can be about 45–50% of the total energy consumed by the lighting installation (Dzhusupova, 2012). This is due to the necessity of high illuminance levels (luminous flux received per unit of surface) to avoid the impairment in the visual performance of drivers when going from bright to darker environments. The visual adaptation of drivers is ensured as long as the road luminance (luminous flux reflected per unit of solid angle and surface in one given direction, and directly related to the illuminance on the road) does not decrease below some given ratios when compared with the luminance in the surroundings of the portal gate (CIE Publ. 88, 2004; Mehri et al., 2016). In addition, the dependence of the necessary levels of illuminance on variables such as maximum speed, tunnel location and orientation, optical properties of the elements around the portal, time of the day, season of the year, weather conditions, traffic intensity and human factors of drivers, makes the lighting of each tunnel an almost unique problem, whose solution is expensive in energy consumption and environmental impact.

The strategies to decrease this high consumption include the reduction of luminic requirements, like specific road pavements or luminaires (Salata et al., 2015, 2016; Moretti et al., 2016), special forestation of the portal surroundings (López et al., 2014; Peña-García et al., 2015) and the use of sunlight to partially decrease the electrical power consumption. It is necessary to highlight that, in general, all these ways to save energy are compatible among each other.

1.1. Use of sunlight in road tunnels

One of the most common strategies to use sunlight in tunnels has been the partial shift of the threshold zone, which is the most consuming one, out of the tunnel. It can be implemented by covering the shifted zone with a semi-transparent tension or stiff structures (Fig. 1) that allow some sunlight pass (Gil-Martín et al., 2011; Abdul Salam and Mezher, 2014).

Given the positive results of the first attempts, the subsequent research was devoted to optimize the shape of tension structures to improve their performance (Peña-García et al., 2012) and fit the main photometrical parameters (luminance, illuminance and uniformity) on the road to the requirements of standards like CIE Publ. 88, 2004 or national regulations.

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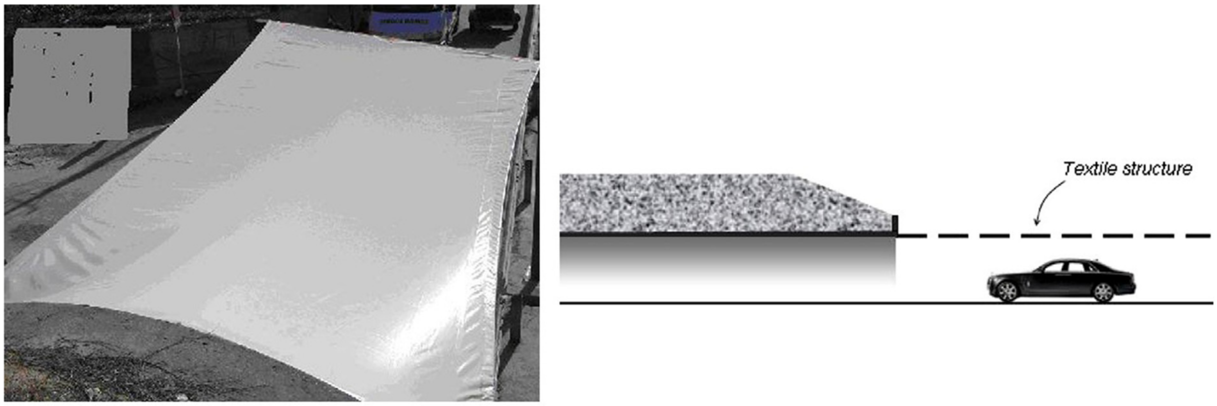


(a) (b)

Fig. 1. (a) Semi-transparent tension structure of polyester set before the tunnel gate. (b) Scheme of threshold zone shift with tension structures (Gil-Martín et al., 2011).

The use of tension structures has the advantage of an excellent illuminance uniformity on the road below the structure. This avoids the traditional problem of flickering that may lead to loss of concentration in drivers inside tunnels.

Nevertheless, the use of tension structures presents some problems like difficult maintenance or their lack of stiffness to support loads of snow, stones falling from the mountain etc. This disadvantage led researchers to consider more robust options to shift the threshold zone with easier maintenance. Among these options, pergolas, traditionally used to support roads crossing above others obliquely, achieved optimal average illuminances on the road. Departing from this premise, the equations of illuminated and shaded areas on the road under pergolas was developed and the most optimal separations between the beams of pergolas calculated (Peña-García and Gil-Martín, 2013). However, the shift with pergolas alone causes very poor uniformity on the road due to the succession of dark and bright zones. It may cause flickering effect and seriously impairs a correct perception of potential obstacles on the road. This problem can be solved with the installation of diffusers in the gaps between the beams with very satisfactory results (Fig. 2) (Gil-Martín et al., 2015).

Besides traditional pergolas, other interesting rigid structures type filter have been proposed to shift the threshold zone of tunnels and use sunlight in their first meters with remarkable energy savings (Drakou et al., 2015, 2016; Wang et al., 2015).

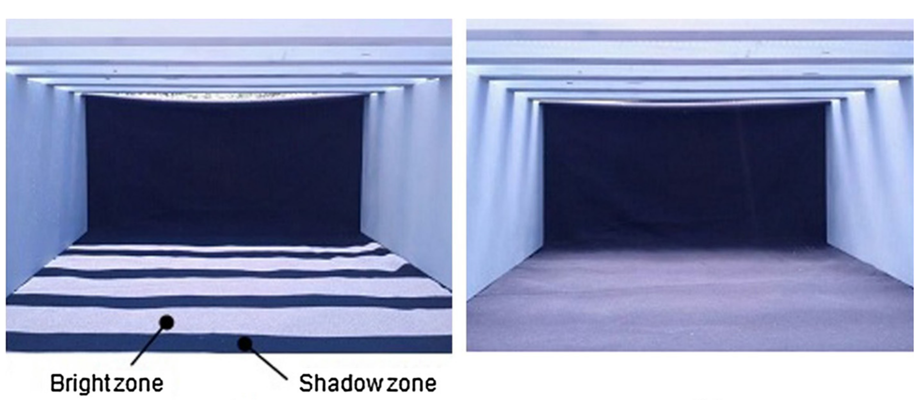
On the other hand, other strategies have been considered to introduce sunlight inside the very instead of enlarging it. Thus, guiding structures based on optical fibers (Qin et al., 2015), light pipes alone (Gil-Martín et al., 2014) or coupled to external heliostats (Peña-García et al., 2016) have been implemented or proposed with good results. Although the use of light pipes to introduce sunlight in buildings had been previously used in other fields (Al-Marwaee and Carter, 2006a, 2006b; Carter, 2002; Wachenfelt et al., 2015; Pacheco-Diéguez et al., 2016), it had not been proposed for road tunnels previously.

In summary, the use of sunlight in road tunnels is becoming a field of maximum interest, where different research groups around the world are proposing challenging alternatives. However, the lack of reliable, quick and cheap tests and trials to decide which strategy is the best in each case, makes their real implementation difficult. For this reason, most of the studies above are based on computational simulations, mock-ups and other approximations.

1.2. The ESTS equation

Some years ago, when the shift of the threshold zone was mostly performed with semi-transparent tension structures, a new tool to decide the most optimal one in terms of shape, material and other parameters was provided by Peña-García et al. (2011).

The Energy Saving under Tension Structures (ESTS) equation evaluates the ratio between the electrical consumption in a threshold zone shifted by a semi-transparent tension structure and the consumption if the zone is not shifted.



(a) (b)

Fig. 2. Pergolas without (a) and with (b) diffuser between the beams. The diffuser material in (b) is Polymethyl Methacrylate, PMMA (Gil-Martín et al., 2015).