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Determination of lighting and energy demands of road tunnels using vehicle based photographs of the portal gates: An accessible and safe tool for tunnel renewal and maintenance

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ABSTRACT

Strategies to make the lighting installations of road tunnels more sustainable constitute a challenging line of research due to the difficulty of decreasing consumption and use of raw materials without impairing traffic safety. The first challenge when designing or optimizing these installations arises at the tunnel access, where the lighting requirements of the whole infrastructure must be determined as a function of several characteristics of the tunnel and its surroundings. This is the determination of the L20 luminance, that nowadays is still controversial due to the important differences between the methods established by the standards and regulations and the technical difficulties to implement them. In this work, a simple and safe method to easily calculate the L20 luminance in tunnels already open to traffic without expensive instruments nor risks for operators is presented. The equations to determine the radius of the L20 cone basis are developed and the potential errors analyzed. Some examples illustrate the methodology and validate it.

1. Introduction

Road tunnels are critical infrastructures due to their impact in terms of safety, traffic flow, landscape integration, construction and maintenance costs, energy and materials consumption.

Most of the energy consumed in road tunnels is due to their lighting installation, which works 24 h a day, 365 days a year. The consumption during daytime along the first zone of the tunnel (the threshold zone) is especially remarkable because the adaptation of the driver eye when going from very bright environments to darker ones is too slow (CIE Publ. 88, 2004; Mehri et al., 2016). Hence, the only solution to avoid visual impairment on drivers is to provide high levels of illuminance (luminous flux received per unit of surface) on the road and walls. This way the pavement reflects a high luminance (luminous flux emitted by unit of surface and solid angle in one given direction), and drivers can perceive the limits of the tunnel.

However, it means that public administrations must face a serious problem when planning new tunnels or improving obsolete ones: high illumination levels during daytime together with an accurate uniformity are absolutely necessary to ensure traffic safety, but the impact on energy consumption, raw materials needs and maintenance is millionaire. Furthermore, the environmental impact of such needs is also remarkable and incompatible with the current efforts in matter of sustainable development (WCED, 1987). Due to these difficult situations, research to maximize energy savings and sustainability of road tunnels installations has become an active line of work in the last years (Dzhusupova, 2012; López et al., 2017; Molina-Moreno et al., 2017).

In particular, some research has been orientated to the decrease of energy demands through the reduction of the luminic necessities. Hence, asphalts (Salata et al., 2015; Moretti et al., 2016, 2017) and surroundings (López et al., 2014; Peña-García et al., 2015) with the accurate reflectance have been sought and are under considerations for implementation in different countries.

On the other hand, and not excluding these strategies to decrease lighting demands, the target of other lines of research is the regulation of the luminous flux from the electrical lighting (Wang and Zhou, 2009; Salata et al., 2016) and the use of sunlight to complement the electrical illumination. These last have considered the shift of the first and most consuming zone of the tunnel (so called threshold zone) with different kind of transition structures allowing sunlight to pass, like pergolas (Peña-García & Gil-Martín, 2013; Gil-Martín et al., 2015) and other kind of structures including textile and other materials (Gil-Martín et al., 2011; Peña-García et al., 2011, 2012; Abdul Salam and Mezher, 2014; Wang et al., 2015; Drakou et al., 2015; Drakou et al., 2016; 2017;

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Cantisani et al., 2017a; 2017b). Another way to use sunlight in road tunnels has been the direct injection with light-pipes (Gil-Martín et al., 2014; Peña-García et al., 2016) or optical fibers (Qin et al., 2015).

The increasing literature on the topic shows the importance of energy saving in road tunnels and the remarkable efforts to achieve this objective, that have led even to the formulation of general models and tools to predict the effects of different strategies to save energy in road tunnels (Peña-García, 2017).

The first point to achieve optimal energy consumption without impairing traffic safety is a correct evaluation of the required levels of luminance. The Commission Internationale de l'Éclairage (CIE) establishes two different methods to calculate this luminance in the different zones of tunnels (CIE Publ. 88, 2004): the perceived contrast method ("L_{seq} method") and the "L20 method". In this work the L20 method, which is simpler and less tidy, will be used because the features of the L_{seq} method do not impact on the way to obtain the images of the portal gate. Further information about the L_{seq} method can be found in the cited CIE standard.

The L20 method consists on the determination of the luminance reaching the driver's eye on a cone with aperture 20° (2 × 10°) when approaching the tunnel entrance from the safety distance (SD). This is the L20 luminance. According to the international standard CIE 88:2004 (2004), the L20 can be measured with a special luminance meter or calculated from the luminance of the portal surroundings inside the cone of 20°. This second option requires one photograph of the portal gate taken from SD at the height of 1.5 m on the road and the tables provided by the CIE. The basis of the L20 cone is drawn on the photograph (Fig. 1, a and b). The visual axis of the luminance meter or camera must be orientated towards one point at the centre of the gate at a height $0.25H_{tun}$, where H_{tun} is the portal height.

Hence, the L20 method requires in site measurements or photographs. Given the high variability of the weather conditions and natural illumination levels along the year, the use of photographs and CIE tables is more exact than the luminance measurement.

Once L20 is known, the luminance levels in the different zones of the tunnel are given by CIE 88:2004 and each national regulation. In all the cases, these luminance levels depend on L20, and they are provided by the electrical lighting installation with a very high energy consumption. Table 1 shows this relationship between L20 and the luminance required in the threshold (L_{th}), transition (L_{tr}), interior (L_{in}) and exit (L_{ex}) zones.

However, taking precise photographs exactly from SD at the centre of the road in working tunnels is almost impossible due to the danger for operators and drivers, especially in roads with high traffic flow. Hence, one of the most used approaches is to take the photograph setting the camera in the road shoulder with the resulting imprecision whereas a remarkable risk for operators remains.

For this reason, the estimated needs in terms of luminance in working tunnels for maintenance or renewal operations, such as replacement of conventional Sodium light sources by LED is, in most of the cases, coarse and over or underestimated.

Table 1
Luminance in each zone of the tunnel. Factor "k" relating L20 and the luminance in the threshold zone, depends on the maximum speed allowed in the tunnel.

ZONE		LUMINANCE
Threshold	1st half	$L_{th} = kL_{20}$
	2nd half	Progressive decrease down to 0.4 L_{th}
Transition		Progressive decrease down to 0.14 L_{th}
Interior		1–10 (cd/m^2)
Exit		5 L_{in}

In this work, an accessible and easy method to precisely calculate the L20, energy consumption and number of necessary luminaries without impairing the safety of workers and drivers, is proposed.

2. Materials and methods

Nine real tunnels in different locations of Spain have been taken as model to validate the proposed methodology. From these, six are located in the Trans-European highway A7 (Andalusia, South of Spain), two more in the National highway A6 (Galicia, North of Spain) and another one in the AS15 highway (Asturias, North of Spain). Their locations are shown in Fig. 2.

This choice seeks the widest variety in the levels of natural illumination before the portal gate (access zone), which highly influences the luminance levels required in each tunnel: the daylight levels in the Southern Spain are very high during the whole year whereas moderate or low in the Northern regions of the country.

The method chosen to calculate the luminance requirements of these tunnels and, hence, the parameters of the lighting installation is the "L20 method" described in international standard CIE 88:2004 (2004).

As described in Introduction, according to the international standard CIE 88:2004 (2004) and most of the national regulations, the luminance in the L20 cone and the tunnel sections is calculated from one photograph of the portal gate taken from SD at a height of 1.5 m over the road surface. The visual axis of the camera must be orientated towards one point at the centre of the gate at $0.25H_{tun}$.

The danger of taking photos under such controlled conditions in tunnels already open to traffic, impairs the precise calculation of luminance requirements and exact adaptation to the changing conditions of the portal surroundings for maintenance operations or renewal projects. For this reason, the present research demonstrates that arbitrary photos of the portal gates, taken even from moving vehicles, can provide the required parameters in an easier and cheaper way.

The photos of their portal gates used in this research have been

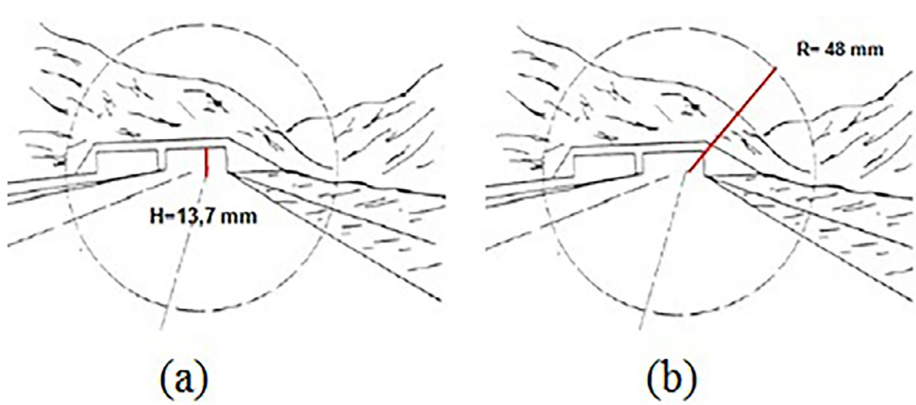

Fig. 1. Basis of the L20 cone (a) and its radius (b) on a picture of the portal gate (adapted from Fig. A.1.1 (CIE Publ. 88, 2004)).