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Decrease of energy demands of lighting installations in road tunnels based in the forestation of portal surroundings with climbing plants

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ABSTRACT

The lighting installations demand the biggest part of the energy consumed in road tunnels. This demand is much higher during daytime, when the visual adaptation of the drivers coming from bright environments, requests very intense illumination levels, especially in the first part of the tunnel, the so called threshold zone. The lighting necessities in road tunnels depend on three main critical parameters: maximum speed allowed in the tunnel, tunnel orientation and the characteristics of the portal gate surroundings. In this work, actions on this last parameter have been evaluated: four different species of climbing plants have been tested as candidates to forest the surroundings of portal gates in an environment of Mediterranean climate. The lighting demands in the threshold zone arising from the choice of each species have been quantified by luminance measurement. As a result, the common ivy (*Hedera helix*) is proposed as the best candidate to fully forest the surroundings of portal gates optimizing the binomial energy consumption-landscape integration in a Mediterranean climate.

1. Introduction

It is well known that lighting installations demand most of the energy consumed in road tunnels. Paradoxically, the required lighting levels are much higher during daytime (Adrian, 1982; Schreuder, 1971; CIE Publ. 88, 2004). This is due to the slow visual adaptation to darkness of humans. When we develop our visual tasks in bright environments (photopic conditions of vision), the visual process is carried out by the retinal cells called cones. Cones allow a high visual acuity and color perception, but they are completely blind when the illumination levels decrease under a certain threshold. When the visual tasks are carried out in environments with low illumination levels, the visual process is carried out by other retinal cells called rods. Rods allow the detection of faint objects, but are unable to detect colors and cannot work under intense illumination levels. The problem arises when we suddenly go from bright environments to darker ones. Fig. 1 shows the time needed to achieve visual adaptation as a function of the lighting levels.

The analysis of this figure highlights the nature of the main problem in tunnel lighting: when the illumination levels quickly decrease, people are visually unadapted during several minutes. Even a not complete but relatively accurate visual adaptation to low illumination levels takes around 8 min, which is absolutely unacceptable in driving, where, vehicles travelling at 100 km/h, are running 28 m in one single second. It means that any single delay in visual reaction time can cause an accident.

Thus, the illumination levels in road tunnels during daytime (when drivers come from bright environments), must be high enough, especially during the first meters of the tunnel (Mashimo, 2002; CIE Publ. 88, 2004), to ensure a correct visual adaptation. The consequence in this first part of the tunnel, called "threshold zone" (starting in the portal gate and with a length between one and two times the safety distance, that is, 100–200 m) (Adrian, 1982; CIE Publ. 88, 2004) is a huge energy consumption of the lighting installations. Besides the use of the most accurate electrical light sources (Wencheng et al., 2008) and lighting distribution (Pachamanov and Pachamanova, 2008; Yang and Wang, 2010) or special systems to optimize the work of the lighting installation (Ceriotti et al., 2011), the reduction of this consumption, especially in the threshold zone, has become a matter of strong interest and the research has followed two directions.

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There are two ways, compatible among them, to save energy in the lighting of road tunnels:

1. Use of sunlight to complement the electrical lighting, so that the luminaries must not work at 100% during all the daytime. There are two ways to use sunlight in the threshold zone of a road tunnel:
   (a) Shifting the threshold zone out of the road tunnel by means of a semitransparent structure (Hernández-Montes et al., 2006; Gil-Martín et al., 2011; Peña-García et al., 2012) or a pergola (Peña-García and Gil-Martín, 2013). This philosophy requires the enlargement of the tunnel, but allows really remarkable savings in terms of electrical energy, light sources and luminaries with low investments and almost no maintenance in the case of pergolas. It is necessary to remark that shifting the threshold zone does not mean to enlarge the threshold zone (which would be counterproductive), but to displace it in such way that one part of the threshold zone is inside the tunnel and the other part is out of the tunnel, thus making possible to use sunlight by partial transmission through a semitransparent medium (tension structures) or total transmission between alternative opaque elements (pergolas). The use of the ESTS equation (Energy Saving under Tension Structures), also applicable to pergolas, allows us to evaluate the potential savings and even decide the best way to implement the structure before building it (Peña-García et al., 2012; Peña-García and Gil-Martín, 2013).
   (b) Guide and distribution of sunlight by means of optical devices such as light-pipes (Gil-Martín et al., 2014). This way to use sunlight does not require to enlarge the tunnel, but directly introduces and distributes it inside the tunnel. The capitation system and the optimal distribution are currently matters of active research.
2. Decrease the lighting levels requests: according to the CIE recommendations (Onaygil et al., 2003; CIE Publ. 88, 2004), the lighting requirements in one road tunnel are determined by L_{20}. It is the luminance (luminous flux emitted per square meter and solid angle in one given direction, measured in candelas per square meter, cd/m^2) of the surroundings of the portal gate within a cone of 20° measured from the safety distance (see Fig. 2) according to Eq. (1):

$$L_{20} \approx \gamma L_S + \rho L_R + e L_E \tag{1}$$

L_S, L_R and L_E in (1) are the average luminances of sky, road, and surroundings respectively, whereas γ, ρ, and e are the respective

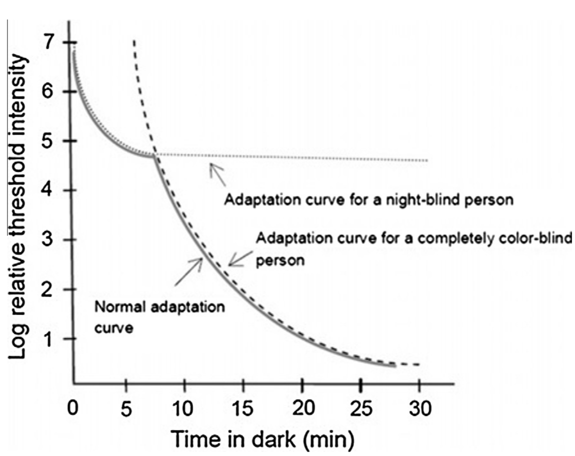

Fig. 1. Adaptation curve from bright to dark environments. From (Peña-García et al., 2012).

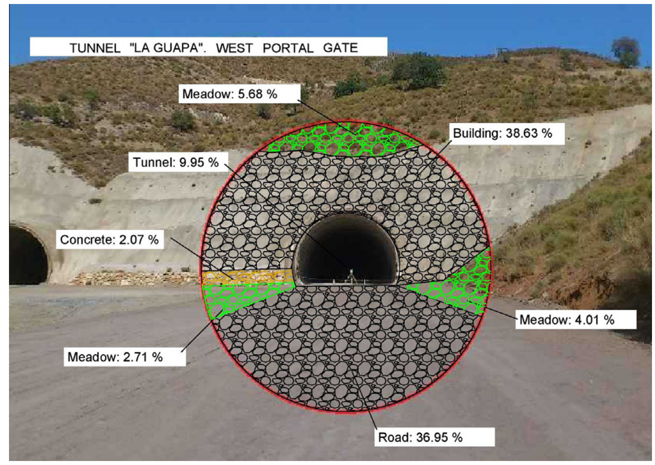

Fig. 2. Cone of 20° seen from the safety distance in a road tunnel in the Southeast of Spain.

percentages of sky, road and surroundings. Note that the surroundings can be very different according to the sunlight reflected (rocks, snow, meadow, buildings…). Thus, the contribution of surroundings to the tunnel lighting (Ye et al., 2012) are always considered according to their nature and have different contributions to the 20° cone as shown in Fig. 2.

The contribution of each zone within the 20° cone to L_{20}, is given in Table 1.

According to Table 1, the introduction of vegetation in the surroundings of the portal gate will remarkably decrease the lighting levels required in the road tunnel whatever its orientation. However, tunnels are generally forested with species that do not fully cover all the surroundings of the portal gate because the nature of the plants used (trees, bushes…) do not easily allow this total covering that would allow the proper consideration of 2 kcd/m^2 (Table 1) for the illumination levels required for the road tunnel. In this work, climbing plants are considered in order to achieve a complete forestation of the surroundings.

L_{20}, which takes account of the lighting conditions before going into the tunnel, is related to the luminance necessary in the first part of the threshold zone (that is, the first zone with electrical lighting), L_{th}, which is the most consuming zone of the tunnel by Eq. (2):

$$L_{th} = k L_{20} \tag{2}$$

where k is a constant depending on the maximum speed allowed in the tunnel. In a tunnel with maximum speed v_{max} = 120 km/h ⇒ k = 0.10, whereas in one tunnel with v_{max} = 80 km/h ⇒ k = 0.06.

The considerations above, together with a careful analysis of Table 1, highlight that an accurate design of the tunnels portal and surroundings is extremely important to decrease the L_{20} and, thus, achieve the lowest consumption from the lighting installation. Hence, the architectural and landscape aspects related to tunnel portals become very important as the awareness of environment protection by designers gives rise to elevated concerns of integrating an infrastructure with its surroundings (Peila and Pelizza, 2002).

On the other hand, the actuation on portal and surroundings to decrease L_{20} gives the designer two different possibilities: to mimic its surroundings or to be signified with prominent works. This difficult choice is summarized by Fei et al. (2012): landscaping tunnel portals is a comprehensive art, involving creativity, landscape architecture, architecture, local culture, bionomics, psychology, environment protection, optical techniques, safety techniques, and the application of new materials and new technical arts.