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Use of sunlight in road tunnels: An approach to the improvement of light-pipes' efficacy through heliostats

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ABSTRACT

A coupled system consisting on a heliostat and a matrix of light-pipes inside one road tunnel where the heliostat injects sunlight, is proposed. Its reliability and efficiency from theoretical calculations and a mock-up, is analyzed as a function of tunnel orientation. The heliostat is fixed above the road some meters before the portal gate of the road tunnels. It continuously seeks the correct orientation so that the angle between sun, heliostat and light-pipes in the portal gate, injects of parallel sunrays every moment. Then, these rays are guided through the light-pipes and distributed on the road in the threshold zone with a remarkable improvement of the efficacy of light-pipes and the relevant savings in electrical consumption and number of luminaries. The results of calculations and measurements on mock-up, that show energy savings above 20% in the most favorable tunnel orientations and 14% in arbitrary orientations, as well as a discussion about the most accurate tunnel orientations are analyzed and presented.

1. Introduction

The energy consumption in the threshold zone of road tunnels is a well-known problem whose potential solutions have become matter of active research in the last years. Due to the long time needed by the human eye to get adapted to lower illumination levels (CIE Publ. 88, 2004; Mehri et al., 2016), the luminance levels (luminous flux per unit of solid angle and surface in one given direction) needed in the threshold zone of the tunnels are really remarkable if compared with other infrastructures (CIE Publ. 115, 2010). They are calculated according to the tunnel orientation, maximum speed and portal surroundings (CIE Publ. 88, 2004; Blaser and Dudli, 1993).

These high levels of luminance, which demand huge electrical consumptions, have led researchers to look for more efficient solutions from four different points of view:

(1) Actuations in the surroundings of the portal to decrease the lighting requirements established in regulations and standards (CIE Publ. 88, 2004). E.g.: the introduction of vegetal species around the portal have led to significant lower requirements in terms of luminance (López et al., 2014; Peña-García et al., 2015).
(2) Actuations inside the tunnel to decrease the lighting requirements and facilitate maintenance by means of more efficient light sources and/or asphalts with better reflexive properties (Salata et al., 2015; Moretti et al., 2016).
(3) Partial shift of the threshold zone out of the tunnel to take part of the sunlight in this zone, which is the most consuming one in the whole tunnel. This shift has been carried out with semi-transparent tension structures (Gil-Martín et al., 2011; Peña-García et al., 2011, 2012), pergolas without (Peña-García and Gil-Martín, 2013) and with diffusers (Gil-Martín et al., 2015) and other kinds of shading or shifting structures (Abdul Salam and Mezher, 2014; Drakou et al., 2015; Wang et al., 2015). The use of diffusers is becoming a key tool to spread and enhance the homogeneity in other infrastructures where the sunlight can be used (El-Henawy et al., 2014).
(4) Introduction of sunlight inside the tunnel with light–pipes (Gil-Martín et al., 2014) or optical fibers (Qin et al., 2015).

Concerning this last strategy, the use of light-pipes similar to periscopes with internal mirrors to introduce sunlight in buildings and closed spaces has been known for ages in other kind of infrastructures where the economical impact of lighting is really remarkable (Al-Marwaee and Carter, 2006a,b; Carter, 2002;

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Nomenclature

Horizontal illuminance, E_H illuminance on one horizontal surface
Illuminance or illumination, E received flux per unit of surface. Unit: lx (lm m^{-2})
Luminance, L luminous flux emitted per unit of solid angle and surface in one given direction. Unit: cd m^{-2}
Luminous flux, ϕ power emitted, transmitted or received as luminous energy. Unit: lumen (lm)
Normal illuminance, E_N illuminance on one plane normal to the incidence of sunrays
Reflectance or reflection coefficient, ρ ratio between reflected and incident luminous flux in one surface
Vertical illuminance, E_V illuminance on one vertical surface

Wachenfelt et al., 2015; Pacheco-Diéguez et al., 2016), but no study had been performed in road tunnels before the work of Gil-Martín et al. (2014), that obtained remarkably energy savings in one mock-up with light-pipes ending in one diffuser to improve light distribution on the road and avoid lack of uniformity and light spots on the road.

In spite of the good results, the biggest problems were the caption of light to be injected and guided through the light-pipes. It is due to major inconveniences like mechanical interferences of the caption system with the own portal gate and with the mountain, the technologies to track the apparent movement of the sun to collect as much sunlight as possible, the coupling among the caption system and light-pipes and maintenance among other.

Concerning the first, there are several ways to introduce sunlight into a given device. Generally, the caption process consists on a first step of light concentration and a second one of redirection. Both can be achieved via refraction (use of lenses changing the direction of the light) or via reflection (use or mirrors for the same purpose). Regarding this second way, it is interesting to consider heliostats as potential candidates for sunlight caption and injection. Heliostats are devices that incorporate one mirror or a set of independent mirrors that reflect sunlight towards one given target, compensating for the sun's apparent motions in the sky.

In this work, a caption system based in the principles of heliostats, is proposed as a solution to introduce sunlight in the light-pipes. Departing from these basis, the amount of light injected in the light-pipes has been calculated considering the angles sun-mirrors-light-pipes in each situation. These angles must be the necessary to reflect the rays from the sun parallel to the walls of the light-pipes installed in the threshold zone of the tunnel (Fig. 1).

The importance of light injection parallel to the pipe wall arises from to two main reasons:

(1) Even in ideal systems, there are looses every time light is reflected on one surface. Hence, if the rays are parallel to the pipes surface, there will be only one reflection in the 45° mirror to descend towards the tunnel (Fig. 1). In the case of skew rays, there would be multiple reflections on the pipe with the subsequent loss in luminous flux.
(2) When rays enter parallel to the axis of the pipe, the 45° mirror reflects them perpendicular to the road (see Fig. 1). Then, one diffuser at the end of the light-pipe distributes the light so that there are no spots on the road. However, if light did not enter parallel to the pipe axis, the 45° mirror would not direct them vertical to the road with a bad uniformity or light spots on the road.

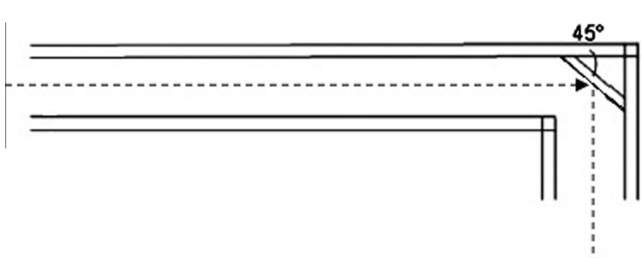

Fig. 1. Rays injected parallel to the light-pipes axis are reflected only once, minimizing looses.

The reason above highlight the importance of one system allowing injection of sunlight in accurate conditions thus improving the efficacy of light-pipes.

In summary, the main objective of this research is to establish the bases for the introduction and distribution of light inside the threshold zone as well as checking the feasibility of light-pipes for this purpose in real conditions. The performance of this system and the potential results in terms of introduced luminous flux and energy savings are presented and analyzed.

2. Materials and methods

Two real tunnels with perfect East-West and South-North orientations respectively have been taken as model to check reliability and performance of future implementations of coupled systems heliostat-light-pipes. The tunnels conditions, as well as the coupled system under consideration, are determined from theoretical data and simulated with a mock-up located in an open air area in the Faculty of Civil Engineering of the University of Granada (Spain).

The mock-up consists on a scale model of a heliostat luminically coupled to two matrixes of light-pipes fixed to the ceiling of a scaled road tunnel. It has two parts:

(1) A scaled tunnel with two matrixes of metalized light-pipes fixed to the tunnel ceiling. The dimensions of the tunnel are: length = 1850 mm; width = 800 mm and maximum height = 360 mm. It is built in coated and painted wood. Every matrix incorporates 12 light-pipes of different lengths over each lane of the tunnel. All the pipes have rectangular cross sections (15 mm height and 20 mm width). Several lengths, from 75 to 1725 mm with an increasing rate of 150 mm, are used in order to introduce and distribute the sunlight beside the theoretical location of each electrical luminary. A 45° tilted mirror properly placed at the end of the pipe allows light to be introduced into the tunnel. A diffuser is fixed in the leakage of each pipe to distribute the guided light inside the tunnel as shown in Fig. 2(a) and (b) (Gil-Martín et al., 2014).
(2) The heliostat, consisting on a rotating 160 cm^2 mirror set on the middle of the road with two poles just like indicator panels (Fig. 3).

This mock-up will be used to reproduce, identify potential problems and validate the performance of coupled systems heliostat-light-pipes installed in real tunnels in short term future research. The target configuration in tunnels is shown in Figs. 4 and 5.