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Installation of solar panels in the surroundings of tunnel portals: A double-targeted strategy to decrease lighting requirements and consumption

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ABSTRACT

The optimization of the lighting installations in road tunnels has become a matter of the highest concern due to their high consumption in energy, raw materials and financial resources. In addition, they have complex maintenance and high environmental impact due to energy production and manufacturing processes of projectors, wiring and electrical devices. Although the use of solar panels is widely spread in all kinds of infrastructures, they have never been proposed with an intention different from producing clean energy from the solar radiation. In this work, a double-targeted perspective is proposed: the installation of solar panels around the portal gate of tunnels, to contribute to power the tunnel installation (lighting, ventilation, emergency), but mainly to decrease the reflectance of the tunnel surroundings and, hence, the well-known L20, the main contributor to the electrical luminance levels required in road tunnels. The strategy and the measurements in real panels, as well as the savings achieved in one particular model of tunnel (between 18.7% and almost 24%, depending on the use of the generated power), are presented and analyzed in this work.

1. Introduction

Tunnel lighting is a challenging problem from the perspectives of Safety, Economy and Environment. Indeed, the special characteristics of tunnels and other underground spaces, where the psychological load of driving is heavier and the consequences of accidents more severe (Caliendo and De Guglielmo, 2012), require an accurate environment allowing drivers the shortest reaction times to avoid unexpected maneuvers of other vehicles, obstacles on the road, etc.

The inverse relationship between stimuli luminance (CIE Publ. S017/E:2011, 2011) and the visual reaction time (VRT) to detect them, given by Pieron's Law (Pins and Bonnet, 1996) requires high luminance levels on road and tunnel walls in order to ensure a quick response of drivers in case of emergency. These luminance levels are especially high in tunnels during daytime, when the visual systems of drivers is adapted to the high brightness and cannot abruptly enter in a weakly illuminated tunnel (Adrian, 1982; CIE Publ. 88:2004, 2004; Mehri et al., 2017, 2018, 2019).

Hence, road tunnels need high luminance levels during daytime and lower ones during nighttime which, given the continuous working 24 h/day, 365 days/year, make a very high consumption of energy and money from the lighting installation. In addition, the energy consumption of the ventilation installation must also be considered. The consumption of both installations, lighting and ventilation, are about 80% and 20% of the overall tunnel consumption respectively.

But the impact of lighting does not constraint to safety and energy itself and its economical value. The high luminance levels also require a high number of projectors (more than 100 in not very long tunnels) needing the relevant light sources, auxiliary devices and wiring. This means a remarkable need of raw materials, consumed energy in manufacture processes, waste management, greenhouse gases emissions, maintenance and future recycling with the evident environmental impact.

In summary, tunnel lighting installations are critical from many perspectives. This has led researchers to investigate strategies to decrease the required luminance levels, profit from sunlight or decrease maintenance expenses.

1.1. Strategies to decrease the impact of tunnel lighting installations

Researchers all over the world have lately advanced very much in their vision of tunnel lighting as a general problem that must be considered from a multidisciplinary point of view.

Some research has focused on the decrease of luminance demands through a smoother visual adaptation of drivers when entering road tunnels during daytime. In this line, the forestation of tunnel portal

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Nomenclature

CIE	Commission Internationale de l'Éclairage
E	Illuminance or illumination. Received flux per unit of surface. Unit: lux (lx, lmm^{-2})
E_H	Horizontal illuminance. Illuminance on one horizontal surface
E_N	Normal illuminance. Illuminance on one plane normal to the incidence of sunrays
E_V	Vertical illuminance. Illuminance on one vertical surface
L	Luminance. Luminous flux emitted per unit of solid angle and surface in one given direction. Unit: candela/square meter (cd m^{-2})
ϕ	Luminous flux. Power emitted, transmitted or received as luminous energy. Unit: lumen (lm)
ρ	Reflectance or reflection coefficient. Ratio between reflected and incident luminous flux in one surface
VRT (in driving)	Visual Reaction Time. Time required to carry out the relevant actions when one obstacle appears. Unit: second (S)

surroundings with low reflectance species has demonstrated to decrease the luminance in driver's eye when approaching the tunnel (L20 luminance). This means a lower luminance to be supplied by the lighting installation in conditions of good visual adaptation. Common Ivy has been identified as a resistant, versatile and accurate specie in tunnels located in very different zones, going from the Mediterranean climates (Peña-García et al., 2015) to Alpine ones (García-Trenas et al., 2018). Other species besides common ivy have been also considered with pros and contras (López et al., 2014).

Other research have worked with different kinds of pavements inside the tunnels to increase its reflectance to the luminous flux emitted from the projectors and achieve the required luminance with lower consumed power (Moretti et al., 2016, 2017a, 2017b). The results have been very positive in terms of saved energy, good economic profitability and lower environmental impact. Complementary research has dealt with LED technology, which came late to tunnels because of the high demands in terms of projectors, and its capability to be dimmed according to the different circumstances in each part of the tunnels (Wang and Zhou, 2009; Salata et al., 2015a,b, 2016; Qin et al., 2017a, 2017b; Renzler et al., 2018; Moretti et al., 2019; Doulos et al., 2019).

In a parallel framework, other research lines, not so easy to implement, but already proven to be very profitable at mid term, focus on the use of sunlight in the tunnel or other similar infrastructures. Some of them are based on the introduction of this natural light through different ways to collect, concentrate and distribute it on the pavement like electrical projectors do (Gil-Martín et al., 2014; Qin et al., 2015; Peña-García et al., 2016; Bystronski1 et al., 2018), whereas other strategies demonstrate that the shift of some dozens meters of the threshold zone out of the very tunnel, compensate the enlargement with the direct introduction of solar flux in that zone, which is the most consuming one (Peña-García et al., 2010, Gil-Martín et al., 2011; Peña García et al., 2011; Peña-García and Gil-Martín, 2013; Abdul Salam and Mezher, 2014; Drakou et al., 2015, 2016, 2017; Gil-Martín et al., 2015; Wang et al., 2015; Cantisani et al., 2018a, 2018b). A few researchers have considered the use of renewable energies to partially supply the power needed in tunnels (Dzhusupova et al., 2012; Salata et al., 2015a,b; Janssen et al., 2017). One of these research (Sun et al., 2019) even simulated the feasibility of using semitransparent photovoltaics elements to shift the threshold zone and, simultaneously, profit from the power production in the photovoltaic elements.

Concerning the management of so many strategies to use of sunlight in tunnels, the necessity of predicting the savings and costs in each case, has led to the development of tools and methods like the SLT equation (Peña-García, 2017). This equationcan evaluate the most accurate strategy for each particular tunnel depending on factors like tunnel orientation, desired savings and other parameters.

In this work, a double strategy never considered up to date to save energy, raw materials, greenhouse gases emissionsand financial resources, will be presented. It consists on:

(1) Darkening of portals surroundings with black photovoltaic panels. This darkening leads to lower luminance requirements inside the tunnel as shown by the results of this research.
(2) Profit from the usedphotovoltaicsto produced power.

In the following sections, the hypothetical installation of PV modules for the abovementioned purposes in one real tunnel will be compared with its current situation.

2. Materials and method

One virtual tunnel (VT) with around 7 m height and 14 m widthhas been simulated on a concrete wall in the Faculty of Civil Engineering of the University of Granada (Spain). Two standard solar panels have been

Fig. 1. (a and b) Solar panels in an opencast space for luminance measurements and their location.

installed above the virtual portal at a height of 9 m, which is a typical height of elements inside the L20 cone whose reflected light has influence on the visual adaptation of drivers. The panels were mounted on a structure fixing them in vertical positions. The setup and its location are shown in Fig. 1a and b:

The luminance reflected by the panels has been measured meter from the safety distance (SD), as would be perceived by drivers approaching the tunnel (Fig. 2).

The luminance produced by the sun light, reflected by panelsfor several relative positions panel-sun, was measured with a calibrated Hagner Universal Photometer S3 in luminance measurement mode (range 0.01–200,000 cd/m^2; accuracy ± 3%). The luminance meter incorporates a telescopic sight: once the object is focused, the observer sees a black point, which covers an angular extension of 1°. Vertical, horizontal and normal illuminance on the panels were also measured at different hours with a CL 200-A lux meter (range 0.1–99,990 lx; accuracy ± 2%).

The measurements have been taken during several sunny days at 14:00 in the month of July, where the environmental luminance is very high and, hence, the visual adaptation of drivers require higher consumption in tunnels.

The results of luminance measurements have been extrapolated to one real tunnel with South-North orientation (349.41°) in the National Highway A4 (Province of Jaén, South of Spain) whose portal gate has been simulated to be partially covered with solar panels. The luminance requirements of the real tunnel with and without PV modules covering have been evaluated departing from the L20 method (CIE Publ. 88:2004, 2004).

The electrical power produced by the panels has been calculated from the irradiance data in the tunnel location obtained with the tool PVGIS (PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM), a free and open access tool supplied by the European Commission updated on 21/09/2017 (European Commission, 2017).

With these values, the main parameters of the lighting installation and their impact in both configurations are calculated and analyzed in the following section.

3. Results

The luminance of the panels fix in vertical position on the virtual tunnel (VT) described in section “Materials and method”, was measured throughout the sunny days in July 2019 in the most unfavorable time in terms of high luminance and worse visual adaptation of drivers (14:00). Their average value was $L_{av-VT} = 1472 cd/m^2$. This value is lower than the lowest value assigned to any element in the L20 cone by CIE 88:2004 (2004), the international standard of reference in tunnel lighting (Table 1).

In addition, the vertical illuminance on the portal was $E_V = 68300$ lux, whereas the luminance from the concrete wall surrounding the tunnel was $L_{Wall} = 15810$ cd/m^2.

With these values, the portal gate of the tunnel with South-North orientation described in Section 2, has beentaken as model. The main parameters of its lighting installation are calculated in its current state (Fig. 3a) and after hypothetical installations of 64 solar panels with the same reflected luminance than the ones measured in the virtual tunnel. The simulated situation is shown in Fig. 3b.

The main parameters of the lighting installations in its current status, without installing any kind of panel, are shown in Table 2.

In Table 3, the main parameters of the tunnel are calculated before considering the power generated by the panels, which will be added later in Table 4. Thus the values in Table 3 just show the savings achieved with the mere decrease in the L20, that is, due to the very low reflectance of the PV modules.

In both tables, the results are limited to the Threshold and Transition zones of the tunnel because they are the most consuming and the ones that depend on L20.

The calculations for costs and CO$_2$ emissions have been made according to the reference values in Spain in 2017, where theCO$_2$ factor was 0,31 kg/kWh (National Commission on Markets and Competition of Spain, 2017) and the cost per industrial kWh was 0,083 € (Government of Spain, 2017).

In summary, the values obtained show that the installation of PV within the L20 cone is clearly favorable. The comparison of the parameters before and after their installation is shown in Fig. 4.

Going further, the effect of installing solar panels is not limited to the decrease of the electrical lighting requirements: there is also the contribution of the power generated by the panels. In the simulated tunnels, the yearly power generated by the 64 panels has been calculated with a standard tool (European Commission, 2017) and results to be 15.7MWh. No CO$_2$ emissions result from the production of electricity according to the national Spanish standard (National Commission on Markets and Competition of Spain, 2017). Like in Spain, most national standards assign zero emissions to the production of energy with renewable sources.

The injection of the power generated in the panels is shown in Table 4 where, once the decrease in lighting requirements due to the darkening in the L20 cone is applied, the parameters including or not the power generated are presented.

It is necessary to remark that the latitude of the considered zone requires an inclination of 37° with respect to the horizontal, as well aspanels orientation towards the South. This rather horizontal position means that very low panel surface in the L20 cone would be exposed to the sun in the critical hours of summertime, when the sun is high. In addition, the gaps between inclined panels would be a problem for maintenance due to the entry of dust, water and even animals.

For these reasons, the vertical orientation of panels has been chosen as the best solution: even if the power generation is not the highest, the number of installed panels and their maintenance is the lowest. Paradoxically, in winter, when the sun is lower, the vertical installation is quite favorable in terms of profited solar irradiance.

In summary, the very positive effect of low reflectance panels, ($L = 1472$ cd/m^2 of PV modules against $L = 8000$ cd/m^2 of concrete or $L = 1472$ cd/m^2 of vegetation as shown in Table 1) allows that the power generated is not the main target of this strategy. It is just a plus

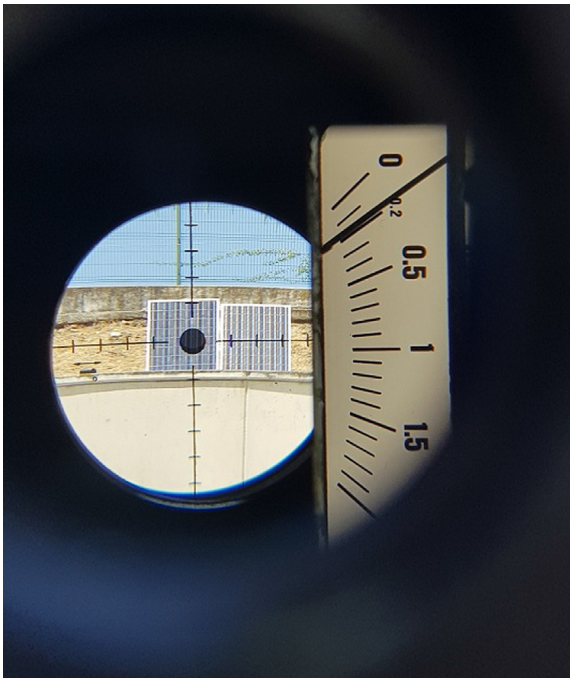

Fig. 2. Measurement of luminance reflected by the panels with a S3 Hagner luminance meter with telescopic sight.

Table 1
Luminance of different elements within the L20 cone (CIE Publ. 88:2004, 2004).

Driving direction (N. Hem.)	L_S (kcd/m^2)	L_R (kcd/m^2)	L_E (kcd/m^2)			
			Rocks	Buildings	Snow	Meadow
N	8	3	3	8	15	2
E-W	12	4	2	6	10 (V) 15 (H)	2
S	16	5	1	4	5 (V) 15 (H)	2

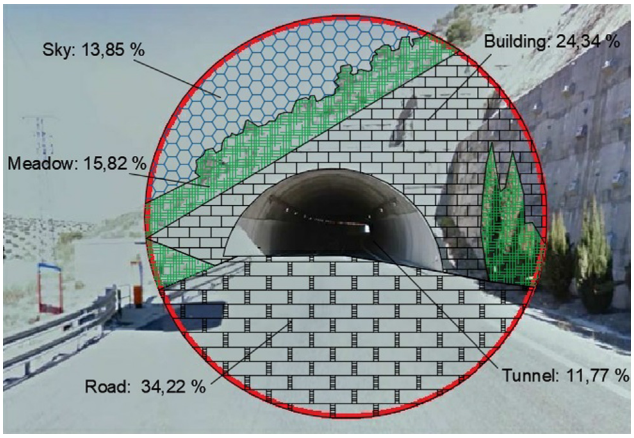

Fig. 3a. L20 cone before tunnel portal in the Province of Jaén (Spain). Current state.

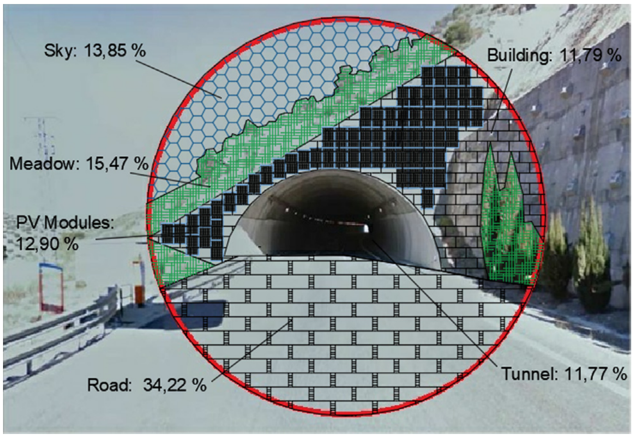

Fig. 3b. L20 cone before tunnel portal in the in the Province of Jaén (Spain) with 64 solar panels (PV modules) in the building zone.

because tunnel orientation and other characteristics of the portal determine the position of the panels that, in general, will not be the optimal for a maximum power generation.

The ratio between the parameters of both installations are shown in Table 5.

The results obtained demonstrate that the installation of solar panels in the surroundings of portal gates achieves double and complementary savings: lower L20, which decreases the energy requirements in the whole tunnel, and energy productionin the panels. This last can lead to remarkable savings if injected to the electrical network powering the main lighting installation or, instead, used to light the emergency lighting the ventilation or other supplementary installations.

4. Conclusions

The results presented in this work show that the installation of black solar panels in the surroundings of tunnels portal gates, can achieve remarkable savings in consumed energy, number of installed projectors, emissions of CO_2 and financial impact of the lighting installation.

These savings are due to two complementary factors:

(1) The reflectance of sun panels is much lower than the reflectance of concrete building, rock or even some kind of vegetation. Hence, the L20 luminance, which is calculated with the contribution of each element in a 20° cone from the safety distance, is also lower. Since the electrical power and necessary projectors consumed inside the tunnel is proportional to L20, the saving is clear as demonstrated in this research (around 19%).
(2) The electrical power generated by the PV modules can be injected in the network or used for other purposes like power of signaling elements, ventilation, etc. This decreases the final amount of energy consumed by the lighting installation (around 24%) and its auxiliary installations, as well as the environmental and financial impact.

Based on these results and, as consequence, the foreseeable increase of solar panels installed around the portal gates with the double double-targeted strategy presented in this work, it seems reasonable to humbly suggest CIE to include the lighting-related aspects of installing of solar panels in the surroundings of portal gates in next revisions of CIE Publ. 88:2004 and its amendments. Obviously, besides CIE standards, this suggestion is extended to all the national regulations in order to adapt to the potential framework in the next years.

In the case of CIE standard on tunnel lighting, such inclusion would consist, at least, on the calculation of average luminance reflected by solar panels in typical tunnel environments and its inclusion in the currently labeled as Table 6.2.3 (CIE Publ. 88:2004).

As main limitation, the installation of black solar panels blocks the forestation with plants in the zone where they are set. Although this work proves that the installation of PV modules reduces the energy consumption more than the forestation, this strategy does not contribute to increase the vegetal mass in the roads.

It is necessary to remark that in general, PV modules installed in the surroundings of tunnel portals will rarely fulfill the conditions of inclination and orientation to produce maximum electrical power. It is natural since the orientation of tunnels depends of the mountains and

Table 2
Main parameters of lighting installation of tunnel in its current state.

Current tunnel	Luminance (cd/m^2)	Length (m)	Number projectors	Yearly cons. (MWh)	Yearly CO_2 emiss. (tn)	Yearly costs energy (€)
Threshold zone − 1	265.8	49.2	46	68.4	21.2	5,675
Threshold zone − 2	225.9	24.6	20	29.1	9.0	2,412
Threshold zone − 3	186.1	24.6	16	23.9	7.4	1,987
Transition zone − 1	106.3	148	100	82.3	25.5	6,827
Transition zone − 3	79.7	148	74	61.7	19.1	5,119
Transition zone − 3	53.2	148	50	41.2	12.8	3,417
TOTAL		**542.5**	**306**	**306.5**	**95.0**	**25,437**

Table 3
Main parameters of lighting installation of tunnel if solar panels are installed inside the L20 cone. Electrical production of panels is not considered yet.

Current tunnel	Luminance (cd/m^2)	Length (m)	Number projectors	Yearly cons. (MWh)	Yearly CO$_2$ emiss. (tn)	Yearly costs energy (€)
Threshold zone − 1	216,2	49.2	38	55.6	17.2	4,616
Threshold zone − 2	183,8	24.6	16	23.6	7.3	1,962
Threshold zone − 3	151,3	24.6	14	19.5	6.0	1,615
Transition zone − 1	86,5	148	80	66.9	20.8	5,556
Transition zone − 3	64,9	148	60	50.2	15.6	4,168
Transition zone − 3	43,2	148	40	33.4	10.4	2,775
TOTAL		**542.5**	**248**	**249.3**	**77.3**	**20,692**

Table 4
Impact of the power generated by the solar panels on the main parameters of the lighting installation.

	Number projectors	Yearly cons. (MWh)	Yearly CO$_2$ emiss. (tn)	Yearly costs of energy (€)
Without injection of generated power	248	249.3	77.3	20,692
After injection of generated power	248	233.6	72.4	19,389

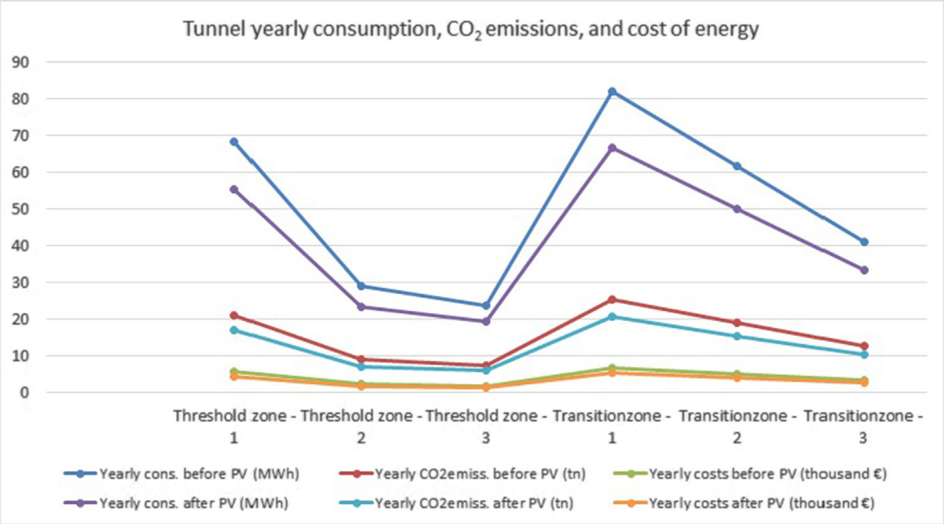

Fig. 4. Comparison of the main parameters of the lighting installation before and after darkening of the L20 cone with PV modules.

Table 5
Savings with PV modules installed around tunnel portal Vs. current state considering or not the power generated.

	Number of projectors	Yearly energy consumption	Yearly CO$_2$ emissions	Yearly costs of energy (€)
Savings only darkening (%)	19.0	18.7	18.7	18.7
Savings darkening + power injection (%)	19.0	23.8	23.8	23.8

other geotechnical factors, so the orientation of panels must be adapted to these factors. Anyhow, the energy produced, higher or lower, is a plus to the decrease in the electrical lighting requirements.

Future lines of research in this field will focus on the search of panels with lower reflectance, optimizing the configuration of groups of panels, and algorithms to determine what tunnels can benefit most from this strategy depending on their orientation and orography of surroundings.

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CRediT authorship contribution statement

A. Peña-García: Conceptualization, Methodology, Investigation, Writing - original draft, Validation, Writing - review & editing. **D. Gómez-Lorente:** Conceptualization, Methodology, Investigation, Writing - original draft, Validation, Writing - review & editing.

Declaration of Competing Interest

Antonio Peña-García and Daniel Gómez-Lorente don't have any financial and personal relationships with other people or organizations that could inappropriately influence (bias) their work or state if there are no interests to declare.

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