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Daylighting of road tunnels through external ground-based light-pipes and complex reflective geometry

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ABSTRACT

The transfer of solar light to the interior of tunnels to complement electrical lighting during daytime, contributes to save energy and decrease the number of installed projectors. The solutions traditionally implemented, based on light-pipes hanging from the vault, seemed reasonable because the leakages of light-pipes can emit luminous flux like projectors, but had the disadvantage of needing higher clearance gauges with the consequent costs in drilling, building materials, works and maintenance. Furthermore, these hanging light-pipes cannot be installed in working tunnels if they were not foreseen in the initial project. In this article, a new concept of light injection and distribution in tunnels is proposed. It consists of the coupling of three main elements: collectors, light-pipes, and one reflecting vault whose design is optimized to ensure the photometric requirements on the pavement. The proposed system can collect more than 1.5 Mlm of solar flux with not excessively large collectors installed on the ground of the road shoulder, and project them to the vault that finally distributes the light towards the pavement. With this flux, average illuminances of 3478 lx and uniformities of 0.73 can be achieved, which means pavement luminance around 350–400 cd/m2, in good agreement with the requirements during daytime. The savings can be higher than 40 %. Besides these savings, this system can be easily implemented in existing tunnels. The proposal and some estimations are discussed.

1. Introduction

The singularity of road tunnels and underground passes greatly impacts the way their users behave in them and, hence, their safety, comfort and stress (Caliendo& De Guglielmo, 2012; Miller & Boyle, 2015; Wang et al., 2018; Sun et al., 2021; Danishmal & Zainullah, 2021) mediated by physiological and psychological parameters strongly dependent on the lighting conditions. The great importance of the way in which a tunnel is illuminated becomes higher if we consider that there are several facts making visual perception even more complicated in these infrastructures.

Among these facts, the slow adaptation of humans to weakly lighting conditions (Adrian, 1982; CIE Publ. 88:2004, 2004; Mehri et al., 2017, 2018, 2019, 2020) and the black-hole effect in the entrance (Si-qi and Xiao-ming, 2015) together with the flicker effect in the interior and longer tunnels (Iacomussi, Radis & Rossi, 2018; Peña-García, 2018; Du et al., 2020) play a key role.

In order to avoid the danger derived from these effects, the luminance (a luminous flux reflected by a unit surface into a unit solid angle, in a given direction, (CIE Publ. S017, 2015)) from pavements and walls of the tunnels must be remarkably high during daytime, especially in the first meters after the entrance, the threshold zone (CIE Publ. 88:2004, 2004). The consequences of these high levels of luminance are high energy consumption, high number of installed projectors with the consequent demands in raw materials, manufacturing hours, transportation, environmental impact, maintenance and, of course, financial resources. Given the high number of existing tunnels and the current trend to build new and longer ones, it seems necessary to develop strategies to decrease the impact of their lighting installations, especially during daytime when the abovementioned effects take place. They will be presented in the following subsection.

1.1. Strategies to decrease the impact of the lighting installations of tunnels

The actions planned and implemented up to date, have been divided

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into two main categories (Peña-García, 2022a; Peña-García, 2022b): strategies to decrease the energy demands inherent to the tunnel itself, and strategies to use the light of the sun to satisfy those energy demands. Both are fully compatible and should be complementary.

Among the actions to decrease the energy demands during daytime, the following have been proposed up to now:

1) Darkening the surroundings of the portal gate surroundings to decrease its reflectance and the L20 luminance in the eye of the incoming driver. This L20 luminance is the outer and natural luminance directed to the eye of the driver and is proportional to the luminance necessary in the threshold zone of the tunnel, L_{th} (CIE Publ. 88:2004, 2004; Zhang et al, 2019). Hence, a decrease of L20 results in a decrease of luminance of electrical origin and the consequent lower energy demands. The climbing plants, especially the common ivy (López et al., 2014), have demonstrated to achieve a full cover and lowest reflectance in Mediterranean (Peña-García, López &Grindlay, 2015) and high mountain climates (García-Trenas, López& Peña-García, 2018). The forestation of portal surroundings also contributes to certain metrics evaluating the sustainability of the whole tunnel (López, Grindlay & Peña-García, 2017). Other research has proposed to decrease the L20 luminance through the installation of black solar panels whose energy output can be used to power auxiliary lighting and other installations (Sun et al., 2019; Peña-García & Gómez-Lorente, 2020). A simulated view is presented in Fig. 1.
2) Decrease of the maximum speed allowed in the tunnel. This measure decreases the length of the most consuming zones, the threshold and the transition, and also the coefficients of proportionality between outer (L29) and inner (L_{th}) luminance (Peña-García, Salata & Golasi, 2019).
3) Use of pavements with higher reflectance allowing the desired luminance with less consumed power (Cantisani, Di Mascio & Moretti, 2018a; Moretti et al., 2016, 2017a, 2017b, 2019).
4) Use of control systems to dim and manage the flux emitted by the projectors, generally including LED technologies, according to the traffic, weather and other parameters (Yao, Cheng& Lin, 2008; Leitao et al., 2009; Wang& Zhou, 2009; Ye, 2013; Lai et al., 2014;Salata et al., 2015;Salata et al., 2016; Qin et al., 2017a; Qin et al., 2017b; Renzler et al., 2018; Bouroussis, Nikolaou & Topalis, 2019; Doulos et al., 2019; Spor, Kiyak & Solak, 2019; Zhao et al., 2019; Wang et al., 2020; Qin et al., 2021; Zhao, Feng & Yang, 2021).

On the other hand, once the energy demands of the tunnel are defined, it is possible to partially fulfill them by profiting from the sunlight. The way to use this natural light in road tunnels can be divided into two main categories whose mathematical description can be reduced to general expressions (Peña-García, 2017):

1) Shift of the threshold zone out of the tunnel: the required luminance levels during daytime are highest to avoid temporal glare due to the slow visual adaptation when arriving from bright environments. If this zone is totally or partially displaced out of the tunnel (Fig. 2), the tunnel lighting will be partially supplied by daylighting with the consequent beneficial savings of energy and amount of installed projectors.

Among the solutions proposed and implemented for this purpose, we can find semi-transparent structures (Abdul Salam and Mezher, 2014; Peña-García et al., 2010, 2011,2012; Gil-Martín et al., 2011, Peña-García, 2019); pergolas with empty space between beams (Peña-García and Gil-Martín, 2013) or using diffusive materials to avoid flicker effect on the road (Gil-Martín et al., 2015; Peña-García et al., 2016a); and structures with different patterns of holes (García Garay et al., 2012; Drakou et al., 2015, 2016,2017; Cantisani et al., 2018b; Cantisani et al, 2018c).

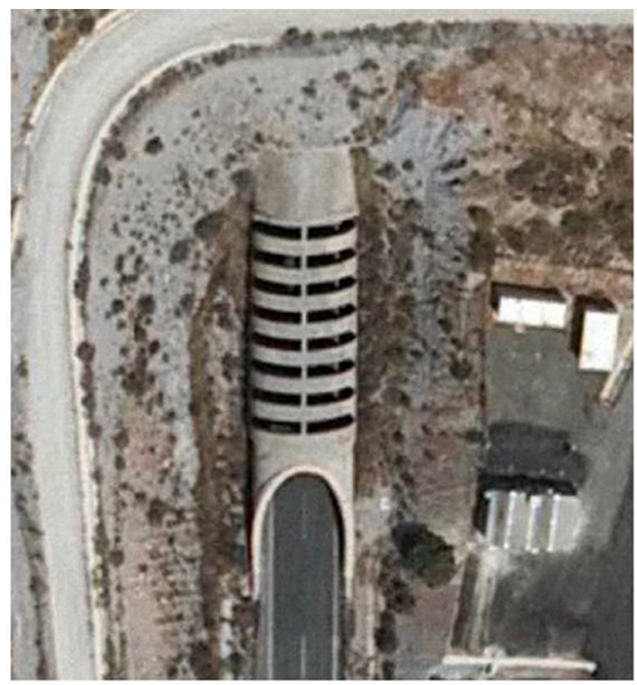

Fig. 2. Concrete pergola shifting the threshold zone in the Lorca (Spain) (Peña-García and Gil-Martín, 2013).

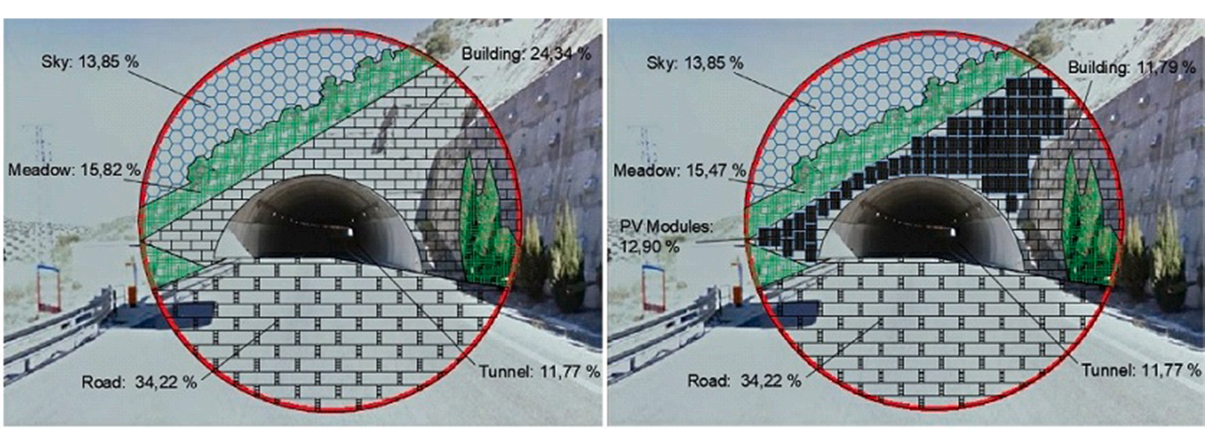

Fig. 1. Simulated darkening of the portal surroundings inJaén (Spain) with 64 black solar panels (Peña-García & Gómez-Lorente, 2020).

2) Transfer of sunlight inside the tunnel: this solution does not require threshold displacement, but just the installation to collect and distribute the solar luminous flux inside the tunnel. The proposals up to date have considered mirrored light-pipes without (Gil-Martín et al., 2014) or with collecting heliostat as shown in Fig. 3 (Peña-García et al., 2016b; Bystronski et al., 2018), as well as systems based on optical fibers (Qin et al., 2015).

Among the proposed solutions injecting solar flux inside the tunnel, it is very illustrative to see the abovementioned and currently implemented in Huashuyan Tunnel (Northern China). In Fig. 4 it is shown that the injected light provides a good luminance that is complemented with the electrical projectors.

The injection has the advantage of not enlarging the tunnel, but it requires higher clearance with the obvious expenses and technical problems during the building.

It is interesting to remark that the proposals to decrease the impact of tunnel lighting have considered only external added structures without profiting from those inherent to the tunnel itself like the vault.

1.2. Purpose of the work

The purpose of this work is to present one system based on the most injection of solar flux inside the tunnels from a completely new perspective: the collected flux will not be transferred in height, but through ground-based systems of collectors and light-pipes.

Another novelty is that the final distribution towards the pavement will be carried out precisely by reflection on one specific tunnel vault, which has a complex geometry designed with both, structural and reflective purposes. Its main properties will be presented in the next section.

The remaining sections are devoted to present the design features and properties o the mentioned collectors and pipes.

Finally, the advantages and potential limitations of this proposal are discussed in the Conclusions.

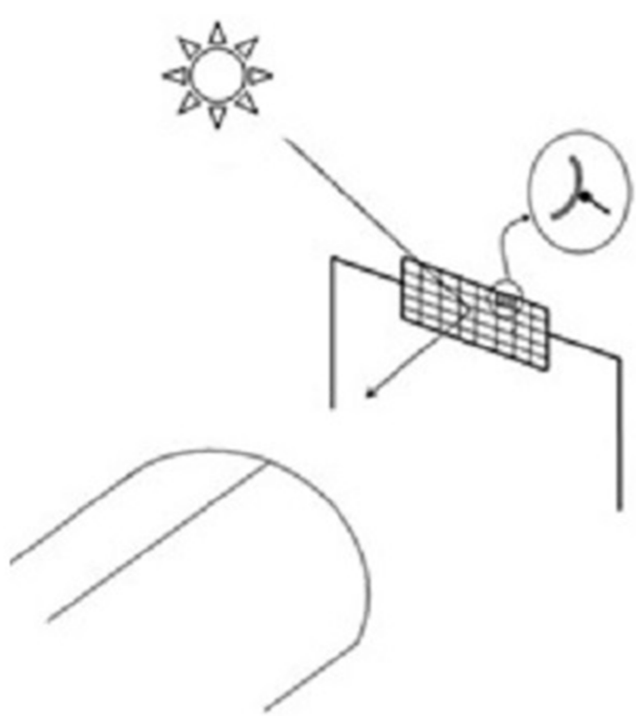

Fig. 3. Heliostat injecting sunlight in matrix of light pipes (Peña-García et al., 2016b).

2. Tunnel vaults as new elements to support the use of sunlight

The particular vault geometry of tunnels which is fundamentally based on the semi-cylinder (Fig. 5), presents severe hindrances in terms of accurate calculations of its radiative transfer. The form factors for semicircles and semi-cylinders are not well known although significant improvements have been produced in recent times (Cabeza-Lainez & Rodríguez-Cunill, 2019).

However, in spite of the good reflective properties of concrete, this geometry has not been precisely optimized to achieve the necessary luminance levels at the road in the tunnel.

In this context, a new hyper-geometry developed by the authors (Cabeza-Lainez, 2022), which originates in the conoid shape but evolves subsequently to provide a new continuous shape, can be suitable to reflect previously injected luminous flux and provide the necessary luminance in tunnels. Fig. 6 a. to b., show a mock-up of this unusual geometry.

This hyper-geometry was originally conceived to improve aerodynamics and sound pressure in the tunnel with substantial decrease of material costs due to the reduced surface that its warping induces.

It has been obtained through algorithms of differential geometry and the authors have demonstrated that it presents important advantages in structural resistance, drainage within the tunnel, acoustics (reduction in noise conduction) and especially reflection of light.

In mathematical terms the most important feature of the proposed geometry is that the sectional area remains constant while the shape of any section of the continuum is always different as shown in Fig. 7, and the generatrix lines are all straight since this form is a special kind of closed ruled surface. This can be one of the reasons why the implementation of this design strategy is innovative (Fig. 8).

That said, we judge that a revolution of forms is required in the issue of tunnel vaulting. The research of years by the authors (Cabeza-Lainez, 2022) has been fruitful in the sense that a whole new array of tubular surfaces is available and tested against aerodynamics, structural adaptability, lighting and acoustics among different promising capabilities.

With these advances, new techniques to improve the transfer of solar flux are possible. They are performed by collection outside the tunnel and reflection on the newly simulated vault towards the pavement. Hence, a customized distribution of light in the hyper-geometry is entirely feasible as a novel way of vaulting road tunnels.

3. Proposed system

Once the different techniques to use sunlight in road tunnels have been analyzed and the last advances in vault design presented, a new injection system will be presented. It is formed by three coupled sub-systems:

1) Two collectors, one on each side of the road.
2) Two ground-based light-pipes, one coupled to each collector.
3) One reflecting complex vault.

The three sub-systems will be first described separately and then analyzed as a whole.

3.1. The collectors

As seen, a high amount of solar flux must be injected in the tunnel. For this reason, the first sub-system consists of two sealed tanks collecting the required luminous flux, especially in sunny days in spring and summer.

Although the geometry and number of collectors may be variable depending on the geometry of the zone adjacent to the road and the tunnel, just as approach it is proposed to install two rectangular collectors on each side of the road, near to the shoulder in an area free of

Fig. 4. Injection system based on fiber optics (Qin et al., 2015).

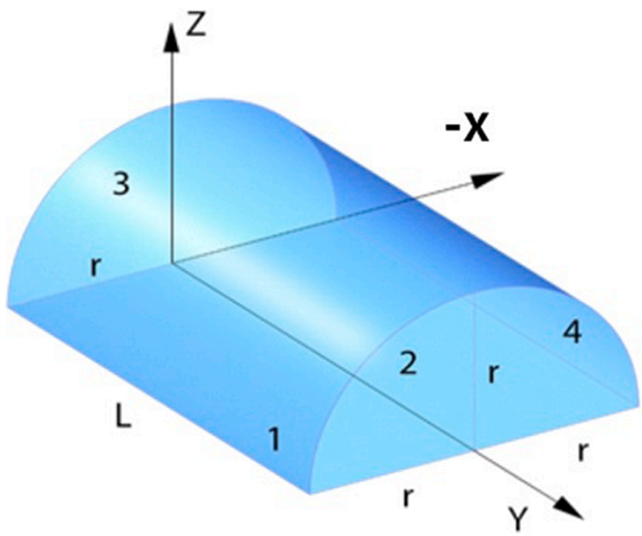

Fig. 5. Classical tunnel vault based in semicylinder geometry, where r is the main radius of the tunnel and L its length. The standard form is composed of four limiting surfaces: a rectangle of dimensions 2rL (named 1 in the Fig.), two semicircles (2 and 3) and a semi-cylinder (4).

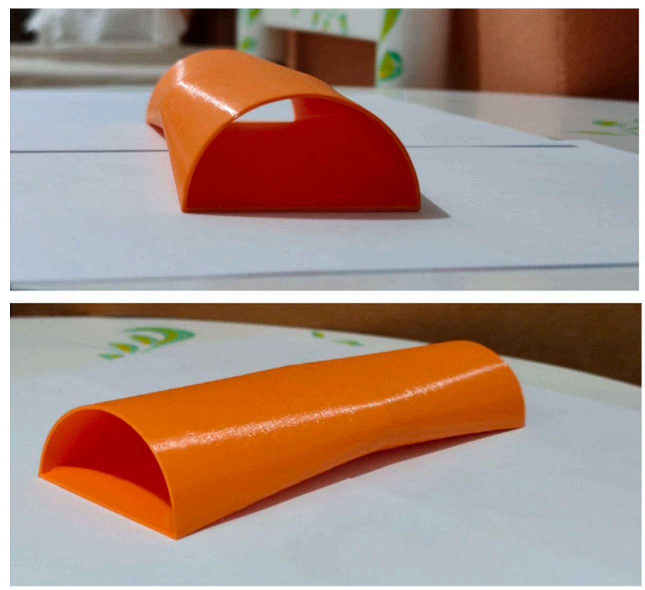

Fig. 6. (a) and (b). New vault geometry designed to reflect luminous flux towards the road.

trees and bushes or other obstacles that could difficult the collection of solar flux (Fig. 9).

The collectors must be hermetically sealed (IP68) with a thin layer of tempered glass, polycarbonate, PMMA or any transparent material with high resistance and both, anti UV and anti IR coatings. The strong sealing requirements in terms of IP are essential to keep the interior of the system clean and highly reflective to avoid solar flux losses. Equally, the anti UV coating ensures the blocking of the UV solar radiation which causes yellowing in the layer and would decrease the total transmittance of the system. The anti IR coating avoids radiative heat to increase the temperature of the whole system as well as dilatations and other damages impairing performance. The recent advances in anti IR filters and coatings allow visible light transmittance above 80 % (Woo et al., 2022).

Just for estimation, approximate dimensions of 6 m long, 1.5 m width They both make a total collecting surface $C_s = 18$ m^2. For a typical illuminance E = 100,000 lx in one zone with latitudes similar to Spain (Peña-García et al., 2016b), the luminous flux collected by the described set of two collectors would be $F = E\ C_s = 1.8 \times 10^6$ lm. Even with a restrictive coefficient of transmittance $T = 0.8$ due to the anti IR and anti UV filters as well as other loses, the available flux would be around 1.5×10^6 lm, that can be raised just building bigger collectors whenever the area adjacent to the road allows it.

Besides the loses due to the filters, one key factor to collect the required luminous flux is to maximize the transmittance of the transparent sealing layer. Consequently, it is necessary to continuously eliminate depositions of dust, sand, leaves, excrements of birds and many other undesired deposits decreasing the maintenance factor and, hence, the injected solar flux. For this reason, the collectors should incorporate automatic systems blowing or watering the transparent layers at high pressure in regular intervals of time.

Inside the collectors, some mirrored surfaces with the necessary inclination will direct the collected solar flux to the second sub-system, the light-pipe that transports it inside the tunnel. This scheme is shown in Fig. 10.

3.2. The light-pipes

Each of the proposed collectors has a derivation to a light-pipe that transports the luminous flux with the minimum losses. Although light-pipes have been proposed to transport luminous flux in a wide variety of situations, including road tunnels, such devices have been designed in a relatively simple manner and also the light guidance was performed through empty tubes with redirecting inner mirrors (Gil-Martín et al., 2014; Peña-García et al., 2016b) or fiber optics (Qin et al., 2015). In this case the proposed pipes are much more complex with the aim of minimizing their section during the transport from collectors to the interior

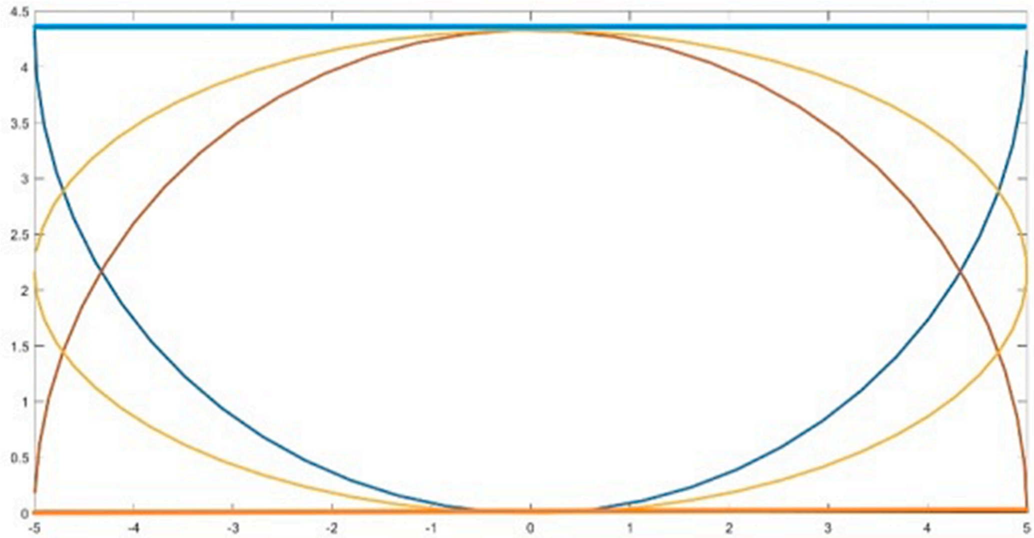

Fig. 7. The three main vertical sections through the proposed new vault.

of the tunnel and increase it again before diffusing the light to the tunnel vault through a transparent sealing layer similar to that of the collectors. The objective of this last increase in size is to distribute it to the largest possible area.

The phases of the transport after the collection will are the following (Fig. 8):

Collimation of the collected flux by means of mirrors in the interface between the collector and the light-pipe. Such collimation is needed to obtain a beam of parallel rays inside the pipe to minimize losses and increase the availability of light.

Opening of the beam with two coupled lenses: one convergent in the focus of a divergent one.

Redirection of the beam upwards towards the reflecting vault.

In order to protect the system and its inner components, the IR radiation entering the light-pipes must be minimum. This is the reason why the initial transmissive layer must be treated with anti IR coatings or filters as explained in the preceding subsection. Equally, the body of the light-pipes will be under the ground or protected with reflective treatment in order to avoid external heating.

3.3. *Reflection on the vault*

A simulation has been conducted by the authors taking as a model one standard tunnel and including all possible reflections from each curved surface. It is known (Salguero et al. 2020) that radiation is regulated by the canonical equation (1) as illustrated in Fig. 11:

$$\nabla^2(\phi_{ij}) = (E_i - E_j)\cos\theta_i\cos\theta_j\frac{dA_i dA_j}{\pi r_{ij}^2} \quad (1)$$

With E_i and E_j standing for the quantity of energy (in W/m^2) expelled by surfaces *i* and *j*.

θ_i and θ_j represent, respectively, the angular quantities enclosed by the normal vectors to the infinitesimal areas dA_i and dA_j through which the flux passes in the first virtual iteration.

$\mathbf{r}_{ij}$ is an arbitrary vector that colligates the unit surface sources dA_i and dA_j.

As a result of the said simulation with the software DianaX, illuminance distribution on the pavement for the estimated luminous flux (1.8 $\times$ 10^6 lm) collected through the system is shown in Figs. 12 and 13.

As shown in Figs. 12 and 13, the average illuminance on the pavement is 3478 lx, and the average uniformity, U_m = 0.73. Since the required illuminance on the pavement of a standard zone in the most unfavourable conditions can be about 8222 lx (Gil-Martín et al., 2011), savings of 42 % in consumed energy are achieved with the proposed system. Concerning uniformity, it must be higher than 0.4, which proves that the solution proposed is highly uniform and completely avoids flickering effects.

In summary, the proposed system based on the optical coupling of collectors and light-pipes with a special reflecting vault is a novel and perhaps revolutionary technique which can achieve remarkable savings as detailed in the next section.

4. Conclusions

A new system to inject sunlight in road tunnels during daytime has been presented. It consists of the coupling of three main elements: flux collectors, light-pipes and reflecting complex vault.

The main novelties compared to others proposed and implemented up to date are the following:

1) The sunlight collectors and the light-pipes transferring the solar flux from the collectors to the distribution system are placed on the ground, not hanging from the ceiling.
2) The distribution system is the tunnel vault itself. A new geometry capable to reflect the solar flux injected by the light-pipes towards the road while fulfilling its normal structural functions has been proposed.

The simulations carried out with the software DianaX, departing from an estimated luminous flux of about 1.8 $\times$ 10^6 lm, yield an average illuminance on the pavement about 3478 lx, with average uniformity, U_m = 0.73. Since one standard tunnel can require about 8222 lx in the threshold zone, 42 % of the consumed energy can be saved.

Besides these savings, the presented system has several advantages compared to existing ones. The most relevant are the following:

1) It is not necessary to have a high gauge, which implies that this system can be implemented in existing tunnels. It means that thousands of tunnels around the world (only in Spain there are 513) could benefit from the simple and inexpensive retrofit installation of the proposed system.
2) In these existing tunnels, a built-in vault connected to the old one can be easily adapted with a minimum decrease in the tunnel gauge.

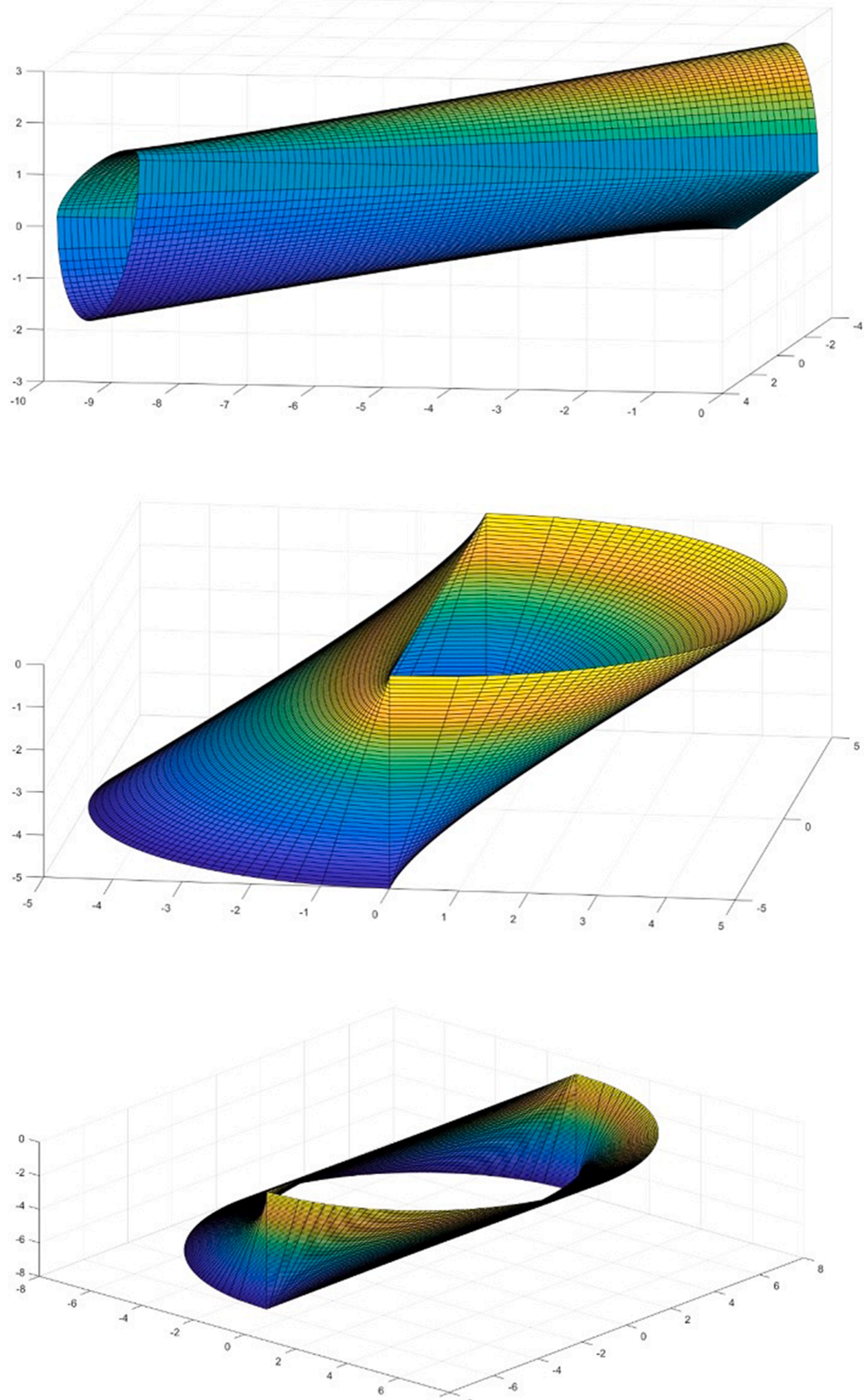

Fig. 8. (a), (b), (c) and (d). Differential geometry phases obtained in the modeling of the complex shape of the new tunnel vault.

3) The maintenance of the ground-based light-pipes is much easier than in those models where the pipes came through the ceiling.
4) Given that the solar flux is collected in the opencast zone near the road in swimming-pool like collectors, their size can be very high in many cases, achieving as much flux as necessary to increase the profitability of the system.

As main limitation, the total transmittance between maintenance periods of the collector surfaces is still to be determined, even if the automatic systems to blow or water the transparent layers eliminate the depositions of dirt. It highlights a clear need to build a scale mock-up to evaluate the luminous flux losses in real opencast conditions. Ignoting the precise value of transmittance, implicitly makes us guess a

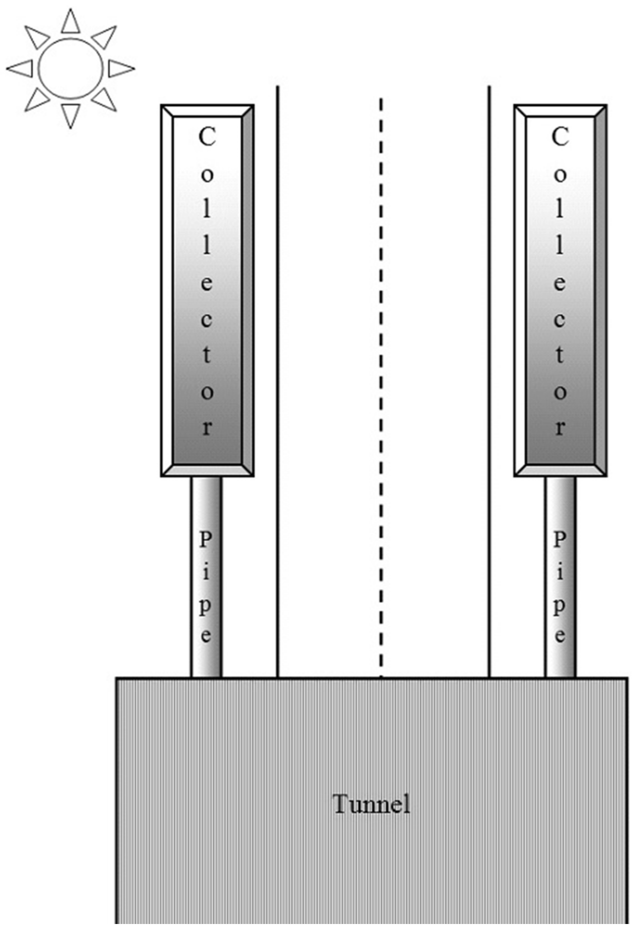

Fig. 9. Sealed sun collectors in both shoulders of the road coupled to the light-pipes.

maintenance factor $m_f = 1$ when calculating the illuminance on the pavement in section 3.3, which is a limitation of this study.

The construction of these mock-ups is a priority action that will allow to estimate the illuminance on the pavement with higher precision. Although it is expected to carry out similar research with highly reflective materials, the next step in this line of research is the mentioned construction of these scale models.

CRediT authorship contribution statement

A. Peña-García: Data curation, Writing – original draft,

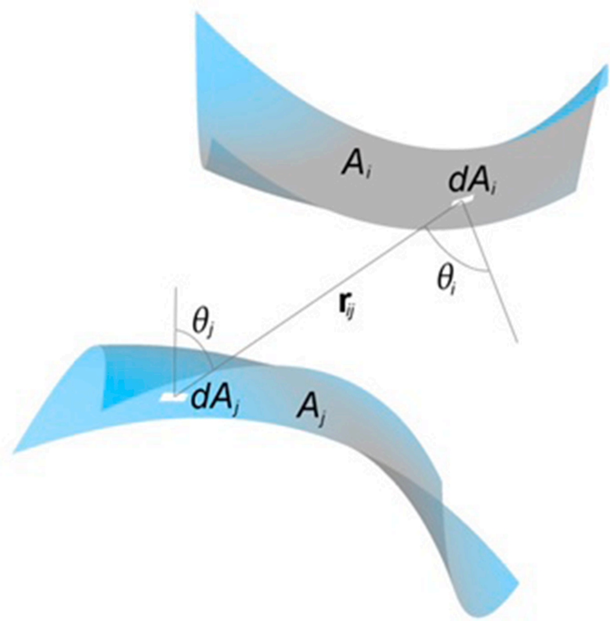

Fig. 11. Radiative transfer quantities involved between two surfaces Ai and Aj following Eq. (1).

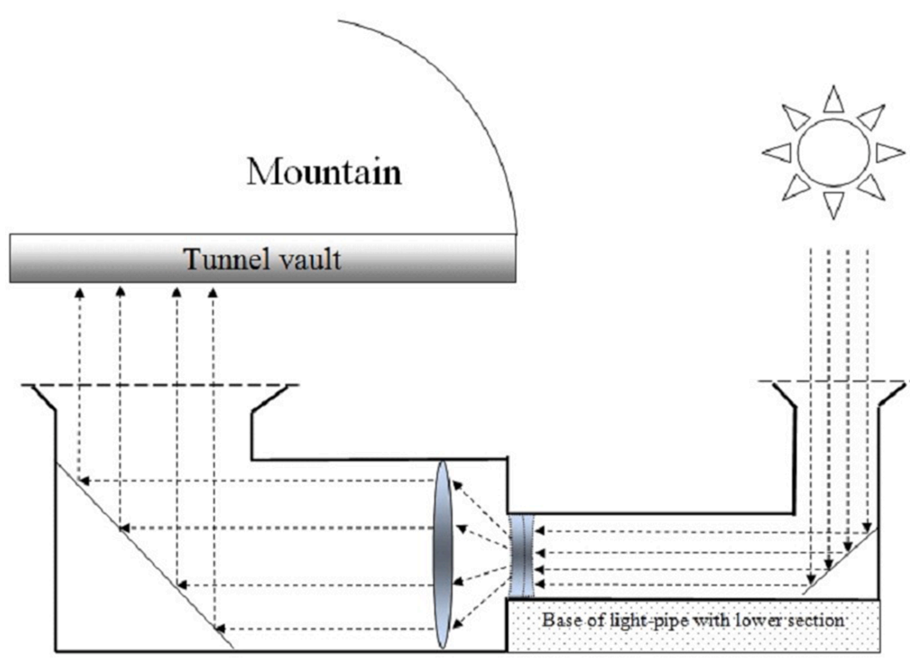

Fig. 10. Longitudinal section of one of the two systems employed in one side of the road. The luminous flux is captured by the collectors and then transported through the light-pipes up to the interior of the tunnel where it is distributed towards a complex shaped reflecting vault.

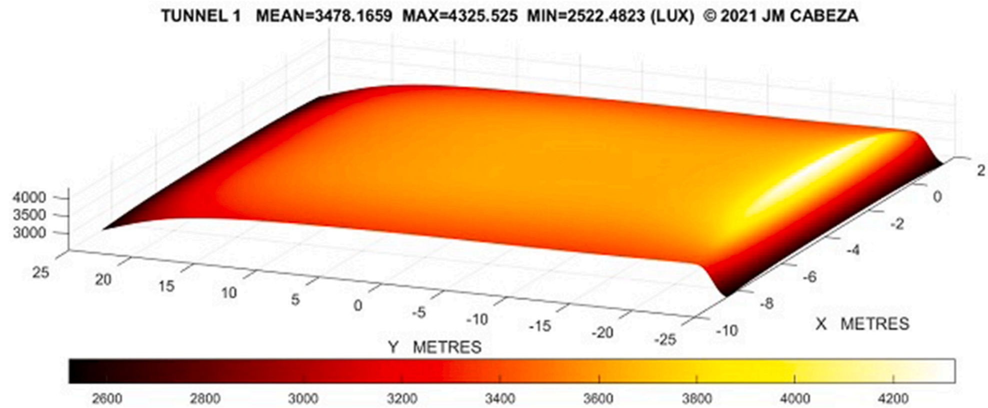

Fig. 12. Illuminance distribution on the pavement of a standard tunnel (Tunnel 1) for the estimated collected flux with vehicle entrance to the right side of the radiation map. The illuminances marked on the horizontal colour scale are in lux (lm/m^2).

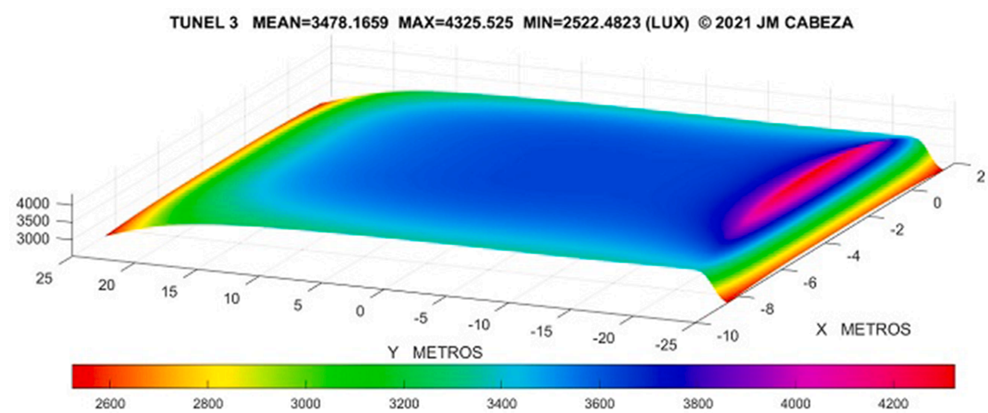

Fig. 13. Illuminance distribution in lux over the pavement of a second proposed model of tunnel (Tunnel 3) showing negligible variations (less than 1%).

Visualization, Investigation, Writing – review & editing. **J. Cabeza-Lainez:** Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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