Tunnelling and Underground Space Technology 148 (2024) 105779

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology incorporating Trenchless Technology Research

journal homepage: www.elsevier.com/locate/tust

# Scaled hillsides to decrease the energy consumption of lighting installations in road tunnels

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ARTICLE INFO

*Keywords:*
Tunnel lighting
Light distribution
Energy savings
Reflection
Sunlight

ABSTRACT

The reduction of energy demands of the lighting installations in road tunnels, has become a matter of active research in the last years. Among the different strategies, the decrease of reflectance in the surroundings of portal gate, has been pursued by means of forestation or installation of elements with lower reflectance than concrete. However, these strategies are difficult to carry out due to remarkable problems like initial implementation, maintenance, shape of the mountain and other properties of the terrain. Furthermore, they consider only the decrease in the reflectance without controlling the directions where the light is reflected. This work proposes the introduction in the hillside around the portal of discrete surfaces with given orientation to deviate the reflected light from the visual field of drivers. The target is to ease the visual adaptation, making the visual transition smoother, and decrease the glare and luminance in the zone of the road that determines the lighting requirements inside the tunnel. The result is a scaled-like zone around the portal whose parameters are calculated, analyzed, and presented in this work.

## 1. Introduction

The high consumption of lighting installations in tunnels in terms of energy, number of projectors, wiring and auxiliary devices as well as the financial and environmental impact from their production and demanding maintenance, have been a matter of concern for Public Administrations for ages (Peña-García, 2022 a, b). Thus, most countries have specific regulations on tunnel lighting. In addition to these regulations and generally in good agreement with them, the standard CIE 88:2004 (CIE Publ. 88:2004, 2004) from the International Commission on Illumination (CIE), is a document of reference followed in most scientific studies including this one.

The energy consumption is especially high during daytime due to the long time needed by the human visual system to adapt from high luminance levels (photopic conditions) to lower luminance, the so-called mesopic conditions (Mehri et al., 2017, 2019, 2020). The peculiarities of mesopic vision, is one major challenge in modern lighting not only in tunnels, but also in a wide variety of activities related to driving (Eloholma, 2005; CIE Publ. 191:2010, 2010; Fryc et al., 2021). Since long adaptation times are unacceptable in driving, the classical way to avoid the abrupt visual transition when entering the tunnels during daytime, is to provide high luminance levels in the threshold zone (Peña-García et al., 2010; Gil-Martín et al., 2011; Drakou et al., 2015, 2016, 2017). This quantity, luminance (L), is the luminous flux per unit of surface and solid angle from pavement and walls to the drivers' eyes (CIE Publ. S017, 2020).

Thus, whereas the required luminance levels are constant and relatively low during nighttime, they must be very high during the day, especially in the first dozens of meters inside the tunnel. Then, they progressively decrease following a strict pattern to minimize the consumption while ensuring visual adaptation and traffic safety. It is necessary to remark that the link between tunnel lighting and traffic safety is essential since about 80 % of inputs, are perceived through the sense of sight (Fitzgerald, 2019). In this complex diurnal context, the target of this research, the luminance levels and profile along the tunnel, depend on several factors. They are mostly determined by the luminance out of the tunnel, that comes from the sky and the sunlight reflected in different elements of the road and portal.

The external luminance can be calculated with the "L20 method" (CIE Publ. 88:2004, 2004). It consists of the evaluation of the luminance, L20, inside one cone of 20° aperture from the portal gate seen by one approaching driver at the safety distance.

Fig. 1 shows the basis of this cone with several sectors contributing to L20 (sky, road, concrete…). The higher the contribution in luminance of each sector, the higher L20 and, hence, higher luminance demands during daytime, consumption, and number of projectors in the threshold and transition zones.

Several research up to date have been focused on reducing the reflectance of the portal surroundings to decrease the L20. Some of them have been based on the forestation with vegetal species with more or less

https://doi.org/10.1016/j.tust.2024.105779
Received 20 March 2024; Received in revised form 18 April 2024; Accepted 22 April 2024
Available online 27 April 2024

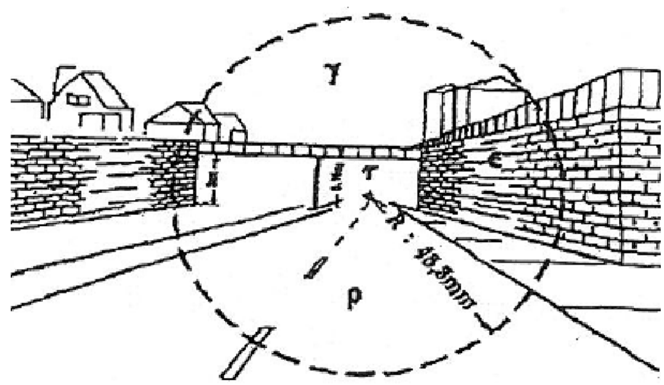

**Fig. 1.** Basis of the L20 cone. The different areas in the circle have different contributions to the L20 luminance. Figure taken from CIE Publ. 88:2004 (2004).

dark leaves (López et al., 2014; Peña-García et al., 2015; García-Trenas et al., 2018), whereas others have proposed the installation of dark solar panels to also get some power to light the emergency projectors or similar (Peña-García and Gómez-Lorente, 2020) as shown in Fig. 2 or other means to profit from solar energy (Sun et al., 2019).

However, the forestation or installation of elements in the portal surroundings is expensive and, frequently, difficult to implement and keep safely along the time. Furthermore, the risks associated to these installations include fall off leaves, branches, or other elements to the road at the entrance to the tunnel. These circumstances demand very strict, expensive and risky works of maintenance. Another solution could be painting the portal surroundings in dark colors but, although the inner walls of some tunnels have been painted with different intentions (Ling et al., 2021), it is necessary to keep a good landscape integration of the portal (Lingli and Dongping, 2008; Fei et al., 2012; López et al., 2017) to avoid distractions and ensure driving performance (Miller and Boyle, 2015).

As parallel or complementary measures, it has been proposed to reduce the maximum speed allowed in the tunnel, which also results in a reduction of the required L20 (Peña-García et al., 2019), and the implementation of actions on the pavement to decrease the luminous flux needed to reach the required luminance (Salata et al., 2015; Moretti et al., 2016, 2017a, 2017b, 2019; Cantisani et al., 2018, Wang et al., 2021).

In summary, new strategies to decrease the L20 luminance with lower impact on investments and maintenance, are necessary. In this framework, the redirection of solar rays out of the cone has not been proposed up to date. The next section presents a proposal based on scaled-like hills including elements with specific orientations to reflect solar rays out of the L20 cone. The target is to facilitate the visual adaptation and avoiding the glare to drivers.

## 2. The model

As said, the "L20 cone" is a cone with aperture of 20° whose edge is in the driver eye when facing one point of the portal at 0,25$H_T$, (height of tunnel portal) from the safety distance (SD). The radius of its basis, R20, extends on the gate surroundings defining the area whose elements (rocks, concrete, vegetation…) contribute to the L20 (CIE Publ. 88:2004, 2004; López and Peña-García, 2018) (Fig. 3). It is given by:

$$R_{20} = SDtan10\hat{A}^{o} \quad (1)$$

In standard tunnels with maximum speed v = 100 km/h, SD = 159 m so, R20 = 28 m. If the zone where reflected rays can increase the L20 is approximately the upper half of this circle, its area, S = 1231,5 $m^2$, is quite large.

The proposal of this work is the configuration of scaled-like hillsides through the introduction of surfaces with specific orientations in the surroundings of portals to deviate solar rays out of the L20 cone. It will be carried out in two steps: a bidimensional approach considering only the solar elevation $\theta$, and then, the definitive model, incorporating the solar azimuth, $\varphi$.

### 2.1. *Tunnels perfectly aligned with the solar ecliptic ($\varphi = 0$)*

As bidimensional case of tunnel perfectly aligned with the solar ecliptic ($\varphi = 0$), will be used introduce the main concepts and methodology that will allow easy derivation of the general model for tunnels with arbitrary orientation. Under this approach, only the solar elevation, $\theta$, changes along the day for each season of the year. The results obtained can be valid in good approximation for tunnels with W-E and E-W orientation.

Let there be the tunnel in Fig. 4, with W-E or E-W orientation and clearance, $H_T$. Since the solar rays come parallel due to the distance Sun-Earth, for a given $\theta_i$, some rays will be reflected on the hillside, whilst other will enter the tunnel. Among the reflected ones, some will enter the L20 cone increasing the L20 luminance. Other rays will pass above the driver at SD, falling on the road behind without contributing to L20. The rays reflected on the road between the car and the tunnel, can increase the luminance towards the driver.

Fig. 4 also shows that the position of each point where light is reflected, can be referred to the ground ($H_p$) or to the portal edge ($h_p$), being $H_p = H_T + h_p$. There is also a "limit ray" reflected on the portal edge towards the driver eyes contributing to L20.

Furthermore, each point on the hillside is characterized by three parameters:

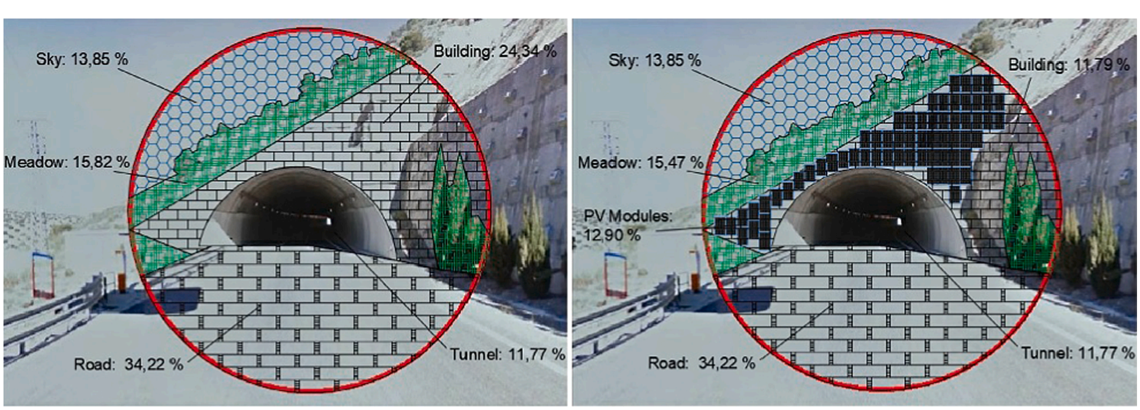


**Fig. 2.** L20 cone before tunnel portal with (a) clear concrete, (b) Simulated installation of 64 black solar panels (Peña-García and Gómez-Lorente, 2020).

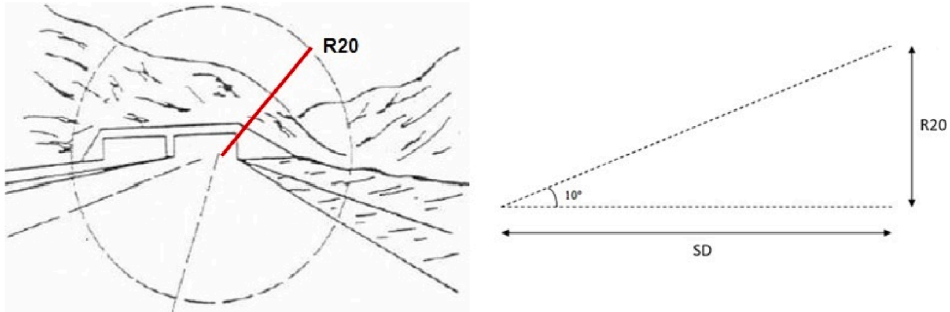


**Fig. 3.** The radius R20 of the L20 cone basis (angle not in real scale).

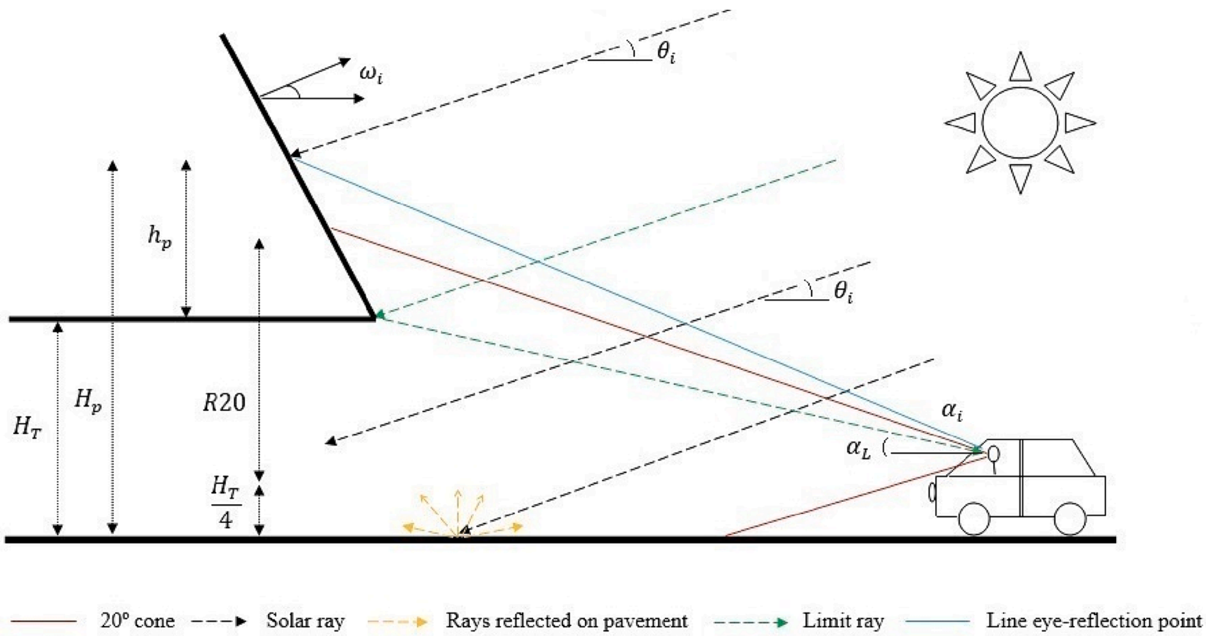


**Fig. 4.** Tunnel portal during daytime with solar elevation, $\theta_i$. Angle of generic reflection point, $\omega_i$, and angles from driver eyes, $\alpha_i$ and $\alpha_L$, are displayed.

- $h_p$: height of the point over the portal top. It is independent of tunnel characteristics.
- $\omega_i$: angle between the perpendicular to the plane tangent to the mountain in the point, and the horizontal. It depends on the morphology of the hillside.
- $\alpha_i$: angle between the point and the horizontal line to the driver eyes at SD. Since SD depends on the maximum speed, inclination of road and reaction time defined by the relevant regulation, $\alpha_i$ depends on the tunnel characteristics. For standard position of driver eyes at 1,5 m (CIE Publ. 88:2004, 2004), it can be expressed as:

$$\tan\alpha_i = \frac{H_T + h_p - 1.5}{SD} \tag{2}$$

There is also a "limit angle", $\alpha_L$, between the reflected limit ray, and the horizontal line to the driver eye at SD. Since it depends in $H_T$ and SD, it is specific for each tunnel:

$$\tan\alpha_L = \frac{H_T - 1.5}{SD} \tag{3}$$

$$Combining(2)and(3):\tan\alpha_i = \frac{h_p}{SD} + \tan\alpha_L \Rightarrow \alpha_i > \alpha_L \tag{4}$$

These four parameters, determine what rays will enter the L20 cone and, consequently, the external luminance defining the lighting installation.

In the particular case of vertical hillsides ($\omega_i = 0$), the angle of reflection on each point of the mountain equals to $\theta_i$. So, any ray reflected on $h_p$, will fall out of the L20 cone if $\theta_i < \alpha_i$. This requires very low angles since for typical parameters SD = 159 m and $H_p = 12m \Rightarrow \alpha_i = 3{,}8^\circ$.

According to these figures, vertical hillsides always reflect the solar rays inside the L20 cone unless the solar elevation, $\theta_i$, is very low (sunrise or sunset). So, these tunnels may have higher L20 luminance and be more impacting. Even the limited hours when rays are reflected out of the cone, are not meaningful because the luminance is low, and the visual adaptation is not so demanding. Furthermore, the car headlamps are lit and the projectors inside the tunnel are dimmed (Lai et al., 2014; Salata et al., 2016; Qin et al., 2017; Zhao et al., 2021), so the energy consumption is not very high.

However, when hillsides are not vertical ($\omega_i \neq 0$), the smoother their slope, the more rays reflected out of the L20 cone. It means that a scaled configuration of the portal surroundings with inclined surfaces, would deviate more rays from the L20 cone (Fig. 5):

Once the basic geometry of rays and portal surroundings has been presented, the parameters of the surfaces that can reflect out of the L20 cone as many rays as possible, can be calculated. Fig. 6 shows that, if all the scales faced the Sun (making an angle $\beta_i = \frac{\pi}{2} - \theta_i$ with the horizontal), all the solar rays would be reflected back instead entering the L20 cone and, furthermore, decreasing the glare to drivers.

Despite its pros, this solution is not realistic because the solar

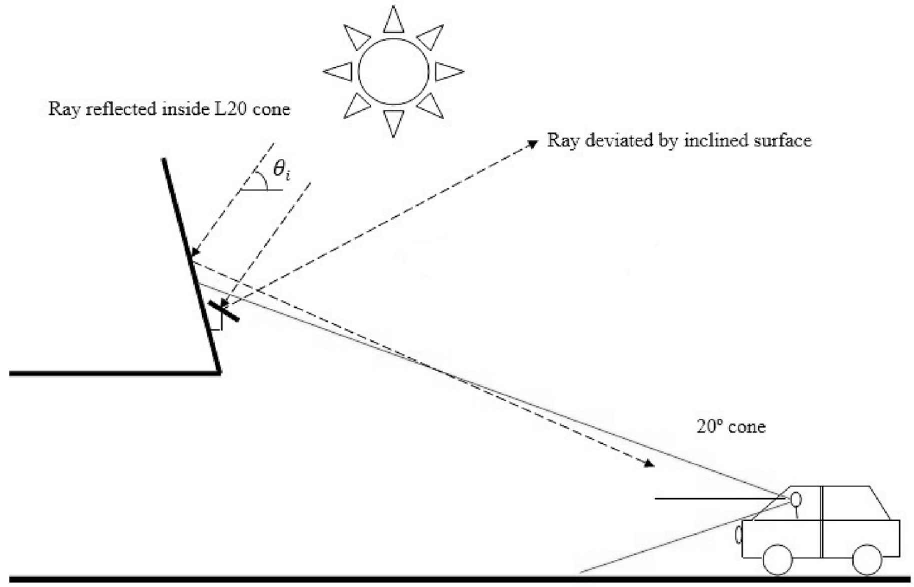


**Fig. 5.** Reflection of solar rays in and out of the L20 cone by inclined surfaces.

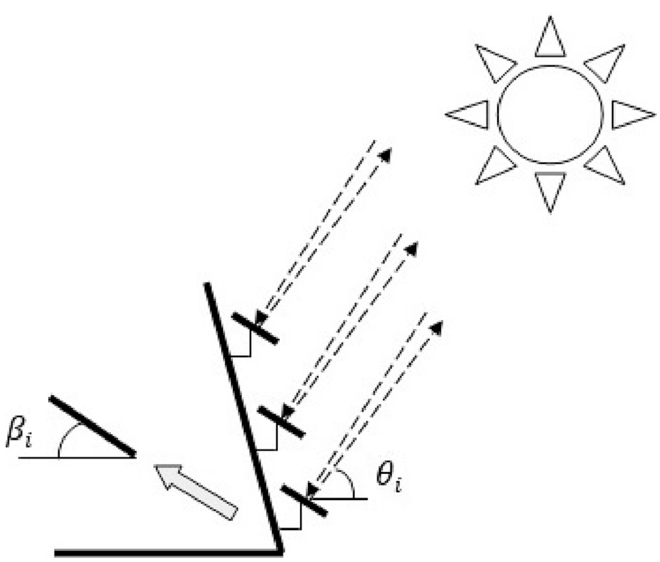


**Fig. 6.** Scaled hillside where each individual surface, faces the Sun with inclination $\beta_i$, reflecting the rays back towards it.

elevation, $\theta_i$, is not a static parameter, but changes along the day and the year. Even the mechanization of the surfaces with engines or other devices to track the ecliptic, would be expensive and consuming in power and maintenance. It makes necessary a conservative solution.

If the surfaces are fixed the highest yearly solar elevation in one given location, $\theta_{Max}$, no ray is reflected inside the cone at lower $\theta_i$, but towards the mountain. In other words, scaled-like hillsides (or sectors near the tunnel portal) formed by surfaces with inclination $\beta = \frac{\pi}{2} - \theta_{Max}$, would minimize the L20 luminance, decreasing the energy, materials, emissions, maintenance, and resources consumed by the lighting installation. The benefits of this geometry go beyond energy savings because, reflecting the light back to the Sun or upwards, minimizes the glare to the drivers, that will not receive direct rays from the Sun.

For example, in Spain, where $\theta_{Max} \approx 73Â^{o}$ (June 21st), tunnels with almost perfect E-W or W-E, having hillsides made of scaled with inclination $\beta = 27Â^{o}$, request lower consumptions in lighting. In this case, for square surfaces of 1 m x 1 m, the vertical projection on the mountain is $1 \bullet sin27Â^{o} = 0.45m$. A typical basis of the L20 cone has R = 28 m, that can be covered with 62 surfaces of 1 m x 1 m.

In the case of tropical locations, where $\theta_{Max} \approx 90Â^{o}$, it would be necessary to install almost completely horizontal surfaces. It is a problem because the vertical gaps between them can reflect rays inside the L20 cone and require complex maintenance (Fig. 7).

In this unfavorable case, the surfaces need to be inclined to overlap as much as possible whilst ensuring that no reflected ray enters the L20 cone. A detailed analysis of the angles involved in this condition is shown in Fig. 8:

Where $x_i$ is he angle between the surface and the line between the point and the driver eyes at SD. It can be deduced that $\omega_i + \alpha_i + x_i = \frac{\pi}{2}$.

It can be deduced from the figure that orientating surfaces so that $x_i = 0$, makes their edges point to the eyes of one driver at SD, defining the limit where solar flux influences the installed power inside the tunnel. This is equivalent to make an angle $\alpha_i$ between the surface and the horizontal in each point. In this case, whatever the solar elevation $\theta_i$, all the reflected rays would go to the eyes of the driver causing glare. So, a slight rotation of each the surface towards the horizontal, making angles slightly lower than $\alpha_i$, deviates all the rays out of the L20 cone without concentrating them on the drivers.

To define "slightly lower than $\alpha_i$", let there be one point in the hillside around the portal of one tunnel with maximum allowed speed of 100 km/h. The height of this point above the ground can be, for example, 12 m. For this point:

$$\tan\alpha_{12} = \frac{H_p - 1.5}{SD} = 3.78Â^{o}$$

If the angle is decreased in $1^{\circ}$,.$\alpha_{12} - 1Â^{o} = 2.78Â^{o} \Rightarrow D = \frac{10.5}{\tan(2.7Â^{o})} = 216.24\,m$

If the angle is decreased in $0.5^{\circ}$,.$\alpha_{12} - 0.5Â^{o} = 3.28Â^{o} \Rightarrow D = 183.22m$

These figures show that, a slight decrease in $0.5^{\circ}$ in the angle of the edge of the surface at 12 m, results in the reflection 24 m behind the limit of the L20 cone, which seems enough. Since different surfaces are installed at different heights, the reflected rays would never concentrate in any point of the road, avoiding glare to drivers.

In summary, in tunnels aligned with the solar ecliptic, the installation of surfaces facing the maximum local yearly solar elevation ($\theta_{Max}$), ensures minimum reflection in the zone of the road that determining the visual adaptation and the lighting profile inside the tunnel. If the tunnel

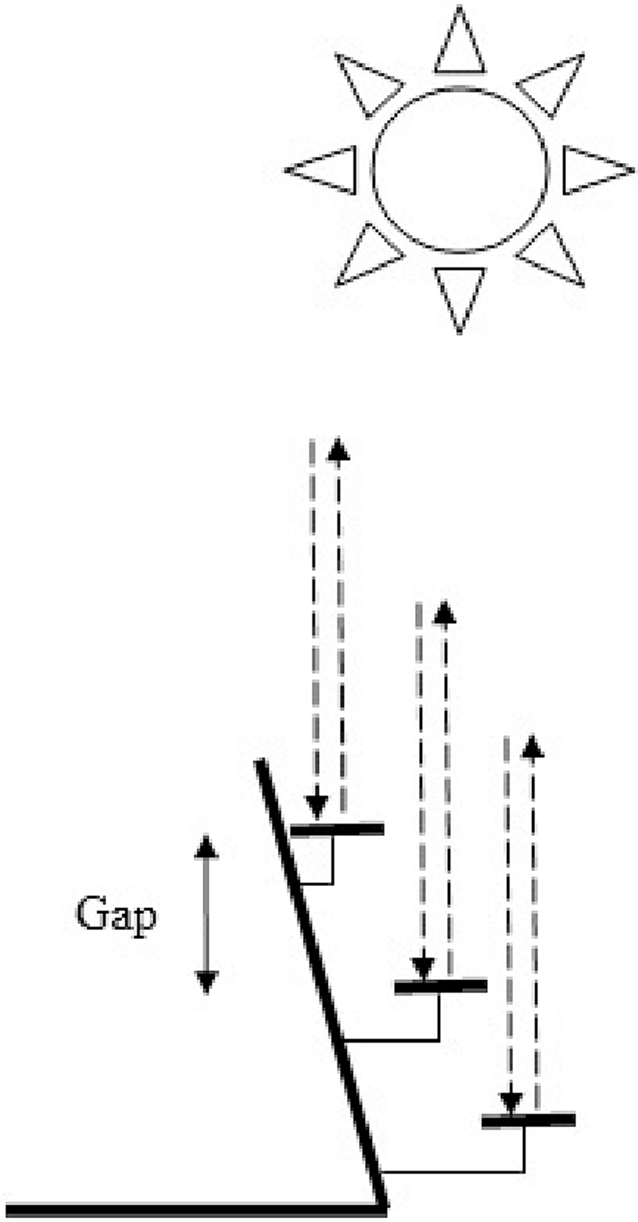


**Fig. 7.** Scaled hillside in places with $\theta_{Max} \approx 90Â^{o}$. The horizontal surfaces make vertical gaps.

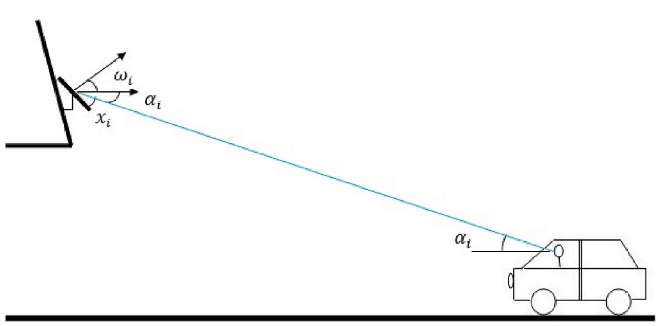


**Fig. 8.** Angles of arbitrary inclined surface.

is near to tropical zones $\theta_{Max} \approx 90Â^{o}$, the surfaces should be horizontal, which causes vertical gaps between them. In this case, the maximum inclination ensuring that the reflected rays will not enter the L20 cone nor glare the drivers, is $\alpha_i$- 0.5°.

In the next subsection, the general case of tunnels with any orientation is approached.

### 2.2. Tunnels with arbitrary orientation ($\varphi \neq 0$)

The results above, demonstrate that the configuration of scaled-like areas on the hillside near the gate, with surfaces facing the maximum yearly solar elevation, can minimize solar light in the L20 cone. However, these results have been deduced for tunnels under the ecliptic, that is, approximately E-W or W-E orientation. In most cases, the relative position between tunnel portals and the solar rays presents an azimuthal angle, $\varphi$ as shown in Fig. 9 (Peña-García et al., 2016).

For this reason, besides the maximum yearly solar elevation, $\theta_{Max}$, the surfaces must be also inclined towards the maximum yearly azimuth, $\varphi_{Max}$. This way, in the most critical solar position, the rays will be reflected back, whereas intermediate positions of the Sun will result in reflections towards zones out of the road as shown in Fig. 10. In this figure, the reflection of rays from three different solar positions (extreme left, right and center) is shown in the most unfavorable situation, S-N or N-S orientation. As in the bidimensional case, this configuration avoids rays to be reflected towards the road.

The overall result is a scaled-like hillside with low luminance reflected toward the zone determining the installed power inside the tunnel. This proposal is applicable to both, vertical and sloped hillsides, although the lower the slope, the lower the number of surfaces and the overall maintenance. Furthermore, the absence of aesthetical purposes of these simple surfaces, avoids potential distractions of drivers, that would not perceive any image or scene impairing their attention.

This could be also applied to an emerging field, the study of adaptations to grouped tunnels, one configuration more and more frequent (Wang et al., 2018; Peña-García, 2019; Sun et al., 2021).

## 3. Conclusions

Lighting installations of road tunnels have a deep economic and environmental impact due to their high consumption of energy and raw

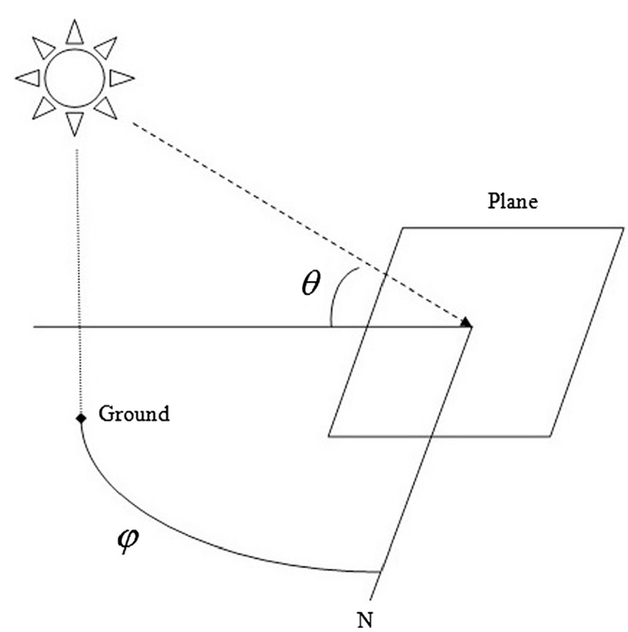


**Fig. 9.** Solar angles for plane with arbitrary orientation (Peña-García et al., 2016).

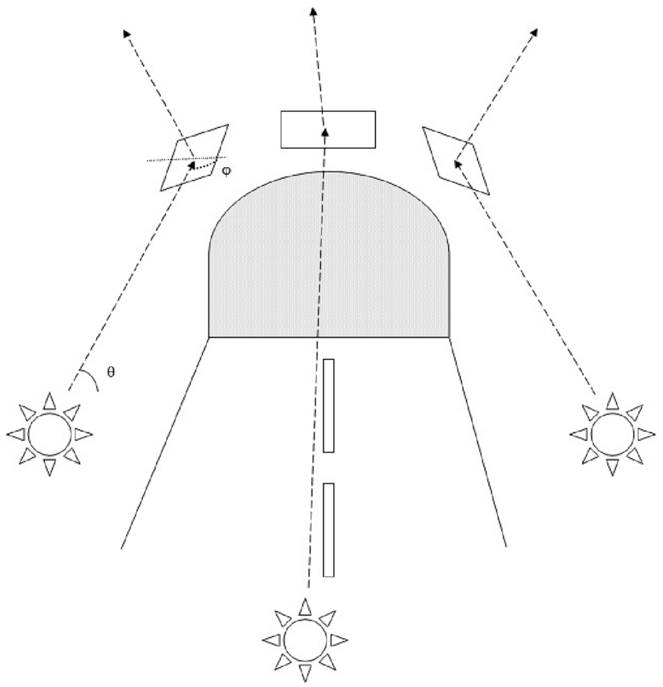


**Fig. 10.** Frontal view of the reflection on inclined panels for three solar positions in tunnel with S-N orientation.

materials. In addition, the production of energy and manufacture of projectors, wiring and electrical devices, causes emissions of greenhouse gases, contamination, and very high financial expenses. Even more, the maintenance of these installations is expensive, complex, and dangerous. These facts make it clear that the lighting requirements in road tunnels must be decreased while keeping the highest safety and comfort of drivers.

This work presents a new strategy to reduce the luminance requirements through decrease of the environmental luminance in the visual field of drivers approaching the tunnels. By first time, the main (but not unique) target of one strategy of this nature, is not the introduction of elements with low reflectance in the surroundings of tunnel portals, but the redirection of solar rays out of the L20 cone, which is the zone influencing the visual adaptation of drivers.

Departing from these premises, the model developed and presented in this work, leads to some important conclusions:

1) The previous works on the decrease of reflectance of portal surroundings to decrease the luminance levels inside the tunnel, required in most cases forestation with very specific evergreen vegetal species. The coverage of the area should be complete to ensure lower reflected solar flux and, the maintenance and hard work from initial planting and during the whole life of the tunnel, should be very consuming in time, money, and other resources.
2) The configuration of scaled-like hillsides with oriented surfaces as defined in this work, is feasible and adaptable to each tunnel. It allows smooth visual adaptation, luminance reduction and savings in financial resources, consumed energy, materials, maintenance, and emissions.
3) The reflection of rays out of the L20 cone, also decreases the glare to the drives.
4) Since reflecting the rays back to the Sun is difficult in high latitudes, in these regions it is recommendable a progressive change the inclination of the surfaces along the hillside, avoiding also the concentration of the reflected solar flux on the driver eyes.
5) This strategy is fully compatible with the reduction of reflectance of the elements in the portal surroundings. Dark-grey cement, synthetic or other materials resistant to the atmospheric elements with low maintenance, seem fine.
6) In matter of maintenance, dirt is not a problem since it reduces reflectance and diffuses light even more. It results in lower cleaning, which is a remarkable saving compared to other solutions to decrease light consumption in tunnels.

The approximations assumed in this work and some of its potential limitations are the basis of next research that must be undertaken. They are the following:

1) Although specular reflection is assumed in some calculations, common building materials reflect a more diffuse pattern. This is not a problem because the proposal of this work is conservative and there is always a geometric shading of the L20 cone. Anyhow, the characterization of the reflection patterns of the different materials candidates to build these scales, could give predictions of L20 luminance.
2) The inclined surfaces can be orientable or not. If their angles could be changed along the year to better track the apparent path of the Sun, the accuracy of the scaled-like solution would be higher. However, any mechanism to change their orientation has risk of failure and requires maintenance. The consideration of pros and contras must be approached in future research.
3) Scaled-like sidehills are not valid in any tunnel because they do not reflect light out of the L20 cone whatever the solar position. When the Sun is behind a not very high mountain, it is front of the incoming drivers with the evident risk of glare. In this situation, the surfaces in the opposite face of the hillside, can not reflect light.

In summary, scaled-like hillsides made with inclined surfaces with low reflectance and specific orientations, deviate solar rays out of the L20 cone. This result, not proposed up to date, is an accurate solution to decrease glare and lighting requirements in tunnels.

## CRediT authorship contribution statement

**A. Peña-García:** Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

## 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

No data was used for the research described in the article.

## References

Cantisani, G., Di Mascio, P., Moretti, L., 2018. Comparative Life Cycle Assessment of lighting systems and road pavements in an Italian twin- tube road tunnel. Sustainability 10, 4165.
Commission Internationale de l'Éclairage, CIE, 2004. Guide for the lighting of road tunnels and underpasses, CIE Publ. 88, Vienna.
Commission Internationale de l'Éclairage, CIE, 20010. Recommended System for Mesopic Photometry Based on Visual Performance, CIE 191:2010, Vienna.
Commission Internationale de l'Éclairage, CIE, 2020. ILV: International Lighting Vocabulary, CIE Publ. S017/E:2020, Vienna.
Drakou, D., Burattini, C., Bisegna, F., Gugliermetti, F., 2015. Study of a daylight "filter" zone in tunnels. In: In: Proceedings of the IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC), pp. 649–652.
Drakou, D., Burattini, C., Mangione, A., Bisegna, F., 2017. Exploring the daylight simulation of filter panels in a pre-tunnel structure. In: In: Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), pp. 1–5.

Drakou, D., Celucci, L., Burattini, C., Nardecchia, F., Gugliermetti, F., 2016. Study for optimizing the daylight "filter" in a pre-tunnel structure. Study for optimizing the daylight "filter" in a pre-tunnel structure. In: Proceedings of the IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC).p. 4.
Eloholma, M., Viikari, M., Halonen, L., Walkey, H., Goodman, T., Alferdinck, J., Freiding, A., Bodrogi, P., Várady, G., 2005. Mesopic models—From brightness matching to visual performance in night-time driving: a review. Light. Res. Technol. 37, 155–175.
Fei, Y., Chuan, H., Shi-min, W., Jin-long, Z., 2012. Landscape design of mountain highway tunnel portals in China. Tunn. Undergr. Space Technol. 29, 52–68.
Fitzgerald, R., 2019. How can we optimize evolving lighting design to enhance health and well-being? [Online] https://www.stantec.com/en/ideas/topic/buildings/how-can-we-optimize-evolving-lighting-design-to-enhance-health-and-well-being.
Fryc, I., Czyżewski, D., Fan, J., Gălăţanu, C., 2021. The Drive towards Optimization of Road Lighting Energy Consumption Based on Mesopic Vision—A Suburban Street Case Study. Energies 14, 1175.
García-Trenas, T., López, J.C., Peña-García, A., 2018. Proposal to forest Alpine tunnels surroundings to enhance energy savings from the lighting installations. Towards a standard procedure. Tunn. Undergr. Space Technol. 78, 1–7.
Gil-Martín, L.M., Peña-García, A., Hernández-Montes, E., Espín-Estrella, A., 2011. Tension structures: a way towards sustainable lighting in road tunnels. Tunn. Undergr. Space Technol. 26, 223–227.
Lai, J., Qiu, J., Chen, J., Wang, Y., Fan, H., 2014. Application of wireless intelligent control system for HPS lamps and LEDs Combined illumination in road tunnel. Comput. Intell. Neurosci. 2014, 1–7.
Ling, J., Zheng, Y., Chen, X., Wang, S., 2021. Virtual simulation technology for the design of the interior environment in an ultralong tunnel. IOP Conf. Series: earth and environmental. Science 861, 072025.
Lingli, J., Dongping, Z., 2008. A study on the trend of development and present state of tunnel entrance landscaping [J]. Chin. Civil Eng. J. 1, 88–92.
López, J.C., Grindlay, A.L., Carpio, M.C., Peña-García, A., 2014. Strategies for the optimization of binomial energy saving landscape integration in road tunnels. WIT Trans. Ecol. Environ. 190, 511–520.
López, J.C., Grindlay, A.L., Peña-García, A., 2017. A proposal for evaluation of energy consumption and sustainability of road tunnels: the sustainability vector. Tunn. Undergr. Space Technol. 65, 53–61.
López, J.C., Peña-García, A., 2018. 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. Tunn. Undergr. Space Technol. 78, 8–15.
Mehri, A., Hajizadeh, R., Dehghan, S.F., Nassiri, P., Jafari, S.M., Taheri, F., Zakerian, S. A., 2017. Safety evaluation of the lighting at the entrance of a very long road tunnel: a case study in Ilam. Safety Health at Work 8, 151–155.
Mehri, A., Sajedifar, J., Abbasi, M., Naimabadi, A., Mohammadi, A.A., Teimori, G.H., Zakerian, S.A., 2019. Safety evaluation of lighting at very long tunnels on the basis of visual adaptation. Saf. Sci. 116, 196–207.
Mehri, A., Sajedifar, J., Abbasi, M., Jalali, M., Gholampour, J., Salehian, T., Zakerian, S. A., Faghihnia Torshizi, Y., 2020. The evaluation of luminance in a road tunnel based on CIE88-2004 standard to reduce road accidents. Iran Occupational Health 29, 17–23.
Miller, E.E., Boyle, L.N., 2015. Driver behavior in road tunnels association with driver stress and performance. Transp. Res. Rec. 2518, 60–67.
Moretti, L., Cantisani, G., Mascio, P.D., 2016. Management of road tunnels: construction, maintenance and lighting costs. Tunn. Undergr. Space Technol. 51, 84–89.
Moretti, L., Cantisani, G., Di Mascio, P., Caro, S., 2017a. Technical and economic evaluation of lighting and pavement in Italian road tunnels. Tunn. Undergr. Space Technol. 65, 42–52.
Moretti, L., Mandrone, V., D'Andrea, A., Caro, S., 2017b. Comparative "from cradle to gate" Life Cycle Assessments of Hot Mix Asphalt (HMA) Materials. Sustainability 9, 400.
Moretti, L., Cantisani, G., Carrarini, L., Bezzi, F., Cherubini, V., Nicotra, S., 2019. Italian Road Tunnels: economic and Environmental Effects of an On-Going Project to Reduce Lighting Consumption. Sustainability 11, 4631.
Peña-García, A., 2019. Optical coupling of grouped tunnels to decrease the energy and materials consumption of their lighting installations. Tunn. Undergr. Space Technol. 91, 103007.
Peña-García, A., 2022. Sustainable tunnel lighting: One decade of proposals, advances and open points. Tunn. Undergr. Space Technol. 119, 104227 (9 pp).
Peña-García, A., Gil-Martín, L.M., Espín-Estrella, A., Aznar-Dols, F., 2010. Energy saving in road tunnels by means of transparent tension structures. In: International Conference on Renewable Energies and Power Quality (ICREPQ'10). Granada (Spain).
Peña-García, A., Gil-Martín, L.M., Hernández-Montes, E., 2016. Use of sunlight in road tunnels: an approach to the improvement of light-pipes' efficacy through heliostats. Tunn. Undergr. Space Technol. 60, 135–140.
Peña-García, A., Gómez-Lorente, D., 2020. Installation of solar panels in the surroundings of tunnel portals: a double-targeted strategy to decrease lighting requirements and consumption. Tunn. Undergr. Space Technol. 97.
Peña-García, A., López, J., Grindlay, A., 2015. Decrease of energy demands of lighting installations in road tunnels based in the forestation of portal surroundings with climbing plants. Tunn. Undergr. Space Technol. 46, 111–115.
Peña-García, A., Salata, F., Golasi, I., 2019. Decrease of the Maximum Speed in Highway Tunnels as a Measure to Foster Energy Savings and Sustainability. Energies 12, 685.
Peña-García, A., 2022b. Strategies to decrease energy consumption in tunnel lighting: the feasible compromise between Safety and Sustainability. International Conference on Energy Efficiency in Domestic & Light Sources (LS:17). Toulouse (France), 1-3 June 2022.
Qin, L., Dong, L.L., Xu, W.H., Zhang, L.D., Leon, A.S., 2017. An Intelligent Luminance Control Method for Tunnel Lighting Based on Traffic Volume. Sustainability 9, 2208.
Salata, F., Golasi, I., Bovenzi, S., Vollaro, E., Pagliaro, F., Cellucci, L., Coppi, M., Gugliermetti, F., Vollaro, A., 2015. Energy optimization of road tunnel lighting systems. Sustainability 7, 9664–9680.
Salata, F., Golasi, I., Poliziani, A., Futia, A., de Lieto Vollaro, E., Coppi, M., de Lieto Vollaro, A., 2016. Management Optimization of the Luminous Flux Regulation of a Lighting System in Road Tunnels. A First Approach to the Exertion of Predictive Control Systems. Sustainability 8, 1092.
Sun, D., Athienitis, A., D'Avignon, K., 2019. Application of semitransparent photovoltaics in transportation infrastructure for energy savings and solar electricity production: toward novel net-zero energy tunnel design. Prog. Photovoltaics Res. Appl. 27 (11), 1034–1044.
Sun, Z., Liu, S., Tang, J., Wu, P., Tang, B., 2021. Exploring the Impacts of Driving Environment on Crashes in Tunnel–Bridge–Tunnel Groups: an Eight-Zone Analytic Approach. Sustainability 13, 2272.
Wang, J., Pervez, A., Wang, Z., Han, C., Hu, L., Huang, H., 2018. Crash analysis of Chinese freeway tunnel groups using a five-zone analytic approach. Tunn. Undergr. Space Technol. 82, 358–365.
Wang, W., Sha, A., Lu, Z., Yuan, D., Jiang, W., Liu, Z., 2021. Cement filled with phosphorescent materials for pavement: after glow decay mechanism and properties. Constr. Build. Mater. 284, 122798.
Zhao, J., Feng, Y., Yang, C., 2021. Intelligent control and energy saving evaluation of highway tunnel lighting: based on three-dimensional simulation and long short-term memory optimization algorithm. Tunn. Undergr. Space Technol. 109, 103768.