



Review Article

An introduction to tunnel lighting: Basis, calculations, and future lines in the interface between safety and sustainability

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Abstract

The exponential increase in the number of new tunnels, their length, and complexity makes safe and comfortable driving in these infrastructures a must. Among all the technical characteristics necessary to achieve this target, accurate lighting is the most important. However, the peculiarities of driving in tunnels, narrowly linked to the infrastructure itself, but also to physiological and psychological characteristics of drivers, make good lighting complex and highly consuming in terms of energy, financial resources, use of raw materials, environmental impact, and maintenance. The relatively recent introduction of LEDs in tunnels and the new strategies to decrease energy demands and profit from sunlight, whose energy savings can reach 40% in a wide variety of cases, together with the progressive aging of drivers, are challenges for researchers in this field, that currently seek new perspectives affecting the tunnel, the roads before and after, and the portal surroundings. This work approaches the principles of tunnel lighting, its singularities, open points with difficult solutions, and some others that are already contributing to safer and more sustainable tunnels and underground roads.

Keywords: Tunnel lighting; Road safety; Flicker effect; Glare; Energy consumption

1 Introduction

The exponential growth in terms of population and people's needs requires a deep optimization of resources to achieve a truly sustainable development, ensuring the needs of future generations ([World Commission on Environment and Development, 1987](#)). Although there is exhaustive literature on the optimization of raw materials, financial resources, emissions, maintenance, etc., and a wide range of actions are being planned and implemented, less reflection on the optimization of space and time in people's daily lives and activities. This is paradoxical since the optimization of space and time directly impacts better management of the mentioned factors.

Among the variety of options to optimize space and time, the use of underground spaces must play a central role. This use can be approached from two philosophies: use for activities where people invest relatively long periods of time (residential, commercial, cultural, etc.) ([Durmisevic, 1999](#); [Chen et al., 2018](#)), and use for travelling between points that cannot be easily connected by opencast infrastructures because of mountains, rivers, seas or simply, to preserve natural landscapes and habitats ([Peña-García, 2018](#)). The challenges of both uses of underground space are different, but human health, safety, and well-being are always present.

In this framework, whilst underground spaces for permanent or semipermanent activities must ensure the circadian entrainment ([Figueiro et al., 2018](#)) and other factors linked to well-being ([Roberts et al., 2016](#)), the spaces used for transport, basically tunnels and underground roads, must be designed and managed to ensure the attention and performance of drivers avoiding accidents and watch-

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Nomenclature

CIE	Commission Internationale de l'Éclairage (International Commission on Illumination).	VLUR	Very long underground road
E	illuminance. Received flux per unit of surface. Unit: lx (1 lx = 1 m/m ²).	VRT (in driving)	visual reaction time. Time required to carry out the relevant actions when an obstacle appears. Unit: s.
I	luminous intensity. Luminous flux emitted per unit of solid angle by a punctual light source. Unit: cd.	ρ	reflectance or reflection coefficient. Ratio between reflected and incident luminous flux on one surface.
L	luminance. Luminous flux emitted per unit of solid angle and surface in one given direction. Unit: cd/m ² .	Φ	luminous flux. Power emitted, transmitted, or received as luminous energy. Unit: lm.

ing over the safety of their users (Peña-García, 2018; Pervez et al., 2020).

Whatever its finality, every use of underground space is inherently linked to its lighting, which is maybe the most important variable to control.

The next sections of this work, mainly focused on tunnels and underground roads for vehicle traffic, will approach their lighting (in the following, just “tunnel lighting” for simplicity), through the following milestones: (1) situation in the general framework of infrastructure lighting and common elements with other kinds of roads; (2) peculiarities and basic fundamentals; (3) principles of electrical tunnel lighting, objectives, methods, and results; (4) strategies for sustainable lighting and future lines of work.

Following this scheme, the pros and challenges of tunnel lighting, as well as some highlights on the necessary equilibrium between safety and sustainability, will be analyzed and presented.

2 Basic process of lighting for drivers in tunnels

The technical advances and the increasing demand for quicker, shorter, and safer road communications have increased and revolutionized the construction of tunnels, underwater (Du et al., 2020), and underground roads (Ministry of Transport of the People's Republic of China, 2023), especially the very long ones, also denominated very long underground roads (VLUR) (Peña-García, 2018).

However, despite the improvements, there are several reasons why driving in tunnels is a critical task:

- (1) Potential crashes with walls of concrete have more severe consequences than crashes with barriers in opencast roads.
- (2) Fires inside tunnels also have much more serious consequences.
- (3) Visual tasks of drivers are much more demanding in tunnels.

- (4) Psychological loads for drivers, including fear, anxiety, dizziness, distraction, and visual effects, are more frequent and acute in tunnels.

Among these factors, (1) and (2), supported by research (Amundsen & Ranes, 2000; Caliendo & De Guglielmo, 2012; Danishmal & Zainullah, 2021), depend on the physical characteristics of tunnels, whereas (3) and (4) depend on the drivers (Flø & Jenssen, 2007; Larue et al., 2011; Kircher & Ahlstrom, 2012; Miller & Boyle, 2015; Guan et al., 2025). Furthermore, (4) is also conditioned by the consciousness of the danger expressed in (1) and (2). All these plots form a complex panorama whose central element is an accurate lighting installation.

In this sense, the characteristics of the lighting installation, its environment, and the peculiarities of the visual system converge on the basic process of lighting (BPL) (Peña-García et al., 2024), which describes the core of lighting civil infrastructures like streets, roads, or tunnels. In these last, the target of this work, the BPL can be summarized as

- (1) Projectors emit luminous flux, Φ , with luminous intensity distribution $I(\alpha, \beta)$.
- (2) The road and walls receive an illuminance, E .
- (3) They reflect the flux according to its reflectance in each direction, $\rho(\theta, \varphi)$, and spectral absorptance.
- (4) A luminance, $L(\theta, \varphi)$, is reflected towards the eyes of the driver.
- (5) From the visual input $L(\theta, \varphi)$ and other circumstances related to the situation, C , each observer will have a physical and behavioral output, O .

Φ , $I(\alpha, \beta)$, E , and $L(\theta, \varphi)$ are the basic photometric quantities as defined by the Commission Internationale de l'Éclairage (CIE) in the technical report “ILV: International Lighting Vocabulary, 2nd Edition” (CIE S 017/E:2020, 2020).

From these points, it is important to highlight that the drivers have two main visual planes in tunnels, the road surface and the walls, whereas the main visual plane for drivers in opencast roads is only the road surface.

Thus, most regulations and standards on tunnel lighting establish a minimum luminance from the road, but also from the walls up to a given height to ensure correct perception, visual guiding and avoid stress and fear (Illuminating Engineering Society of North America (IESNA), 2011; CIE, 2004; Government of Italy, 2005; Government of Spain, 2015; Ministry of Transport of the People's Republic of China, 2014). However, this differential fact is a challenge since requiring the same luminance from both elements simultaneously is difficult to achieve because their reflectance is rather different. Thus, one standard tunnel where the different nature of the materials of the road and walls gives place to different luminance towards the drivers' eyes. In real projects, adaptation to the required luminance from the walls is often sacrificed in favor of compliance with the road, which is a problem. Thus, the walls can look too dark, with the consequent lack of visibility and difficulty for drivers to estimate the distance to them, or too bright, which can produce glare and lack of adaptation to the decreasing luminance levels inside the tunnel.

Like in other roads, one of the main targets of tunnel lighting is to minimize the visual reaction time (VRT), that is, the interval of time between the application of visual stimuli and the detection of a response from one observer (Luce, 1986). When applied to driving, the visual stimulus can be potential obstacles (the standard one in tunnel lighting is a 20 cm × 20 cm square on the road), or other dangerous eventualities. This information must be quickly processed, and the accurate reaction must be performed.

The VRT follows Piéron's law in a wide variety of conditions. This law expresses that VRT has an inverse dependence on variations in luminance during detection tasks (Pins & Bonnet, 1996; Burr & Corsale, 2001). This is the reason why tasks demanding very short VRT require more intense illumination.

Once the primary visual tasks in tunnels are established, it is clear that there are common elements with openroad roads, but also remarkable differential facts inherent to driving in tunnels itself. In addition to these last, it is necessary to study some peculiarities of the human visual system that sharpen in tunnels, making their lighting a special matter whose solutions can hardly be exact or accurate for everyone.

3 What makes tunnel lighting special?

The main characteristic of tunnel lighting is its strong conditioning to the features of the human visual system, which is extremely complex (Schiller & Tehovnik, 2015). Hence, an accurate understanding of human vision is essential to approach the design and maintenance of lighting installations, as well as their optimization to enhance safety and sustainability. This section briefly summarizes the main visual peculiarities influencing driving in tunnels.

The retina has three kinds of photoreceptors, that is, cells converting light into electrical impulses. On one hand,

the cones and rods initiate a neural path reaching zones of the brain that create images. It is the "visual path". Cones and rods work at high and low luminance, respectively, where luminance is a measure of the luminous flux emitted or reflected by one surface within one solid angle in one given direction (CIE S 017/E:2020, 2020) and is perceived as its brightness. On the other hand, the intrinsically photosensitive retinal ganglion cells (ipRGCs) (Berson, 2003; Zaidi et al., 2007) initiate "non-visual paths" like the melatonin or the cortisol ones, that regulate the circadian entrainment, alertness, sleep-wake cycle, and other important oscillations with high impact on human health and well-being. Moreover, the influence of non-visual paths of light on important effects for safe driving, like anxiety, arousal, and attention (Yang et al., 2025), makes their full understanding necessary.

Strongly related to attention and other aspects of driving, partially related to the non-visual paths, Chen et al. (2020) demonstrated that the presence of a decorated sidewall provides drivers with better spatial and speed perception, so it could contribute to reducing accidents associated with speed judgment. Flø and Jenssen (2007) studied the customization of VLUR with artistic motives and even implemented the results in real tunnels. Other researchers, like Du et al. (2020), considered a visual induction system to reconstruct a visual reference system to enhance drivers' comfort. Anyhow, further research to profit from the benefit of these proposals without causing fatal distractions is necessary.

Nevertheless, regulations and standards on tunnel lighting do not deal with non-visual paths yet and fully focus on the visual path, the main target of this work.

From this visual approach, one key feature of the human eye is its slow adaptation from high to lower luminance levels, which is a typical situation when entering tunnels during daytime. It is due to the low capability of cones to work with low lighting levels and the high time needed by rods to desaturate when coming from bright environments, which takes several minutes (Fig. 1), something inadmissible in driving where the car advances about 28 m/s (100 km/h) on roads.

As a consequence, adaptation to low luminance is necessary on sunny days unless the electrical lighting equals the external conditions. It can require luminance up to 50 times more intensive and energy-consuming in the first part of the tunnel during daytime, when compared to the night. Furthermore, depending on the external conditions, tunnel installations must incorporate sunset, sunrise levels, cloudy, and adverse weather levels between 40% and 60% of the sunny day level.

So, tunnels must be strongly illuminated during daytime, at least in their first meters, to avoid transitory blindness due to the slow adaptation (Mehri et al., 2019, 2020). The high luminance is also necessary to avoid the "black-hole effect" (Wang & Huang, 2015), perceived by drivers when approaching tunnels from bright environments if their portals are not illuminated enough (Fig. 2).

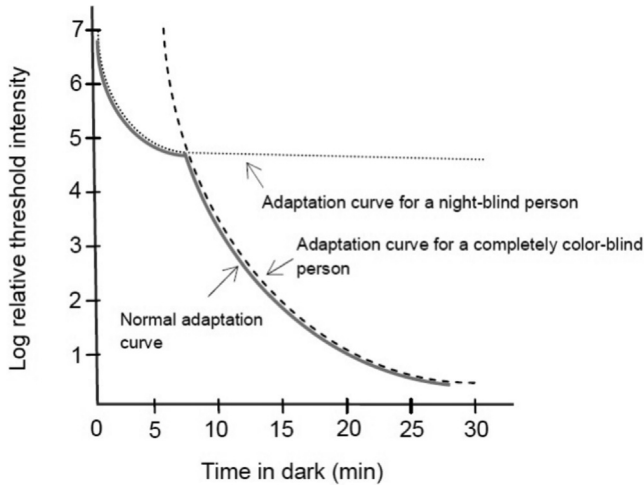


Fig. 1. Adaptation curve from high to low luminance levels (from Peña-García et al., 2012).

Although the visual shift from rods to cones is less problematic due to the quicker adaptation of these latter, visual impairment when departing from tunnels during daytime has also been reported. It is the so-called “white-hole effect” (Wagdy et al., 2020) (Fig. 3). In this case, the transition from a weakly illuminated tunnel interior to a brighter exterior may cause glare. However, the shift from the use of retinal cones and rods to only cones is less problematic than in the inverse case due to the quicker adaptation of cones.

Another visual phenomenon threatening safety in tunnels is the “flicker effect”, that is, the succession of bright and dark zones due to the limited mounting height of projectors in tunnels, as shown in Fig. 4 (Peña-García, 2018; Peña-García & Cabeza-Láinez, 2023b). Due to the move-

ment along the tunnel (Iacomussi et al., 2018), the periodicity in the perception of the strips with frequencies between 4 and 11 Hz during periods above 20 s can cause discomfort, headache, and distractions. Regulations and standards like CIE 88:2004 (2004) establish the ranges of frequencies that may cause this effect by calculating the ratio between the maximum speed allowed in the tunnel and the separation between projectors. Another cause of the flicker effect may be the installation of pergolas before or after the tunnels with different targets that may include energy savings (Peña-García & Gil-Martín, 2013), noise protection (Dondi et al., 2012), and support of upper roads.

Besides the obvious and highly impactful measure of decreasing the distance between projectors (that is, increasing their number) so that the light cones can overlap, different strategies to avoid the flicker effect have been proposed. They include the installation of continuous lines of LED projectors (Peña-García, 2018) and the installation of diffusers between beams of pergolas (Gil-Martín et al., 2015).

The considerations above show that the peculiarities of the human visual system, together with the inherent characteristics of tunnels, may cause undesired effects compromising safety. In general, the solutions demand high levels of luminance and uniformity, which determines the design and operation of lighting installations and increases their impact in terms of energy consumed, materials, waste, and emissions.

This compromise between safety and impact of tunnel lighting is becoming more critical in recent years because of the exponential increase in the construction of new and longer tunnels. The figures in China (Table 1) clearly show this trend and justify the efforts to optimize the lighting installations for the sake of safety and sustainability.



Fig. 2. Black-hole effect (from Peña-García, 2022).



Fig. 3. White-hole effect near the tunnel exit.

Departing from this justification, the principles of tunnel lighting, including these constraints, will be presented and analyzed in the next section.

4 Principles of tunnel lighting

There are three key items to consider in the design of tunnel lighting installations: regulatory framework, luminance levels, and lighting technology and technique.

4.1 Regulatory framework: common elements and critical differences

Although many countries have their own regulations on tunnel lighting (Illuminating Engineering Society of North

Table 1
Evolution in the number of road tunnels in China (Ministry of Transport of the People’s Republic of China, 2017, 2020, 2021, 2024).

Year	Number of road tunnels	Increase
2023	27 297	2447
2022	24 850	3534
2020	21 316	3578
2019	17 738	2557
2016	15 181	
Average length per tunnel > 1000 m		

America (IESNA), 2011; Government of Italy, 2005; Government of Spain, 2015; Ministry of Transport of the People’s Republic of China, 2014), they generally follow the master lines of the “Guide for the lighting of road tunnels and underpasses” (CIE 88:2004, 2004), elaborated by the Commission Internationale de l’Éclairage (CIE). The parameters and methodology established in this technical report are followed in research works, where general results are sought, and also in projects in countries lacking specific regulations. Furthermore, most national regulations refer to this document for additional information or in case of doubt.

Among the common elements among all standards, there is a division into several zones with progressive decay in luminance levels during daytime, and the philosophy to establish these zones.

However, there are important differences between regulations and the CIE report that must be kept in mind by designers. Hence, the first step is to have it clear which regulation is applicable to the project under consideration.

Among these differences is the reaction time for the detection of obstacles, which remarkably changes between regulations. For example, CIE 88:2004 (2004) establishes a reaction time $t_0 = 1$ s, whereas the Spanish Regulation establishes $t_0 = 2$ s. This difference is critical because t_0 determines the safety distance (SD) and hence, the length of the zones that divide the daytime level of lighting. The differences can be very remarkable in the number of projectors and consumed energy. Another parameter that changes between regulations is the coefficient of proportionality between inner and outer luminance (k), which directly defines the lighting levels, consumption, and number of projectors.

Although the mentioned parameters will be properly introduced in the next sections, the intention now is to highlight that, despite the similarities, there are important differences in the technical parameters of different regulatory frameworks.

4.2 Luminance levels

Once the regulation applicable to the lighting installation under consideration is known, it is necessary to deter-

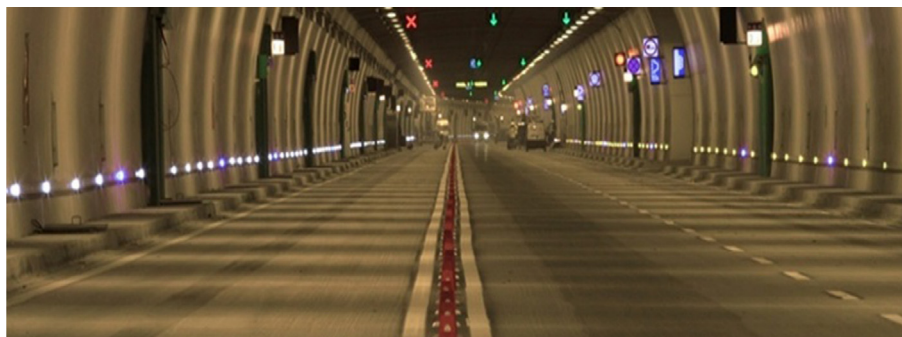


Fig. 4. Succession of bright and dark bands that can cause flicker effect.

mine the necessary luminance levels in each zone. It is not a direct task because they are not fixed like in road lighting, but particular for each tunnel, whose luminance levels depend on the applicable regulation, maximum speed, traffic intensity, orientation, and portal surroundings. Even when these particular levels are determined, they may change with the time of the day, meteorological conditions, and the zone of the tunnel.

As said, the peculiarities of the human visual system demand different luminance levels in tunnels depending on the outer conditions. The most demanding is the daytime level due to the slow adaptation from high to low brightness, so, in the absence of specifications, the following refers to this level.

To design the lighting installation of long tunnels in daytime mode, tunnels are divided into several zones with different luminance requirements. They are the following (CIE 88:2004, 2004):

- (1) Access zone: located in the opencast road from the portal up to the safety distance (SD). It determines the luminance towards the eyes of incoming drivers within a cone of 20° edge centered at $0.25H_T$, being H_T the height of the gate. It is denominated L20 and depends on the reflectance of the portal surroundings, tunnel orientation, and the maximum allowed speed. The determination of L20 is one of the most critical tasks when designing a lighting installation (López & Peña-García, 2018).
- (2) Threshold zone: the first zone located inside the tunnel and hence, incorporates electrical lighting. The required luminance is proportional to L20 with a factor depending on the maximum speed and, in some regulations (Government of Spain, 2015), the type of traffic. Although its length is short (SD), its consumption per unit of length is the highest in the whole tunnel, exceeding 50% of the total. Its luminance, L_{th} , is constant in its first half and then decreases down to $0.4L_{th}$.
- (3) Transition zone: immediately after the threshold zone, its length is covered by a vehicle at its maximum speed during 20 s. Its luminance, L_{tr} , decreases from $0.4L_{th}$ to $0.14L_{th}$.
- (4) Interior zone: between the end of the transition zone and the beginning of the departure zone. Its luminance, L_{in} , the lowest in the whole tunnel, is constant between 1 and 10 cd/m^2 depending on the traffic intensity and other factors.
- (5) Exit zone: from the end of the interior zone up to the exit of the tunnel. Its length is SD calculated for dry pavement. Its luminance, L_{ex} , goes from L_{in} up to $5L_{in}$. Since it is a zone where the exterior luminance has a remarkable weight on the visual process of drivers, its last 20 m do not need to incorporate projectors.
- (6) Departure zone: the zone immediately after the tunnel exit, where there can be potential abrupt changes

in luminance, causing glare or adaptation problems. For this reason, some of them incorporate transition structures and/or luminaries.

As seen, the zonification of tunnels follows a constant decrease in luminance levels to minimize energy consumption and the number of installed projectors without impairing safety. These levels are summarized in Table 2.

One practical question is the way to implement the required “progressive decrease” of the luminance level. Since regulations do not provide specifications, it is generally done by establishing one or more intermediate levels, that is, a “step approach”.

Although the luminance provided in the threshold zone is just about 10% of the natural brightness out of the tunnel and, as shown in Table 2, the levels continuously decay up to relatively low values, the overall energy consumption to keep visual performance and avoid the undesired effects seen in Section 3, is very high. Its minimization whilst keeping safety will be the main principle when facing a new design or optimizing an existing installation.

4.3 Lighting technology and technique

Besides current lines of research like the strategies to introduce natural light inside tunnels, tunnel lighting is implemented almost exclusively with electrical light sources inserted into luminaries called projectors because they generally concentrate the luminous flux in relatively narrow solid angles. For this reason, once the luminance levels in each zone and situation are known, it is necessary to decide the technology of the light sources to use, and how to use them to fulfill the requirements.

The evolution of the light sources used in tunnels has been different from those followed in infrastructures like street, road, or sports lighting. Thus, low-pressure sodium (LPS) lamps were used for ages due to their high efficiency and lifetime. This last is a very important parameter due to the high risk of lamp replacement in tunnels. However, their poor color reproduction and their big size gave way to their progressive replacement by high-pressure sodium (HPS) lamps, that have been widely used in tunnels around the world in recent years. Other sources with lower presence have been metal halide (MH) and even fluorescent tubes, whose white light could be more accurate for drivers.

Currently, although LED projectors are not universally used in tunnels, they are gaining more and more ground on HPS and other discharge sources (Yao et al., 2008; Ye,

Table 2
Daytime luminance levels in the zones of road tunnels.

Zone		Luminance
Threshold	1st half	L_{th}
	2nd half	Progressive decrease to $0.4L_{th}$
Transition		Progressive decrease to $0.14L_{th}$
Interior		1–10 cd/m^2
Exit		$5L_{in}$

2013). It is important to highlight the temporal shift between the implementation of LED in street lighting (almost generalized) and with respect to tunnels. One reason is that not long ago, the lower flux output of LED made it necessary to use many projectors, especially in the first dozen meters. Although this problem is already solved, tunnels frequently incorporate one basic LED installation for nighttime and zones with lower luminance requirements together with HPS reinforcement in the first meters for daytime (Lai et al., 2014). Among the advantages of LED, their higher efficiency compared to HPS (not so high compared to LPS yet), their compact integration in the projector, and most importantly, their versatility to be switched on and off and dimmed up to several levels of flux without impacting their lifetime and output, which is not possible in the mentioned discharge lamps. This groundbreaking capability of LED has allowed tunnel lighting to enter a new era in the matter of intelligent control based on traffic flow, external lighting, and other conditions. These strategies will be treated in more detail in Section 5.2.

For all these reasons, the current trend is the installation of LED in new tunnels and a progressive replacement of HPS with LED in working ones.

Beyond their light sources, projectors are designed and installed seeking different strategies to direct the luminous flux towards the road. Three kinds of tunnel lighting are possible:

- (1) Counter-beam light (CBL): the beams from projectors are tilted against the incoming traffic so any obstacle on the road will be illuminated from behind and will appear darker than its surroundings, that is, a negative contrast (Liao et al., 2021) as shown in Fig. 5. It is demonstrated that the VRT is shorter with this illumination (van Bommel, 2015), which is the most used in the first part of the tunnels (threshold zone).
- (2) Pro-beam lighting (PBL): the beams are tilted in the same direction of traffic as shown in Fig. 6. Hence, any obstacle on the road will be illuminated frontally and will appear brighter than its surroundings, that is, a positive contrast (Liao et al., 2021). Some research has shown better performance of this kind of lighting (Renzler et al., 2018) in disagreement with the abovementioned literature in favor of CBL, which highlights the complexity of tunnel lighting, the dependence of each concrete situation, and the need for more research.
- (3) Symmetrical beam: the beams are symmetrical with respect to their vertical axis (Dijon & Winkin, 1991) as shown in Fig. 7. In general, obstacles will be brighter than their surroundings. This kind of lighting is common in bidirectional tunnels.

From these lighting strategies, different ratios between the road surface luminance and the illuminance from the

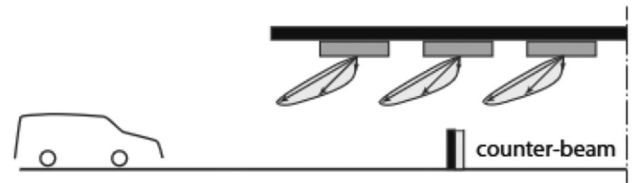


Fig. 5. Counter-beam lighting (van Bommel, 2015; reproduced with permission, courtesy of the author).

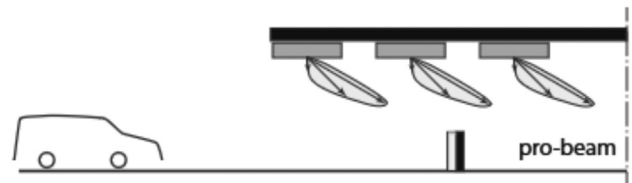


Fig. 6. Pro-beam lighting (van Bommel, 2015; reproduced with permission, courtesy of the author).

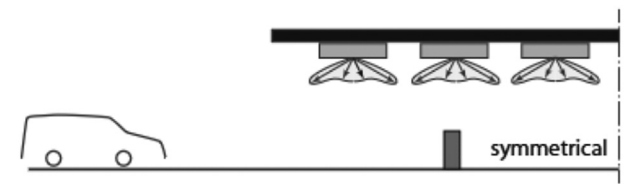


Fig. 7. Symmetrical lighting (van Bommel, 2015; reproduced with permission, courtesy of the author).

projectors on a vertical plane on the road can be achieved (Weng et al., 2019). This ratio, q_c , called “contrast revealing coefficient”, gives an idea of the contrast and hence, the visual performance and output of drivers.

Besides the technology used and the strategy of lighting, as said, tunnels are illuminated in different ways depending on the outer luminance. So, as said before, installations must provide at least two completely different levels of lighting depending on the retinal cells working in each condition: nighttime level (cones and rods work) and daytime level (only cones work due to the high luminosity that saturates the rods). This last is the most demanding in terms of luminance levels towards the eyes of the driver (Adrian, 1982). Other intermediate levels (adverse weather, sunset, sunrise, etc.) can also be incorporated. Independent from their normal lighting, to make it possible to see the road, walls, and other vehicles, tunnels also incorporate safety and evacuation lighting installations, as well as retroreflective and light-emitting devices for signaling (European Parliament and the Council of the European Union, 2004).

In the absence of other specifications, the contents of this work focus on the daytime level due to its importance in terms of safety, environmental, and economic impact. In this context, given the necessity of minimizing the impact, a

continuous descent in lighting levels is sought through the division of the tunnel into several zones.

4.4 Example of installation pre-dimensioning

In this subsection, the principles presented will be applied and extended to carry out a simple pre-dimensioning of the threshold zone installation in one arbitrary tunnel. Given the current limitations of lighting software with regard to tunnels, good pre-dimensioning with the lumen method used here is essential.

Let there be a road tunnel with the following data:

Applicable regulation: CIE 88:2004 (2004)

Portal height: 7.13 m

Tunnel width: 10 m

$V_{max} = 80$ km/h

SD: 99 m. This parameter is also the length of the threshold zone.

Orientation: W-E

The portal picture is shown in Fig. 8.

The first step is the determination of L20, that is, the natural luminance within the L20 cone. As mentioned, this magnitude is calculated from one picture taken from the SD, but taking them in working tunnels is, in general, difficult and dangerous. However, arbitrary pictures from Google Earth or other means can be used by applying the re-scaling methodology proposed by López and Peña-García (2018).

In Fig. 8, the portal has a height of 1.6 cm. The radius of the L20 cone on the photo is:

$$R_{pic-Dx} = \frac{H_{pic-Dx} SD \tan 10^\circ}{H_{tun}} = 3.90 \text{ cm}, \tag{1}$$

where R_{pic-Dx} is the cone radius in a picture taken from unknown distance D_x , H_{pic-Dx} is the height of the portal

in a picture taken from unknown distance D_x , and H_{tun} is the real height of the tunnel portal.

Then, with the help of software like AutoCAD, the portions of each element with different reflectance, as established by document CIE 88:2004 (2004), give the following percentages (Fig. 9).

$$L20 = \gamma L_s + r L_R + \varepsilon L_e = 3602 \text{ cd/m}^2,$$

where L_s is the luminance of the sky (not applicable in this tunnel), L_R is the luminance of the road, and L_e is the luminance of each portion of the environment (meadow, building, or rock) as established by CIE 88:2004 (2004). The parameters γ , r , and ε are the proportion of these elements in the picture as shown in Fig. 9.

Once L20 is known, the luminance required in the threshold zone can be calculated:

$$L_{th} = k L20 = 0.06 \times 3602 \text{ cd/m}^2 = 216 \text{ cd/m}^2.$$

- 1st half threshold zone: $L_{th} = 216 \text{ cd/m}^2$;
- 2nd half threshold zone: progressive decay from 216 to 86 cd/m^2 .

As said in Section 4.2, one important question is how to implement the progressive decay. The most general solution is to establish intermediate steps. Since the length of the half threshold zone is 49 m, that is, about 2 s at maximum speed, it seems enough to establish just one intermediate level, which can be the median: 151 cd/m^2 .

Thus, there will be three sub-zones in the threshold zone with their respective luminance:

- 1st half, from 0 to 49 m: $L_{th-1} = 216 \text{ cd/m}^2$.
- 2nd half-1, from 49 to 74 m: $L_{th-2-1} = 151 \text{ cd/m}^2$.
- 2nd half-2, from 74 to 99 m: $L_{th-2-2} = 86 \text{ cd/m}^2$.

To calculate the remaining parameters of the installation (mainly the number of projectors and their spacing), an



Fig. 8. Image and L20 cone basis of the tunnel under consideration. Picture taken from an arbitrary distance.

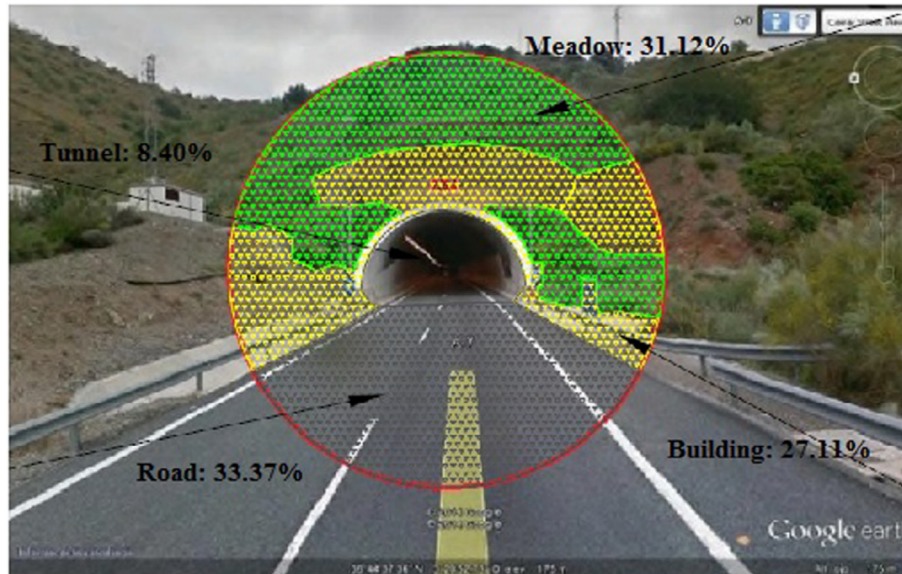


Fig. 9. Percentage of elements in the L20 cone (López & Peña-García, 2018).

inverse method is followed in each zone and sub-zone: (1) calculation of the illuminance, E , giving the given luminance L , (2) calculation of the luminous flux, Φ , producing E , and (3) calculation of the number of projectors, producing Φ .

The relationship between L and E for typical pavements follows the Lambertian approach:

$$E = \frac{L\pi}{\rho}, \quad (2)$$

where ρ is the reflectance of the pavement, $\rho \approx 0.3$.

So, the illuminance in the threshold zone is:

- 1st half, from 0 to 49 m: $E_{th-1} = 2261$ lx.
- 2nd half-1, from 49 to 74 m: $E_{th-2-1} = 1580$ lx.
- 2nd half-2, from 74 to 99 m: $E_{th-2-2} = 900$ lx.

The relationship between the number of projectors emitting a given flux, Φ_p , and the illuminance on the road is given by

$$N = \frac{Ewl}{C_u C_m \Phi_p}, \quad (3)$$

where w is the width of the tunnel, l is the length of the zone under consideration, c_u is the utilization coefficient, and c_m is the maintenance coefficient (Parise et al., 2007).

For typical values $c_u = 0.7$, $c_m = 0.85$, and $\Phi_p = 40\,000$ lm, we have:

- 1st half, from 0 to 49 m: $N_{th-1} \approx 46$;
- 2nd half-1, from 49 to 74 m: $N_{th-2-1} \approx 16$;
- 2nd half-2, from 74 to 99 m: $N_{th-2-2} \approx 10$.

Here, the results are rounded to the nearest odd number because modern highway tunnels generally have paired projectors at both sides.

Finally, from simple geometric considerations, the spacing S among N adjacent projectors is:

$$S = \frac{l}{(N/2) - 1}. \quad (4)$$

- 1st half, from 0 to 49 m: $S_{th-1} \approx 2.2$ m;
- 2nd half-1, from 49 to 74 m: $S_{th-2-1} \approx 3.6$ m;
- 2nd half-2, from 74 to 99 m: $S_{th-2-2} \approx 6.3$ m.

As seen, the spacing between adjacent projectors grows as we penetrate the tunnel because the required luminance decreases. This would lead to large separations and low uniformities. However, each tunnel incorporates several models of projectors with different fluxes, placing the highest ones at the beginning, where more luminance is needed, and those with lower flux, inside the tunnel to find a compromise between the number of projectors and uniformity. In this simple example, only one kind of projector emitting 40 000 lm has been used.

From the point of view of lighting, the number of projectors and spacing fulfilling the required luminance in each zone are the main parameters for the daytime level. The calculations for other zones and levels are similar. Although there can be several configurations, permanent nighttime lighting is always lit, and auxiliary projectors in the threshold and transition zones work during daytime and intermediate levels, like on cloudy days.

From this example, it is clear that the number of projectors and thus the consumption and impact are very high. The next section focuses on the strategies to achieve more sustainable installations.

5 Way towards more sustainable tunnels

Given the high levels of luminance necessary to ensure accurate visual perception and safe driving, especially during daytime, the impact in terms of energy consumed, number of projectors, electrical auxiliary devices, and

consequently, raw materials, maintenance, and others, is very high. The minimization of this impact without decreasing safety is an active matter of research whose last achievements need continuous update (Peña-García, 2022).

Besides the abovementioned introduction of LED projectors, whose efficiency and versatility to be adapted to the instantaneous needs are high, the efforts up to date concentrate on three families of strategies: decrease of luminous flux needs, adaptive luminance, and use of sunlight. These strategies are not exclusive, but complementary and can be simultaneously implemented in each tunnel.

5.1 Decrease in luminous flux needs

There are two main effective ways to decrease the needs for luminous flux and, consequently, the energy consumption in tunnels: the reduction of the luminance required for visual adaptation, and the increase in the efficiency to convert luminous flux into luminance towards drivers' eyes (Steps (1)–(4) in the BPL).

The first family of strategies has focused on decreasing the flux reflected by portal surroundings inside the L20 cone, which is considered the visual field of incoming drivers and determines the L20 luminance and the levels inside the tunnel. It can be achieved in two complementary ways: deviating the reflected rays out of the cone, and using materials of low reflectance in the portal surroundings.

A strategy to deviate the rays without causing glare in other directions has been recently proposed by Peña-García (2024). It consisted of the installation of discrete surfaces conveniently orientated to deviate the reflected light from the L20 cone, giving the hillside a scaled aspect.

Among the research to decrease reflectance of the portal surroundings, its forestation with low reflective vegetal species capable of adapting to the climatic and hydrological conditions of the zone, has been proved with different candidates (López et al., 2014). The most effective in a wide variety of climates has been the common ivy or *Hedera helix* (Peña-García et al., 2015; García-Trenas et al., 2018), with energy savings in the threshold zone around 50%. One advantage of forestation is the better landscape integration of the tunnel, a topic of increasing importance in recent years (Peila & Pelizza, 2002; Zhou, 2006; Jia & Zhao, 2008; Fei et al., 2012; López et al., 2017) that has at least two advantages: soil containment and avoidance of distractions among drivers through smooth transitions. However, in spite of the efforts to date, the landscape integration of tunnel gates in such a way that energy and economic demands are not very high, the attention of drivers is not impaired, and the mental load is decreased, is still an open point to be considered in future research.

Beyond portal integration, other studies on the reflectance decrease of portal surroundings have also been carried out with black photovoltaic panels (Peña-García & Gómez-Lorente, 2020). Independent from the mentioned decrease of L20, the installation of solar panels in the sur-

roundings allows the use of the produced energy for other needs like emergency lights or signalization, even if they do not decrease the reflectance (Sun et al., 2019).

The second family of strategies seeks to decrease the luminous flux emitted by the projectors without decreasing the luminance needs through the construction of the pavement with concrete or other clear materials (Wang, 2018; Moretti et al., 2017, 2019; Cantisani et al., 2018a). Other interesting efforts in this direction have included the use of light emitting asphalts (Wang et al., 2021). One of the cons of this family of strategies is the decrease in the contrast of painted horizontal signaling.

5.2 Adaptive luminance

The luminance requirements established by regulations and standards are static for each zone. The only change between different times of the day or the atmospheric conditions is the establishment of regulation levels like daytime, nighttime, adverse weather, sunset, or sunrise. However, no adaptation to the changing conditions of lighting, traffic flow, or instantaneous needs is established. For this reason, lots of research and real projects have considered the dimming of light sources in recent years. Although it had a negative impact on the lifetime, spectral distribution, and color of light (Bubenheim et al., 1995) in HPS, LPS, and MH lamps, the introduction of LED, besides their lower consumption, allows an almost continuous dimming without problems.

The dimming of light installations, frequently involving advances techniques of data analysis and decision (Leitao et al., 2009; Wang & Zhou, 2009, 2020; Qin et al., 2017; Spor et al., 2019; Zhao et al., 2019, 2021), has been based on the instantaneous luminance conditions out of the tunnel (Salata et al., 2016; Morrison, 2017; Bouroussis et al., 2019; Doulos et al., 2019; Zhang et al., 2019; Li et al., 2021; Lai et al., 2024), in interior changes like reflectance variations (Caicedo et al., 2014; Jiao et al., 2023) or traffic flow (Lai et al., 2014), or several parameters simultaneously (Qin et al., 2021; Zhao et al., 2021).

Despite these promising works, common communication protocols and software ensuring future maintenance and changes in projector models beyond companies, that may not even exist in such long periods, are necessary. For this reason, public administrations must contract these kinds of products, ensuring the total control of the installation in the future.

5.3 Use of sunlight

The intention to introduce sunlight inside the tunnels has been considered for decades, but its implementation is still far from being a reality in working tunnels.

Since the aim of this work is an introduction to the general principles of tunnel lighting, and this matter is almost exclusively based on electrical technology, the strategies to

profit from natural light will be summarized. Deeper information can be found in ad hoc reviews in this field (Peña-García, 2022).

The proposals to use sunlight in tunnels can be divided into two main categories: shift of the threshold zone and injection of light inside the tunnel.

5.3.1 Shift of threshold zone

Given that the highest energy consumption and number of projectors are concentrated in this zone to ease the visual adaptation during daytime, some proposals focus on shifting part of it out of the tunnel by means of pergolas, holed or semitransparent structures allowing a certain amount of luminous flux to pass.

Each of these techniques has its own pros and cons. Pergolas are resistant and require low maintenance (Wang et al., 2015), but the succession of bright and dark zones causes a lack of uniformity that may cause a flicker effect (Peña-García & Gil-Martín, 2013). This can be avoided with the installation of diffuser materials among the beams, reaching excellent uniformities (Gil-Martín et al., 2015) and energy savings near to 40% in the threshold zone. Semitransparent structures allow good transmission of light and excellent uniformity, but may require complex maintenance and present problems with big loads of snow or other adverse eventualities (Gil-Martín et al., 2011; Peña-García et al., 2010, 2011, 2012; Abdul Salam & Mezher, 2014). Structures allowing the pass of light by means of holes or other shapes have been proposed with good results in terms of luminance levels and uniformity (García Garay et al., 2012; Cantisani et al., 2018b, 2018c; Drakou et al., 2015, 2016, 2017) but, like in the case of pergolas, they are too compact and in spite of the energy savings, the final result is a longer tunnel with the consequent problems of more severe accidents, fear and insecurity.

5.3.2 Injection of sunlight

The introduction of natural light without extending the tunnel has been proposed through the use of light-pipes alone (Gil-Martín et al., 2014), with fiberoptics (Qin et al., 2015) or optically coupled to heliostats (Peña-García et al., 2016; Bystronski et al., 2017) or external light-collectors (Peña-García & Cabeza-Laínez, 2023a). Besides the higher price and more complex maintenance, the main pro of this strategy is that the tunnel length is not increased, but the tunnel height must, in most cases, be larger. This last problem is avoided in the proposal of Peña-García and Cabeza-Laínez (2023a) that considers ground-based light-pipes combined with reflection on the tunnel vault. In optimal cases, the savings in energy and the number of projectors reach 40%.

Given these strategies, one major concern is to decide which one to adopt and its parameters (separation between beams if pergolas, length, size of light-pipes if injection, etc). The “SunLight in Tunnel” (SLT) equation (Peña-García, 2017) can predict the energy savings of any system

or coupling of systems installed in threshold zones to use the light of the Sun by comparison with the same threshold zone without the system. It can also calculate the parameters of the best option, so it is expected to become a tool of reference for predictive lighting design in tunnels, combining electrical and solar lighting. Thus, the STL can foster quicker and cheaper development of strategies to use natural light, which can become widely used.

6 Conclusions

The interest of the scientific community working on underground space, and more specifically the current trends in tunnel lighting, focuses on maintaining and enhancing safety whilst decreasing its environmental and economic impact, that is, safer and more sustainable tunnels.

However, the peculiarities of tunnels combined with the physiological and psychological basis of visual perception make every lighting installation unique, turning design into a complex task with multiple levels of luminance in different zones and times of the day. Even if this non-conventional design and implementation is successful, the wide variety of conditions among drivers, together with the complex maintenance, makes tunnel lighting a topic without universal solutions.

In this work, an introduction to tunnel lighting has been presented within the general framework of the BPL, highlighting common and divergent points with the lighting of other infrastructures. Once the differential points requiring the mentioned customization are explained, the technology and techniques used have been presented together with a pre-dimensioning example.

Departing from this approach, the current strategies to decrease the economic and environmental impact, both implemented and under research, have been presented.

In this context, continuous research is a must. In concrete, the current trends seem to point towards the need for more work on some hot topics in the near future:

- (1) Understanding and optimization of the non-visual effects of light with spectral distributions and intensities to avoid sleepiness, stress, and anxiety during driving in tunnels.
- (2) As a consequence of (1), avoidance of monotony during long periods of driving in the more and more frequent VLUR. The decoration of sidewalls is under active research but still seems controversial.
- (3) Research on the impact of sidewalls on the visual process, attention, and visual reaction time. This effect of the walls must not be considered isolated, but combined with the road, whose reflectance is rather different and cannot easily provide the same visual stimulus. Thus, specific and different requirements for wall luminance and/or the use of materials and configurations to reach the required luminance without defect or excess are necessary.

- (4) Improvement of specific software for tunnel lighting design.
- (5) Adaptation of artificial intelligence-based technologies to minimize and fit the luminance and consumption to the real needs of drivers in each moment and circumstance.
- (6) Unification of protocols and assurance of access to adaptive control installations for future maintenance and other operations.
- (7) Real implementation of strategies to decrease luminance requirements and use of sunlight, as well as the tools to calculate and compare them. As discussed in this work, the savings can reach 40% of the consumed energy in the threshold zone, which is the most consuming one.
- (8) Further research on predictive tools like the SLT equation can save expensive experiments and construction of mock-ups to determine the most suitable strategies for the use of sunlight in each particular case.

The panorama presented in this work highlights this singularity and critical impact of tunnel lighting on safety and sustainability, as well as the scientific, technical, and administrative needs that make it necessary to summarize the current knowledge, challenges, and incoming advances.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CRedit authorship contribution statement

Antonio Peña-García: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

Dr. Antonio Peña-García is an editorial board member for *Underground Space* and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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