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The impact of lighting on drivers well-being and safety in very long underground roads: New challenges for new infrastructures

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ABSTRACT

Lighting installations in underground roads and tunnels have been focused on the classical problems of road tunnels, that is, provide high luminance levels ensuring a correct visual adaptation of drivers during daytime and, hence, a safe driving and underground transport. The achievement of such levels with a minimum consumption in energy and raw materials, has become an active field of research during the last years. However, this line of work is mainly focused on tunnels, that rarely exceed two kilometers long. The increasing number of very long underground roads (VLUR) like those under rivers and seas, has enhanced the importance of some factors directly related to well-being and highly influenced by the lighting and visual conditions. These factors, that go from higher stress and anxiety to more distraction or fear, seriously impair safety and constitute a new challenge for designers of lighting installations. In this work, some of these problems and their potential solutions will be analyzed and the conclusions presented.

1. Introduction

Driving in underground environments is a critical task due to a wide variety of factors. On one hand, the severity and consequences of accidents and eventual fires is higher. In addition, collisions with the walls and limited space to avoid obstacles also increase the danger of this task.

This real and objective danger leads to some factors of psychological nature hindering driving in tunnels and underground roads.

The psychological factors affecting drivers in tunnels and underground roads include fear, feeling of insecurity and anxiety. Other important psychological factors are the hesitations arisen when approaching tunnels due to the black-hole effect, the natural trend of drivers to invade the central lane, due to the fear of collisions with the walls, or the higher anxiety in underground roads, that sometimes come from the fear to more severe accidents. Some interesting attempts to attenuate anxiety and fear have been carried out. Flø and Jenssen (2007), studied the customization of very long underground roads (VLUR) with artistic motives taking special care to avoid distractions that could be fatal. They used simulated tunnel driving to test aesthetic interventions designed to reduce monotony and improve comfort in long road tunnels. The changes that were most successful were then implemented into a real road tunnel.

On the other hand, the impairment in underground driving is also due to other factors related with the particularities of the human visual system. Some of these factors are the slow adaptation of the visual system and our limited capability to fusion periodical visual stimuli.

Here it is important to briefly analyze the close relationship between visual factors, the lighting installation and its performance. The main problem in classical short and medium tunnels going through mountains is the slow visual adaptation of the human eye when going from highly illuminated to darker environments. That is the case for drivers entering road tunnels during daytime, especially in countries and atmospheric conditions where the environmental brightness is very high. This important problem must be palliated with very high luminance levels (luminous flux emitted by unit of road/wall surface in one given solid angle) in the threshold zone, at the beginning of the tunnels (CIE Publ. 88, 2004). These high luminance levels progressively decay up to a relatively low plateau in the interior zone. Anyhow, the lighting installation of one tunnel can consume between 40 and 50% of the total energy in the first 100–150 m of the threshold zone. This single datum shows the very remarkable impact of tunnel entrances in energy consumption, use of raw materials and maintenance.

For this reason, the effects of adaptation at the entrance have been the most important variables affecting safety in these traditionally short tunnels. In addition, the optimization of the binomial safety-energy savings through accurate lighting installations (Wang and Zhou, 2009; Salata et al., 2016; Qin et al., 2017a, 2017b), pavement (Salata et al.,

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2015; Moretti et al., 2016, 2017a, 2017b) and tunnel surroundings (López et al., 2014; Peña-García et al., 2015a) has been the most important target in matter of road safety for designers and Administrations, as well as an active line of research. As consequence, newer and more sophisticated tools to evaluate the sustainability of tunnels are arising lately (López et al., 2017; Peña-García, 2017).

This predominance of adaptation effects is supported by the relatively short length of most of the tunnels, whose vast majority are shorter than 3000 m. For example in such a mountainous country like Spain, among 513 tubes depending from the National Network of Roads, only 7 are longer than 3000 m (about 1.4%) whereas 444 are shorter than 1000 m (86.5%). It means that drivers seldom stay inside these infrastructure more than one or two minutes.

Finally, there are psychophysiological factors like the increased sleepiness or excessive arousal related to melatonin and cortisol release or inhibition. The prolonged exposure to certain light intensities and spectral distributions are directly related with the secretion of these hormones (Thapan et al., 2001; Herljevic et al., 2005, Revell and Skene, 2007; Figueiro and Rea, 2010) and, hence, with their effects on drivers.

In summary, in addition to the increased severity of accidents inside underground roads, there are three fundamental groups of hindrances affecting driving in these infrastructures: psychological factors directly impairing a safe driving, visual factors mainly related with the human visual system and psychophysiological factors linking hormones secretion with drivers behavior and performance. The inherent relationship and interactions between all these factors, makes the situation even more complex. However, these problems have a common nexus because, one way or another, they are closely related to lighting. It means that driving in underground roads could be facilitated by means of accurate lighting installations.

This work will be focused on one particular kind of underground roads that will be referred to as Very Long Underground Roads (VLUR) and the actions on their lighting installations to improve well-being and safety.

1.1. Short and medium tunnels vs. very long underground roads

The fast development of underground technologies has allowed the construction of longer and longer tunnels and pharaonic underground roads under rivers, seas, cities, mountain chains and even in areas where the lack of space makes it difficult to build opencast roads. These VLUR, whose number is quickly increasing, can easily exceed 10 km, which requires drivers stays of many minutes. This fact dramatically increases the importance of some factors that are not so important in short and medium-sized tunnels.

Table 1 shows the longest underground roads in the world that are working or near to be opened (data from September 2017) and the time drivers spend inside in conditions of fluent traffic at 80 km/h.

A careful analysis of Table 1 highlights three important details:

(1) Only one tunnel (Gotthard) started to work before 2000. In fact, except Gotthard and Lærdal, all the working tunnels or underground roads are less than 10 years old.
(2) Five from the 10 longest underground roads, are still in construction. It demonstrates that VLUR are a consequence of the last advances in underground technology.
(3) Time needed to go along VLUR is very long. If the flicker effect (CIE Publ. 88, 2004) is not perfectly controlled, its consequences will arise.

The data presented in Table 1 also show that in VLUR, the distance needed for eye adaptation is negligible when compared with their whole length. It means that the negative effects caused from a long underground driving can arise and even beat the traditional problems in classical tunnels, where optimizing the binomial high luminance levels – sustainability is the most important concern. One of these problems is the flicker effect, whose negative impact increases with time under periodical changes in luminance.

2. The flicker effect

In road tunnels, the required luminance levels decrease as time goes by and driver eyes get adapted. For this reason, the spacing between luminaries progressively raises in the last part of transition and interior zones. This makes the installation cheaper and its consumption lower, but the increasing distance between luminaries often leads to a remarkable lack of homogeneity due to the succession of bright and dark zones, which can become really disturbing for drivers. In not very long tunnels (the vast majority), it is not a big problem because vehicles rarely need a long time to go through these zones.

However, when drivers perceive a periodical succession of bright and dark bands on walls and road under certain conditions of speed, light distribution, separation of luminaries or natural light leakages during a relatively long time, the flicker effect may appear. It can cause discomfort, distraction, headache and dizziness with the subsequent danger for safety. A typical situation of potential flicker effect is shown in Fig. 1.

This periodical change in the luminance reflected in pavement and walls causes a decrease in the global luminance uniformity, U_0, which is defined by CIE International Standard S 017/E:2015 (2011) as:

$$U_0 = \frac{L_{\min}}{L_{av}} \tag{1}$$

where $L_{\min}$ and L_{av} are the minimum and average luminance on the considered portion of the road or wall. Most regulations require $U_0 > 0.4$ to ensure a good distribution of light and avoid undesirable effects like flicker.

CIE Publ. 88 (2004), establishes that the flicker effect can arise when the periodical bright and dark bands appear with frequencies between 4 and 11 Hz for more than 20 s. The flicker frequency, f, can be easily calculated by the following formula:

Table 1
The 10 longest underground roads in the world in September 2017.
Source: own elaboration

Denomination	Length (m)	Location	Year	Use	Travel time at 80 km/h (minutes)
Rogfast	26,700	Harestad-Arsvågen, Norway	Under construction	Undersea	20.0
Lærdal	24,510	Lærdal – Aurland, Norway	2001	Under mountains	18.4
WestConnex	19,000	Sydney, Australia	Under construction		14.3
Yamate	18,200 (2 tubes)	Tokyo, Japan	2015	Underpass in city	13.7
Qinling Zhongnanshan	18,040 (2 tubes)	Shaanxi, China	2007	Under mountains	13.5
Jingpingshan Tunnel	17,540 (2 tubes)	Sichuan, China	2011		13.2
Gotthard	16,918	Uri – Ticino, Switzerland	1980	Under mountains	12.7
Bypass Stockholm	16,500	Stockholm, Sweden	Under construction		12.4
New Mount Zigana Tunnel	14,481	Maçka – Torul, Turkey	Under construction		10.9
Mount Ovit Tunnel	14,346	İkizdere – İspir, Turkey	Under construction		10.8