FINANCIAL AND ENVIRONMENTAL IMPACT OF COMBINED ACTIONS IN ROAD TUNNELS FOR THE DECREASE OF ENERGY AND RAW MATERIAL CONSUMPTION

FERDINANDO SALATA[1], IACOPO GOLASI[1] & ANTONIO PEÑA-GARCÍA[2,3]
[1]DIAEE – Area Fisica Tecnica, Università degli Studi di Roma "Sapienza", Via Eudossiana, Rome, Italy
[2]Department of Civil Engineering, University of Granada, Spain
[3]Research Group "Lighting Technology for Safety and Sustainability", University of Granada, Spain

ABSTRACT
Road tunnels are critical infrastructures for the economic and social development due to the remarkable improvement in transport and travel time in mountainous zones. However, the impact of tunnels is rather contradictory from all the perspectives: they contribute to safety since traffic in narrow roads bordering mountains and cliffs, sometimes in adverse weather conditions is avoided, but the severity of accidents in their interior is higher; tunnels contribute to savings in fuel, CO_2 emissions and raw materials because time and distance is shorted, but their construction costs are very high and the energy consumption of their installations really remarkable. Anyhow, the balance is positive, and most countries are building longer and more modern tunnels whenever they are necessary. Since the trend towards more, better and safer tunnels is a reality, it is necessary to optimize their costs from all the perspectives. One of the deepest impact of these infrastructures on economy and sustainability are their lighting installations, whose yearly invoice frequently exceeds 1M€ in not too long tunnels. In the last years, intensive research has been carried out to decrease the consumption in terms of energy and materials in these installations. As consequence, interesting strategies have been proposed: use sunlight, introduction of pavements with special reflection patterns, regulation of luminaries in flux depending on the conditions etc. In spite of the increasing studies from a strictly technical perspective, the amount of works focused on combined strategies and mainly on their economic and environmental impact is rather low. In this work, the impact of some of these combined actions are considered in terms of CO_2 emissions and financial balance. The results and their interpretation as well as some recommendations for future implementations are presented.
Keywords: tunnel lighting, energy savings, sustainability, environmental impact.

1 INTRODUCTION

The special features of the human visual system result in a very slow visual adaptation when going from very bright to darker environments. This fact has very deep consequences in the safety, energy consumption and environmental impact of the installations in road tunnels.
For this reason, an apparently paradoxical fact takes place in these infrastructures: the luminous flux supplied by the lighting installation must be much stronger during daytime that at night, when the driver eyes are used to lower levels.

Attempts to decrease the impact of these installations have become a very active line of research between groups around the world.

To date, only two ways to decrease this huge consumption have been reported: use of sunlight and actions on the tunnel and its environment to decrease the energy demands.
The use of the light coming from the sun has been considered from different perspectives. One of them has been the introduction of the flux inside the tunnel through light-pipes, light guides or heliostats [1]–[3]. Similar techniques have been applied to other infrastructures different from tunnels with remarkable success [4]–[8]. Other attempts were based on the

WIT Transactions on Ecology and the Environment, Vol 215,
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/EID180341

shift of the first and most consuming part of the tunnel by means of tension structures [9]–[11], pergolas [12], [13] or other kind of shifting structures [14]–[18].

On the other hand, it is also possible to decrease the required flux with special pavements [19], [20] and forestation of tunnel surroundings [21]–[23].

Independently of the strategies above, interesting proposals to dim the luminous flux based on LED technology have been proposed [24], [25], whereas other researchers are currently working on methods to quantify the real energy savings [26], and the sustainability of tunnels from a more global perspective [27], [28].

The aforementioned general lines are just a proof of the scientific community concern on road tunnels and their impact, especially during daytime. Given the increasing number of proposals to save energy, raw materials, CO_2 emissions and, of course, money in these infrastructures, it is time to evaluate the real effects of these strategies when considered from a global perspective. This is the target of this work.

2 MATERIALS AND METHOD

A model road tunnel incorporating some of the main proposals to save energy has been considered. Such proposals are: forestation of portal surroundings, use of pavement with high reflectance, flux regulation of LED projectors and one pergola before the portal gate.

The selected tunnel is located in the South-East of Spain. It has been considered in its construction phase in order to compute the energy consumption from the very beginning and thus adapt the project before the infrastructure is working.

The decrease of luminance requirements is calculated with the models based on reflectance measurements [22], [23], whereas the evaluation of the energy savings achieved with the flux regulation are based in the work of Salata et al. [25]. The savings in the pergola are evaluated by means of the SLT equation [26], which can be used to compute the performance of any system for the use of sunlight. The evaluation of the CO_2 emissions related with the energy saving has been carried out according to the recommendations of the Spanish National Centre of Environmental Education (Government of Spain) (www.mapama.gob.es/es/ceneam).

The considerations above will be applied to the threshold and transition zones of the tunnel, because the luminance levels required in the interior and exit zones do not depend on the environment of the tunnel, and they will be assumed not to change. Thus, the comparison between the threshold and transition zones before and after actions implementation for daytime conditions will show the effect of such actions more accurately.

3 RESULTS

With regard to the considered tunnel, the lighting requirements can be calculated according to the L20 method established by the International Commission on Illumination (CIE) CIE Publ. 88:2004 [29]. Fig. 1 shows the so called L20 cone with the percentages of the different elements (concrete, vegetation, building, tunnel and road) in the surroundings of the portal gate.

The contributions of each part of the cone to the L20 luminance is specified by the CIE standard as well as the different national regulations in matter of tunnel lighting. They are shown in Table 1.

According to these percentages and the methodology established by CIE, the luminance in the cone is (eqn (1)):

$$L_{20} \approx \gamma\, L_S + \rho\, L_R + e\, L_E = 4168 cd/m^2 . \tag{1}$$

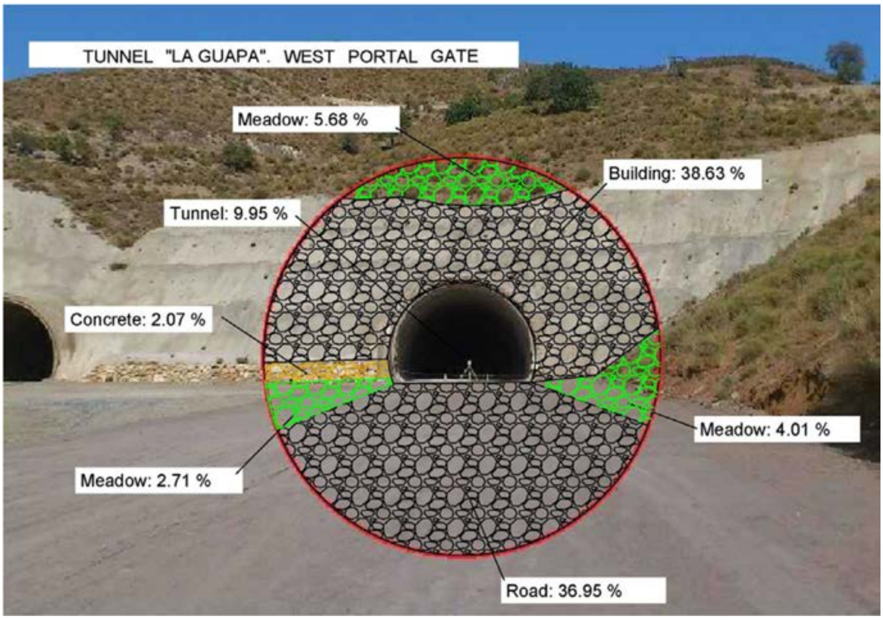

Figure 1: L20 cone with surroundings percentages [22].

Table 1: Contribution of the different sections of the 20º cone according to CIE Publ. 88:2004.

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

This is the luminance in the eye of one driver approaching the tunnel from the safety distance. Hence, the lighting installation of the tunnel must be able to achieve a progressive and accurate adaptation of the driver's eye to the conditions in the tunnel interior whose luminance must be lower in order to consume less energy and materials.

The first part of the tunnel in terms of lighting is the threshold zone. The luminance in this zone is stronger than in the rest of the tunnel because the first step of the visual adaptation takes place there. This luminance (L_{th}) depends on the maximum speed allowed in the tunnel and is given by (eqn (2)):

$$L_{th} = k\,L_{20}\,. \tag{2}$$

For normal tunnels in the South of Spain, the maximum speed allowed is 100 km/h. Thus, according to CIE 88:2004 [29], $k = 0.08$. It means that the luminance in the first meters of the tunnel is $L_{th} = 333.4 cd / m^2$.

We consider the threshold and transition zones, that are the most consuming ones and divide each into three subzones as usually done. The energy consumption during daytime under sunny conditions, that is, the lighting installation working at its maximum power during 10 h, is presented in Table 2.

It is necessary to remark that the calculations above have been carried with the parameters of typical installations in typical tunnels. They are the following:

- Pavement reflectance: $\rho = 0.25$.
- Light source in projectors: high pressure sodium (HPS). Two different commercial lamps have been considered for threshold and transition zones respectively. The first has a luminousflux output $\phi = 55800lm$, whereas the second, for the transition has a lower output $\phi = 31334lm$. Both have an estimated efficiency $\eta = 137lm/W$.
- Cost per kWh: 0,088112 €.

As shown in Table 2, the impact of the lighting installation of this tunnel is really remarkable from financial and environmental perspective. For this reason, it is really important to implement as many strategies as possible and compatible in order to decrease the energy demands. In concrete, the following ones will be considered:

1. Forestation of tunnel surroundings with common ivy, which has been proved to be the most suitable specie for portal forestation with the lowest reflectance.
2. New asphalt with higher reflectance: 0.25 to 0.35.
3. Replacement of the current High-pressure sodium luminaries by other incorporating LED. This is possible because the measures above will decrease the luminance requirements. Otherwise, the number of LED projectors and the cost of the new installation would be to high. In addition, the maintenance coefficient of the used LED projectors is higher than the one of the HPS ones (from 0.80 to 0.85).

Table 2: The main parameters of lighting installation impact before implementation of the proposed actions.

	Luminance (cd/m^2)	Luminous flux (lm)	Nr. of HPS projectors	Yearly consumpt. MWh	Yearly CO_2 emissions (Tons)	Yearly costs (€)
Threshold zone – 1	333.4	5,201,665	94	138.6	48.5	12,212
Threshold zone – 2	283.4	2,213,567	40	59.0	20.6	5,199
Threshold zone – 3	233.4	1,823,029	34	48.6	17.0	4,282
Transition zone – 1	133.4	4,835,400	154	128.8	45.0	11,349
Transition zone – 2	100.0	3,624,738	116	96.6	33.8	8,512
Transition zone – 3	66.7	2,417,700	78	64.4	22.5	5,674
TOTAL		**9,238,261**	**516**	**535.9**	**187.6**	**47,219**

Concerning the first action, the forestation of concrete and building yields new and lower luminance requirements in the L20 cone. They are given by the following expressions (eqns (3), (4)):

$$L_{20\,forest} \approx \gamma\, L_S + \rho\, L_R + e\, L_E = 2540 cd/m^2\,, \tag{3}$$

$$L_{th\ forest} = 0.08x2540 cd/m^2 = 203.2 cd/m^2\,. \tag{4}$$

Departing from the luminance requirements after forestation and considering the actions to be implemented (more reflective asphalts, change of HPS by LED) the parameters of the new installation in terms of environmental impact are presented in Table 3. The threshold and transition zones are divided in three parts as indicated in the table according to their different lighting requirements:

The calculations above have been carried with the following parameters:

- Pavement reflectance: $\rho = 0.35$

- Light source in projectors: two different commercial LED projectors have been considered for threshold and transition zones respectively. The first has a luminous flux output $\phi = 21700 lm$, whereas the second, for the transition has a lower output $\phi = 17000 lm$. Both have an estimated efficiency $\eta = 180 lm/W$.

- Cost per kWh: 0.088112 €.

The comparison of the impact of tunnel lighting before and after consideration of the proposed actions are presented in Table 4.

Table 3: Main parameters of lighting installation impact after forestation of portal surroundings, change from HPS to LED and pavement with higher reflectance.

	Luminance (cd/m^2)	Luminous flux (lm)	Nr. of LED projectors	Yearly consumpt. MWh	Yearly CO_2 emissions (Tons)	Yearly costs (€)
Threshold zone – 1	203.2	2,131,295	98	43.2	15.1	3,806
Threshold zone – 2	172,7	906,835	42	18.4	6.4	1,621
Threshold zone – 3	142,2	746,681	34	15.1	5.3	1,330
Transition zone – 1	81.3	1,981,117	118	40.2	14.1	3,542
Transition zone – 2	61.0	1,486,447	88	30.1	10.6	2,652
Transition zone – 3	40.6	989,340	58	20.1	7.0	1,771
TOTAL		**8,241,715**	**438**	**167.1**	**58.5**	**14,724**

www.witpress.com, ISSN 1743-3541 (on-line)

Table 4: Impact of the tunnel lighting installation before and after the proposed actions and their savings.

	Before actuation	After actuation	Savings (%)
Number of projectors	516	438	15.1
Annual energy consumption in daytime mode (MWh)	535.9	167.1	68.8
Annual CO_2 emissions (Tons)	187.6	58.5	68.8
Energy costs (€)	47,219	14,724	68.8

4 CONCLUSIONS

The results obtained in this research lead to the following conclusions.

1) The combination of some existing strategies to decrease luminance requirements with other strategies used to achieve more efficient systems result show a good synergy and are proven to be an excellent solution for the decrease of energy consumption, use of raw materials (less projectors are needed), financial costs and emissions of greenhouse gases like CO2.
2) The benefits of these combined strategies allow the use of a reasonable number of LED projectors even in the threshold zone of road tunnels, which is nowadays a problem because of the excessive number needed in this zone and their price, higher than HPS projectors. To date, the use of LED projectors in tunnels has been mainly limited to the transition, interior and exit zones.
3) The increased use of LED projectors in tunnels should make authorities reconsider their recycling policies, since the components of HPS lamps and LED are rather different.
4) This trend towards zero energy tunnels seems to be an excellent opportunity for the introduction of new philosophies of design and construction, like those based in the circular economy.

ACKNOWLEDGEMENT

This work was supported by the Spanish Ministry of Economy, Industry and Competitiveness as part of the Research Project ENE2015-67031-R (MINECO/FEDER).

REFERENCES

[1] Gil-Martín, L.M., Peña-García, A., Jiménez, A.E. & Hernández-Montes, E., Study of Light-pipes for the use of sunlight in road tunnels: from a scale model to real tunnels. *Tunnelling and Underground Space Technology*, **41**, pp. 82–87, 2014.

[2] Qin, X., Zhang, X., Qi, S. & Han, H., Design of solar optical fiber lighting system for enhanced lighting in highway tunnel threshold zone: a case study of Huashuyan tunnel in China. *International Journal of Photoenergy*, **2015**, 10 pp., 2015.

[3] Peña-García, A., Gil-Martín, L.M. & Hernández-Montes, E., Use of sunlight in road tunnels: an approach to the improvement of light-pipes' efficacy through heliostats. *Tunnelling and Underground Space Technology*, **60**, pp. 135–140, 2016.

[4] Wachenfelt, H.V., Vakouli, V., Pacheco-Diéguez, A., Gentile, N., Dubois, M.C. & Jeppsson, K.H., Lighting energy saving with light pipe in farm animal production. *Journal of Daylighting*, **2**, pp. 21–31. 2015.

[5] Pacheco-Diéguez, A., Gentile, N., Wachenfelt, H.V. & Duboisba, M.C., Daylight utilization with light pipe in farm animal production: a simulation approach. *Journal of Daylighting*, **3**, pp. 1–11, 2016.

[6] Spacek, A.D. et al., Proposal for an experimental methodology for evaluation of natural lighting systems applied in buildings. *Energies,* **10**, pp. 1013–1025, 2017.
[7] Spacek, A.D., Mota Neto, J., Dagostin Biléssimo, L., Ando Junior, O.H., Ferreira de Santana, M.V. & De Fraga Malfatti, C., Proposal of the tubular daylight system using acrylonitrile butadiene styrene (abs) metalized with aluminum for reflective tube structure. *Energies*, **11**, pp. 199–211, 2018.
[8] Song, J., Luo, G., Li, L., Tong, K., Yang, Y. & Zhao, J., Application of heliostat in interior sunlight illumination for large buildings. *Renewable Energy*, **121**, pp. 19–27, 2018.
[9] Gil-Martín, L.M., Peña-García, A., Hernández-Montes, E. & Espín-Estrella, A., Tension structures: a way towards sustainable lighting in road tunnels. *Tunnelling and Underground Space Technology*, **26**, pp. 223–227, 2011.
[10] Peña-García, A., Gil-Martín, L.M., Escribano, R. & Espín-Estrella, A., A scale model of tension structures in road tunnels to optimize the use of solar light for energy saving. *International Journal of Photo Energy*, p. 9, 2011,
[11] Peña-García, A., Escribano, R., Gil-Martín, L.M. & Espín-Estrella, A., Computational optimization of semi-transparent tension structures for the use of solar light in road tunnels. *Tunnelling and Underground Space Technology*, **32**, pp. 127–131, 2012.
[12] Peña-García, A. & Gil-Martín, L.M., Study of pergolas for energy savings in road tunnels. Comparison with tension structures. *Tunnelling and Underground Space Technology*, **35**, pp. 172–177, 2013.
[13] Gil-Martín, L.M., Gómez-Guzmán, A. & Peña-García, A., Use of diffusers materials to improve the homogeneity of sunlight under pergolas installed in road tunnels portals for energy savings. *Tunnelling and Underground Space Technology*, **48**, pp. 123–128, 2015.
[14] Abdul Salam, A.O. & Mezher, K.A., Energy Saving in Tunnels Lighting using Shading Structures. *Proceedings of the 2014 International Renewable and Sustainable Energy Conference (IRSEC)*, pp. 519–524, 2014
[15] Wang, B.L., Ye, Y. & Yan, B., Experimental research on application of the natural light to tunnel lighting engineering. *Journal of Light & Visual Environment*, **39**, pp. 43–51, 2015.
[16] Drakou, D., Burattini, C., Bisegna, F. & Gugliermetti, F., Study of a daylight “filter” zone in tunnels. *Proceedings of the IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC)*, pp. 649–652, 2015.
[17] Drakou, D., Celucci, L., Burattini, C., Nardecchia, F. & Gugliermetti, F., Study for optimizing the daylight “filter” in a pre-tunnel structure. Study for optimizing the daylight “filter” in a pre-tunnel structure. *Proceedings of the IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, p. 4, 2016.
[18] Drakou, D., Burattini, C., Mangione, A. & Bisegna, F., Exploring the daylight simulation of filter panels in a pre-tunnel structure. *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, 2017.
[19] Salata, F. et al., Energy optimization of road tunnel lighting systems. *Sustainability*, **7**, pp. 9664–9680, 2015.
[20] Moretti, L., Cantisani, G. & Mascio, P.D., Management of road tunnels: construction, maintenance and lighting costs. *Tunnelling and Underground Space Technology*, **51**, pp. 84–89, 2016.

[21] López, J.C., Grindlay, A.L., Carpio, M.C. & Peña-García, A., Strategies for the optimization of binomial energy saving landscape integration in road tunnels. *WIT Transactions on Ecology and the Environment*, vol. 190, pp. 511–520, 2014.
[22] Peña-García, A., López, J. & Grindlay, A., Decrease of energy demands of lighting installations in road tunnels based in the forestation of portal surroundings with climbing plants. *Tunnelling and Underground Space Technology*, **46**, pp. 111–115, 2015.
[23] García-Trenas, T., López, J.C. & Peña-García, A., Proposal to forest Alpine tunnels surroundings to enhance energy savings from the lighting installations. Towards a standard procedure. *Tunnelling and Underground Space Technology*, **78**, pp. 1–7, 2018.
[24] Wang, X. & Zhou, J., The application of stepless intelligent control system to LED illuminating brightness in city tunnel. *Transportation Science & Technology*, **1**, pp. 92–94, 2009.
[25] Salata, F. et al., 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**, p. 1092, 2016.
[26] Peña-García, A., The SLT equation: a tool to predict and evaluate energy savings in road tunnels with sunlight systems. *Tunnelling and Underground Space Technology*, **64**, pp. 43–50. 2017.
[27] López, J.C., Grindlay, A.L. & Peña-García, A., A proposal for evaluation of energy consumption and sustainability of road tunnels: the sustainability vector. *Tunnelling and Underground Space Technology*, **65**, pp. 53–61. 2017.
[28] Molina-Moreno, V., Leyva-Díaz, J.C., Sánchez-Molina, J. & Peña-García, A., Proposal to foster sustainability through circular economy-based engineering: a profitable chain from Waste Management to Tunnel Lighting. *Sustainability*, **9**, p. 9, 2017.
[29] Commission Internationale de l'Éclairage, CIE, *Guide for the Lighting of Road Tunnels and Underpasses*, CIE Publ. 88, Vienna, 2004.