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Management of road tunnels: Construction, maintenance and lighting costs

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ABSTRACT

This paper presents a life cycle cost analysis, which compares construction, maintenance, and lighting costs needed to manage a highway tunnel. As regards the decision making process, it often considers only construction costs. Instead even maintenance and lighting, especially related to road tunnels, cause important cash flows. Therefore, both construction and managing costs have to be planned, in order to assess the cheapest solution. The lighting system of a road tunnel must guarantee the visual guidance for users moving at design speed and without hazardous actions.

In this case study, the authors designed the pavement according to Italian standards and the lighting system according to Italian and European technical rules (UNI and UNI EN standards). They used LED technologies to maximize energy saving and road safety. The examined case study shows the importance of the surface pavement material, since it may contribute to the inter-reflected light and reduce electric energy consumption.

1. Introduction

Economic evaluation of transport infrastructure is as important as its technical and structural design: often stakeholders tend to calculate only the construction costs when evaluating economic project sustainability. But, maintenance costs have a strong influence on the total costs in order to be covered during the whole life infrastructure'; moreover, the performances retention of an infrastructure, over its whole life-cycle, need both economic and technical efforts (Loprencipe et al., 2015). In addition, road management costs increase when roads include tunnels. In fact, safety measures for tunnels and their overall equipment involve a high-energy consumption. For example, lighting costs represent up to 25% of the total budget for management of the road network (Löfsjögård and Silfwerbrand, 2004; Municipality of Abu Dhabi City, 2012).

The main objective of this study is to compare construction and maintenance costs of pavement laying and lighting in road tunnels. The paper deals with the management costs of two different kinds of surface pavement material: concrete (CP) and asphalt (AP), over 30-year service life.

This paper examines three road pavements. It refers to a case study of an Italian highway tunnel. The considered twin-tube tunnel (Tube A and Tube B) is about 600 m long and has two 3.75 m wide lanes for each traffic direction and two 0.75 m wide symmetric shoulders. The total width of each roadway is 9.00 m. A Continuously Reinforced Concrete Pavement (CRCP), a Jointed Plain Concrete Pavement (JPCP) and an Asphalt Pavement (AP) have been examined.

For each pavement type, the lighting system has been verified by ProLITE 7.0 software edited by Gewiss; LED technology has been adopted in order to achieve sustainable lighting, long-term efficiency and quality for environment and people. LED technology, in fact, provides high levels of optical comfort and gives reduction in energy consumption and CO_2 emission: it is cheaper than High-Pressure Sodium or Low-Pressure Sodium and Mercury Vapor lamps usually adopted for these installations.

1.1. Lighting literature review

The road lighting system is one of the major expenses of transportation infrastructure management: various methods and technologies are adopted to reduce energy consumption and related costs, especially in road tunnels (Maheswari et al., 2009; Sunky and Mohit, 2012; Peña-García et al., 2015).

The aim of tunnel lighting is to allow traffic to flow safely without modifying the design speed and to ensure visibility for the

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sight stopping distance (Wenchenga et al., 2008). Adequate illumination helps drivers to adjust to the interior light when passing through a tunnel.

Recently, attention research has been relevant to the use of sunlight to reduce consumption in this field (Gil-Martín et al., 2014), both inside the tunnels and in the threshold zone. Tension structures placed at the entrance of the tunnel allow remarkable energy savings depending on their geometry of structure and orientation, latitude, and longitude of the tunnel (Peña-García et al., 2011). The installation of pergolas in the portal gate of road tunnels evidences lower energy savings and easier maintenance than tension structures (Peña-García and Gil-Martín, 2013).

Furthermore, pavement reflection properties play a fundamental role in the design process, since the lighting system of a tunnel is strongly affected by surface reflectivity (Fotios et al., 2005). High surface reflectance contributes to the inter-reflected light and the visual guidance for users, allowing the reduction in luminous flux and electric energy consumption. The reduction of the road tunnel lighting costs is about 20–30% if concrete instead of asphalt pavements are used: calculations for dry pavements performed by Löfsjögård (2000) confirm this.

Concrete pavement has construction costs higher than asphalt pavement. Di Mascio et al. (2012) and Moretti (2014) showed lifelong maintenance costs make flexible solutions become more expensive. A broader framework needs to estimate lighting costs and take account of environmental issues (Moretti et al., 2013).

The lighting requirements in tunnels vary during the day: there is a high contrast during daytime, while during night-time it is lower and reversed. During nighttime, the lighting system must provide luminance levels that ensure an inside level being at least equal to the one outside. During daytime, the design is affected by external conditions and the human visual system. The adaptation process of the visual system is not immediate, the greater the difference between outside and inside tunnel lighting level, the longer the adaptation time.

In Europe, the relevant legislation of tunnel lighting is:

- Dossier pilote des tunnels – November 2000 (Centre d'etudes des Tunnels [CETU], 2000);
- CIE 88-2004: Guide for the lighting of road tunnels and underpasses (Commission Internationale de l'Eclairage [CIE] 88-2004, 2004);
- Aanbevelingen voor de verlichting van lange tunnels voor het gemotoriseerde verkeer (Nederlandse Stichting Voor Verlichtingskunde [NSVV], 1991);
- Road lighting Part 2: Code of Practice for the design of road lighting (British Standard [BS], 2003);
- UNI 11095:2011 Luce e illuminazione – Illuminazione delle gallerie (Ente Nazionale Italiano di Normazione [UNI], 2011).

Recently, a big interest in LED has given rise to a new lighting system in tunnels. LED is the most efficient available technology. Its main characteristics are: long life, energy efficiency, environmentally friendly, zero UV emissions: LED illumination produces little infrared light and close to no UV emissions, color rendering (Mao et al., 2008).

2. Materials and methods

2.1. Construction and maintenance design of pavements

The authors of this paper have analysed three pavement structures derived from the Italian Pavement Design Catalogue (Consiglio Nazionale delle Ricerche [CNR], 1995) taking into account the annual average daily traffic of the examined tunnel of a highway near Rome.

The annual variable increasing rate of the traffic over its service life took into account the economic forecasts of GDP trends in Italy in the coming decades.

The choice of a road pavement has to be addressed on the basis of both structural and functional performances. In this sense, also the interactions with vehicles, due to different pavement characteristics (Bonin et al., 2007), and the context in which the infrastructure is located (Cantisani et al., 2012) are important factors to evaluate.

On account of this, the paper considers the three types of pavements described below.

The CRCP structure is composed of concrete layer 25 cm thick with longitudinal and transversal steel reinforcement; bituminous layer 5 cm thick; unbound granular mix subbase layer 25 cm thick. The concrete modulus of rupture is 5 MPa.

The JPCP is composed of concrete slabs 25 cm thick, 4.15 cm wide and 5.00 m long; reinforcement with steel dowel bars ∅30 mm 500 mm long, spaced at 35 cm center-to center and tie bars ∅20 mm 800 mm long; bituminous layer 5 cm thick; unbound granular mix subbase layer 25 cm thick. The modulus of rupture of concrete is 5 MPa.

The AP structure includes the following layers: porous asphalt concrete surface layer 6 cm thick; asphalt concrete binder layer 9 cm thick; asphalt concrete base layer 13 cm; cement-bound granular mix subbase layer 30 cm thick. The subgrade resilient modulus has been estimated equal to 90 MPa.

All pavements have been designed for 30-year service life.

The construction and maintenance methodology of the examined concrete pavements agrees with procedures currently adopted as international good practices.

Construction costs depend on project geometrical characteristics, materials, labour, machinery and equipment unit costs.

As for the concrete pavement, the inset slipform paver rides on treads over the area to be paved: for each side, the crawler tracks run on the groundwater collector drain, on the tunnel arch footing and on the concrete curb/sidewalk (Fig. 1). The total available width is 18 cm, requisite for truck passage. A hydraulic system provides concrete delivering and supplying to paving area. The pavement reinforcement is installed on the platform area and the concrete supplying equipment is anchored to the tunnel calotte.

As for the asphalt pavement, the authors considered that layering works are done in two parallel strips, each half the width of the tunnel. The method has been adopted because it is impossible to pump the bituminous concrete.

Construction costs were estimated using Italian road price lists; for both tubes, they are listed in Table 1.

The maintenance plan takes into account the damage induced by traffic and the management procedures reported in the literature (Holt et al., 2011; Scheving, 2011; Torres-Machi et al., 2014).

The work scheduling expects activities of pavement preservation, pavement rehabilitation and pavement reconstruction (Federal Highway Administration [FHWA], 2005). As for concrete pavements, the planned maintenance works are joint sealing, grinding, demolition and patching, washing and cleaning surface. As for bituminous pavements, the planned maintenance works are crack sealing, pothole patching and repair, resurfacing.

Discounted maintenance costs are estimated using the Italian road price lists, the prevision of inflation rate and the premium risk for Italian economy over the next three decades (Di Mascio et al., 2014; Banca d'Italia, 2015; Camera di Commercio di Reggio Emilia, 2015). For both tubes, the discounted values are calculated according to the method of cash flow (Di Mascio et al., 2012) and are listed in Table 2.