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Technical and economic evaluation of lighting and pavement in Italian road tunnels

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ABSTRACT

This work computes and compares the life cycle costs of two different road tunnel pavements and their corresponding lighting systems. The study evaluated rigid and flexible pavements during life periods of 20 and 30 years for different traffic conditions and for tunnel lengths between 750 m to 2000 m. The design of the pavements and lightening systems, and their corresponding maintenance strategies, followed the requirements stated in current Italian standards. This information was used to estimate the net present values of the construction and maintenance costs for both the pavements and the tunnel lighting systems, using official unit prices valid in Italy. The results showed that for tunnels equal or shorter than 1000 m, the option of using a concrete pavement offered a better economic and technical solution from the initial year of service in comparison to the flexible structure. For tunnels equal or longer than 1200 m, the discounted costs related to concrete pavements were slightly higher than those obtained for the asphalt pavement. However, due to the low pavement maintenance and lightening system costs, the concrete pavement reaches a break-even point in these cases after a few years of service. The results also suggest that the expected traffic level in the tunnel has a neglectable impact in the economic analyses, independently of the type of pavement or tunnel length. This study demonstrates that the quantification of the life cycle costs related with the selection of the road type is an efficient practice to support decision-making processes during the design stage of a tunnel structure.

1. Introduction

Cement concrete road pavements, also known as rigid pavements, are a widely used technology in many Northern European countries and in North America, mainly because the use of this material offers a good alternative to the solutions commonly provided by asphalt concrete (Federal Highway Administration, 2007). Due to their high durability and low maintenance characteristics, rigid pavements require overall lower costs during their service life (Moretti, 2014). Furthermore, these pavements can be particularly advantageous in road tunnels (Onaygil et al., 2003) because they offer additional advantages in terms of road safety and management, including the following:

- the lighter colour of the pavement ensures better visibility for road users. Moreover, it provides a reduction in the installed power needed to achieve the minimum illumination requirements for safe driving in comparison to traditional asphalt pavements (Moretti et al., 2016). This condition reduces the consumption of electrical energy (i.e. up to a 30% decrease in the installation and management costs of the plant) and, consequently, it also reduces the amount of greenhouse gas emissions (e.g. CO_2). This aspect has important environmental implications that should be considered when conducting comparative studies among pavement structures (Moretti et al., 2013). It is noteworthy that there are recent studies that have assessed the use of modifiers to clear and coloured flexible pavements (e.g., Synnefa et al., 2011). Although such technologies would impact the design of tunnels lighting systems, they are currently not included as part of the standards and regulations that provide design guidelines for these systems;
- concrete pavement ensures a good level of smoothness and grip due to the slow decay of skid resistance (Haider et al., 2006);

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- the low amount of maintenance activities needed for this type of pavement reduces the likelihood of accidents for workers. This aspect is particular relevant when considering that road accidents represent the main cause of death on work in Italy (INAIL, 2016). Moreover, the reduced number and frequency of the required maintenance works increase the traffic safety (i.e. reduction in the necessity of lane changes on the carriageway due to the presence of work site activities) (Federal Highway Administration, 2008); and
- in case of fire, the concrete is an incombustible (DIN 4102-1, 1998) and non-toxic material (International Technical Committee for the Prevention and Extinction of Fire, 2002). The European Standard EN 13501-1 (2009) classifies the reaction to fire of building products in the following categories: inflammability, combustibility, flame propagation, smoke development and dropping while burning. Concrete and its components are considered as '*materials that do not burn at temperatures that usually occur during a fire*' (EN, 2009). The German standard DIN 4102-1 (1998) attributes the highest category, A1 or non-combustible, to concrete, while asphalt concrete is classified as B2, which corresponds to a normal flammability building material. Furthermore, The International Technical Committee for the Prevention and Extinction of Fire (2002) declared that "*concrete should be preferred* [in tunnels] *as material to the traditionally used bituminous mixture pavements* because is incombustible, does not emit toxic smoke and has a clear colour which improves visibility". Nevertheless, it should be noted that the fire reaction of asphalt concrete could be improved through the use of flame retardant additives and fillers, as explained by Wu et al. (2006) and Cong et al. (2008).

Data currently available in the literature could be efficiently used to compare concrete and bituminous pavements in road tunnels. A comparison of this nature, however, should include not only aspects related to the pavement structure itself (e.g., design life, materials, maintenance strategies, etc.) but also aspects related to the tunnel lightening system. This consideration is important because tunnel lightening is critical in promoting safety-related operations, since this component provides 24 h of artificial light under different daylight conditions (Queensland Department of Main Roads-South Coast Hinterland District, 2004). The relationships between lightening systems and pavements in road tunnels have been assessed by several authors in the past. Myran and Hedalen (1992), for example, demonstrated that 60–65% of light the total in tunnels is reflected by the surface of the pavement, while the rest of it is reflected by walls and roofs. Some of these studies have pointed out that tunnel lighting is particularly critical when using conventional asphalt pavements. Salata et al. (2015) conducted a work in this direction where they evaluated different technical scenarios to optimize energy consumption of the lighting system in road tunnels with asphalt pavements. Other similar models and technologies have been also developed to obtain energy-saving effects in these systems (Shuguang, 2015; Peña-García et al., 2015); moreover, the European Asphalt Pavement Association (2008) suggests the use of bright coloured asphalt or a white-coloured aggregate to reduce lighting costs.

Conducting studies on this topic is particularly relevant given the results of several technical, scientific and legislative initiatives undertaken by different European institutions with the common goal of improving safety in road tunnels. For example, the European Directive 2004/54/CE defined additional measures to provide adequate safety levels in tunnels of more than 500 m long that belong to the Trans European Network (TEN). Italy is the Member State of the European Union with the highest number of kilometres of tunnels enclosed in the TEN, as represented in Fig. 1. However, even though some European countries have issued regulations,

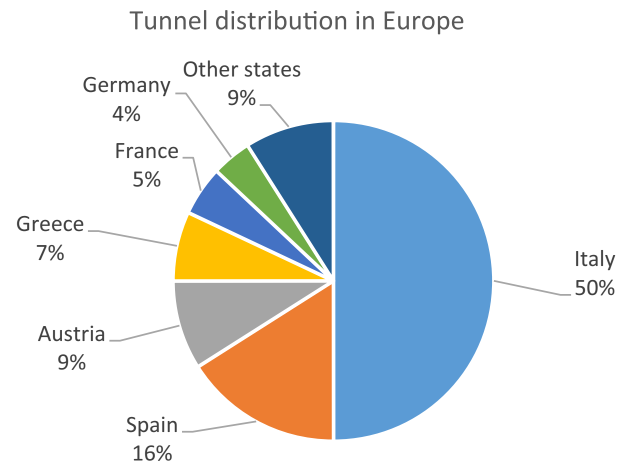

Fig. 1. Tunnel distribution in Europe (percentage of kilometres with respect to the total in TEN network) (Segnalini, 2012).

recommendations or guidelines about suitable materials for tunnel pavements (for Austria: RVS 09–01-23, 2009; for Germany: ZTV-ING Teil 5, 2007; for Slovenia: Republiki Sloveniji, 2006; for Spain: Real Decreto 635, 2006), current Italian regulations for road tunnels do not consider the type of material to be used in the pavement as a preventive safety measurement. For this reason, technical and economic studies on pavement and lightening systems in road tunnels are paramount for the country.

The scope of this paper is to quantify and compare the pavement and lighting costs associated with the use of concrete (rigid) or asphalt (flexible) pavements in Italian tunnels located in secondary roads over their service lives. Specifically, the study estimates both the construction and maintenance costs of the pavements and the construction and maintenance cost of the tunnel lighting, taking into account official Italian unit price lists. The study evaluated five different tunnel lengths, ranging from 750 m to 2000 m, and different traffic levels during the service life of the structures. The results of this study could be used to support decision-making processes when selecting the type of pavement to be used in a specific tunnel project.

2. Pavements design and costs

2.1. Materials and methods

The input data used to design the pavements correspond to average values of materials properties, traffic levels and weather conditions typical in the central Italian region. As explained previously, the two types of pavement typologies considered in the study were flexible and rigid. The first structure is composed by a wearing, a binder and, in some cases, one or more base courses composed by bituminous concrete, and a subbase layer with unbound granular material. The second type consists on a Jointed Plain Concrete Pavement (JPCP), composed by unreinforced cast-in-place concrete slabs, an unbound granular base, and a cement stabilized aggregate subbase. The concrete slabs were assumed to be doweled at transverse joints, and tied at longitudinal joints. For both pavements, the subgrade bearing capacity was defined through the resilient modulus of the soil, and it was supposed to be equal to 90 MPa.

The design of the pavements was performed after considering the traffic (Table 1) and climatic conditions (Table 2) defined in the Italian Road Pavement Catalogue for Central Italy (CNR, 1995), for two different service life values (i.e. 20 and 30 years).