Issues and Perspectives in Railway Management from a Sustainability Standpoint

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ABSTRACT: In this paper a method is set up for assessing the best strategy for the management of a railway infrastructure over time. A model to evaluate the total costs of competing track alternatives in a long-term perspective is proposed. Tangible and intangible costs, as well as internal (e.g., agency and user costs) and external costs (CO2-related, etc.) are considered. Life cycle costs are estimated based on agency, environmental, and user present values. The detailed analysis of the costs over the entire life of the track allows assessing the trend of agency (AC, e.g., construction, maintenance and renewal), user (UC, e.g., delays, etc.), and externality (EC, e.g., related to CO2e emissions, etc.) costs of the alternatives. An application of the proposed method is carried out comparing two track alternatives (ballasted vs. ballast-less). The trend of total present values (TPV) shows that solutions more affordable in the short time can yield maintenance and renewal processes which are economically unfavourable. Furthermore, not only the breakeven point (ballast-less versus ballasted present values) is very far from the construction time but also the “distance” between the TPV of the two solutions becomes too small to yield sound conclusions in favour of one solution.

INTRODUCTION

The railways, as any other transport infrastructures, require relevant resources to guarantee their efficiency and functionality over the time. The total annual spending in railway sector can be divided into three main categories: the cost to run, the cost to maintain, and the cost to grow and modernize the railroads [AAR, 2013]. As for the costs to run, they prevail (66%) and include fuel, wages, rentals, purchased services, and taxes. The cost to maintain reaches approximately the percentage of 14% of total costs and it is mainly related to the materials and supplies necessary for maintaining both the infrastructure and the equipment used to provide the service (power supply, signalling), while the costs to modernize and expand the capacity of the rail network and purchase equipment can be considered as “grow costs” and they account for the 20% of total cost. Costs related to the infrastructure (construction, maintenance renewal) can be derived from maintain and grow cost and can be estimated as the 18% of total costs.

In Europe, the construction cost of track ranges from 0.4 to 0.6 million of euros/km for single tracks, while the maintenance costs range from 30.000 to 100.000 €/km per year [Baumgartner, 2001; Jimenez-Redondo et al. 2012]. The railways owner generally supports these costs.

Other important costs, not directly supported by the owners but affecting the community, relate with the environmental impacts connected to the construction and
maintenance/renewal of track. Few data are available regarding the environmental costs even if the environmental concerns have an increasing importance in design and maintenance decision-making process [Milford and Allwood, 2010, Lee, 2008].

From the technical standpoint, in the last decades, there is a worldwide trend towards higher axle loads and train speeds. The tracks are therefore subject to a wide range of bearing and bending stresses in the rails, pads, fasteners, sleepers/slabs, ballast and subgrade due to static and dynamic actions [Tzanakakis, 2013]. In these conditions, the ballast-less slab track systems exhibit a good performance, especially when high-speed passenger and freight train share the same track. Ballast-less track is a continuous slab of concrete in which the rails are supported directly on the upper surface by using resilient pad. In comparison to the traditional ballasted track, still widely used in high-speed lines, it has many advantages: low maintenance costs (approximately 20-30% less) (see Bilow & Randich, 2000), higher availability, increased service life (50-60 years); higher lateral stability; reduction of weight and height of the track; easier and more economic vegetation control. On the other side, weaknesses of slab track are: higher construction cost; higher noise radiation (Esveld, 2001; Lichtberger, 2005).

In general, the need to make the track suitable to withstand increased stresses requires an accurate design (considering advantage and disadvantages of competing track solutions) and includes enhanced maintenance concepts for ballasted tracks, new or improved construction methods for slab tracks [Esveld, 2001; Gautier, 2015]. Therefore, since the early stage of inception, it is important to take into account the various phases of the life cycle (design, construction, operation, maintenance, and disposal). In fact, it is very difficult to modify the initial track design, while, on the other side, the performance of the infrastructure depends largely on maintenance and renewals. The track design phase needs to carefully consider costs (agency cost, user cost, externality cost) during the life (Life Cycle Cost Assessment, LCCA) and performance such as Reliability, Availability, Maintainability, and Safety (RAMS) at system and component level. After construction and installation, LCCA and RAMS assessment can provide a useful aid for making effective maintenance and operational decisions.

In the light of the above considerations in the present paper an LCCA-based model able to evaluate the total costs of competing track solutions is set up. The model aims at assessing the alternatives in long-term perspective and considering tangible and intangible costs, as well as internal (e.g., agency and user costs) and external costs (CO2-related, etc.).

METHOD

The conceptual framework of the LCCA-based method herein proposed starts from the consideration that a comprehensive cost analysis needs to take into account both technical issues and environmental concerns.

To this purpose, in the model set up in the present work, the total cost associated to a track solution is the sum of agency cost (AC), user cost (UC), and externality cost (EXC) [Praticò, 2011; Pratico and Vaiana, 2012; Praticò et. al. 2014]. The algorithms defined and applied are shown in table 1 and discussed hereafter.
Table 1. Algorithms set-up for LCCA.

<table>
<thead>
<tr>
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<th>Formula</th>
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<tbody>
<tr>
<td>Agency costs, AC</td>
<td>$AC = CC_s + MC_s + RNWC_s$</td>
</tr>
<tr>
<td>User costs, UC</td>
<td>$UC = CD = CD_M + CD_{RNW}$</td>
</tr>
<tr>
<td>Externality costs, EXC</td>
<td>$EXC = \sum_k \sum_j CX_{kj} = \sum_k \sum_j Q_{kj} \cdot UP_{kj}$</td>
</tr>
<tr>
<td>$PV_{AC}$</td>
<td>$PV_{AC} = CC_s + \sum_k C_M \cdot R^{E_{M}} + \sum_k C_{RNW} \cdot R^{E_{RNW}} \quad R = \frac{1 + i}{1 + r}$</td>
</tr>
<tr>
<td>$PV_{UC}$</td>
<td>$PV_{UC} = PV_D = \sum C_{DM} \cdot R^{E_{M}} + \sum C_{DRNW} \cdot R^{E_{RNW}}$</td>
</tr>
<tr>
<td>$PV_{EX}$</td>
<td>$PV_{EX} = EX_0 + \sum_k EX_k \cdot R^{E_{i}}$</td>
</tr>
<tr>
<td>Costs balancing factor, $\nu$</td>
<td>$\nu = \min_{i=1,2,3} \frac{PV_{AC} + PV_{UC}}{PV_{EX}}$</td>
</tr>
<tr>
<td>TPV</td>
<td>$TPV = PV_{AC} + PV_{UC} + \nu \cdot PV_{EX}$</td>
</tr>
</tbody>
</table>

The agency cost comprises the construction costs ($CC_s$) and the running costs due to maintenance ($MC_s$) and renewal ($RNWC_s$) activities. The construction cost refers to the sum of all costs supported to supply and install the track components (rails, sleepers/slab, ballast, sub-ballast, embankment, fastenings, baseplates, fixings, and pad). The worth of these costs can be derived from projects and literature.

Maintenance encompasses all the minor activities aiming at repairing (corrective maintenance) or preventing (preventive maintenance) the track failures. Typical maintenance activities are: rail grinding, replacement of defective rails and sleepers, tamping, track stabilization, ballast injection, etc. Frequencies and costs of these activities are variable. Costs due to maintenance depend on traffic (typically the Millions of Gross Tonnes) and speed, and can be distributed annually [Calvo et al. 2012].

Renewal refers to the substitution of the main components of track (ballast, rails, sleepers, slabs, etc.). This activity is linked to the service life of the components. The related costs comprise the costs for disposal and re-construction.

Regarding user costs, they can be related to the delays ($D$), originated by work zones of given length and duration. In general, delays can be divided into two general categories: routine (experienced during normal operations, including crew changes, meets, passes, and civil speed restrictions) and irregular (including maintenance, accidents, and short-term speed restrictions based on track conditions), (see Lovett et al, 2015). In the present study, based on owner’s standpoint, the irregular delays due to maintenance and renewal and related costs, respectively $CD_M$ and $CD_{RNW}$, are considered.

The externality cost refers to the sum of all costs associated to the impacts on the environment in terms of climate change ($CO_2e$), air quality (SOx, NOx, CO, VOC, PM, etc.), noise, water quality, soil quality, biodiversity, land take, quarries, landfills, and visual effects (Yin and Siriphong, 2006; Olof, 1997; Ian et al., 2009) produced by activities and processes carried out during construction/maintenance/renewal, (i.e. transportation, quarrying, landfill use, cement/steel/rubber production).
Each j-th impact produced by the k-th process \((Q_{kj})\), can be associated to a unit cost \((UP_{kj})\). Due to the difficulty to quantify these costs, in this work the quantity of CO\(_2\) equivalent corresponding to the given process and material has been considered. Regarding the cost of a ton of CO\(_2\), note that it is extremely variable. Consequently a sort of equilibrium between the sum of agency and user costs (tangible costs) and externality cost (intangible costs) was pursued, by means of the calculation of costs balancing factor \((v)\) defined as the minimum ratio tangible to intangible costs (see table 1).

In order to make all the costs discussed above comparable the cash flows occurring during the analysed life span are discounted to a base in which the choice of the suitable alternative is done (i.e. construction year). Discounting includes interest (r) and inflation (i) rates as well as expected life of maintenance \((E_M)\) and renewal \((E_{RNW})\). The total present value (TPV) of a given alternative is the sum of the present values of all costs related to them.

**MODEL APPLICATION AND RESULTS**

The proposed method was applied to a case study. Two competing track alternatives were considered, ballasted and ballast-less. Various types of innovative ballast-less track systems are in service around the world. The most popular are the Bögl, Shinkansen, Rheda, Sonneville-LVT, Züblin, Stedef and Infundo-Edilon [Esveld, 2001]. In the present work the Shinkansen system is considered.

Table 2 shows the main characteristics of the track components for the two considered alternatives. For each component an average service life is assumed [see Milford, et al. 2010].

<table>
<thead>
<tr>
<th>Components</th>
<th>Type</th>
<th>Service life [Years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail</td>
<td>60 UNI, mass= 60,1 Kg/ml</td>
<td>28</td>
</tr>
<tr>
<td>Sleepers equipped with baseplate</td>
<td>Pre-stressed mono-block, L= 2.60 m, mass= 325 Kg</td>
<td>40</td>
</tr>
<tr>
<td>Fastenings</td>
<td>Elastic type Vossloh W14 AV</td>
<td>40</td>
</tr>
<tr>
<td>Ballast</td>
<td>Crushed stones, 500 mm (aver. depth)</td>
<td>40</td>
</tr>
<tr>
<td>Subballast/Concrete road-bed</td>
<td>Cement treated layer 200 mm depth</td>
<td>40</td>
</tr>
<tr>
<td>Slab</td>
<td>Pre-stressed concrete with cylindrical bollard 4,93 m x 2,34 m x 0,19 m; mass = 5 tons</td>
<td>60</td>
</tr>
</tbody>
</table>

The proposed model, applied to a stretch of 1 km of track, allowed the derivation of the trend of the total present value for each alternative (i.e. ballasted and slab track). Results are shown in Figure 1, where y-axis represents the total present value (TPV, table 1) while x-axis refers to the time (years).
As it can be observed, at end of construction stage (year 0), the total cost of slab track is approximately 1.5 times higher than the one of the ballasted track [Schilder and Diederich, 2007; Pichler and Fenske, 2013; Gautier, 2015]. Note that in this case the total cost encompasses both construction and externality costs. After 26 years a breakeven between the total present value of slab and the one of ballasted track can be observed. After 40 years the total present value of slab track remains lower than the ballasted, even if the difference between the two costs is small.

Figures 2 to 7 illustrate how the different components of cost (construction, maintenance and renewal, M&R, user cost UC, externalities, EX’) vary over the time. Six different periods of analysis are considered (0, 20, 40, 60, 80 and 120 years). The detailed analysis of the components of the TPV (construction, maintenance and renewal, user and externality) permits to evaluate better the performance of the two solutions from both a technical and an environmental standpoint. In particular, considering the TPV at end of construction and after 20, 40, 60, 80 and 120 years, the percentage of each component with respect to the total cost is shown in figures below.
At the end of construction, for ballasted tracks the percentage of the construction cost with respect to the total cost are higher (57%) than the externality cost (43%) while an opposite tendency can be observed for the slab solution (48% vs. 52%) (see figure 2). It means that, apart from the higher construction costs of the slab solution, the costs of the produced environmental impacts (mainly related to the production of the cement) are significant. During the life of the track, other costs contribute to the total cost, namely, user costs and agency costs due to maintenance and renewal. The percentages of these costs in respect of the total cost vary significantly for the two track solutions. In fact, for ballasted track the percentage of maintenance and renewal costs increase from 16% (at year 20) to 26% (at year 120) (see figures from 3 to 7), while for slab track the percentages at same years are lower and vary from 4% to 13%. As expected the higher service life of the components of the slab track system together with the intrinsic higher
stability of track require minor maintenance and renewal activities and consequently lower costs. The same tendency can be noted for the user costs. For ballasted track, they vary from 8% (at 20-th year) to 13% (at 120-th year), while for slab track from 2% to 6% in the same years.

It noted that the externality costs represent a noteworthy component of the total cost for both the solutions (higher than the 39%). This implies that the consideration of the external, intangible costs is essential in the assessment of the global performance of a track solution, and plays an outstanding role in the decision-making process.

CONCLUSIONS

In order to compare different track solutions and recognize the most cost-effective, carrying out a comprehensive life cycle cost analysis appears a proper methodology. In the present work a LCCA based model has been defined and applied to two track alternatives. The model considers agency, user and externality costs and their evolution over the time. Results show that solutions that are more affordable in the short time can yield maintenance and renewal processes which are unfavourable or less sustainable. Furthermore, when tangible and intangible costs are considered over track life, not only the breakeven point (ballast-less versus ballast present values) is very far from the construction time (which may impact public opinion and overall judgment) but the “distance” between the total present value of the two solutions becomes too small to yield sound conclusions in favour of the ballast-less versus the ballasted solution.

REFERENCES