

An Integrative Approach RAMS-LCC to Support Decision on Design and Maintenance of Rail Track

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Abstract. In this paper a RAMS (Reliability, Availability, Maintainability, Safety)–LCCA (Life Cycle Cost Analysis) mixed approach is proposed in order to support decisions on design and maintenance strategies of rail tracks. RAMS management, usually applied in railway sector, lacks a life-cycle cost perspective and balance, while LCCA supports decisions on design options and maintenance strategies by means of an economic analysis in which costs and performance are assessed. Therefore, a Decision Support System, based on Life-Cycle Costing (LCC) analysis, should be developed, balancing short and long-term costs with performance (RAMS target). The model proposed accounts for a comprehensive life cycle cost analysis based not only on agency (e.g., construction, inspection, maintenance and renewal), and user costs (e.g., delay-related, etc.), but also on environmental costs (e.g., related to CO₂e emissions). For RAMS analysis, a new method to measure the RAMS components and to define an overall indicator is proposed. Results show that the RAMS of a slab track is generally higher than the one of a ballasted track. In terms of present value of two solutions, the breakeven point between them is very far from the end of construction and this may impact public opinion and overall judgment.

Keywords: LCCA, RAMS, Railway track.

Conference topic: Roads and railways.

Introduction

Current issues in the transport sector, such as rising traffic demand, congestion, pollution, security of energy supply and global warming, require, as indicated in the Union Commission’s 2011 Transport White Paper, that the railway sector takes on a larger share of transport demand in the next few decades. To achieve this goal main challenges in railway transport are: making infrastructure more reliable and resilient, keeping pace with the growing mobility requirements, reducing the impact of infrastructure on the environment (carbon footprint), maintaining and upgrade deteriorating infrastructures (renewal processes), applying innovative track design and materials.

As for the railway track, in the last decades, there is a world-wide trend towards increased pressures caused by the increase in axle loads and train speeds. The track is therefore subject to a wide range of bearing and bending stresses in the rails, pads, fasteners, sleepers/slabs, ballast and subgrade due to: i) the static mass of the vehicles; ii) the dynamic actions, such as lateral centrifugal forces on curves, longitudinal acceleration and braking forces; iii) vertical inertial forces from the motion of the wheel-set and its suspension, vibrational forces induced from imperfections in the rail surface (corrugations, joints, welds, defects) and in the wheels (flats and shells); iv) the dynamic response of the track components to the above actions (Tzanakakis 2013).

The need to make the track suitable to withstand these stresses requires an accurate inception and design and includes enhanced maintenance concepts for ballasted track, new or improved construction of slab track (Esveld 2001; Gautier 2015). The track design phase needs to consider together with the costs (agency cost, user cost, externality cost) during the life (Life Cycle Cost Assessment) also properties like: Reliability, Availability, Maintainability, and Safety (RAMS) at system and component level (INNOTRACK 2006). After construction and installation, during the operation and maintenance phase LCC assessment and RAMS target can provide a useful aid for making effective maintenance decisions (Smith 2005; Villemeur 1992).

RAMS analyses represent a kind of proof of quality of the system, and can follow a number of European standards, such as CENELEC EN 50126, BS5760, MIL-HDBK-217 and Def Stan 00-40. RAMS can be considered as a characteristic of a system and it acts as a performance indicator for its quality and performance. EN 50126 (1999) defines the basic RAMS elements as:

Reliability, the probability that the track or its components can perform a required function under given conditions for a given time interval. Reliability parameters are Mean Time To Failure (MTTF) and Mean Distance To Failure (MDTF), for non-repairable system, Mean Time Between Failure (MTBF) and Mean Distance Between Failure (MDBF) for repairable system.

Maintainability, the easy with which the track can be repaired or maintained, and it is usually measured by Mean Time To Repair (MTTR), this time encompasses access time and repair/replacement time. Maintainability is also represented by Mean Time Between Maintenance (MTBM) or Mean Distance Between Maintenance (MDBM). MTBM and MDBM include both unscheduled and preventive maintenance.

Availability, the probability that the track or its components will be operational at any random time, t . This is very similar to the reliability function in that it gives a probability that a system will function at the given time, t . Unlike reliability, the measure of the availability incorporates maintainability information. Inherent availability can be defined as $A_I = \text{MDBF} / (\text{MDBF} + \text{MTTR})$.

Safety, the state of technical system freedom from unacceptable risk of harm. Safety is the requirement not to harm people, environment, or any other assets during a system's life cycle. Typical safety parameters that have been used for the track are: Mean Time Between Hazardous Failure (MTBHF), Mean Time Between Safety System Failure (MTBSF), Hazard rate $H(t)$.

Safety and availability are considered as the output of any RAMS analysis and any conflicts between safety and availability requirements should be avoided in order to have a dependable system (EN 50126 1999). In summarising, it is possible to observe that reliability (time to failure), maintainability (time to be maintained), availability (not failed neither undergoing a repair action), and safety (it doesn't harm) are conditions which affect the life cycle cost of a ballasted or ballast-less track.

As for life cycle cost, according to ISO 15686-5 it can be defined as "the cost of an asset or its parts throughout its life cycle, while fulfilling the performance requirements". The LCC analysis allows comparing the relative merits of competing alternatives, ballasted/ballast-less track. Minimizing the track system life cycle costs (present worth value, PWV or PV, or equivalent uniform annual cost, EUAC) will increase the sustainability of the rail superstructure. The detailed analysis of the costs over the entire life cycle of each track solution allows assessing the trend of agency (AC, e.g., construction, inspection, maintenance and renewal), user (UC, e.g., time, accidents, ...), and externality (EC, e.g., related to CO₂e emissions, etc.) costs of the alternatives and recognizing the most convenient (Zoeteman 2001; Praticò, Giunta 2016a, 2016b; Giunta 2016).

A life cycle costing assessment considering also Reliability, Availability, Maintainability & Safety (RAMS) analysis will provide a way to optimise the maintenance strategy, considering the short-term budget requirements as well as long term costs of agency. To achieve overall RAMS requirements and LCC objectives of the system, it is important to follow systematic RAMS/ LCC assessments throughout the life cycle of the system. One of the important phases of the life cycle of track system is the operation and maintenance phase in which, due to its long duration, RAMS and LCC are to be optimised. RAMS parameters play a very big role in determining the costs, since as stated above, failures will bring costs to the system, i.e. the cost of a corrective maintenance operation on a rail track which requires an impediment/limitation of traffic, the cost of accidents which might involve serious injuries or death, the cost of a train to be stopped due to a signalling system failure, among others.

Based on the above, the main objectives of the study presented in this paper is the proposal and implementation of a methodology to analyse different track solutions, ballasted and slab, considering both LCCA and RAMS. As for RAMS analysis, a new method to measure the RAMS parameters and to define an overall indicator of RAMS components is proposed. Furthermore, a LCCA based model to evaluate the total costs, tangible and intangible, of competing solutions (e.g., traditional rail track and slab track) is set up. A solution for solving the issues of CO₂ cost fluctuation and external costs quantification is also proposed and applied.

Method

The method set up and applied to compare two track solutions (ballasted and slab) includes the following steps:

- Step 1 – Modelling of RAMS in terms of main parameters and derivation of an overall indicator;
- Step 2 – Modelling of the Present Values (PVs) in terms of agency, user and externality costs;
- Step 3 – Application to a case-study;
- Step 4 – Analysis of results.

RAMS analysis and modelling (Step 1)

In the pursuit of RAMS modelling, RAMS subsets are analysed in the following. Figure 1 illustrates the complex superposition of track, traffic and external factors in determining the track overall RAMS Indicator (ORI). The method builds on the normalization of the main parameters in order to set up a theoretical framework in which the four main components synergistically impact the overall result, i.e., RAMS (ORI).

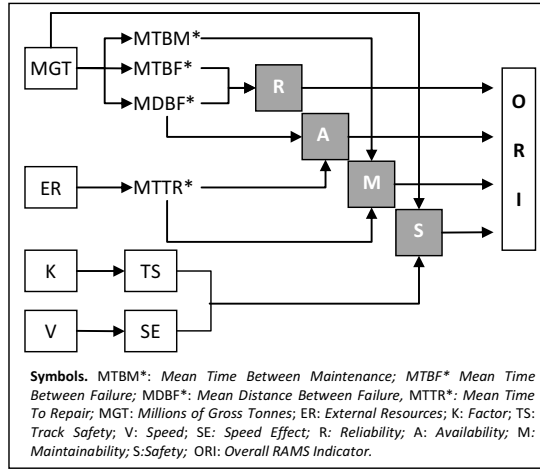


Fig. 1. Work flow for the derivation of ORI

Reliability (R) is quantified based on Mean Time Between Failure (MTBF) and Mean Distance Between Failure (MDBF). According to Patra (2007) and Medeiros Pais Simoes (2008), the reliability parameter is obtained from failure rate. The cumulative traffic load (generally measured in millions of Gross Tonnes, MGT) is the main unit which controls failure rate grows (failure modes are due to mechanical fatigue and/or cracking). Failure rates usually grow with MGT. Consequently MTBF and MDBF decrease when traffic loads increase. In order to take into account the dependency on the traffic load and to obtain a value of reliability ranging from 0 to 1, a normalization process of the quoted parameters was performed using the logistic function defined below.

$$MTBF^* = 1 - \frac{a_1 - b_1 \cdot e^{-\frac{MGT}{\tau_{1n}}}}{c_1 - d_1 \cdot e^{-\frac{MGT}{\tau_{1d}}}}; \quad (1)$$

$$MDBF^* = 1 - \frac{a_2 - b_2 \cdot e^{-\frac{MGT}{\tau_{2n}}}}{c_2 - d_2 \cdot e^{-\frac{MGT}{\tau_{2d}}}}; \quad (2)$$

where MGT is the traffic expressed in terms of millions of gross tons, $a_1 = b_1 = c_1$ and $a_2 = b_2 = c_2$, while τ_{1n} , τ_{1d} , c_1 and d_1 are calibration factors, $MTBF^*$ and $MDBF^*$ represent the parameters normalized.

Based on the above, the reliability has been defined as:

$$R^* = \sqrt{MTBF^* \cdot MDBF^*}. \quad (3)$$

The Availability (A) depends on MDBF and on the time occurred to repair a track after a failure. The Mean Time to Repair (MTTR) is a measurable factor that allows evaluating this RAMS component. MTTR depends on the external resources provided and available for maintenance (competent personnel, tools and technologies, ability and expertise) and on the traffic level. MTTR is also normalised and related to the traffic by means of the following function:

$$MTTR^* = 1 - \frac{a_3 - b_3 \cdot e^{-\frac{ER}{\tau_{32n}}}}{c_3 - d_3 \cdot e^{-\frac{ER}{\tau_{3d}}}}; \quad (4)$$

where ER is a coefficient that takes into account the external resources available for maintenance, $a_3 = b_3 = c_3$, while τ_{3n} , τ_{3d} , c_3 and d_3 are coefficients to calibrate. Under the previous assumptions, the availability can be derived as follows:

$$A^* = \frac{MDBF^*}{MDBF^* + MTTR^*}. \quad (5)$$

The availability, as defined in this study, depends only on failure parameters. Consequently it is inherent to the system and doesn't depend on how the system operates (Andrés *et al.* 2015).

For the maintainability (M), the Mean Time Between Maintenance (MTBM) is expressed as a function of traffic as follows:

$$MTBM^* = 1 - \frac{a_4 - b_4 \cdot e^{-\frac{MGT}{\tau_{4n}}}}{c_4 - d_4 \cdot e^{-\frac{MGT}{\tau_{4d}}}}, \quad (6)$$

where $a_4 = b_4 = c_4$, while τ_{4n} , τ_{4d} , c_4 and d_4 are coefficients to calibrate.

Maintainability has been evaluated by means the equations:

$$M^* = \sqrt{MTBM^* \cdot (1 - MTTR^*)}. \quad (7)$$

Safety (S) depends mainly on track geometry and structures, traffic (the higher the traffic the lower the safety), and on speed. It depends also on maintainability (M). Track defects have become the leading cause of train accidents (He *et al.* 2015). Defects can be categorized into one of two groups: structural defects and geometry defects (Sadeghi, Askarinejad 2010). Track structural defects are generated from the structural conditions of the track, which include the condition of the rail, sleeper, fastening systems, subgrade and drainage systems. On the other hand, track geometry defects indicate severe ill-conditioned geometry parameters such as profile, alignment, gage, etc. Coefficients related to inherent track safety (TS) and speed effect (SE) are defined as follows:

$$TS = \frac{K}{100}, \quad (8)$$

where K is a coefficient which ranges from 0 to 100 (based on the conditions of the track). High K (good conditions, TS close to 1) and low K (unsatisfactory conditions, TS close to 0) impact the normalised safety of the track (S^* , see equation 10, below). The speed effect (SE) is defined as follows:

$$SE = 1 - \frac{a_5 - b_5 \cdot e^{-\frac{V}{\tau_{5n}}}}{c_5 - d_5 \cdot e^{-\frac{V}{\tau_{5d}}}}, \quad (9)$$

where V is the line speed in Km/h, $a_5 = b_5 = c_5$, while τ_{5n} , τ_{5d} , c_5 and d_5 are coefficients to calibrate.

Based on the above, safety can be expressed by means the equation:

$$S^* = \sqrt[4]{1 - \frac{a_5 - b_5 \cdot e^{-\frac{V}{\tau_{5n}}}}{c_5 - d_5 \cdot e^{-\frac{V}{\tau_{5d}}}} \cdot M^* \cdot TS \cdot SE}. \quad (10)$$

Based on the above definition, the RAMS level expected have been defined as:

$$O.R.I. = \sqrt[4]{R^* \cdot A^* \cdot M^* \cdot S^*}, \quad (11)$$

where ORI stands for Overall Rams Indicator, R^* is derived through Eq. (3), A^* through Eq. (5), M^* refers to Eq. (7), and S^* to Eq. (10). Note that the five main RAMS indicators (as per Eq. (11)) range from 0 to 100%.

LCCA – Determination of Present values (Step 2)

The life cycle cost assessment involved the estimation of three main classes of costs (agency, user, and externality costs). The main tasks for the application of the method (see Fig. 2) are the following:

- Task 1. Materials and construction-related processes inventory for the considered alternatives.
- Task 2. Cost analysis (agency costs, user costs, externality costs).
- Task 3. Balancing (v in Fig. 2).
- Task 4. Gains.

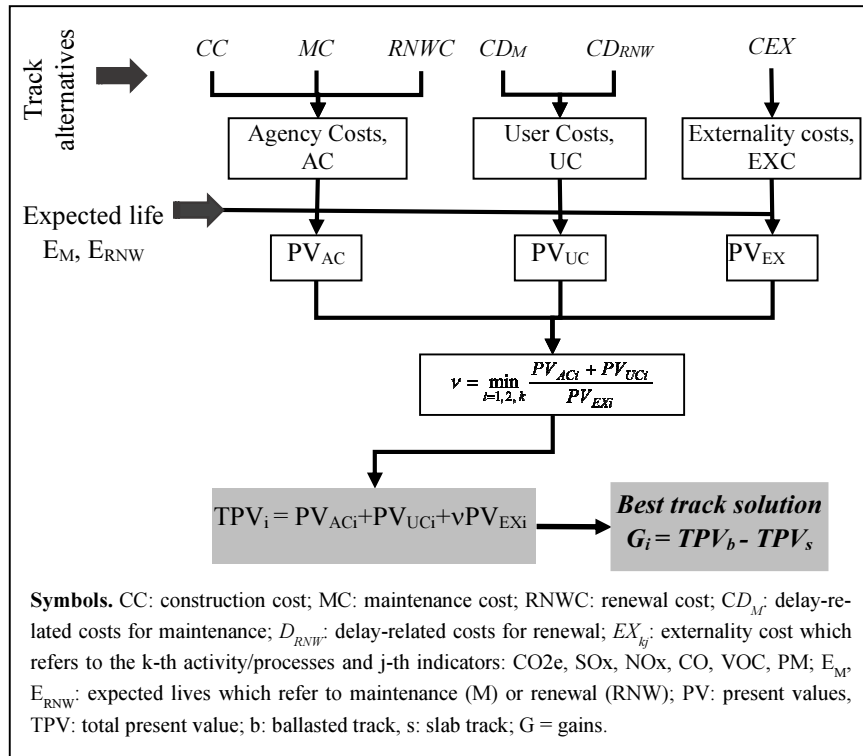


Fig. 2. LCCA modelling

In the model set up, the total costs associated to a track solution is the sum of agency costs (AC), user costs (UC), and externality costs (EXC) (Praticò, Giunta 2016a, 2016b; Giunta 2016; Giunta, Praticò 2017). The algorithms defined and applied are showed in Table 1, and discussed hereafter.

The agency costs comprise the construction costs (CC_s) and the running costs due to maintenance (MC_s) and renewal ($RNWC_s$) activities. Construction costs refer to the sum of all costs needed to supply and install the track components (rails, sleepers/slab, ballast, subballast, embankment, fastenings, baseplates, fixings, pad, etc..). These costs can be derived from projects and literature (Baumgartner 2001). Maintenance encompasses all the activities carried out in the short term (1–3 years), aiming at repairing (corrective maintenance) or preventing (preventive maintenance) the main track failures. Typical maintenance activities are: rail grinding, replacement of defective rails and sleepers, tamping, track stabilization, ballast injection, etc. Frequency and costs of these activities are variables. Due to maintenance, costs depend on traffic and speed, and can be distributed annually (Calvo *et al.* 2013). Renewal refers to the substitution of the main components of track (ballast, rails, sleepers, slabs, etc...). This activity is connected with the service life of the components. The related costs comprise the cost for disposal and re-construction.

For the 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 this 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 costs refer to the sum of all costs associated to the impacts on the environment in terms of climate change (CO₂e), air quality (SO_x, NO_x, CO, VOC, PM, etc.), noise, water quality, soil quality, biodiversity, land take, quarries, landfills, and visual effects (Yin, 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). To each impact j-th, produced by the k-th process (Q_{kj}), a unit cost (UP_{kj}) is associated. Due to the difficulty to quantify these costs, in this work, the quantity of CO₂ equivalent corresponding to the given process and material has been considered. Regarding the cost of a ton of CO₂, note that it is extremely variable. Consequently a standardisation between the sum of agency and user costs (tangible costs) and externality costs (intangible costs) has been carried out by means of the calculation of a cost factor (v) defined as the minimum ratio of tangible to intangible costs.

In order to make comparable all the costs discussed above and express them in equivalent currency units, namely present value (PV), the cash flows occurring during the analyzed life span are discounted to a base (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 the pertaining costs.

Table 1. Algorithms set-up for LCCA

Agency costs AC	$AC = CC_s + MC_s + RNWC_s$
User costs, UC	$UC = CD = CD_M + CD_{RNW}$
Externality costs, EXC	$EXC = \sum_k \sum_j CEX_{kj} = \sum_k \sum_j Q_{kj} \cdot UP_{kj}$
PV _{AC}	$PV_{AC} = CC_s + \sum C_M \cdot R^{E_M} + \sum C_{RNW} \cdot R^{E_{RNW}}$ $R = \frac{1+i}{1+r}$
PV _{UC}	$PV_{UC} = PV_D = \sum C_{DM} \cdot R^{E_M} + \sum C_{DRNW} \cdot R^{E_{RNW}}$
PV _{EX}	$PV_{EX} = EX_0 + \sum_k EX_k \cdot R^{E_k}$
Costs balancing factor, v	$v = \min_{i=1,2,..,k} \frac{PV_{AC_i} + PV_{UC_i}}{PV_{EX_i}}$
TPV	$TPV = PV_{AC} + PV_{UC} + v \cdot PV_{EX}$

Application to a case study and results discussion (Steps 3 and 4)

In pursuit of the implementation of the method, two design alternatives (ballasted and ballast-less track) were considered. In both the cases, a double-track, high-speed railroad was considered. The method application was referred to a hypothetical stretch of 1000 m of track.

For the traditional, ballasted track, the main components considered are detailed below:

- Rail: type 60 E1 (UIC 60), 60 Kg/ml, continuous welded rail (CWR).
- Sleepers: pre-stressed mono-block type RFI 260V- AV, equipped with given baseplates.
- Fastenings: elastic fastening type Vossloh W14 AV.
- Ballast: crushed stones (average depth = 500 mm).
- Subballast: cement treated layer (lift =200 mm).

The slab track system considered in this paper is the Japanese Shinkansen that consists in a sub-layer stabilized with cement, cylindrical bollard to prevent lateral and longitudinal movements, and reinforced pre-stressed concrete slabs 5-tonne heavy and measuring 4.93×2.34×0.19 m (Esveld 2001).

For the two alternatives, construction cost includes the costs of the following components: rails, sleepers/concrete slabs, fastenings, baseplate, ballast/elastomeric pad, subballast/concrete base, embankment. As for the externality costs, note that for each component the amounts of CO2 released when making or using them have been derived (Milford, Allwood 2010; Leung 2009). User costs have been calculated starting from the data on delays related to maintenance and renewal activities. Based on the international literature (Esveld 2001; Milford, Allwood 2010; Calvo *et al.* 2013), on pieces of information gathered for real tracks, and based on materials (geometry, quality and quantity), the typical service lives for the main items considered are summarised in Table 2.

Table 2. Reference service life of track components

Component	Service life (years)
Rail	28
Ballast + sleepers	40
Slab	60

In the pursuit of the implementation of RAMS model the main task carried out was the calibration of the five functions above set up (equations, (1), (2), (4), (6), (9)) based on data gathered from literature and interviews. In the calibration process (last square method) attention was focused on: i) zero response (value when the independent variable approaches zero); ii) slope factors (which control the transition zero to infinite); iii) infinite response; iv) inflection point. Note that the RAMS indicator was derived under the following hypotheses:

- Given boundary operational conditions on the line (traffic, millions of gross tons per year, MGT/year and speed V Km/h). Four main conditions are considered based on traffic rate (6, 10, 20 MGT per year) and on speed (200 or 300 Km/h);

- The reliability and availability of the slab track have been considered higher than the ones of ballasted track (Tzanakakis 2013). In fact, slab tracks exhibit a higher structural and geometrical stability and require little routine maintenance. Consequently, fewer closures of the track are required for maintenance, increasing the availability of the track for running trains.

Results are shown in Figures 3–6.

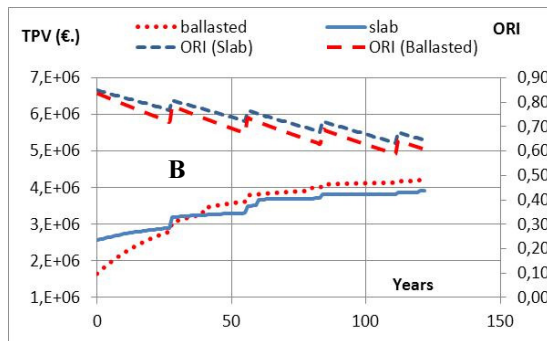


Fig. 3. PV and ORI [MGT per year = 6, V = 200 Km/h]

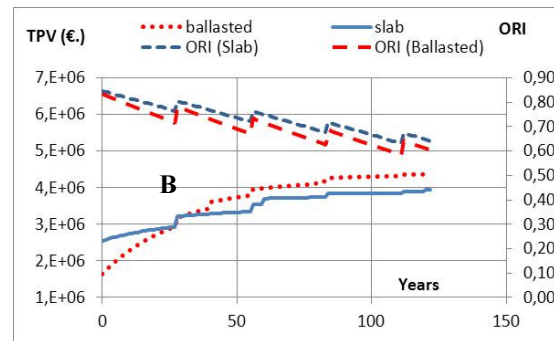


Fig. 4. PV and ORI [MGT per year = 6, V = 300 Km/h]

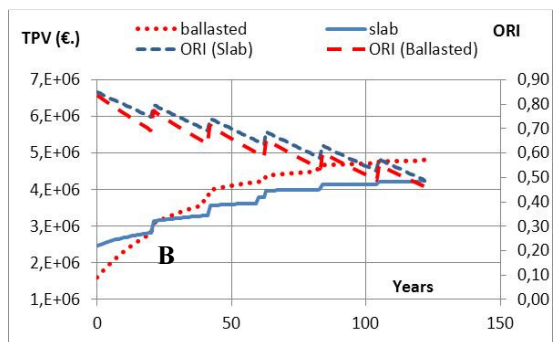


Fig. 5. PV and ORI [MGT per year = 10, V = 200 Km/h]

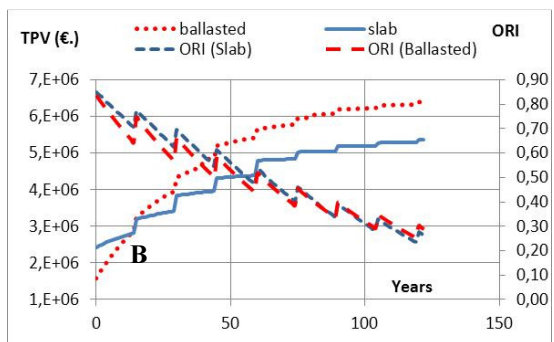


Fig. 6. PV and ORI [MGT per year = 20, V = 200 Km/h]

As expected, it is possible to note that traffic greatly affects both PV and ORI. As for PV, the higher the traffic is, the closer to construction the breakeven point (B) is. Furthermore the “distance” between the total present value (TPV) of the two solutions under analysis increases over time. This makes slab track solutions more favourable than ballasted ones (in the long term). Regarding the ORI, the oscillation range of this parameter is very high when traffic load increases and ballasted systems are considered. Furthermore the minimum ORI approaches very low values. The ballasted solution usually exhibits a reduction which is steeper than the one of the slab track (e.g., Fig.4).

Based on the above, speed has an outstanding role in affecting a track safety, even if it can impact also track reliability, availability and maintainability. High speeds imply low values of SE, S* and ORI. Furthermore high speeds can imply different calibration factors based on R* (Equation (3)), A* (Equation (5)) and M* (Equation (7)). Figures 3–6 show that for the tracks under analysis speeds mainly impact SE and Safety.

Conclusions

High speed and increasing axle load of the trains require more stable tracks. The choice of the appropriate design solution (e.g., ballasted or ballast-less track) and the maintenance strategies during the life are key-factors in the decision-making process for the identification of the most competitive and sustainable solution. The RAMS-LCCA approach proposed allows considering technical, environmental, and economical concerns and entails their balance through a specific and innovative algorithm. Authors are aware that conducting a so comprehensive analysis is a difficult task which requires big data sets. This notwithstanding, based on data gathered and analyses carried out, the following conclusions may be drawn for the two systems considered:

- For agency costs, solutions and systems which could be more affordable in the short time can yield maintenance and renewal processes which are unfavourable. It turns out that the best initial solution might be the worst in the long term;
- Maintenance and renewal processes affect both long term agency costs and user costs, due to delays.
- Under the hypotheses considered in this study, ballasted tracks present an environmental impact which is lower than the one of the slab track system. Carbon footprint associated to the production of cement is appreciable and might hinder slab track systems diffusion, especially for several applications;

- From a more comprehensive standpoint, it is noted that when tangible and intangible costs are considered over track life the two solutions yield a breakeven point (when ballast and ballast-less curve intersect) which is very far from the beginning of the process (construction time). This may impact public opinion and overall judgment;
- Ballasted solutions yield the best performance in terms of costs, even if the RAMS indicator of ballast-less solutions performs better. By referring to long term analyses, due to the impact of expected life on AC, slab-based solutions seem to perform better in terms of both RAMS and LCCA.

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