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Proposal of a Key Performance Indicator for Railway Track Based on LCC and RAMS Analyses

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(Article begins on next page)

1 **Proposal of a Key Performance Indicator (KPI) of railway track based on LCC**
2 **and RAMS analyses**

3 Filippo Giammaria Praticò

4 *DIEES Department University Mediterranea of Reggio Calabria*

5 *Via Graziella, Feo di Vito 89100 Reggio Calabria*

6 *filippo.pratico@unirc.it, phone/fax number +39 0965 1693230*

7
8 Marinella Giunta¹

9 *DICEAM Department University Mediterranea of Reggio Calabria*

10 *Via Graziella, Feo di Vito 89100 Reggio Calabria*

11 *marinella.giunta@unirc.it, phone number +39 0965 1692471*

12
13 **Abstract**

14 The performance of railway tracks can be assessed by applying separately different approaches such
15 as RAMS and LCC, where RAMS is an acronym which stands for Reliability, Availability,
16 Maintainability, Safety, while LCC stands for Life Cycle Costing. Results of these approaches are not
17 comprehensive because RAMS management lacks a life-cycle cost perspective and balance while LCC
18 develops an economic analysis but does not address specific issues of railway performance. Based on
19 the considerations above, in this study a Key Performance Indicator (KPI) for railway tracks is defined
20 merging the LCC and RAMS approaches at a given time. Innovative algorithms are set up for LCC,
21 RAMS and their relationship in the definition of KPI. Algorithms are applied to two different track
22 alternatives (ballasted and ballastless) and KPI trend over time is assessed. Case study results show
23 that in the short-term the KPI of ballasted tracks is higher, while in the long-term the slab track
24 performs better. The trend of KPI for the two solutions under investigation shows that the breakeven
25 point depends on traffic and speed in the railway lines. The method set up as well the results

¹ corresponding author

26 obtained contribute to the body of knowledge of construction engineering because: i) the equations
27 set up allow deriving agency-based algorithms through calibration; ii) the model set up and
28 implemented allows agencies to handle basic technical instances (RAMS) and life cycle-related issues
29 (where sustainability is considered) in a synergistic and quantitative way; iii) the abovementioned KPI
30 has the potential to quantitatively affect decision making across the entire cycle of life (design,
31 maintenance, renewal).

32 **Key works:** rail track, KPI, LCC, RAMS

33 **Introduction and objectives**

34 As indicated in the Union Commission's 2011 Transport White Paper, nowadays issues in the
35 transport sector refer to: i) rising traffic demand and congestion; ii) increasing energy supply
36 demand; iii) effects on global warming and carbon footprint; iv) need for a more balanced and
37 sustainable transport modes, and for a modal shift towards sustainable modes.

38 Consequently, the railway sector is expected: i) to take on a larger share of transport demand in the
39 next few decades; ii) to better perform in terms of management (service, costs, interoperability,
40 capacity, new business, organizational and logistics solutions, new partnerships, and finally new
41 technologies); iii) to face the new challenges through enhanced technologies, higher speeds and axle
42 loads; iv) to better perform from an environmental standpoint (e.g., noise reduction and carbon
43 footprint).

44 To achieve the goals above and to evaluate railway performance, not only advanced materials,
45 technologies, and solutions are needed but also more comprehensive methods (Stenström et al.
46 2012). Railway performance depends on the performance of its main components: Rolling stock,
47 Operations, Traffic management, Infrastructure. The definition of a Key Performance Indicator for
48 the infrastructure, and particularly for the track has to consider synergistically the complexity of
49 different approaches and methodologies, such as Reliability, Availability, Maintainability, Safety

50 (RAMS, cf, Ahrén and Parida, 2009), and Life Cycle Cost Costing (LCC). RAMS and LCC are both crucial
51 for railways: RAMS focuses on vital performance and technicalities, while LCC addresses the life cycle
52 vision. Despite this, with limited relationships exist between RAMS and LCC and consequently a
53 synergetic framework is required.

54 Based on the above, the main objectives of the study presented in this paper are to set up and
55 validate a methodology to analyse different track solutions by defining a Key Performance Indicator
56 (KPI) that takes into account both LCC and RAMS. To this aim, each component of the KPI is properly
57 addressed. For RAMS analysis, a new method to assess the RAMS parameters and to define an
58 overall indicator of RAMS components is herein proposed. Furthermore, a LCC-based model to
59 evaluate the total costs of competing solutions (e.g., traditional rail track and slab track) is set up.
60 Tangible and intangible costs are considered and a solution for solving the issues of CO₂ cost
61 fluctuation and external costs quantification is set up. RAMS and LCC are finally merged in the KPI.
62 The remaining parts of the paper are organised as follows. In the next section the analysis of the
63 concerned literature is illustrated. The successive sections deal with the proposed method and its
64 application to a case study. Finally conclusions are drawn and references are listed.

65 **Literature review**

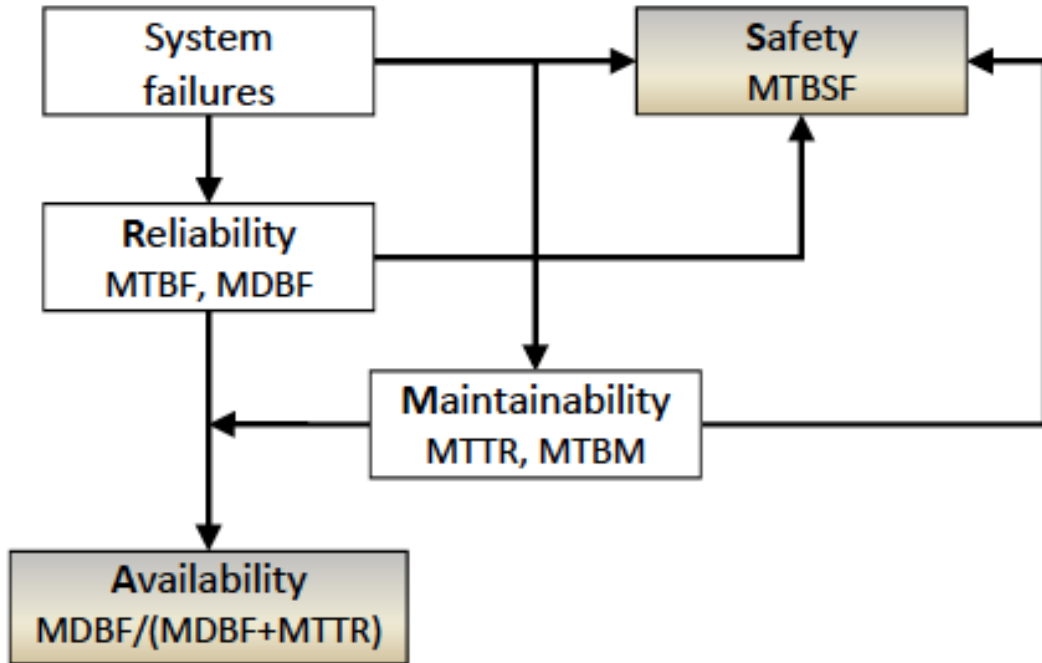
66 For railway tracks, there is a world-wide trend towards increases in axle loads and train speeds. Track
67 is therefore subject to a wide range of bearing and bending stresses in the rails, pads, fasteners,
68 sleepers/slabs, ballast and subgrade due to: i) the static mass of the vehicles; ii) dynamic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

73 The need to make the track suitable to withstand these stresses requires accurate design and
74 maintenance concepts for both ballasted tracks and slab tracks (Esveld, 2001; Gautier, 2015).
75 Furthermore, it is important, since the early stage of the design process, to take into account the
76 various phases of the life cycle, i.e., design, construction, operation, maintenance, and disposal. In
77 fact, it is very difficult to modify, during the life, the initial track design, while, on the other side, the
78 performance of the infrastructure depends largely on the maintenance and renewal decisions taken
79 during its life cycle. In track design, costs (agency cost, user cost, externality cost), life cycle (Life
80 Cycle Cost Assessment), and system technical requirements (Reliability, Availability, Maintainability,
81 and Safety) have to be considered (INNOTRACK, 2006). After construction and installation, during the
82 operation and maintenance phase, LCC and RAMS can provide a useful aid for making effective
83 maintenance decisions (Smith, 2005). On the other side, the use of global performance indicators
84 that accounts for all these aspects may be very effective in transport infrastructure management and
85 in the selection of the right options (Liyin et al. 2011; Stenström et al. 2012).

86 RAMS analysis represents a kind of proof of quality of the system, and can follow a number of
87 European standards, such as CENELEC EN 50126, BS5760, MIL-HDBK-217 and Def Stan 00-40. RAMS
88 can be considered as a characteristic of a system and it acts as a performance indicator for its quality
89 and performance. EN 50126 (1999) defines the following basic RAMS elements: i) *Reliability* is the
90 probability that an item can perform a required function under given conditions for a given time
91 interval; ii) *Maintainability* is the probability that a given active maintenance action, for an item
92 under given conditions of use, can be carried out within a stated time interval when the maintenance
93 is performed under stated conditions and using stated procedures and resources; iii) *Availability*: is
94 the probability that a system or its components will be operational at any random time, t ; iv) *Safety*
95 can be defined as the state of technical system freedom from unacceptable risk of harm. Safety is the
96 requirement not to harm people, environment, or any other assets during a system's life cycle. Safety
97 and availability are considered as the output of any RAMS analysis and any conflicts between safety

98 and availability requirements may prevent in achieving a dependable system (EN 50126, 1999).

99 Figure 1 illustrates the relationships among the RAMS components.



100

101 Figure 1. Relationship among RAMS components

102 Different parameters are used to quantify the RAMS factors (see, Figure 1 and Table 1), while

103 reference values for RAMS analysis, derived from literature, are reported in Table 2 .

104 **Table 1. Parameters used to measure RAMS factors**

RAMS FACTOR	PARAMETER
Reliability	Mean Time To Failure (MTTF) Mean Distance To Failure (MDTF) Mean Time Between Failure (MTBF) Mean Distance Between Failure (MDBF)
Maintainability	Mean Time To Repair (MTTR) Mean Time Between Maintenance (MTBM) Mean Distance Between Maintenance (MDBM)
Availability	$MDBF / (MDBF + MTTR)$
Safety	Mean Time Between Safety Failure (MTBSF)

105

106 Table 2 below summarises reference values (symbols are explained in the last row).

107 **Table 2. Reference values for RAMS analyses**

Parameter	Threshold/example values	References
Axle load	5-35 tonnes	Patra, 2007; Esveld, 2001
Daily tonnage	10000-30000 t <i>per</i> day	Esveld, 2001
MGT per year	3-28MGT; 25 MGT (1MGT=8896 MN)	Patra, 2007; Transportation Safety Board of Canada, 2016
MTBF	1-3 years (geometrical failure) 30 to 60 MGT; 16-28 years (rail replacement) 400 to 700 MGT	Profillidis, 2014
MTTR	75-550 MGT; 3-22 years	Patra, 2007
MTTF	125-575 MGT; 5-23 years; \cong 100MGT; \cong 10MGT	Patra, 2007; Indian railways website; Transportation Safety Board of Canada, 2016
V, Speed	Branch-secondary lines: 30-12km/h; main/high speed lines: 100-300 km/h	Esveld, 2001

Symbols. MGT: Millions of Gross Tonnes; V: line speed; MTBF: Mean Time Between Failure, MDBF: Mean Distance Between Failure, MTTR: Mean Time To Repair, MTBM: Mean Time Between Maintenance; MTBSF: Mean Time Between Safety failure.

108

109 According to the ISO 15686-5, Life cycle cost can be defined as “the cost of an asset or its parts
110 throughout its life cycle, while fulfilling the performance requirements”. The LCC analysis allows
111 comparing the relative merits of competing alternatives, ballasted/ballast-less track. Minimizing the
112 track system life cycle costs (present worth value, PWV or PV, or equivalent uniform annual cost,
113 EUAC) will increase the sustainability of the rail superstructure. The detailed analysis of the costs
114 over the entire life cycle of each track solutions allows assessing the trend of agency (AC, e.g.,
115 construction, inspection, maintenance and renewal), user (UC, e.g., time, accidents, ...), and
116 externality (EC, e.g., related to CO₂e emissions, etc.) costs of the alternatives and recognizing the
117 most convenient one (Zoeteman, 2001, Zoeteman, 2006, Praticò, 2014, Giunta, 2016, Praticò and
118 Giunta 2016a, 2016b, Giunta and Praticò 2017).

119 A synergistic LCC- RAMS analysis would provide a way to optimise the maintenance strategy,
120 considering the short-term budget requirements as well as long term costs of agency. To achieve
121 both RAMS and LCC objectives, it is important to follow systematic RAMS/LCC assessments
122 throughout the life cycle of the system. One of the important phases of the life cycle of track system
123 is the operation and maintenance phase in which, due to its long duration, RAMS and LCC have to be
124 optimised. RAMS parameters play a crucial role in determining the costs since, as stated above,
125 failures will imply costs for the system, i.e. the costs for corrective maintenance operations which
126 require an impediment/limitation of traffic, the costs of accidents which might involve serious
127 injuries or death, the costs of a train to be stopped due to a signalling system failure.

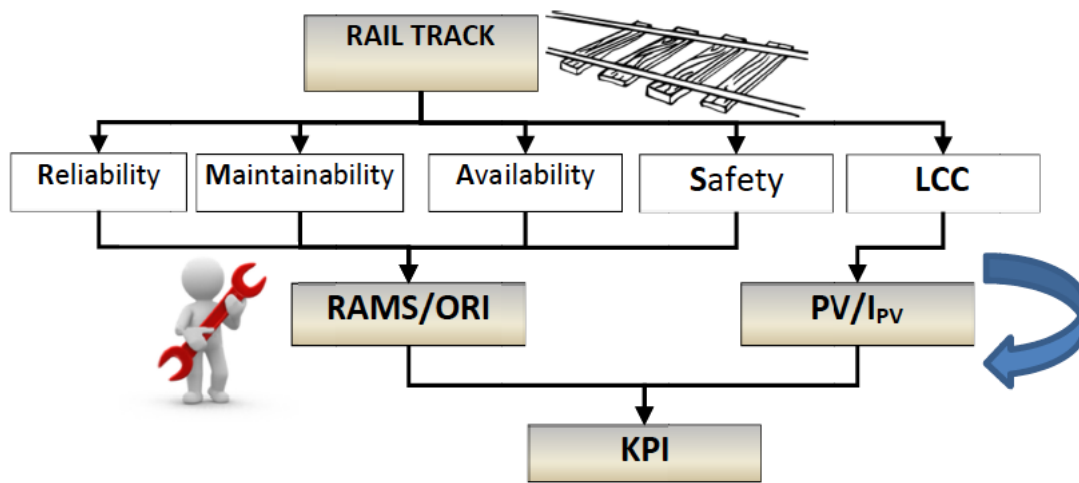
128 Both RAMS and LCC focus on the viability of a project or solution. This notwithstanding, each of them
129 has pros and contras.

130 Note that the following weaknesses may be associated to RAMS analyses: i) where RAMS failures are
131 detected through a RAMS software, analyses need to be supported through dedicated techniques,
132 such as the Fault Tree Analysis (FTA), the Failure Modes, Effects and Criticality Analysis (FMECA), and
133 the Common Cause Failure Analysis (CCFA), otherwise failures might be ignored and RAMS analysis
134 would imply erroneous inferences (González-Arechavala et al., 2010); ii) RAMS activities need time,
135 effort and domain knowledge and experience. Furthermore, RAMS mainly refers to technical
136 performance and no information about costs and environment is provided; iii) RAMS does not
137 provide any cumulative indicators.

138 At the same time, even if LCC provides insights about many issues and encompass a wide spectrum
139 of performance, it is very general and may not address railway specific issues (Bull, 2015).

140 Still on the downside, LCC may lead to mistakes when data are not reliable or/and they refer to a
141 short period of time. Furthermore, other possible drawbacks derive from the uncertainties in terms
142 of product life cycle and their interaction with changes in market conditions, in consumer tastes or
143 the introduction of a new technologies.

144 Based on the above, the measurement of the performance of railway systems calls for three main
 145 advances: i) merging all RAMS-related key indicators into an overall RAMS-related indicator; ii)
 146 merging all LCC indicators into a given overall LCC-based key indicator; iii) defining a Key
 147 Performance Indicator that allows analysing the spectrum of solutions considering two competing
 148 performance indicators, the first mainly technical (RAMS-based), and the second mainly financial
 149 (LCC-based, see Figure. 2).



150
 151 Figure 2. Rail Track: Key Performance Indicator tree

152 Symbols: RAMS: reliability, availability, maintainability, safety; ORI: Overall RAMS indicator; LCC:
 153 life cycle costing; PV: present value; I_{PV} : overall LCC parameter associated to the given track solution;
 154 KPI: key performance indicator that synergistically addresses both RAMS and LCC.

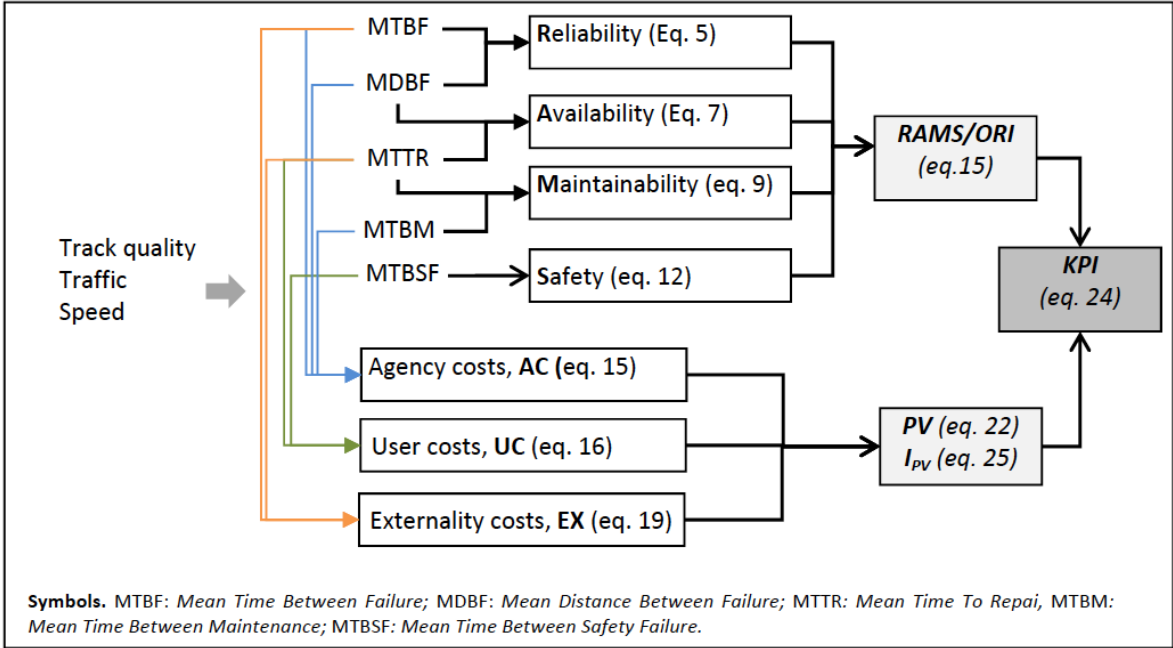
155 Proposed method

156 The method herein set up and applied to compare different track solutions is shown in Figures 2 and
 157 3 and equations 2 to 25. The application includes the following steps:

- 158 - Step 1 - Modelling of RAMS in terms of main parameters and derivation of an overall
 159 indicator (tasks 1 to 4) ;
- 160 - Step 2 - Modelling of the Present Values (PVs) in terms of agency, user and externality costs;

- 161 - Step 3 – Definition of the Key Performance Indicator for track;
- 162 - Step 4 - Application to a case-study (two options, see next section);
- 163 - Step 5 - Analysis of results (see next section).

164 Figure 3 illustrates relationships and main subsets in terms of both RAMS analyses (above) and LCC-
 165 based analyses (below), for a given spectrum of alternatives and input parameters (left). The output
 166 of the process is threefold: i) a RAMS-related indicator (ORI) which expresses the accomplishment of
 167 RAMS targets (see equation 15); ii) the overall present value (or IPV, see equations 22 and 25); iii) the
 168 RAMs- and LCC-related overall indicator, KPI. Out of the 24 equations discussed below, equations 2-
 169 13, 24, and 25 are new while the remaining equations are derived from the international literature.

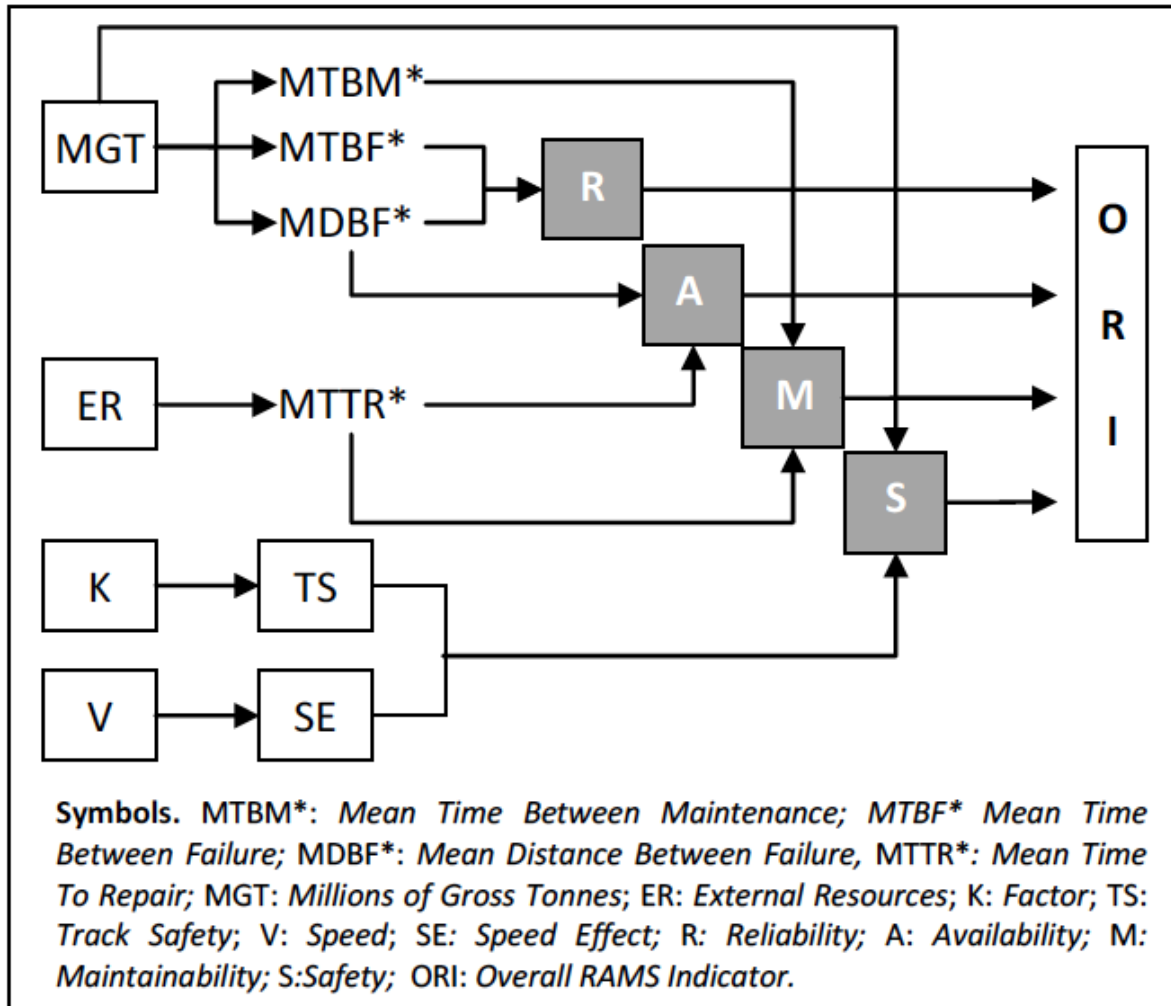


170
 171 Figure 3. RAMS and LCC analysis

172
 173 **RAMS analysis and modelling (Step 1)**

174 In the pursuit of RAMS modelling, RAMS subsets are preliminary analysed in the following. Figure 4
 175 and Table 3 illustrate the complex superposition of track, traffic and external factors in determining
 176 the track overall RAMS Indicator (ORI). The method builds on the normalization of the main

177 parameters in order to set up a theoretical framework in which the four main components(i.e., R, A,
 178 M, S) synergistically impact the overall result, i.e., RAMS (ORI).



179
 180 Figure 4. Work flow for the derivation of ORI

181 Reliability (R), quantified based on Mean Time Between Failure (MTBF), and Mean Distance
 182 Between Failure (MDBF), refer to failure rate (Patra, 2007). The cumulative traffic load (generally measured in
 183 Millions of Gross Tonnes, MGT) is the main unit which controls failure rate grows (failure modes are
 184 due to mechanical fatigue and/or cracking). It depends on passing train loads, type of traffic and
 185 speeds on the line (V). The higher this value is, the higher the stresses applied to the railway line are.
 186 According to Profillidis, 2014 the theoretical traffic load of the track (T_{th}) is as follows:

187
$$T_{th} = S_p \cdot (T_p + k_t \cdot T_{pt}) + S_{fr} \cdot (k_{fr} \cdot T_{fr} + k_t \cdot T_{ft}) \quad [1]$$

188 where T_p is the mean daily passenger tonnage hauled (in gross tons), T_{fr} is the mean daily freight
 189 tonnage hauled (in gross tons), T_{pt} is the mean daily tonnage of locomotives used in passenger traffic
 190 (in tons), T_{ft} is the mean daily tonnage of locomotives used in freight traffic (in tons), $k_{fr}=1.15$ is a
 191 coefficient taking into account effects of both the load and the wear caused by freight bogies, $k_t=1.40$
 192 is the coefficient that takes into account wear resulting from traction locomotives. S_p and S_{fr} are
 193 coefficients related to the running speed of the train and their values range from 1.0 (for $V < 60$
 194 Km/h) to 1.5 ($V > 250$ Km/h).

195 Note that the tonnage controls the failure rate of the track components. Geometrical characteristics
 196 restoration is carried out after 30 to 60 million tonnes, while rail replacements or grinding actions
 197 can occur after about 400 to 700 million tonnes (Profillidis, 2014). Failure rates usually grow with
 198 MGT (per year per kilometre).

199 Consequently, MTBF and MDBF decrease when traffic loads increase. In order to take into account
 200 the dependency on the traffic load and to obtain a value of reliability ranging from 0 to 1, a
 201 normalization process of the quoted parameters has to be performed, using the logistic function
 202 defined below (see Table 3 and equations 2-11). Note that in order make them easily distinguishable,
 203 a superscript “*” is used when normalised parameters are considered. Consequently, for example,
 204 MTBF*, normalised mean time between failure, ranges from 0 to 1 and corresponds to MTBF (which
 205 does not range from 0 to 1). Table 3 illustrates the relationships among RAMs, normalised
 206 components (e.g., MTBF*) and the main inputs and coefficients listed in the first column (e.g., MGT).

207 **Table 3. Main links among variables and outputs**

Main inputs and coefficients	Main outputs									
	MTBF* (eq.2)	MDBF* (eq.3)	MTTR* (eq.6)	MTBM* (eq.8)	SE (eq.11)	R* (eq.5)	A* (eq.7)	M* (eq.9)	S* (eq.12)	ORI (eq.13)
MGT (eq.4)	X	X		X		X	X	X	X	X
ER			X				X	X	X	X
TS (eq.10)									X	X
V					X				X	X
$a_1, b_1, c_1, \tau_{1n}, \tau_{1d}$ (eq.2)	X					X	X			X

$a_2, b_2, c_2, d_2,$ τ_{2n}, τ_{2d} (eq.3)		X				X				X
$a_3, b_3, c_3, d_3,$ τ_{3n}, τ_{3d} (eq.6)			X				X	X	X	X
$a_4, b_4, c_4, d_4,$ τ_{4n}, τ_{4d} (eq.8)				X				X	X	X
$a_5, b_5, c_5, d_5,$ τ_{5n}, τ_{5d} (eq.11)					X				X	X

Symbols. MGT: Millions of Gross Tonnes; ER: coefficient that takes into account the external resources available for maintenance and their preparedness; TS: coefficient related to inherent track safety; SE: coefficient related to speed effect; V: line speed; $a_i, b_i, c_i, d_i, \tau_{in}, \tau_{id}$: coefficients to calibrate; ORI: Overall RAMS Indicator; MTBF* MDBF* MTTR* MTBM*: indicators which related to MTBF, MDBF, MTTR, MTBM, respectively; R: reliability; A: availability; M: maintainability; S: safety.

208

209 For MTBF* and MDBF*, it results:

$$210 \quad MTBF^* = 1 - \frac{\frac{MGT}{a_1 - b_1 \cdot e^{-\frac{MGT}{\tau_{1n}}}}}{c_1 - d_1 \cdot e^{-\frac{MGT}{\tau_{1d}}}} \quad [2]$$

$$211 \quad MDBF^* = 1 - \frac{\frac{MGT}{a_2 - b_2 \cdot e^{-\frac{MGT}{\tau_{2n}}}}}{c_2 - d_2 \cdot e^{-\frac{MGT}{\tau_{2d}}}} \quad [3]$$

212 Where MGT is the traffic expressed in terms of millions of gross tons, $a_1 = b_1 = c_1$ and $a_2 = b_2 = c_2$,

213 while $\tau_{in}, \tau_{id}, c_i$ and d_i are calibration factors, MTBF* and MDBF* represent the corresponding

214 parameters normalized.

215 Note that it is:

$$216 \quad MGT = MGT_R + MGT_T \cdot \alpha \quad [4]$$

217 where MGT_R is the cumulative traffic from the last restoration, MGT_T is the cumulative traffic from

218 the construction, and α is a coefficient which takes into account for minor effects. Indeed, even a

219 renewal was carried out (e.g. rail substitution), other parts were not renewed (e.g., subgrade).

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

221

222
$$R^* = \sqrt{MTBF^* \cdot MDBF^*} \quad [5]$$

223 The Availability (A) depends on MDBF and on the time occurred to repair a track after a failure. The
 224 Mean Time to Repair (MTTR) is a measurable factor that allows evaluating these RAMS components.
 225 MTTR depends on the external resources provided and available for maintenance (competent
 226 personnel, tools and technologies, ability and expertise). The higher the number and the skill of the
 227 personnel units are, the higher the number of available tools is, the higher the availability is.
 228 Availability depends also on traffic level: it decreases when traffic increases. In the proposed model,
 229 MTTR is also normalised and related to the traffic by means of the following function:

230
$$MTTR^* = 1 - \frac{a_3 - b_3 \cdot e^{-\frac{ER}{\tau_{3n}}}}{c_3 - d_3 \cdot e^{-\frac{ER}{\tau_{3d}}}} \quad [6]$$

231 where ER is a coefficient that takes into account the external resources available for maintenance, a_3
 232 $= b_3 = c_3$, while τ_{3n} , τ_{3d} , c_3 and d_3 are coefficients to calibrate.

233 Under the previous assumptions, the availability can be derived as follows:

234
$$A^* = \frac{MDBF^*}{MDBF^* + MTTR^*} \quad [7]$$

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

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

240
$$MTBM^* = 1 - \frac{a_4 - b_4 \cdot e^{-\frac{MGT}{\tau_{4n}}}}{c_4 - d_4 \cdot e^{-\frac{MGT}{\tau_{4d}}}} \quad [8]$$

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

242 Maintainability has been evaluated by means the equations:

243

$$M^* = \sqrt{MTBM^* \cdot (1 - MTTR^*)} \quad [9]$$

244 Maintainability depends on the traffic load (it decreases when traffic increases) and on the time
245 required to repair, this last related with available resources.

246 Safety (S) depends mainly on track geometry and structures, on the traffic (the higher the traffic the
247 lower the safety), and on speed. It depends also on maintainability (M).

248 Regarding the track, track defects have become the leading cause of train accidents [He et al. 2015].

249 Defects can be categorized into one of two groups: structural defects and geometric defects (Sadeghi
250 and Askarinejad, 2010). Track structural defects are generated from the structural conditions of the
251 track, which include the condition of the rail, sleeper, fastening systems, subgrade and drainage
252 systems. On the other hand, track geometry defects indicate severe ill-conditioned geometry
253 parameters such as profile, alignment, gage, etc.

254 Coefficients related to inherent track safety (TS) and speed effect (SE) are defined as follows:

$$TS = \frac{K}{100} \quad [10]$$

256 where K is a coefficient which ranges from 0 to 100 (based on the conditions of the track). High K
257 (good conditions, TS close to 1) and low K (unsatisfactory conditions, TS close to 0) impact the
258 normalised safety of the track (S^* , see equation 12, below). The speed effect (SE) is as follows:

$$SE = 1 - \frac{a_5 - b_5 \cdot e^{-\frac{V}{\tau_{5n}}}}{c_5 - d_5 \cdot e^{-\frac{V}{\tau_{5d}}}} \quad [11]$$

260 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.

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

$$S^* = \sqrt[4]{1 - \frac{a_5 - b_5 \cdot e^{-\frac{V}{\tau_{5n}}}}{c_5 - d_5 \cdot e^{-\frac{V}{\tau_{5d}}}} \cdot M^* \cdot TS \cdot SE} \quad [12]$$

263 Based on the above definition, the RAMS level that is expected is defined as follows:

264
$$O.R.I. = \sqrt[4]{R^* \cdot A^* \cdot M^* \cdot S^*} \quad [13]$$

265 Where ORI stands for Overall RAMS Indicator, R* is derived through eq. 5, A* through eq. 7, M* refers
 266 to eq. 9, and S* to eq. 12. Note that the five main RAMS indicators (as per eq. 13) range from 0 to
 267 100%.

268 **Present values (Step 2)**

269 The life cycle cost assessment involves the estimation of three main classes of costs (agency, user,
 270 and externality costs), according to the following main steps:

- 271 i) estimation of the present value (PV) of agency costs by considering the expected life of the
- 272 railway track for the competing options, for each class of activity (rehabilitation,
- 273 maintenance, etc.);
- 274 ii) estimation of the corresponding present value of user costs;
- 275 iii) estimation of the present value of externalities;
- 276 iv) derivation of the overall present value.

277 Table 4 illustrates the main links among RAMS main inputs (namely, MGT, ER, K, V) and LCC main
 278 outputs (e.g., PV_{AC}, PV_{UC}, PV_{EX}).

279 **Table 4. Linking LCC outputs to RAMS inputs**

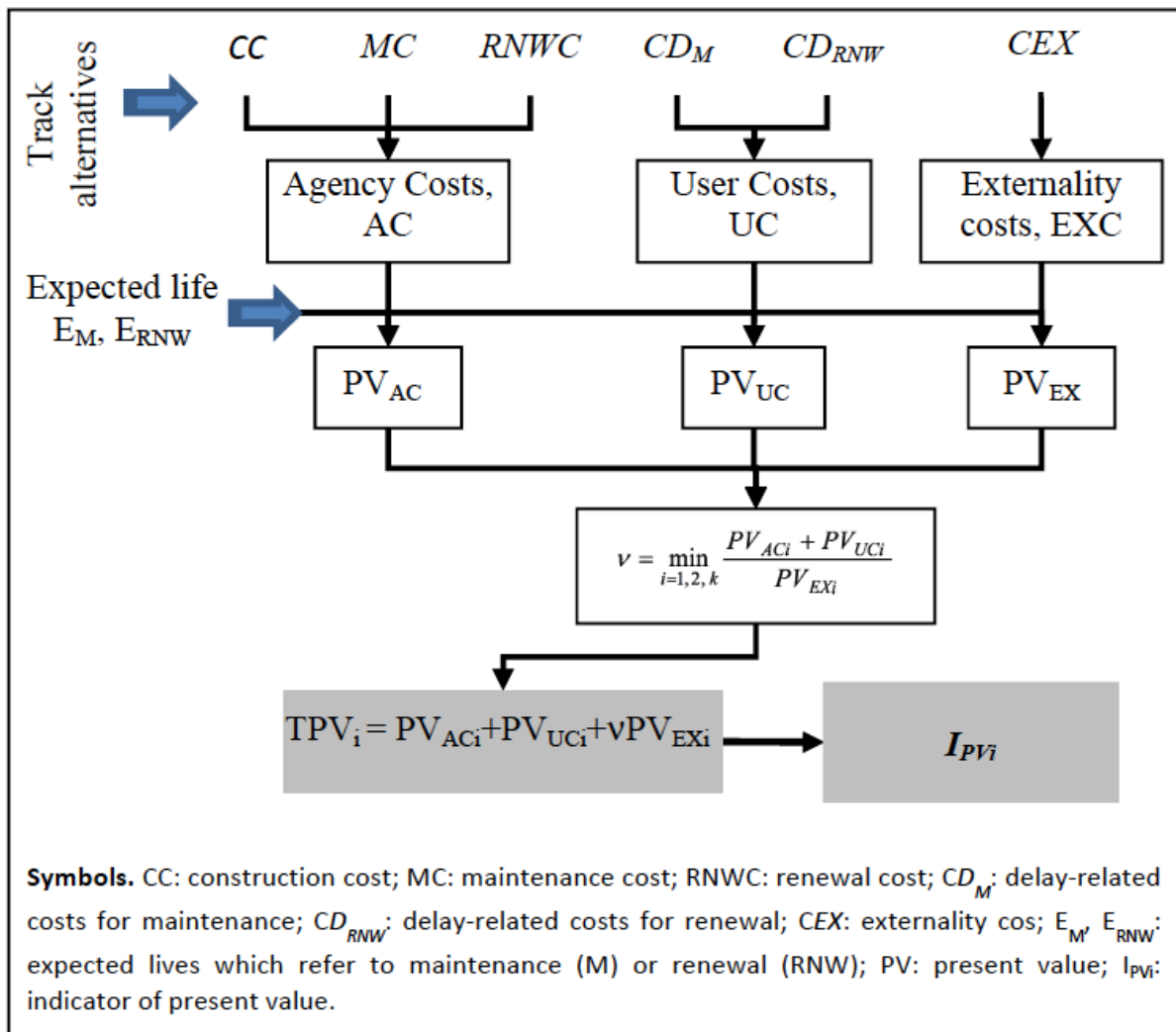
	PV _{AC}	PV _{UC}	PV _{EX}
MGT	x		x
ER	x	x	
K			
V		x	

Symbols. MGT: Millions of Gross Tonnes. ER: coefficient that takes into account the external resources available for maintenance and their preparedness. K: coefficient which ranges from 0 to 100, based on the conditions of the track. V: line speed in Km/h. PV_{AC}, PV_{UC}, PV_{EX}: present value of agency costs, user costs, externality costs, respectively.

280

281 The main tasks for the application of the method in Figure 5 are the following:

- 282 • Task 2.1. Materials and construction-related processes inventory for the considered
- 283 alternatives.
- 284 • Task 2.2 Cost analysis (agency costs, user costs, externality costs)
- 285 • Task 2.3. Balancing (v in figure 5)
- 286 • Task 2.4. Determination of Total Present Value (TPV) and Gains



287
288

Figure 5. Work flow for the derivation of IPV

289 **Task 2.1. Materials and construction-related processes inventory**

290 During this phase all the components of a given track solution are considered. Quantities, unit costs,
291 costs, CO₂ equivalent per given quantity are assessed based on the analysis of the two options put in

292 comparison. For example, for the traditional ballasted track, rails, sleepers, ballast, subballast,
293 embankment, fastenings, baseplates, and fixings are examined in detail.

294 **Task 2.2 Cost analysis**

295 The three main cost components are: agency costs, user cost and externality costs.

296 Agency costs

297 Agency costs include construction, rehabilitation and maintenance activities. Regarding the
298 construction costs, the inventory process carried out in Task 1 allows estimating the construction
299 costs of the two alternatives. For rehabilitation, each component of the given option (i.e., rails) is
300 supposed to undergo a scheduled process of rehabilitation over time. Based on the international
301 literature (Esveld, 2001, Milford and Allwood, 2010, Calvo et al., 2013), on pieces of information
302 gathered for real tracks in the country, and based on materials (geometry, material quality and
303 quantity), the typical service lives for the main items considered are summarised in Table 6.

304 Track maintenance covers all the measures for preserving and re-establishing the nominal condition,
305 such as changing sleepers or tightening loose track components (Kogan, 1992). Track degradation
306 depends on many factors, such as initial quality of construction, the quality of the substructure and
307 the loads on the track.

308 Besides asset degradation, there are other factors that also influence the life cycle costs, such as the
309 RAMS targets for the track, the amount of preventive maintenance, market prices of labour,
310 materials and machines, and the operational characteristics of the line (such as axle loads, traffic
311 intensities and the duration of train free periods).

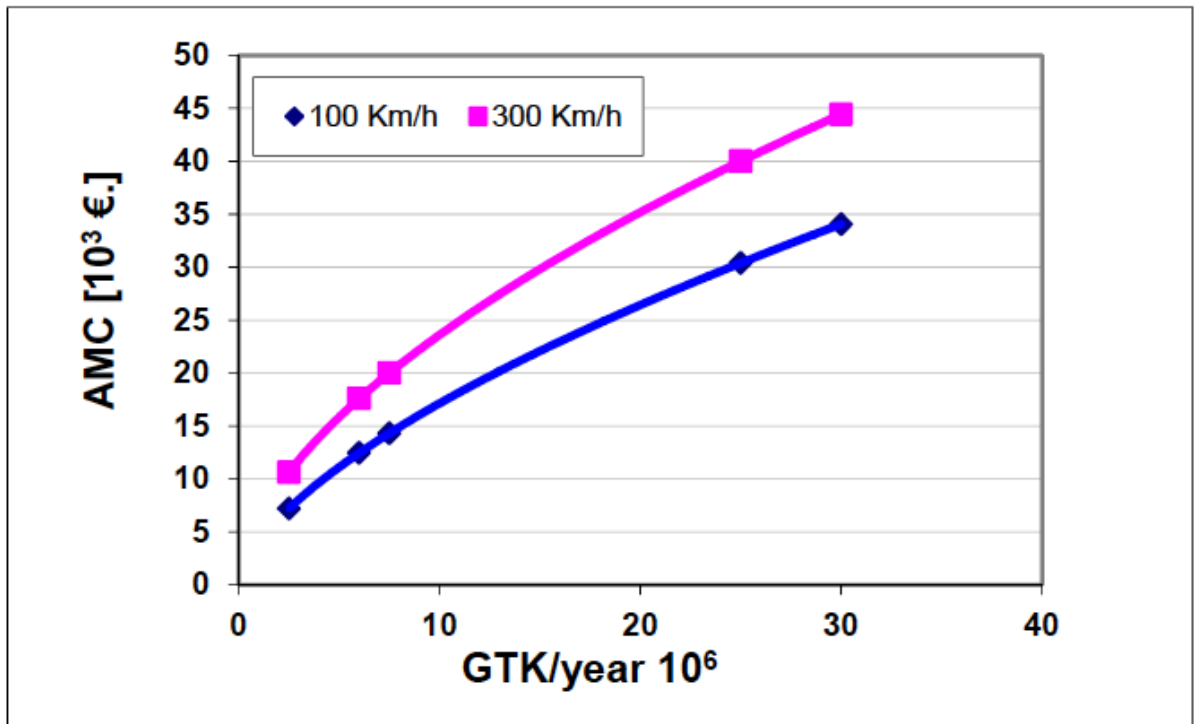
312 All the decisions related to the rail track maintenance are taken in order to keep a balance between
313 economic and safety aspects. The goal is to find the effective maintenance procedure which optimise
314 the track possession period and train speed restriction regime and ultimately increase the track
315 availability.

316 Costs of maintenance activities mainly depend on speed and traffic [Silavong, et al. 2014]. According
 317 to [Calvo et al. 2013], it is possible to consider the maintenance cost as running cost annually
 318 distributed. Based on literature and data gathered, in this study, the following formula for the annual
 319 maintenance cost (AMC, k€, thousands of euros, *per single track, per kilometre*) is set up:

$$320 \quad AMC = \left[2.2 \cdot \frac{(V - 100)}{200} + 4.00 \right] \cdot GTK^{\left[-0.05 \cdot \frac{(V - 100)}{200} + 0.63 \right]} \quad [14]$$

321 Where V is maximum speed allowed in the track [km/h], GTK refers to gross tonne kilometres
 322 [tonne*km], where tonne stands for metric ton.

323 Figure 6 below shows how AMC depends on V and GTK.



324
 325 Figure 6. AMC vs. V

326
 327 Based on the above, for the present value of agency costs (PV_{AC}), the following algorithm is set up:

$$328 \quad PV_{AC} = C_{CONS} + \sum C_{REH} \cdot R^{E_{REH}} + \sum C_{MA} \cdot R^{E_{MA}} - S \quad [15]$$

330 where C_{CONS} is the construction cost, C_{REH} is the rehabilitation cost, C_{MA} is the maintenance cost, R is
 331 the ratio between $(1+i)$ and $(1+r)$, i is the inflation rate and r is the interest rate, and E_{REH} and E_{MA}
 332 refer to rehabilitation and maintenance expected time, respectively, and S is the salvage value.

333 User costs

334 According to Esveld, 2001, the most important feature of a decision support system which deals with
 335 maintenance strategy is the relationships between track use and maintenance.

336 This fact explains the importance of user costs, mainly related to delays (D), originated by work zones
 337 of given length and duration. Delays can be divided into two general categories: routine (experienced
 338 during normal operations, including crew changes, meets, passes, and civil speed restrictions) and
 339 irregular (including maintenance, accidents, and short-term speed restrictions based on track
 340 conditions). The cost of train delay per hour varies based on a variety of factors broken into five main
 341 categories: crew, cars, lading, locomotives, and fuel and most of these costs vary with train and
 342 commodity composition (see Lovett et al, 2015). There have been many attempts to determine the
 343 cost of delays for railroads, which resulted in values ranging from \$200 to more than \$1,000 (Schafer
 344 and Barkan, 2008; Dingler et al., 2011; Schlake et al., 2011; Lai and Barkan, 2009; RSAC, 1999).

345 Assuming an average train composition, then crew, car, lading, and locomotive costs are
 346 approximately \$950 per train-hour (Lovett et al. 2015).

347 Based on the above, the following algorithm applies:

$$348 \quad PV_{UC} = PV_D = \sum C_{DREH} \cdot R^{E_{REH}} + \sum C_{DMA} \cdot R^{E_{MA}} \quad [16]$$

349 where C_{DREH} and C_{DAMC} are user costs for the given track length and type, for the given cycle (element
 350 of the running total), based on the abovementioned literature and based on data gathered for the
 351 specific context of application.

352 Externality costs

353 The most relevant construction/renewal/maintenance activities which refer to tracks and imply
 354 environmental concerns are transportation, quarrying, landfill use, material production (cement,

355 steel, rubber, etc.). The above processes impact on the environment in terms of air quality (SOx,
356 NOx, CO, VOC, PM, etc.), climate change (CO₂e), noise, water quality, soil quality, biodiversity, land
357 take, quarries, landfills, and visual effects (Yin and Siriphong, 2006; Ian et al, 2009).
358 For production-related issues (aggregate, cement, steel, etc.), note that carbon dioxide is one of
359 several heat-trapping greenhouse gases (GHGs) emitted. These gas emissions are said to be the
360 primary cause of global warming (European Commission, 2010). To this end, a carbon dioxide
361 equivalency is usually used (amount of CO₂ that would have the same global warming potential -
362 GWP, when measured over a specified timescale -generally, 100 years). It can be expressed, for
363 example, in g of carbon dioxide equivalents/km or simply gCDE/km. Authors are aware that the
364 quantification of externality costs is difficult. However, if some hypotheses are assumed, this
365 objective can be pursued. This task can be accomplished by considering: i) the quantity of CO₂
366 equivalent corresponding to the given process and material; ii) the cost of a ton of CO₂; iii) the
367 remaining factors associated to the process under consideration (quarrying, landfill, transportation-
368 related emissions, etc.). Based on this discussion, different classes of externalities, EX_{kj}, are
369 considered, where j refers to the j-th impact (e.g., CO₂ equivalent), while k stands for the k-th activity
370 (e.g., construction, EX₀, successive kth rehabilitation/ routine maintenance, EX_k, etc.):

$$371 \quad EX_{kj} = \sum_j Q_{kj} \cdot UP_{kj} \quad [17]$$

372 For example, for CO₂ emissions, the following algorithm can be used:

$$373 \quad EX_{kCO_2} = \sum_j \frac{VN_{kq}}{CA_{kq}} \cdot D_{kq} \cdot EM_{kq} \cdot FC_{kq} \quad [18]$$

374 Where FC (l/km) refers to fuel consumption, the subscript 'k' refers to the kth rehabilitation process,
375 the subscript 'q' refers to the given process-material, VN_{kj} (m³) is the volume of material needed (e.g.
376 slab/soil/stabilizer), CA_{ki} is the average truck capacity (m³), D_{kj} is the average distance to cover (round
377 trip, km), EM_{kj} is an emission surcharge factor (\$/l), FC_{kj} stands for fuel consumption (l/km).

378 Finally, it results:

379
$$PV_{EX} = EX_0 + \sum_k EX_k \cdot R^{E_k} \cdot (1 - R^D)^{-1} \quad [19]$$

380 where E_k takes into account the difference between EXs which refer to rehabilitation/maintenance
 381 and EXs which refer to operations).

382 **Task 2.3 Balancing**

383 This task is accomplished as follows. As is well known, carbon markets, designed to make polluters
 384 (e.g., industries) pay and reduce emissions, are always struggling with market instability. Due to the
 385 fact that the fluctuation of the carbon price is appreciable, an indicator which refers to the most
 386 critical relationship between internal and “internalised” costs is derived (lowest ratio “internal-to-
 387 external”). This indicator is applied to each solution to get a linear magnification of externality costs.
 388 The following procedure is herein proposed in the case of $PV_{EXi} < PV_{ACi} + PV_{UCi}$ (for each i-th design
 389 alternative or solution among the k ones, see task 2), which is the most recurrent case. The first step
 390 is to derive the indicator which refers to the most critical relationship between “internal” and
 391 “internalised” costs:

392
$$v = \min_{i=1, 2, k} \frac{PV_{ACi} + PV_{UCi}}{PV_{EXi}}. \quad [20]$$

393 The second step is to operate in this vector space of the internalised factors to get a linear
 394 magnification:

395
$$PV'_{EXi} = v \cdot PV_{EXi} \quad [21]$$

396 **Task 2.4: Overall Present Value and Gains**

397 Agency costs (AC), user costs (UC) and externality costs (EX) contribute to the overall present value,
 398 PV, as follows:

399
$$PV = PV_{AC} + PV_{UC} + PV'_{EX} \quad [22]$$

400 while the gain (G) originated by one solution k-th with respect to another solution i-th can be
 401 evaluated with consideration of only agency costs (e.g., GAC), or only externalities (e.g., GEX), or any
 402 other combinations as appropriate:

$$\begin{aligned}
 G &= (PV_{AC} + PV_{UC} + PV_{EX})_i - (PV_{AC} + PV_{UC} + PV_{EX})_k \\
 &= [(PV_{AC})_{ii} - (PV_{AC})_k] + [(PV_{UC})_i - (PV_{UC})_k] + [(PV_{EX'})_i - (PV_{EX'})_k] \\
 &= G_{AC} + G_{UC} + G_{EX'}
 \end{aligned}
 \tag{23}$$

405
 406 It should be highlighted that: i) positive gains correspond to solutions that are better than the
 407 traditional one (i.e., ballasted track, i, better than slab, k); ii) care must be taken while deriving the
 408 externality costs for a given scenario, because reasonable assumptions are needed, especially when
 409 relevant laboratory and field data are unavailable for this purpose.

410 **Definition of Key Performance Indicator (Step 3)**

411 In order to get a comparison among different track solution by using just two competing
 412 performance indicators, the first mainly technical (ORI), and the second mainly financial (LCC) a Key
 413 Performance Indicator (KPI) is defined as.

$$KPI_k = ORI_k \cdot I_{PV_k} \tag{24}$$

415 where KPI_k , is the key performance indicator related to the k-th track solution while ORI_k and I_{PV_k} are
 416 respectively the overall RAMS parameter and the LCC parameter associated to the k-th track
 417 solution. It should be noted that, in order to make the KPI variable in the range 0, 1, and in order to
 418 make similar the contribution of the two parameters in the determination of KPI, avoiding the
 419 prevalence of one indicator on the other, the indicator of PV has been defined as follows:

$$I_{PV_k} = \frac{PV_k^{-1}}{\max(PV_1^{-1}, PV_2^{-1}, \dots, PV_k^{-1})}. \tag{25}$$

421

422 The rationale behind the definitions above is as follows: i) high values of present value result in low
 423 value of the PV indicator and in low contribution to KPI (equation 25); ii) the lower value between
 424 ORI and I_{PV} controls KPI (equation 24). Consequently, having just low costs (i.e., I_{PV} high but without
 425 having enough technical soundness), or having just high technical content (i.e., ORI high but without
 426 having reasonably low costs) does not imply obtaining the best rank.

427 **Application to a case study and results discussion (Steps 4 and 5)**

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

431 The slab track system considered in this paper is the Japanese Shinkansen that consists in a sub-layer
 432 stabilized with cement (concrete road-bed), cylindrical bollard to prevent lateral and longitudinal
 433 movement, and reinforced pre-stressed concrete slabs measuring 4,93 m x 2,34 m x 0,19 m. Each
 434 slabs weighs approximately 5 tonnes (Esveld 2001).

435 Main components of the two alternatives and related service life are shown in Table 5.

436 **Table 5. Track components and expected service life (Esveld, 2001, Milford and Allwood, 2010,**
 437 **Calvo et al., 2013)**

Component	Service life [Years]
Rail - <i>60 UNI</i>	28
Sleepers - <i>Pre-stressed mono-block</i>	40
Fastenings - <i>Elastic type Vossloh W14 AV</i>	40
Ballast - <i>Crushed stones, 500 mm. depth</i>	40
Subballast/Concrete road-bed - <i>Cement treated layer 200 mm depth</i>	40
Slab - <i>Pre-stressed concrete with cylindrical bollard</i>	60

438

439 For the two alternatives, the **construction cost** includes the costs of the following components: rails,
 440 sleepers/concrete slabs, fastenings, baseplate, ballast/elastomeric pad, subballast/concrete base,
 441 embankment. As for the externality costs, note that for each component the amounts of CO₂
 442 released when making or using them have been derived (Milford and Allwood, 2010, Leung, 2009).
 443 In the pursuit of the implementation of RAMS model the main task carried out was the calibration of
 444 the five functions above set up (equations, [2], [3], [6], [8], [11], [12]), based on gathered data from
 445 literature, on interviews (see Table 6). In the calibration process (last square method) attention was
 446 focused on: i) zero response (value when the independent variable approaches zero); ii) slope factors
 447 (which control the transition zero to infinite); iii) infinite response; iv) inflection point.

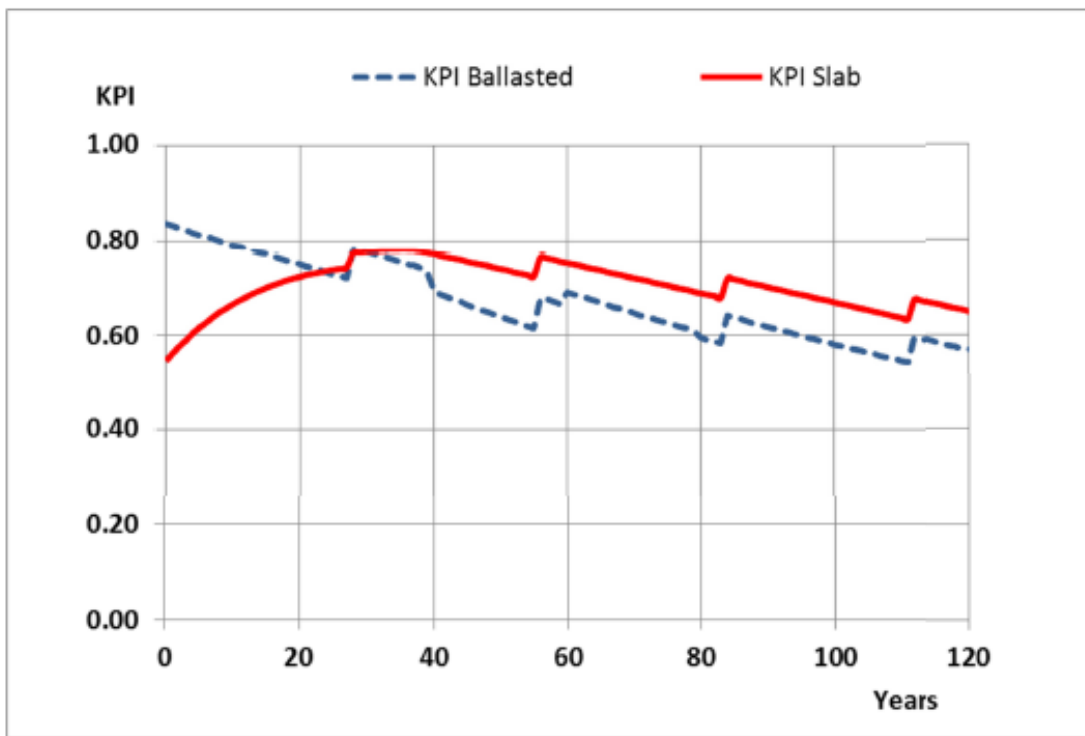
448 **Table 6. Results of calibration process**

Equation	$a=b=c$	d_i	r_{in}	r_{id}
[4]	1000	1	1500	1500
[5]	1000	1	1000	1000
[8]	1	1	700	700
[10]	1000	1000	700	700
[13]	1	1	1000	1000
[14]	1	1	1000	1000

452
 453 Note that the RAMS indicator was derived under the following hypotheses:

- 454 - given boundary operational conditions on the line (traffic, millions of gross tons per year,
 455 MGT/year and line speed V Km/h). Four main conditions are considered based on traffic rate (6,
 456 10 or 20 MGT per year) and on speed (200 or 300 Km/h);
- 457 - the reliability and availability of the slab track have been considered higher than the ones of
 458 ballasted track (Tzanakakis, 2013). In fact, slab tracks exhibit a higher structural and geometrical
 459 stability and require little routine maintenance. Consequently, fewer closures of the track are
 460 required for maintenance, increasing the availability of the track for running trains.

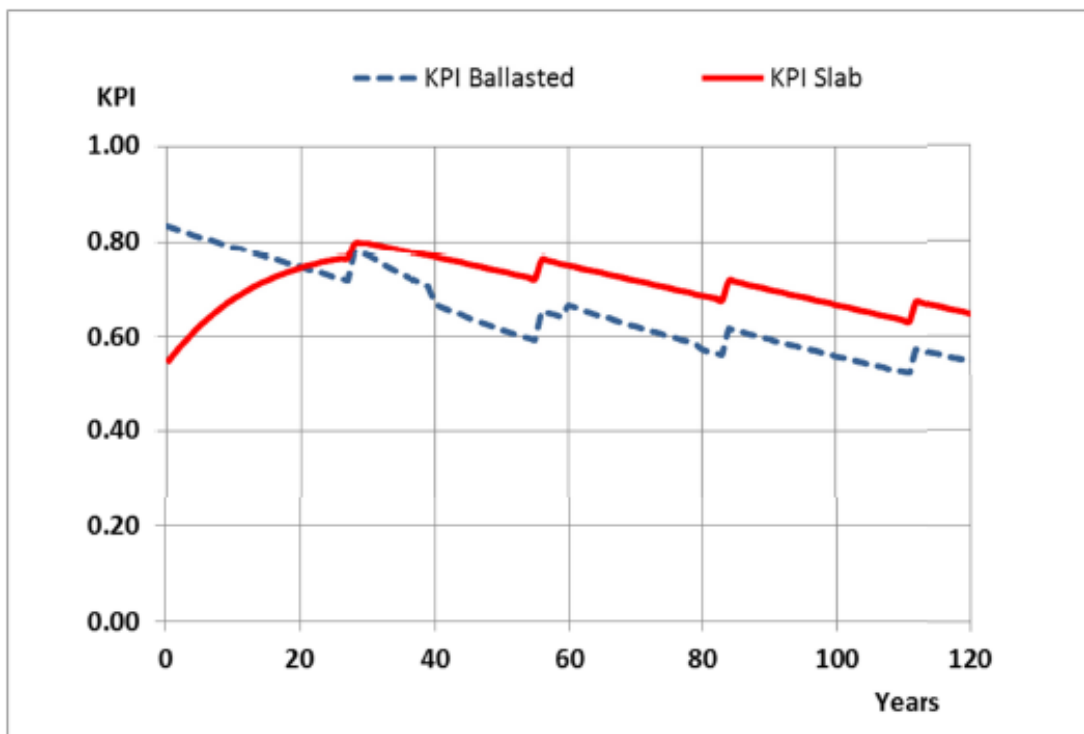
461 Results of the application are shown in Figures 7-10.



462

463

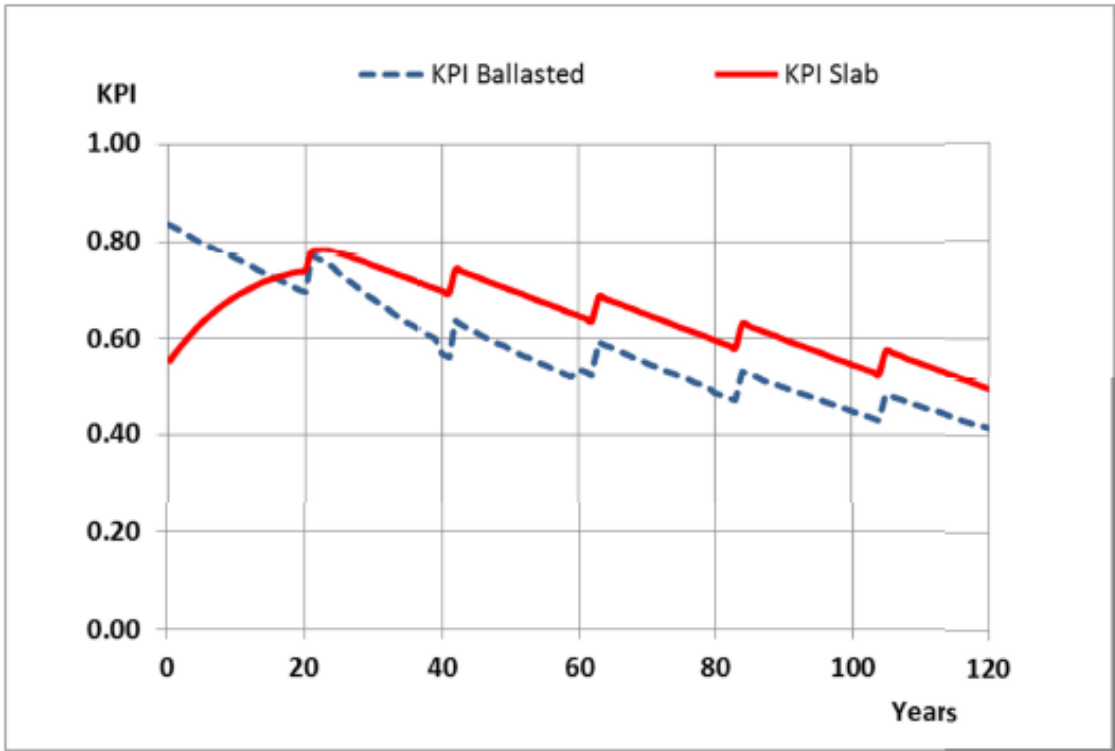
Fig 7. KPI [6 MGT per year; V = 200 Km/h]



464

465

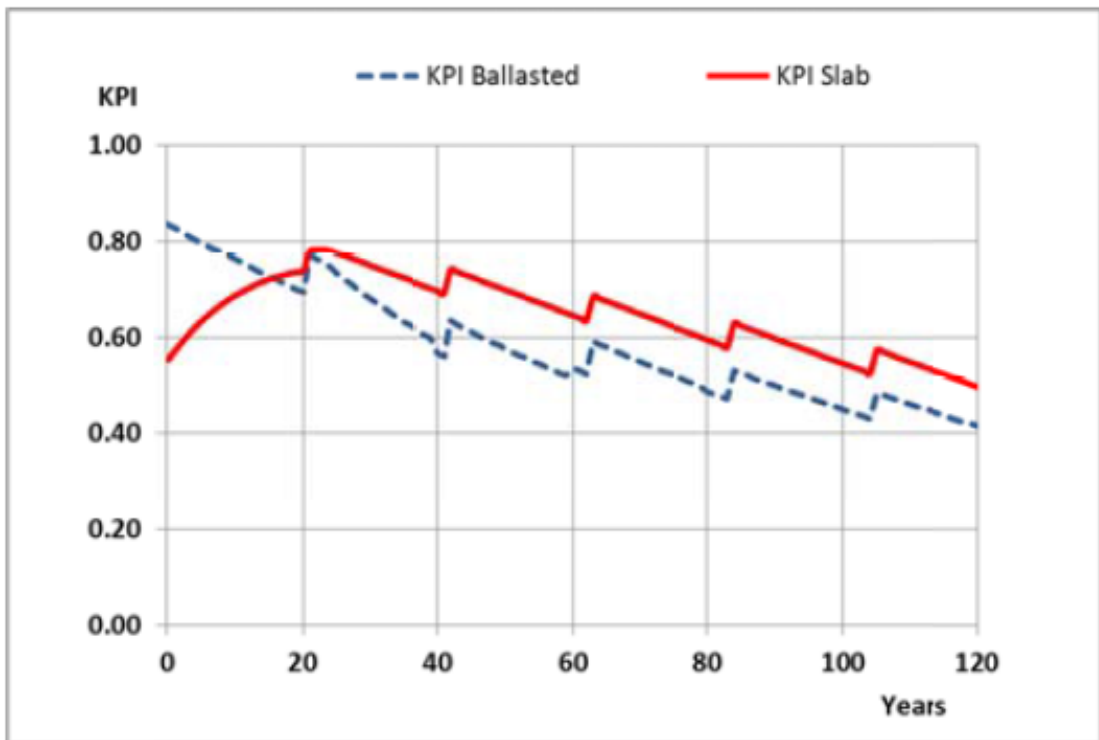
Fig 8. KPI [6 MGT per year; V = 300 Km/h]



466

467

Fig 9. KPI [10 MGT per year, V = 200 Km/h]



468

469

Fig 10. KPI [20 MGT per year; V = 200 Km/h]

470

471 **Discussion and Conclusions**

472 Design and maintenance decisions on railway track need reliable methodologies to evaluate the costs
473 and performance of the possible solutions. Once considered the pros and contras of the different
474 approaches (LCC and RAMS), in this paper a Key Performance Indicator of track able to take into
475 account both economical and technical aspects has been defined and applied to compare two types
476 of tracks (ballasted and ballastless).

477 Regarding the application to a case study, based on the comparison of the traditional ballasted track
478 and the innovative ballast-less track, the trend of KPI in the time allowed doing comprehensive
479 considerations of the two alternatives as a function of the operating conditions of the line (traffic and
480 speed) and considering short and long term perspectives. In particular:

- 481 - The KPI of the ballasted track decreases over time for all the considered operational
482 conditions of the line;
- 483 - The KPI of the slab track increases in the short term, while after about 20 years (depending
484 on traffic and speed conditions) it decreases slowly for low traffic (6 MGT/year)) and quickly
485 for high traffic (10 or 20 MGT/year);
- 486 - In the short term the ballasted track performs better and this finding is mainly due to the
487 lower PV; in the long term perspective the slab track is preferable. This result can be related
488 to the lower maintenance costs over the time and to the higher RAMS of the slab track. In
489 the short time the economical aspects prevail on the RAMS aspects, which is due to the fact
490 that both solutions exhibit high performance at beginning of operations.
- 491 - The breakeven point between the KPI of the two track solutions is quite far from
492 construction in the case of lower traffic conditions;
- 493 - After the breakeven point, the higher the speed is, the higher the difference between KPI of
494 slab track and KPI of ballasted track becomes.
- 495 - The level of traffic greatly affects the trend of KPI in the time, for both track solutions.

496 - Overall, slab track seems to perform better in more demanding operational conditions (high
497 speed, high traffic level).

498 Results demonstrate the appropriateness of this indicator in the evaluation of the global
499 performance of a given track solution and the suitability of its application in comparing different
500 solutions, based on the operating conditions of the railway line.

501 The method set up contributes to the body of knowledge of construction engineering because of its
502 transportability and potential: it allows deriving agency-based algorithms through calibration and
503 permits a synergistic and quantitative approach in decision making. Consequently, agencies,
504 practitioners and researchers can benefit due to the algorithms set up and applied in terms of both
505 design and maintenance and renewal scheduling and optimisation.

506 **Data availability statement**

507 All data generated or analyzed during the study are included in the submitted article

508 Data generated or analyzed during the study are available from the corresponding author by request.

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