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Non-destructive assessment and health monitoring of railway infrastructures

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1 **Non-destructive Assessment and Health Monitoring of Railway** 2 **Infrastructures**

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11 **Abstract:**

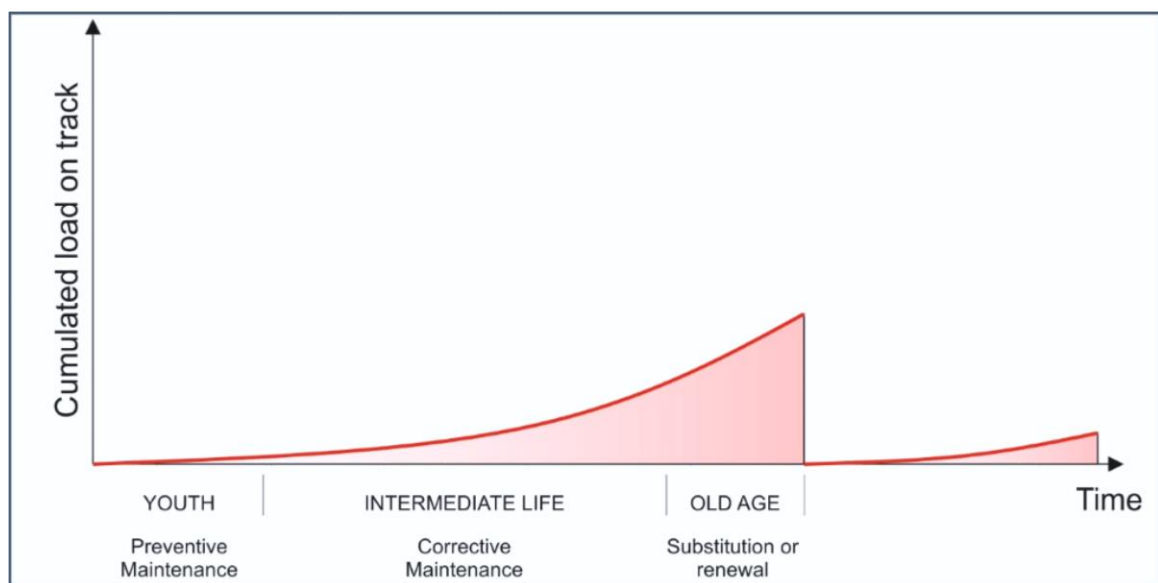
12 A continuous increase of the demand for high-speed traffic, freight tonnage as well as of the train
13 operating frequency is worsening the decay conditions of many railway infrastructures. This
14 occurrence affects economy-related business as well as it contributes to raise maintenance cost. It is
15 known that a failure of a railway track may result in tremendous economic losses, law liabilities,
16 service interruptions and, eventually, fatalities. Parallel to this, requirements to maintain acceptable
17 operational standards are very demanding. In addition to the above, a main issue nowadays in
18 railway engineering is a general lack of funds to allow safety and comfort of the operations as well
19 as a proper maintenance of the infrastructures. This is mostly the result of a traditional approach
20 that, on average, tends to invest on high-priority cost, such as safety-related cost, compromising
21 lower-priority cost (e.g., quality and comfort of the operations). A solution to correct this trend can
22 be to move from a reactive to a proactive action planning approach in order to limit more effectively
23 the likelihood of progressive track decay. Within this context, this paper reports a review on the use
24 of traditional and non-destructive testing (NDT) methods for assessment and health monitoring of
25 railway infrastructures. State-of-the-art research on a stand-alone use of NDT methods or a
26 combination of them for specific maintenance tasks in railways is discussed.

27
28 **Keywords:** railway infrastructures, non-destructive assessment, health monitoring, maintenance,
29 ground penetrating radar (GPR)

30 **1 Introduction**

31 Railway transportation is getting in great request progressively and worldwide both in terms of
32 demand for passengers and freight. A steadily increasing demand on high-speed traffic, freight
33 tonnage and train operating frequency causes a higher decay leading to a shorter economic life and
34 higher maintenance cost for a railway (Nålsund 2014). According to Güler (2017), annual average
35 maintenance and renewal expenses per single kilometer of a track in the West-European railway
36 network cost approximately €50.000. Failures of a railway track can cause enormous economic
37 losses, law liabilities, big delays in remedial works and, eventually, fatalities. Parallel to this,
38 requirements to maintain acceptable operational standards are very demanding (Sharma et al. 2018).
39 According to a traditional approach in the maintenance of railway infrastructures, main aim was to
40 maintain a high level of safety, regardless of budget-controlling-related issues. This strategy has
41 often a negative impact on the budget allocated for operation and maintenance activities, provided
42 that the same level of safety is assured (Lyngby et al. 2008; Khouy 2013). Therefore, railway
43 infrastructure administrators and operators are facing the challenging task of optimising limited
44 funds to competitively ensure and sustain a safe, reliable, punctual and comfortable service capable
45 to meet quality requirements from customers. This complex task can be achieved by modification
46 of the current vision within the operation and the maintenance sectors and moving from a reactive
47 to a proactive action planning approach (Khouy 2013). Within a reactive management scenario (also
48 known as “find and fix” method), time is very restricted after detection of a damage and repair
49 actions are implemented before an unacceptable level of damage is reached. This limitation of time
50 might cause the use of insufficient mitigation interventions (Bond et al. 2011). In the proactive
51 management case, the time constraint is extremely reduced in view of an earlier diagnosis of the
52 decay, that allows more time available for mitigation works (Bond et al. 2011). To that effect, use
53 of non-destructive testing (NDT) methods is crucial as they can effectively accomplish the
54 requirements of a proactive maintenance, such as a timely identification and location of the potential
55 failures, along with the determination of their root causes. NDT methods can provide substantial
56 pieces of information to forecast and better manage potential failures before these may occur. These
57 methods have a significant role in the evaluation of the safety levels of civil engineering structures
58 as they can provide invaluable input to assess their structural integrity (Trampus 2014). Among
59 many factors, the dynamic load exerted on the track is by far the most important parameter causing
60 track deteriorations, whereby wear, fatigue, and settlements can be identified as the main
61 consequences (Tzanakakis 2013). Three basic contributions to the deterioration of a railway track
62 can be counted as (Tzanakakis 2013) i) use (wear and tear by contact, static and dynamic load), ii)
63 environment (effect of climate and water), and iii) failures (defective element and poor construction).

64 According to Tzanakakis (2013), three different life-spans can be identified for a railway track, i.e.,
 65 the youth, the intermediate-life and the old-age periods (Fig. 1). More specifically, the youth period
 66 is the term when the track faces significant deterioration owing to track settlements, and preventive
 67 maintenance is here carried out to avoid early decay. The intermediate-life period is the time interval
 68 where corrective maintenance (rectification of the geometry and partly change of used or defective
 69 materials) is intended to mitigate the decay and guarantee the safety and reliability of the track. The
 70 old-age period is the time stage towards the end of the service life when higher decay are observed.
 71 As a remedial action, the track component has to be partially or fully replaced if the track is not
 72 suitable to meet the requirements dictated by the quality level or in case extraordinary high cost of
 73 maintenance are required to reach a target quality standard level (Tzanakakis 2013).



74
 75 **Fig. 1 Deterioration process of a railway track: life periods and corresponding maintenance actions**
 76 **versus cumulated loads exerted on the track (adapted from (Tzanakakis 2013))**

77 Authors deem that categorization of the typical railway track would serve beneficial to the readers
 78 at this point. According to the literature, a typical railway track system can be grouped into two main
 79 categories, i.e., the superstructure and the substructure, The former comprises rails, sleepers (or ties)
 80 and fastening systems and the latter is composed of ballast, sub-ballast and subgrade layers (Selig
 81 and Waters 1994; Al-Qadi et al. 2010b; Bianchini Ciampoli et al. 2018b). It is anyway worth to note
 82 that the ballast layer can be also considered as part of the superstructure, depending on the
 83 engineering discipline (Tzanakakis 2013; Pyrgidis 2016). However, ballast layer (under sleepers)
 84 will be considered in this paper as a component of the substructure (Fig. 2).

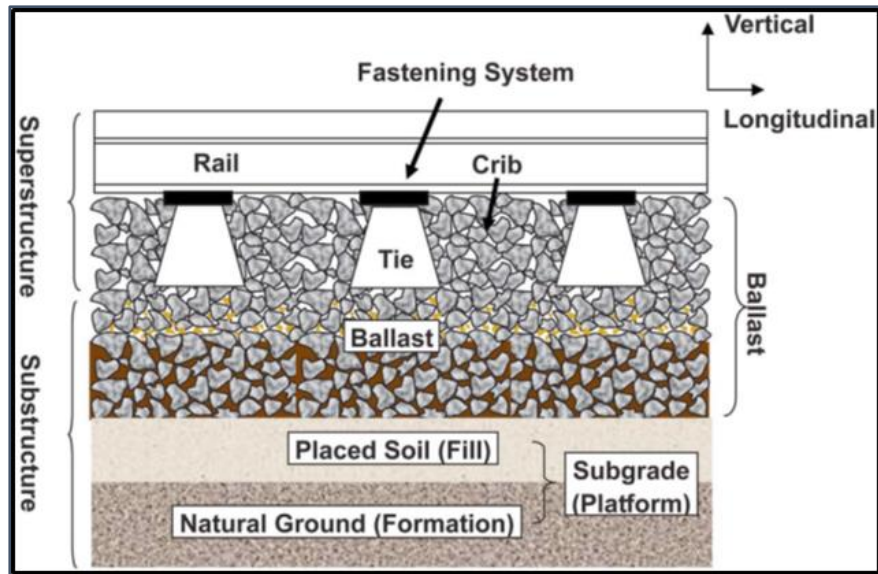


Fig. 2 Track structure (Selig and Waters 1994; Al-Qadi et al. 2010b)

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86

87

88 *1.1 Diagnosis & Maintenance Issues*

89 Maintenance is defined as a series of organised tasks performed with the purpose to minimise the
 90 cost and maintain an asset at the best possible operational conditions for a longer service period
 91 (Tzanakakis 2013). In this respect, a diagnosis and location of defects and degradations in a railway
 92 track structure turn out to be essentially critical in the decision-making process for a rapid, timely
 93 and cost-effective maintenance. Identification of threshold criteria and best timing for a proper
 94 maintenance of a railway track are trivial issues. This is related to the highly complex structure,
 95 which requires to be supported by maintenance decision systems by collection and filtering of data
 96 from diversified sources. These include track health conditions, track availability, use of track time,
 97 performance records and past maintenance activities and repair works (Villarejo et al. 2014).

98 Various approaches exist for the track inspection scheduling problem which can be formulated as a
 99 function of the track, available equipment, labor and time (Bin Osman et al. 2018). In a recent study,
 100 a multi-objective optimisation approach (i.e., maintenance cost and train delays set as objective
 101 functions) is proposed to handle the track maintenance scheduling problem together with a
 102 developed track degradation model. This model considers also the deformations caused by the
 103 maintenance operations (Peralta et al. 2018). A railway track inspection process includes a
 104 considerable volume of short-duration diagnosis tasks (e.g., visual inspections, vehicle-based
 105 inspections, and measurements by varying methods etc.) each of which occurs at disparate
 106 frequencies and time intervals (Bin Osman et al. 2018). A number of studies about railway track
 107 inspection scheduling were reviewed under an optimisation point of view for inspection scheduling
 108 and a gap analysis was undertaken (Bin Osman et al. 2018). These include an elaborated discussion
 109 of various ways in consideration of objective functions and constraints. Identification of the

110 optimised cost-effective inspection interval as one of the several alternatives to minimise the overall
111 track maintenance cost is crucial as the inspection of a track has a larger impact on the total
112 maintenance cost. To that effect, in a lately published paper, track degradation, shock events, and
113 recovery models were developed to propose an integrated long-term model for estimation of the
114 track geometry conditions. Aim of the research was to properly identify optimal cost-based
115 inspection intervals (Soleimanmeigouni et al. 2016). Attaining the trend for the forthcoming
116 development of the track geometry conditions (diagnosis forecasting) plays a key role in the effective
117 and proper planning of maintenance interventions (Quiroga and Schnieder 2013). Lidén (2015)
118 provided an extensive analysis of the railway infrastructure maintenance area with a specific focus
119 on the planning issues. The author presented an archive of planning issues in Sweden and a thorough
120 literature review on the use of mathematical methods and optimisation approaches for solution-
121 related purposes. Attempts were taken to provide an autonomous platform for maintenance planning
122 by developing a model based on the exchange of information between prototype components and
123 related systems (Turner et al. 2017).

124 Track segmentation is a facilitating tool used for diagnosis and maintenance works that splits
125 comprehensive data into homogenous segments with alike track attributes in terms of age and track
126 history. These consider track component types, layout, operational characteristics and presence of
127 structural and operational objects (Tzanakakis 2013). Güler (2017) used track data from sections
128 formed according to the above-mentioned track segmentation in order to develop a condition-based
129 system. The author used genetic algorithms to optimise maintenance and renewal activities. In regard
130 to the criteria for the constraints, the author used international standards (BSEN 13848, BS EN
131 13450, UIC 719 and UIC 714), deterioration models, and expert decisions.

132 Enormous budget is required for maintenance of railway infrastructures with miscellaneous
133 challenging organisational and planning problems (particularly, coordination with train trafficking).
134 However, the most of the research focus has been directed to investigate train traffic operations as
135 opposed to the infrastructure maintenance operations (Lidén 2015). It is also noteworthy that the
136 conditions of the track has an influence on the running dynamics of rail vehicles and the mutual
137 interaction between the track and the rolling stock. To this effect, insecure occurrences depend both
138 on the track and the vehicles along with their wear conditions (RFI 2018). Besides direct track
139 maintenance costs, secondary costs such as those related to rolling stock maintenance, train and
140 shipment delays, and train accidents are also closely connected to track maintenance activities and
141 should be borne in mind (Peng 2011). Cost factors of track construction and maintenance, and also
142 mathematical formulations of maintenance cost modeling including i) materials, equipment, labor,
143 ii) condition monitoring and inspection and, iii) track possession time are discussed in a recently
144 published research by Tzanakakis (2013). Coverage of various cost-efficient maintenance strategies

145 for conventional track structure with an emphasis on effective planning and critical factors for track
146 maintenance cost were recently presented by Prasad (2016).

147 Tzanakakis (2013) sets the basic goals of an overall track maintenance through safety, comfort,
148 availability and economy issues as the lowest number of accidents, highest comfort for passengers
149 along with the lowest environmental impact, maximum availability, and minimised cost,
150 respectively. The author also identifies general types of maintenance strategies as i) Run to Failure
151 Maintenance, ii) Preventive Maintenance, iii) Corrective Maintenance, and iv) Predictive
152 Maintenance (Tzanakakis 2013).

153 The remainder of this paper is organized with an introduction to the degradation modes of railways
154 (Section 2). Common diagnosis and maintenance approaches for railway track are then presented in
155 Section 3. Section 4 provides an overview of the NDT techniques for condition monitoring of the
156 track geometry and components, i.e. rails, sleepers, and track bed layers (ballast, sub-ballast and
157 subgrade). A thorough discussion of innovative NDT techniques along with the conclusions and
158 future perspectives are finally presented in Section 5.

159

160 **2 Degradation Modes of Railways**

161 The following subsections report different types of deformations that may occur on the track
162 substructure and superstructure, respectively.

163

164 ***2.1 Railway Substructure Deformations***

165 Health conditions of the track substructure may affect heavily the entire structural performance.
166 Therefore, it is of utmost importance to collect on-time and accurate information and provide
167 relevant maintenance actions to prevent gradual aging and, eventually, the decay of the track.

168 Maintenance actions require a partial replacement of the track elements with the substructure being
169 often maintained at its original layout. This occurrence does not allow to identify the actual reasons
170 for the overall structural deformations, which are often related to issues in the substructure, such as
171 fouled ballast, poor drainage, ballast pockets and subgrade settlements (De Chiara et al. 2014;
172 Riveiro and Solla 2016). In other words, many superstructure faults may originally generate from
173 decay at the substructure level. A general trend observed in railway asset management when limited
174 funds are available, is to reduce the budget allocated for maintenance tasks such as ballast cleaning
175 and renewal. This approach seems reasonable in a first instance in the shorter term (Solomon 2001).
176 However, the approach could be regarded as a gamble jeopardising the long-term cost-effectiveness
177 of the overall track assets. Overlooking a timely maintenance of a track-bed infrastructure could in

178 fact cause more severe consequences and increase costs (Solomon 2001). A poor track substructure
179 can increase decay of the track geometry leading to higher levels of wear or even failures of rails,
180 sleepers, and fasteners. These occurrences may eventually lead to dramatic consequences such as
181 derailments (Li et al. 2010).

182 The railway ballast layer, which is supposed to be made of coarsely crushed hard rocks, has a pivotal
183 role for the reliability and the overall stability of a track-bed structure since it has vitally significant
184 structural and drainage functions (Solomon 2001). Ballast inherently deteriorates by time upon
185 cyclic loading of trains and weathering processes. Within this context, ballast fouling is defined as
186 a contamination of the ballast that takes place when inter-granular voids gets filled by ballast
187 breakdown and infiltration of other materials. This process takes place from the ballast surface or
188 from the base of the ballast layer (Anbazhagan et al. 2016).

189 Unless the track is drained adequately, water accumulation will start in the body of the track. This
190 occurrence subsequently leads to reduce the shear strength and stiffness of ballast as well as to
191 increase the rate of degradation and fouling (Ibrekk 2015). A poor drainage of the track may result
192 in i) a reduction of the bearing capacity, settlements and failure of the subgrade; ii) ballast pockets
193 and pumping sleepers; iii) shrinkage and cracking of the banks and formation of slush (Chandra and
194 Agarwal 2008). Impact of water on fouled ballast is much higher compared to clean ballast since air
195 voids in clean ballast allow for an immediate drainage. On the opposite, finer particles replacing air
196 voids in fouled ballast obstruct the drainage process. The undrained water accumulating in the ballast
197 pockets results in soft track cases (Tzanakakis 2013).

198 Vegetation on a rail track is also an undesired situation with a severe impact on the ballast, sub-
199 ballast and subgrade layers. Among the various issues, we can mention i) the ballast fouling with
200 vegetation debris preventing drainage, ii) the decay of the track elements, such as concrete sleepers,
201 caused by chemical action and development of roots, iii) obstructed visual inspection activities on
202 the track and the track components (Profillidis 2006).

203 In view of all the above-mentioned information, substructure maintenance and cleaning actions
204 (particularly on the ballast layer) should be performed on time to avoid worse situations. However,
205 the intervention time when ballast should be cleaned of fine materials to prevent more severe issues
206 for drainage, track geometry, and comfort of the service is still a matter of research (Schmidt et al.
207 2017).

208

209 **2.2 *Railway Superstructure Deformations***

210 Rails are exposed to extensive wear and fatigue particularly when traffic load is close to the
211 infrastructure capacity. Main rail faults are abrasive wear, plastic flow, corrugation, fatigue cracking

212 and creep (Tzanakakis 2013). More details on the recognition, notification, and classification of rail
213 defects can be found in UIC (2002).

214 The most relevant superstructure track faults can be sorted into two main groups (Quiroga and
215 Schnieder 2013), i.e., track-geometry-related faults (cross-level, alignment, longitudinal levelling,
216 twist, and gauge) and rail-surface-related faults (surface, corrugation, long and short waves). It was
217 argued that although rail surface quality has no direct influence on the safety and comfort level of a
218 ride, it has a considerable effect on the deterioration rate of the geometry, hence, on the economic
219 life of the track. An accurate condition assessment of a track geometry is fundamental to an
220 appropriate plan and schedule of maintenance strategy (Quiroga and Schnieder 2013).

221 Three threshold levels for track geometry have been identified with an increasing trend of priority
222 in the standard EN 13848-5 (2008):

- 223 a. an “alert limit” beyond which surveys should be carried out regularly;
- 224 b. an “intervention limit” beyond which corrective maintenance actions should be undertaken
225 in order not to attain the immediate action limit prior to the next investigation;
- 226 c. an “immediate action limit”, i.e., the value that, if trespassed, requires strict corrective
227 measures either by reducing the operational speed or by closing the line temporarily.

228 Decay of the sleeper and fastening system is a function of the axle loads, accumulative tonnage,
229 traffic speeds, and maintenance works. These can be listed as i) sleeper cracking, ii) loosening and
230 absence of fastenings and iii) wearing down of the base of the sleepers due to extreme displacements
231 or poor ballast layer (Tzanakakis 2013). A more detailed analysis on the classification of concrete
232 sleeper faults in terms of type and causes at different manufacturing and service stages (i.e.,
233 production phase, coupling phase i.e., track panel, transportation, installation and maintenance
234 phases) can be found in Zakeri and Rezvani (2012) along with a discussion on the methods for
235 reducing sleeper defects.

236

237 **3 Maintenance Activities and Inspection Methods**

238 In this Section, common track maintenance activities are first reported followed by ordinary
239 inspection approaches for both rail substructures and superstructures.

240 **3.1 Common Track Maintenance Activities**

241 According to Ponnuswamy (2012), a good practice for the maintenance of a rail track should aim
242 and succeed at; i) attending to fastenings and fittings, ii) maintaining the track adequately packed
243 together with sustaining the line and level, iii) ensuring the ballast profile to be sufficient and clean,
244 iv) replacing defective sleepers and maintaining the joints with a sufficient gap.

245 In many Asian countries the “through packing” approach is the most common among the non-
246 mechanised traditional maintenance methods. This involves the following processes (Chandra and
247 Agarwal 2008; Ponnuswamy 2012; Prasad 2016):

- 248 • opening of a permanent way and loosening of fastenings,
- 249 • assessment of track elements, squaring of sleepers and alignment correction,
- 250 • gauging, packing of sleepers and re-packing of joint sleepers,
- 251 • boxing the ballast section and dressing.

252 “Overhauling” (mainly with the purpose of improving drainage capability of the track) and “Slack
253 Picking” are the follow-up non-mechanised track maintaining activities to be performed upon the
254 completion of one cycle of “through packing” (Chandra and Agarwal 2008; Ponnuswamy 2012).

255 Profillidis (2006) provides hand tools used for the maintenance of a track and the research by
256 Chandra and Agarwal (2008) can be referred as a comprehensive piece of information about
257 measuring equipment and maintenance tools for tracks along with their functions and sketches.

258 Using mechanised methods in place of manual for maintenance purposes was inevitable due to cost
259 and time constraints. A manual maintenance of a rail track leads to at least ten times more man-
260 hours compared the full-mechanised case (Profillidis 2006). In general terms, for correction and/or
261 prevention of track geometry faults, tamping is carried out whereas grinding is undertaken for rail
262 surface deteriorations (Quiroga and Schnieder 2013). It is worth to remind that although tamping
263 can fix track settlements, it can also yield a faster rate of settlements afterwards (Aursudkij 2007).

264 As mentioned in Aursudkij (2007), progression of tamping operations is given by Selig and Waters
265 (1994) as follows and presented in Fig. 3.

- 266 A. The track and the sleepers are in a random position before the tamping commences.
- 267 B. The track and the sleepers are raised by the tamping machine to a target level, yielding an
268 empty space under the sleeper.
- 269 C. The tamping tines are inserted into the ballast at both sides of the sleeper. Note that this step
270 may lead to ballast segregation.
- 271 D. The tamping tines exert a pressure on the ballast towards the empty space under the sleeper,
272 hence retaining the correct position of the rail and sleeper. This process may also result in
273 ballast segregation.
- 274 E. The tamping tines are lifted from the ballast, and the machine moves on to the next sleeper.

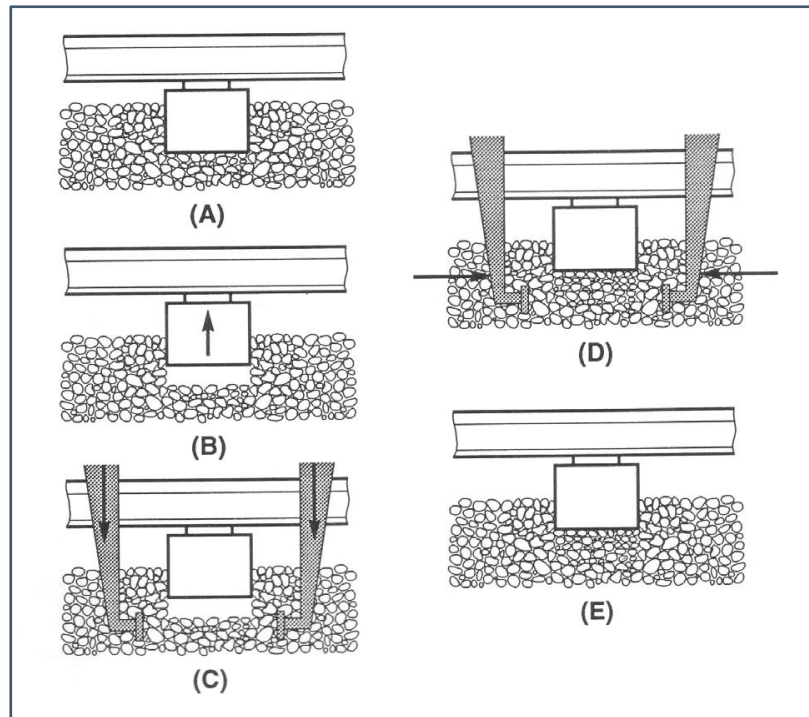


Fig. 3 Tamping progression (Adapted from (Selig and Waters 1994)).

275

276

277

278 A great spectrum of machines has emerged for mechanised maintenance over the past years. There
 279 are a variety of different models for heavy lifting, levelling, lining, tamping, which replaced the
 280 tasks manually performed by track gangs previously (Solomon 2001). After a tamping machine
 281 operates and moves on, other machines such as the ballast compacting and stabilising machines and
 282 the ballast profiling machines follow the line in order to reinforce the stability of the track and ensure
 283 the required ballast cross-section (Profillidis 2006).

284 There exist many types of track maintenance machineries of different complexity. A list of these
 285 includes rail grinding machines, track relaying machines, switch relaying machines, sleeper crib and
 286 shoulder consolidating machines, ballast cleaner and undercutter machines, off-track tampers, light
 287 tamping machines, switch tampers, ditch diggers, sleeper cranes, rail warmer machines, subgrade
 288 rehabilitation machines, plows, water trains, and speeders and hyrails. However, since the focus of
 289 the present paper is the condition monitoring of a track and its components rather than the common
 290 maintenance actions, no further information about the maintaining equipment is given in the
 291 remainder of this document. Comprehensive overviews on the topic can be found in Solomon
 292 (2001), Profillidis (2006), Chandra and Agarwal (2008) and Ponnuswamy (2012).

293 Among the range of processes for fixing a track geometry we can mention ballast cleaning and
 294 renewal, sleeper replacement, joint repair, rail neutralisation, rail replacement, and sub-ballast and
 295 subgrade treatment (Tzanakakis 2013).

296 Profillidis (2006) states that herbicides spraying both manually and by dedicated train convoys are
 297 common practices for vegetation control along the track and the track-bed. The author also suggests
 298 use of an asphalt layer underneath the ballast layer during the construction phase in order to control
 299 vegetation. Information about track maintenance actions and use of machinery in winter time,
 300 especially in snowy conditions, can be found in Solomon (2001).

301 The maintenance option of a renewing exists for the sleepers whereas the fastening systems could
 302 undergo restoring actions such as replacement and rearrangement of elastic pads, repair, and renewal
 303 (Tzanakakis 2013).

304 Table 1 presents the typical life cycles of a busy main railway track according to common
 305 maintenance actions with the traffic load and frequency thereon.

306 **Table 1 . Typical Life cycles on a main line (Adapted from (Lichtberger 2007; Tzanakakis 2013))**

Action on the track	Traffic load	Frequency
Tamping	40-70 mgt	4-5 years
Grinding	20-30 mgt	1-3 years
Ballast cleaning	150-300 mgt	12-15 years
Rail renewal	300-1000 mgt	10-15 years
Timber sleeper renewal	250-600 mgt	20-30 years
Concrete sleeper renewal	350-700 mgt	30-40 years
Fastenings renewal	100-500 mgt	10-30 years
Ballast renewal	200-500 mgt	20-30 years
Subgrade renewal	> 500 mgt	> 40 years

307

308 **3.2 Common Inspection Methods for Track Substructures**

309 The decision to intervene on the ballast is usually taken as a result of field observations and/or
 310 geometry car measurements (Schmidt et al. 2017). Monitoring of a track-bed is nowadays mostly
 311 performed by means of traditional inspection methods, i.e., visual surveys and selective drillings at
 312 the locations where potential deterioration is predicted (Selig and Waters 1994; Clark et al. 2001;
 313 Al-Qadi et al. 2010; Bianchini Ciampoli et al. 2017, 2018). Portable ballast samplers may also
 314 provide information on the condition of the track-bed (Jack and Jackson 1999). However, these
 315 methods are labor- and time-intensive as well as they can provide information at the time/point
 316 location of the sampling (Hugenschmidt 2000; Al-Qadi et al. 2010; Shao et al. 2011).

317 In regard to the rehabilitation of an existing railway track, a set of assessment destructive and NDT
 318 techniques can be mentioned. NDT methods include geophysics/remote sensing, reflection and

319 refraction seismic surveys, magnetic surveys, gravity surveys, resistivity surveys, continuous surface
 320 wave tests, electromagnetic (EM) surveys, ground penetrating radar (GPR) surveys, infrared,
 321 radiometric and light detection and ranging (LiDAR) surveys. Destructive testing methods include
 322 various types of penetrometer tests (including DCP/DPSH/SPT/CPT & CPTU) and test holes/auger
 323 holes/geotechnical drilling/percussion drilling (Van Vreden et al. 2012).

324

325 **3.3 Common Inspection Methods for Track Superstructures**

326 Visual track inspections, (foot, push trolley and the last vehicle of the last fast train), Hallade track
 327 recorder, track recording cars, oscillograph cars and portable accelerometers are the chronological
 328 common track inspection methodologies used in Indian railways (Ponnuswamy 2012). During the
 329 1920s in the US, an induction system built in large defect detection cars was developed by Dr. Elmer
 330 Ambrose Sperry (also known as the Sperry cars). The system was based on the emission of a strong
 331 magnetic field towards the rail and use of a low-voltage current and enabled a diagnosis of internal
 332 rail defects such as transverse fissures (Solomon 2001). This induction testing pioneered the
 333 inspection ways for track defects in American railroads where Sperry cars were considered as mobile
 334 inspection institutes (Solomon 2001). In addition to the magnetic induction, ultrasonic testing
 335 capability, where high-frequency sound signals are emitted into the rail and rail joints in order to
 336 diagnose rail defects, was added to the built-in Sperry cars in 1950s (Solomon 2001).

337 Table 2 below presents as a summary of the above two paragraphs where track geometry inspection
 338 methods and/or cars are discussed along with the measured parameters and assessed elements.

339

340 **Table 2. Common Track Inspection Methodologies: Indian and US case scenarios**

Country Continent	Inspection Method/Car	Measured Parameter(s)	Assessed Element	Measurement Speed and/or Principle	Reference
India Asia	Visual Inspection	overall track	overall track		(Ponnuswamy 2012)
	Hallade Track Recorder	track geometry	track geometry		
	Track Recording Car	track geometry	track geometry		
	Oscillograph Cars	vertical and lateral acceleration	running quality	90 -120 km/h	
	Portable Accelerometer	vertical and lateral acceleration	running quality		

US NA	Visual Inspection	overall track	overall track		(Solomon 2001)
	Sperry cars & Hyrail detection cars	rail defects: transverse fissures	rail	Magnetic Induction	
		rail defects: rail head	rail	Ultrasonic Testing	

341

342 Conventional methods for health monitoring of tracks use measurement tools, such as GPS, levelling
343 or special survey trains. (Chang et al. 2017). Condition monitoring of a track superstructure is mainly
344 handled by special coaches running at different traffic speeds and equipped with measuring devices
345 (Quiroga and Schnieder 2013; De Chiara et al. 2014a; Artagan and Borecky 2015). The importance
346 of track recording cars has found recognition only in recent times in railway infrastructure
347 management, as in the past these were regarded purely as safety-management equipment.
348 Conversely, it is nowadays a common opinion that track geometry cars can provide crucial pieces
349 of inspection information. These can enable better decision-making on maintenance planning, and
350 enhance quality management and automation of inspections (Auer 2013). As an example, use of
351 track geometry cars in the Austrian Federal Railways (ÖBB) had an impact on the grounds where
352 the track decisions were taken. According to Auer (2013), around 80% of the track intervention
353 decisions in 2000 were mostly based on the experience of the local inspectors. This figure has
354 dropped to only about 20% in 2010, meaning that the remaining 80% of decisions were based on the
355 results produced by track recording cars. An increased use of these inspection vehicles led to a
356 general reduction in the numbers of rail breakage and speed restrictions.

357 Most of the European countries, the US and Japan are among the countries making use of track
358 geometry cars (Fig. 4). For the sake of examples, following are given here:

- 359 • Network Rail in the UK employs Eurailscout trains (Eurailscout, 2009). Specifically, the
360 UFM 160 - Universal Rail Measurement Vehicle, travelling up to 160 km/h, is used (De
361 Bold 2011).
- 362 • Infrastructure Agency for Management of Italian Railways, Rete Ferroviaria Italiana (RFI),
363 is the owner of diagnostic trains for the monitoring of railway track structures travelling at
364 360 km/h (RFI 2018). In this regard, the diagnostic train “ARCHIMEDE“ is worthy of
365 mention, as it could be regarded as a pioneer for the current diagnostic fleet of RFI. It has
366 capabilities of measurement tracks, ride quality, overhead line and signalling and
367 telecommunication conditions at a maximum running speed of 200 km/h (Moretti et al.
368 2004).
- 369 • Rail inspection vehicles to measure track safety parameters and assess the rolling stock in
370 the inventory are also used in Turkish railways (Artagan and Borecky 2015).

- 371 • Mauzin synthétique IRIS 320, which can travel up to 320 km/h, is the measuring train used
 372 in France. The train is equipped with mechanical and electrical sensors installed in the
 373 wheels and axles of the train, each using a different chord length for different track
 374 geometry checks (Quiroga and Schnieder 2013).
 375 • In the Japanese example, a track inspection car for Shinkansen tracks collects track
 376 irregularity data stored in a maintenance database system called ‘micro-LABOCS’. (Miura
 377 et al. 1998).
 378 • In the US, various models of track geometry cars (EM-120, EM-GRMS, and T-16) are used
 379 for inspection purposes (Solomon 2001).

380



381

382 Fig. 4 a) UFM 160 (De Bold 2011), b) Diagnostic Trains Fleet of RFI (RFI 2018), c) Mauzin
 383 synthétique IRIS 320 (Quiroga and Schnieder 2013), d) Automatic train examination stations (ATES)
 384 (Artagan and Borecky 2015), Track Geometry Car for Shinkansen tracks (Miura et al. 1998), f) EM-
 385 GMRS track car (Solomon 2001)

386 Table 3. reports a summary of the above-mentioned track geometry cars along with the measured
 387 parameters.

388

Table 3. Track Geometry Cars used in several Countries/Continents

Country Continent	Inspection Method/Car	Measured Parameter(s)	Related Reference
----------------------	--------------------------	-----------------------	----------------------

UK EU	UFM 160 - Universal Rail Measurement Vehicle	track geometry, rail surface, rail cross-section, and overhead wires measurement together with video recordings of track and trackside and positioning	(De Bold 2011)
Italy EU	Several Diagnostic Trains	track geometry, ride quality and comfort, running dynamics, wheel/rail interaction, rail integrity, corrugation, profile, conicity, video inspection, railway clearance gauge, switches	(RFI 2018)
France EU	Track geometry car: Mauzin synthétique IRIS 320	track geometry	(Quiroga and Schnieder 2013)
Turkey Eurasia	Automatic train examination stations (ATES)	track geometry, rail profile and rail corrugation, vehicle measurement systems	(Artagan and Borecky 2015)
Japan Asia	Track Inspection Car for Shinkansen Tracks	track geometry	(Miura et al. 1998)
US NA	Plasser EM-120, EM-GRMS, T-16	track geometry	(Solomon 2001)

389

390 Diagnosis of defects for sleepers and fasteners is performed traditionally by visual inspections on
391 foot or by means of vehicle patrols along the track.

392 **4 Non-destructive Inspection of Track Geometry and Track Components**

393 Various NDT methods have been reported to date for use on assessment and health monitoring of
394 railway tracks (Clark et al. 2004; Narayanan et al. 2004; Eriksen et al. 2006; De Bold 2011; Donohue
395 et al. 2011; Fumeo et al. 2015; Benedetto and Pajewski 2015; Fontul et al. 2016, 2018). Throughout
396 this paper, main techniques for inspection of the structural components of a railway track are
397 reported. To this effect, other methods for the inspection of wearing elements, such as signaling,
398 telecommunication, overhead lines, are not reviewed in this study. A detailed discussion on these
399 topics can be found in He et al. (2016) and Morant et al. (2016).

400 This Section reports the most used monitoring methods for track geometry and track components,
401 i.e. rails, sleepers, and track-bed layers (ballast, sub-ballast and subgrade), sorted according to the
402 inspection task. To this effect, these non-destructive testing techniques can be divided into methods
403 for the assessment of the track geometry and methods for the assessment of the track components.

404 **4.1 Non-destructive Assessment of Track Geometry**

405 A description of common methods for inspection of a track geometry (i.e., visual inspections and
406 track geometry cars) is given in subsection 3.3. Apart from these monitoring techniques, track
407 geometry inspection methods can be sorted into those providing a direct measurement of the track
408 stiffness, and those allowing for calculation of the deformations summed up on the track.

409

410 **4.1.1 Stiffness measurements**

411 The evaluation of the track geometry is mainly related to the detection of vertical displacements at
412 the rail level. Excluding local geometric irregularities due to negligence at the construction stage,
413 these deformations mainly arise in case of local failures in the track stiffness. Variation of track
414 stiffness can take place in both the ballast (e.g. due to a non-uniform compaction of the ballast
415 material), and the substructure of a track, e.g. varying properties of the subgrade. Comprehensive
416 changes in the subgrade stiffness are frequently observed at the transition zones between soil
417 embankments and concrete bridges (Berggren 2009; Varandas et al. 2011) and where hanging
418 sleepers are found (Priest and Powrie 2009). Very rapid stiffness leaps between different materials
419 are in fact a matter of concern for scientists and infrastructure managers. It was reported that
420 embankment/bridge transition zones may require five times higher maintenance frequency and cause
421 two times higher cost compared to a plain track (Pinto et al. 2015). These local issues cause
422 variations of the interaction forces between the trains and the track, leading to fragmentation of the
423 underlying ballast, or to plastic deformations in subgrades and, eventually, to differential settlements
424 (Hunt 2005).

425 Stiffness of a railway track is generally referred to as the overall stiffness of all the layers composing
426 an infrastructure (Kerr 2000). It is possible to classify track stiffness into static and dynamic (Esveld
427 2001; Yang et al. 2009). Static stiffness of a track is defined as its resistance to static loads, which
428 is mostly calculated from the deformation rate subsequent to the application of a load. On the other
429 hand, the dynamic stiffness is referred to as the resistance to the displacement of a track, when this
430 is subject to the application of a time- and space-varying load. This resistance intrinsically relates to
431 the natural frequencies of deformation of a track and, hence, to the performance of the structure in
432 supporting the vibrations caused by the moving loads.

433 Despite the mechanical response of railway tracks is typically measured as a result of static analyses,
434 the rapid growth of high-speed passenger transportation demand has made the estimation of the
435 dynamic stiffness a matter of growing concern.

436 Under a quantitative point of view, it is possible to express the dynamic stiffness modulus k_d of a
437 track as follows:

$$k_d = \frac{|P|}{|Z|} \quad (1)$$

438 with $P = P_0 e^{j\omega t}$ being the vertical harmonic force applied by a passing train on the rails, and $Z =$
439 $Z_0 e^{j(\omega t + f)}$ being the displacement at the point of application of the force.

440 Wang et al. (2016) provide a comprehensive overview of the most common methods for evaluation
441 of the stiffness modulus of railway tracks.

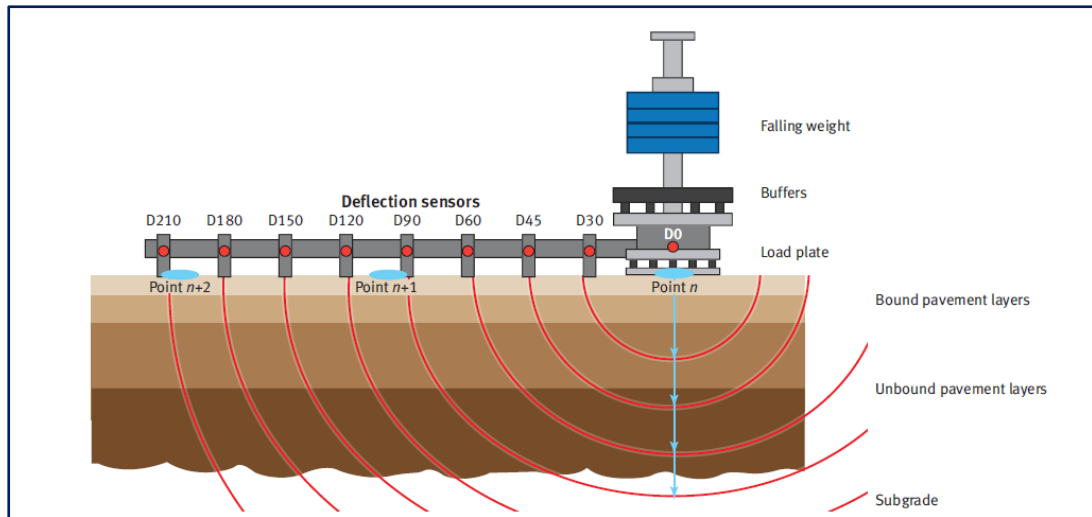
442 The “hydraulic jack-loading” is a traditional method widely used over the last century as an effective
443 technique for measuring the stiffness of ballasted tracks (Kerr 2000; Esveld 2001). The method
444 works by applying a fixed force on a rail and measuring the relevant deflection through a
445 displacement meter. Thereby, the track stiffness can be measured as secant or tangent stiffness on a
446 force-displacement plot obtained from the results of the test.

447 The “impact hammer” method relies on the measurement of the track vibrations by acceleration
448 transducers, directly installed on the rails or sleepers. Vibrations are induced by means of an impact
449 hammer hitting the track, with a frequency ranging from 50 Hz to 1500 Hz (UIC 2010). A force
450 transducer on the head of the hammer measures the impulse exerted, from which it is possible to
451 define the overall track stiffness.

452 The falling weight deflectometer (FWD) is a widespread method based on the dropping of a standard
453 load, usually equal to 125 kN, on the track surface (Burrow et al. 2007; Woodward et al. 2014).
454 Ground-coupled geophones can measure the deflections induced by the drop, which is eventually
455 related to the overall track stiffness. However, it should be noted that FWD is a commonly used
456 method in roadway engineering applications for structural evaluation of pavements. Specifically, it
457 is used in combination with GPR for the estimation of pavement layer stiffness by means of the
458 measured deflections and the estimated thicknesses (Borecky et al. 2019). According to the working
459 principles of the FWD technique, the stress caused by the passage of a heavy vehicle is simulated
460 and the response of the pavement is calculated by measuring the deflections generated (Picoux et al.
461 2011). A schematic presentation of the FWD working principles is given in Fig. 5 (Borecky et al.
462 2019).

463 Based on a significant data series of track modulus and GPR measurements collected from different
464 railway track geometries, a multivariate linear regression model was developed by Narayanan et al.
465 (2004). This is capable to estimate the track modulus from GPR data, and to considerably drop cost
466 and time of operational track maintenance planning (Narayanan et al. 2004).

467



468
469 **Fig. 5 Schematic presentation of the operation principles of a falling weight deflectometer (FWD)**
470 **(Borecky et al. 2019)**

471

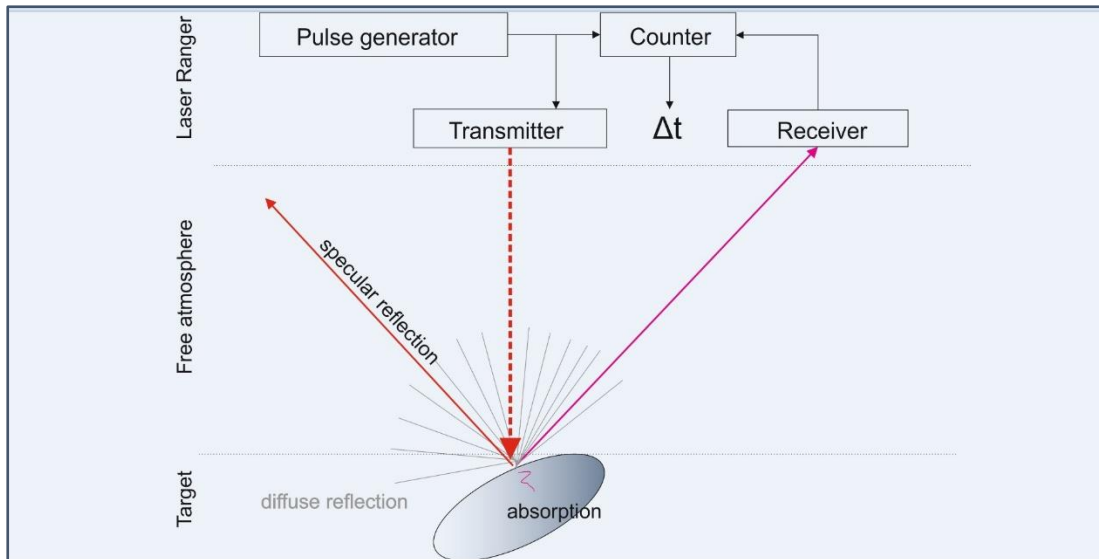
472 4.1.2 Deformation detection

473 Optical-based methods:

474 Berkovic and Shafir (2012) provide a comprehensive overview of numerous non-contact optical-
475 based techniques employed for measurement of distances to objects, and pertinent features like
476 displacements, surface profiles, velocities and vibrations in a comparison wise manner. Intensity-
477 based sensing, triangulation, time-of-flight sensing, confocal sensing, Doppler sensing, and various
478 types of interferometric sensing, are also discussed (Berkovic and Shafir 2012).

479 In case of railways, there is a growing tendency to place optical sensors in the rail vehicle. In this
480 respect, a US patent was issued where an on-board and contactless measurement system (composed
481 of two optical sensors and one camera) was developed for measuring quality track, track stiffness
482 and modulus specific portions of the track (Farritor et al. 2008).

483 Mobile mapping systems, which are composed of an imaging unit (combination of laser scanners
484 and/or digital cameras) and a navigation unit for spatial referencing, perform the task of capturing
485 and providing 3D geometric information by an imaging sensor attached to a moving platform such
486 as a train (Arastounia 2015). To this effect, it worthy of mention that laser scanners acquire data by
487 laser range finding i.e., transmitting a laser beam and measuring the phase change of the reflected
488 beam or the time of flight. During the operations, head of a laser scanner rotates perpendicular to
489 the normal axis of the platform and an oscillating mirror diverts the laser beam to scan the
490 surrounding environment. As a result of this, 3D co-ordinates of points are calculated using the
491 observed range and the angle of the oscillating mirror (Arastounia 2015). A good overview of
492 working principles and applications of laser scanning are given in Pfeifer and Briese (2007). The
493 working process of a pulse laser ranger is represented in Fig. 6.



494

495

Fig. 6 Working principles of a pulse laser ranger (adapted from (Pfeifer and Briese 2007))

496

497 An example of mobile mapping system mounted on a train with a number of three laser scanners
 498 and one navigation unit is depicted in Fig. 7 (Arastounia 2015).

499 Following a detailed discussion on the methods used for measuring rail displacements, Pinto et al.
 500 (2015) presented a contactless method based on optical technologies and validated by static and
 501 dynamic laboratory experiments. The system comprises a diode laser module and a position sensitive
 502 detector to measure rail displacements in an embankment/underpass transition zone at an accuracy
 503 of 0.01 mm for the passage of trains at a speed of 220 km/h (Pinto et al. 2015).



504

505

506

**Fig. 7 An example of mobile mapping system mounted on a train with a number three laser scanners
 and**

507 **one navigation unit. A sample scanning pattern of one of the laser scanners is sketched in red color**
508 **(adapted from(Arastounia 2015))**

509 A static terrestrial laser scanning system is proven to be a powerful technique to scan the railway
510 track geometry and to filter out the shortcomings of target-based traditional methods such as robotic
511 total stations. This is due to its capability to remotely collect large volumes of accurate data at high
512 speed (Soni et al. 2014).

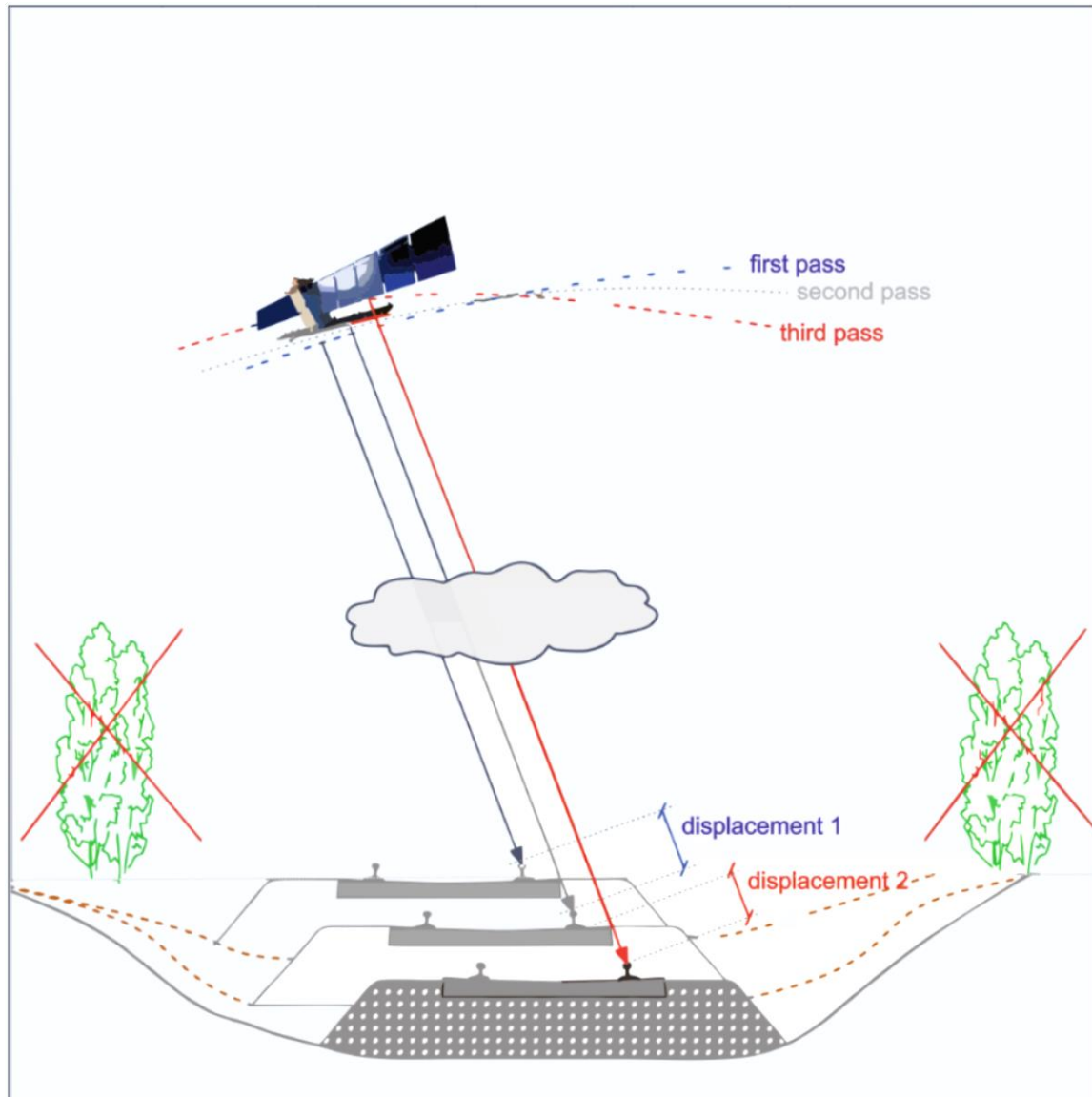
513 A stretch of 550 m of Austrian rural railway corridor was examined using 3D LiDAR data and a
514 methodology for a fully-automated recognition of railroad corridor key elements was proposed
515 (Arastounia 2015). The scan involved rail tracks as well as contact cables, catenary cables, return
516 current cables, masts, and cantilevers. Results both indicated an accurate and precise representation
517 of the current state of the railway infrastructure at both the object level and the point cloud level
518 (Arastounia 2015).

519

520 Remote Sensing:

521 Regular inspections on vibrations and transient displacements of civil engineering infrastructures
522 are crucial for a timely diagnosis of hazardous situations. Contact sensors such as piezoelectric
523 accelerometers or optical targets are used for monitoring purposes. However, accessibility problems,
524 a need for a rapid transmission of data, unavailability of sites for sensors installation, and dangerous
525 states of a structure (seismic shocks, intentional damage, collapses, and blasts) require monitoring
526 from a safe distance. All of the above requirements have given momentum to initiate the use of
527 remote sensing techniques (Pieraccini et al. 2004). Radar interferometry (also known as
528 interferometric radar) is one of the recently favoured effective and reliable remote sensing tools. The
529 scientific background of the technique is derived from space technology, as it is capable to detect
530 small displacements at large distances using the phase information of a back-reflected microwave
531 signal (Pieraccini 2013). The capability to detect such small deformations is very promising,
532 although research is being done to improve current issues arising from collection of extensive
533 database, e.g. the harmonization of different datasets and the communication with experts from
534 several scientific disciplines to assess risk areas (Chang et al. 2017). Radar interferometry can be
535 divided into two main groups as real interferometry radar (RAR) and synthetic interferometry radar
536 (In-SAR). In this regard, RAR uses a narrow beam of energy that is oriented perpendicularly to the
537 advancing direction of the spacecraft, and an image of a narrow strip of terrain is obtained by means
538 of the collected reflections (ESA). In-SAR was developed with the purpose of overcoming the
539 restrictions of RAR with good azimuth not dependent on the slant range to the target, small antennas
540 and, relatively-long wavelengths (ESA).

541 Rosen et al. (2000) reviewed the fundamentals, principles, specific systems and limitations of the
542 In-SAR technique together with its geophysical applications such as ocean current measurement,
543 topographic mapping, earthquake and hazard mapping, detection of glacier movement and,
544 estimation of vegetation. Working principle of In-SAR is given in Fig. 8.



545

546 **Fig. 8 Principles of Interferometric Synthetic Aperture Radar (In-SAR) where satellite-emitted**
547 **EM signals are employed to measure phase differences from displacement along the surface.**
548

549 Chang et al. (2017) proved the applicability of In-SAR for detection of railway instabilities over the
550 entire railway network (3223 km) of the Netherlands. The authors performed 213 acquisitions over
551 3 separate satellite tracks to predict the kinematic time series of millions of Persistent Scatterer In-
552 SAR measurements with a millimeter-level precision. They employed a probabilistic method for In-
553 SAR time series postprocessing for an efficient analysis of the data. Railway instabilities were
554 identified and a risk map of the railway network was produced (Chang et al. 2017).

555 In regard to the detection of displacements in railway structures, Huang et al. (2017) used a
556 “persistent scatter interferometry” approach to identify displacements of the long-span Nanjing
557 Dashengguan Yangtze River high-speed railway bridge in China. As cited in a recent paper by
558 Pieraccini (2013), Beben (2011) integrated use of interferometric radar and inductive gauge to
559 measure displacements of a corrugated steel plate railway culvert. The inductive gauge was used as
560 a validation methods for the results acquired by interferometric radar.

561 Within the context of rail infrastructure management, it is worth to report that radar interferometry
562 has not been yet fully adopted as a routine inspection tool. Nevertheless, the method has proven high
563 potentials in track displacement diagnostics to facilitate monitoring activities, especially in
564 combination with other NDT methods.

565

566 ***4.2 Non-Destructive Inspection of Track Components (Rails, Sleepers and Trackbeds)***

567 A visual inspection performed by track maintenance personnel is the simplest technique for
568 monitoring rail defects. This method can still be the current practice used by a number of railway
569 operators, especially when a limited budget for maintenance is available (Labropoulos et al. 2010).
570 However, effectiveness may be augmented by use of CCD cameras and laser profilometers
571 connected to digital video recorders (Labropoulos et al. 2010).

572 It is worth to mention that magnetic induction testing in chronological development of rail defects
573 monitoring processes. Magnetic induction testing depends on setting up a strong magnetic field in
574 the rail by means of electrical bushes touching the rail and using low voltage current, while a sensing
575 coil diagnoses modifications in the field indicative of a rail flaw (Solomon 2001).

576 A wide spectrum of existing NDT techniques for assessment of rail defects can be listed as follows:
577 visual inspections by the maintenance staff and/or by cameras (portable or mounted on a vehicle)
578 and laser profilometers, ultrasonic defect detection, eddy current testing, EM acoustic transducers,
579 radiography, GPR, laser generation and reception of ultrasonic waves, alternating current potential
580 drop (ACDP), and alternating current field measurement (ACFM), infrared thermography, fibre
581 optics microscopy, and impedance spectroscopy (Labropoulos et al. 2010). The availability of
582 human and financial resources together with the requirements of the railway infrastructure
583 administrator determine the choice of employing these techniques either independently or in
584 combination with others (Labropoulos et al. 2010).

585 A comprehensive review of NDT methodologies in practice around Europe and North America for
586 rail defect detection is given by Papaalias et al. (2008), together with an overview of the background
587 theory and the techniques used to integrate condition data into maintenance actions. The paper gives

588 an elaborated list of non-destructive techniques and corresponding systems available, sorts of rail
589 flaws diagnosed and performance (Papaelias et al. 2008).

590 In view of the tremendous development of both software and hardware components, implementation
591 of NDT methods for health monitoring of track-beds has increased over the last few years.

592 In his dissertation work, De Bold (2011) identifies potential NDT methods for ballast evaluation
593 such as FWD, sonic echo, impulse response, impedance logging, cross-hole sonic logging, parallel
594 seismic, ultrasonic pulse velocity, ultrasonic echo, impact echo, spectral analysis of surface waves
595 and GPR. In an effort to save time and cost for data acquisition, processing and analysis for track
596 substructure maintenance, several non-destructive methods have emerged recently. Among these,
597 GPR has proven potential and found interest of many researchers and practitioners in condition
598 assessment of ballast (Bianchini Ciampoli et al. 2018). Numerous diagnosis methodologies, varying
599 from traditional to most innovative are reviewed in Bianchini Ciampoli et al. (2017), with an
600 emphasis on GPR. GPR is reported to have the advantage of providing dense and accurate data with
601 a higher resolution compared to other NDT techniques such as seismic, transient electromagnetic,
602 electrical and magnetic methods (Benedetto and Pajewski 2015).

603 The video monitoring system for track components (artificial vision system) developed by RFI in
604 Italy supports the maintenance staff to identify locations along the track with a lack of or an excess
605 of ballast (RFI 2018).

606 Clark et al. (2004) presented other NDT methods such as conductivity and infrared thermography
607 together with GPR in visualising the railway track-bed with an emphasis on the speed of the surveys.
608 Barta (2010) demonstrated the viability of using several geophysical methods, such as resistivity
609 tomography, seismic methods and gravimetry for assessment of track defects within the context of
610 INNOTRACK project. Location sites investigated were in Czech Republic, France, Spain, and
611 Sweden.

612 Fontul et al. (2016) reported electric resistivity, seismic waves, gravimetry and electromagnetic
613 methods (GPR) as the main NDT geophysical methods for railway evaluation. The authors argued
614 that a general constrain for a geophysical prospection is the time taken for the installation of the
615 equipment as well as the complexity of data interpretation. Rails are identified as a another drawback
616 in view of their disturbance provided to both electric and electromagnetic methods (Fontul et al.
617 2016). However, use of GPR was suggested for preliminary surveys across an entire network area
618 followed by more localised measurements carried out by electrical resistivity tomography (ERT),
619 seismic wave propagation, and micro-gravimetry at the point location of identified critical areas
620 (Fontul et al. 2016).

621 A multi-channel analysis of surface waves was also used for assessment of ballast fouling, where
622 information from a seismic survey were compared to GPR data (Anbazhagan et al. 2011). GPR and

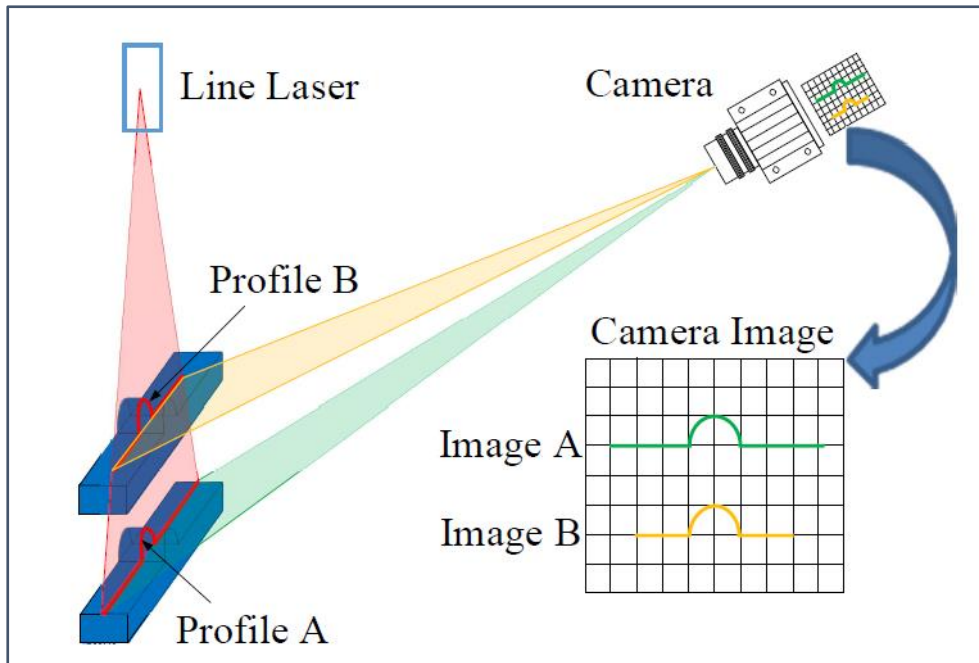
623 FWD data were also used in combination for indirect estimation of track modulus (Narayanan et al.
624 2004). Other combined uses of FWD, light falling weight deflectometer (LFW) and GPR for
625 railway evaluation purposes are reported in Fontul et al. (2016). Fortunato et al. (2016) combined
626 the results of GPR, FWD and plate load tests in order to efficiently reinforce the structure of a
627 trackbed, considering technical and economic issues. Another example of integral use of NDT
628 methods was presented for a geophysical assessment of a railway embankment in the south-east of
629 Ireland. ERT, GPR and multichannel analysis of surface waves were used together with geotechnical
630 tests (Donohue et al. 2011). Sussmann and Thompson II (2017) made a combined use of vertical
631 track deflections and GPR as a quality control tool for precognition of real track conditions and
632 indication of future track performance. In a recent study, it is expressed that coupling the results of
633 the constant head permeability tests with an emerging imaging technology for ballast will support
634 decision-makers to identify the time period when ballast should be cleaned (Schmidt et al. 2017).

635

636 *4.2.1 Optical-based methods*

637 Optical-based methods for track geometry assessment have already been introduced in Subsection
638 4.1.2. Here a few more examples of their use for the non-destructive evaluation of track components
639 are presented.

640 In a recent study, a new 3D laser profiling system (comprising a laser scanner, an odometer, an
641 inertial measurement unit (IMU) and a GPS) was introduced for acquisition of the rail surface profile
642 data. In regard to this, Fig. 9 shows the working principles of the proposed system (Xiong et al.
643 2017). The system i) uses an adaptive iterative closest point algorithm to register the point sets of
644 the measured profile with the standard rail model profile at a sub-millimeter accuracy; ii) it combines
645 together all of the measured profiles to form the rail surface via a high-precision positioning process
646 with the IMU, the odometer and the GPS data; iii) it uses K-means clustering in order to merge the
647 possible defect points into candidate defect regions (Xiong et al. 2017).



648

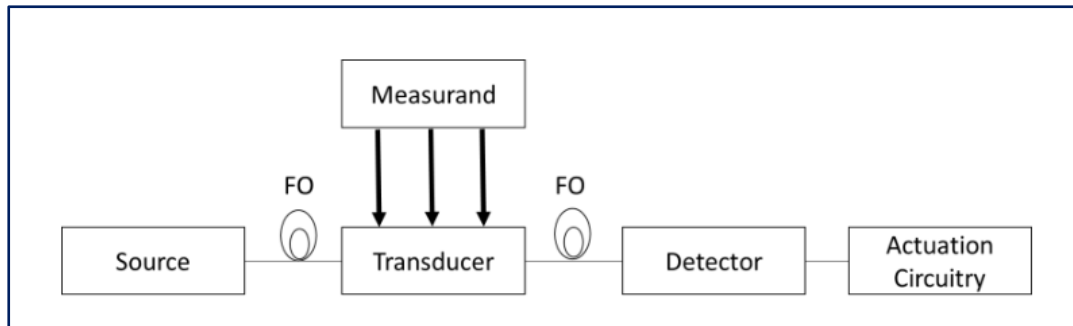
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650

Fig. 9 Measurement principles of the system proposed in Xiong et al. (2017) for capturing the rail surface profile.

651

652 Another laser-based system was developed with the purpose of measuring deflections of a sequence
653 of sleepers at a transition zone. The system turned out to provide a fast evaluation of the quality of
654 the track (Kim et al. 2014).

655 In regard_to optical fiber sensors (OFSs), steady advancements in the sensor technology are
656 accelerating the evolution of structural health monitoring of civil engineering structures (Ye et al.
657 2014). n OFSs system is composed of an optical source that excites the transducer (the sensitive
658 optical element) through a fiber optic cable (FO) (Campanella et al. 2018). The transducer turns the
659 initial signal of the optical source into another signal having dissimilar properties owing to a
660 variation of the measurand. The converted signal is acquired by a detector and processed by the
661 actuation circuitry, which derives the information about the measurand by way of comparison
662 between the initial signal and the signal converted by the transducer (Campanella et al. 2018). A
663 schematic system of OFSs is illustrated in Fig. 10 (Campanella et al. 2018).



664
665 **Fig. 10 A schematic system of OFSs (Campanella et al. 2018)**

666

667 OFSs have specific advantages over other conventional mechanical and electrical sensors. We can
668 mention the light weight, a small size, a less sensitivity to corrosion and EM interference, and an
669 overall effectiveness due to the property of being embedded in the body of a structure (Ye et al.
670 2014). According to Barrias et al. (2016), OFS-based monitoring tools can be used for the non-
671 destructive evaluation of all the types of engineering structures since they endure lightning strikes,
672 resist chemical aggressions, they can be incorporated into very tight areas and eventually can
673 establish sensor chains using a single fiber (Barrias et al. 2016). Campanella et al. (2018) reported a
674 wide spectrum of applications of OFSs such as strain, vibration, electric, acoustic and magnetic
675 fields, acceleration, rotation, pressure, temperature, linear and angular position, humidity, viscosity,
676 chemical measurements, and many others (Campanella et al. 2018).

677 Although there are many different ways to characterize OFSs depending on the property of interest,
678 i.e., modulation and demodulation process, measurement points, application, etc., (Barrias et al.
679 2016), in this paper, OFSs will be classified into two different groups: fiber Bragg grating (FBG)
680 sensors and distributed sensors.

681 Campanella et al. (2018) provided a systematic review of progress on key FBG performance factors
682 of the OFSs, physics of FBG, operation principles of strain sensors based on FBG, interrogation
683 techniques of FBG strain sensors, performance evaluation of FBG, key sectors and main market
684 players of Global FBG strain sensors market.

685 Yan et al. (2011) introduced three FBG-based methods (matched gratings, grating under uneven
686 strain distribution, and semi-free gratings) for strain measurement and axle counting in high-speed
687 railway systems. Pros and cons of these methods were analysed under a feasibility and a cost-
688 efficiency viewpoint through laboratory validation and assessment.

689 Traffic impacts on a short span railway bridge in Northern Portugal was demonstrated. To this
690 purpose, a new hybrid platform deploying the synchronous assessment of signals generated by a
691 sensing network, including both electrical and FBG-based sensors, was presented (da Costa Marques
692 Pimentel et al. 2008). A bridge weight-in-motion algorithm was used to develop a commercial fiber-

693 optic-based train characterisation system and the tested system provided an on-motion acquisition
694 of train speed and weight distribution by using only three FBG sensors (da Costa Marques Pimentel
695 et al. 2008).

696 Ye et al. (2014) reported other FBG applications to railway infrastructure as i) a real-time wheel
697 defect detection system on rail tracks of the Hong Kong mass transit railway (Wei et al. 2011), and
698 ii) a railway security monitoring system on the high-speed line between Madrid and Barcelona. This
699 latter was performed for train identification, axle counting, speed and acceleration detection, wheel
700 imperfection monitoring and dynamic load calculation (Filograno et al. 2012)

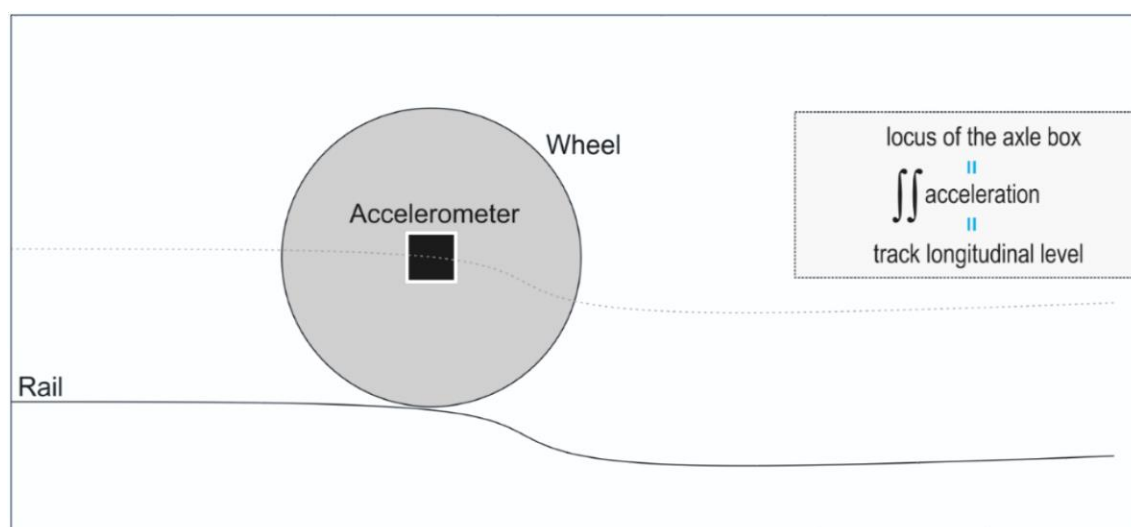
701 Barrias et al. (2016) focused on the progress in the application of distributed optical fiber sensors
702 (DOFS), introducing the theoretical background of DOFS and presenting the current developments.
703 This was achieved by reporting a wide range of laboratory experiments as well as an intensive review
704 of their applications to civil engineering infrastructures.

705 Kerrouche et al. (2008) monitored a deactivated concrete railway bridge in Sweden, which was
706 loaded to failure by use of an FBG-based distributed sensor system.

707

708 4.2.2 Inertial methods

709 Inertial measurements depend on a basic rule where double integration of the acceleration
710 demonstrates a position on an accelerometer. As an example, the vertical position of a wheel can be
711 computed via double integration of the axle-box acceleration (Tsunashima et al. 2012). The result
712 provides the longitudinal level since the wheel is continuously in contact with the rail (Fig. 11)
713 (Tsunashima et al. 2012).



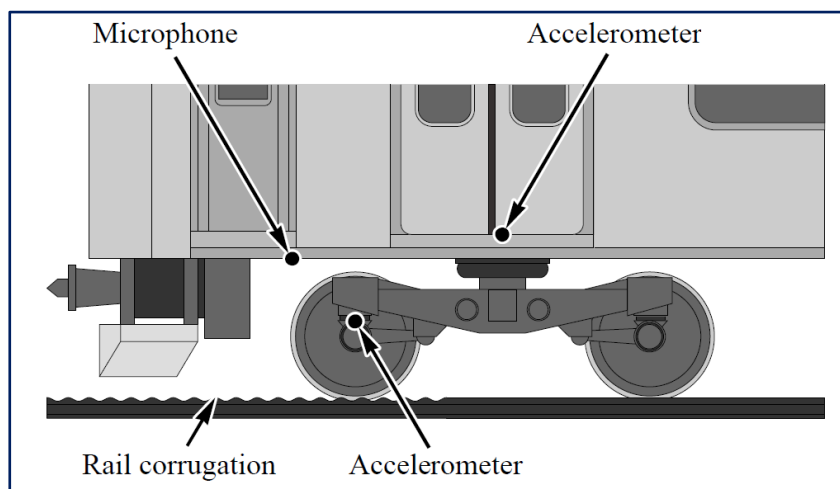
714

715 **Fig. 11 Inertial track measurement in longitudinal level (adapted from (Tsunashima et al. 2012))**

716 Within this context, a model based on taking the input from vertical accelerations generated in
717 railway axles and measured in trains running on routine schedule was developed. The model is
718 capable to compute the rail irregularities and to find the transfer function, using the Fourier
719 transform, in order to relate the input and the output functions in the frequency domain (Real et al.
720 2011). The solution is then transformed into the time domain by implementation of the inverse
721 Fourier transform. Data input from real measurements performed on line 9 of the Madrid subway
722 were used, and the effectiveness of the model was assessed by way of comparison between the
723 outcomes with the rail profile taken by optical methods (Real et al. 2011).

724 A recent work analyses data acquisition and processing techniques to improve track inspections.
725 Tests on the Metropolitan Rail Network of Valencia (Spain) were performed, and axle box
726 accelerations were acquired and analysed (Salvador et al. 2016). Optimum sampling and filtering
727 frequencies along with the positions of accelerometers along the vehicle were set (Salvador et al.
728 2016). In addition, identification of various track defects, singularities and modes of vibration were
729 carried out by means of spectral analysis and time–frequency representations (Salvador et al. 2016).

730 Kojima et al. (2010) developed a multi-resolution analysis method using a wavelet transform
731 approach. Aim of the research was to diagnose rail corrugation from vertical accelerations of a
732 railway vehicle body. Fig. 12 depicts the layout of the investigation equipment as well as the position
733 of the sensors. External noise was measured with a microphone at one of the main lines in Japan,
734 whereas vertical and lateral accelerations of the vehicle body and the axle-box were measured with
735 accelerometers (Kojima et al. 2010).



736
737 **Fig. 12 Layout of the investigation equipment and position of sensors used in Kojima et al. (2010)**

738

739 4.2.3 Acoustic and ultrasonic techniques

740 First use of transmission of high-frequency sound signals into the rail and rail joints for detection of
741 rail defects, i.e, ultrasonic testing, was reported to have been used in the US since the fifties

742 (Solomon 2001). On the other hand, these techniques have started to be employed worldwide since
743 1970s (Labropoulos et al. 2010).

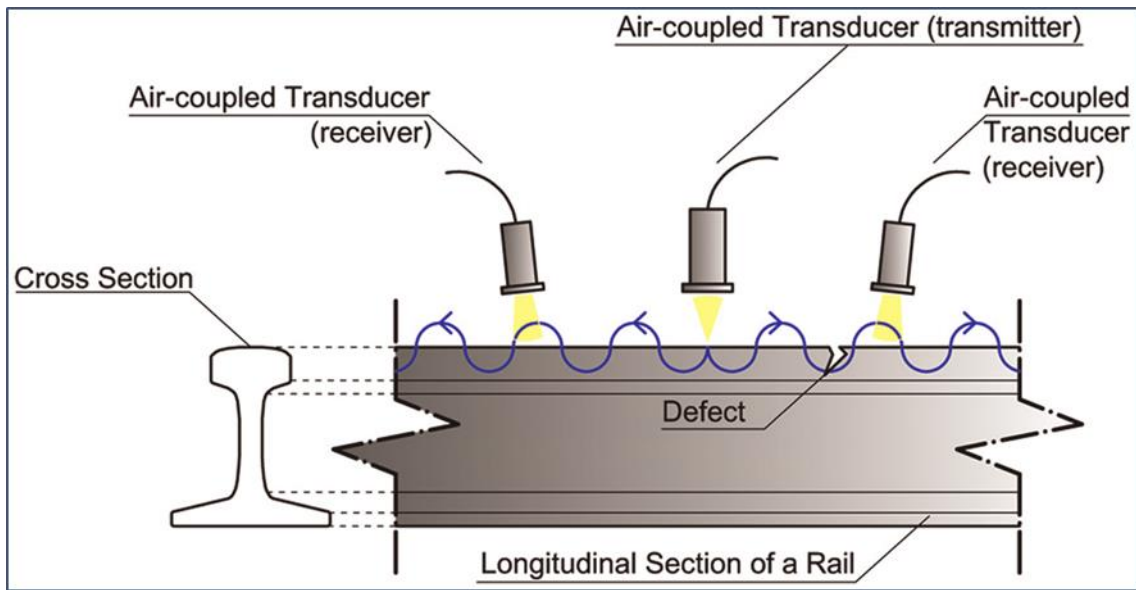
744 Schramm et al. (1993) have used acoustic techniques to quantify stress on a short test segment of a
745 railway track and dealt with the construction of the transducers. Three methods were employed to
746 measure stress by ultrasound, i) birefringence, ii) surface-skimming P-wave velocity and iii)
747 combination of waves.

748 A guided wave ultrasonic rail break diagnosis system was developed and put in practice in a 840
749 km-long line in South Africa. The system had the advantage of inspecting a long span of a one-
750 dimensional waveguide, such as a continuously welded rail, from a single transducer location. This
751 location operated by emitting guided waves between permanently installed transmitters and
752 receivers placed at nearly 1 km distance far from each other (Loveday et al. 2016). The authors
753 argued that the system was beneficial in terms of avoiding at least one derailment, the cost of which
754 is relatively the same as the cost of installing the system over the entire 840 km of the track (Loveday
755 et al. 2016).

756 The non-destructive assessment of the foot area of a rail is an accepted challenge (Moustakidis et al.
757 2014; Loveday et al. 2016). To this effect, categorisation methods for diagnosing automated rail foot
758 flaws was considered as another example of guided wave ultrasound approach (Moustakidis et al.
759 2014).

760 Within this context, a research was developed with the aim to optimise the frequency of the
761 ultrasonic rail defect monitoring works. To this purpose, a model was developed depending on the
762 compensation between safety, cost and effectiveness (Liu et al. 2014).

763 Mariani et al. (2013) presented a new system for high-speed and contactless rail integrity assessment,
764 which used an ultrasonic air-coupled guided wave signal generation and air-coupled a signal
765 detection prototype. In addition to the above, numerical analyses of ultrasonic guided wave
766 propagation in rails were performed to support with the arrangement of the numerous conditions of
767 the prototype. This step was found effective to improve the sensing ability of the system for detection
768 of the rail defects (Mariani et al. 2013). Emission and reception of the signals are illustrated in Fig.
769 13 (Mariani et al. 2013).



770

771

Fig. 13 Illustration of of the air-coupled guided wave transducers (Mariani et al. 2013)

772

773 A combined use of the acoustic emission and the digital image correlation NDT methods has proven
 774 to be beneficial for the inspection of railway concrete sleepers in terms of cracks. Specifically,
 775 acoustic emission was useful to visualise the process of damage as well as to disclose any
 776 modifications in the overall behavior. The digital image correlation technique detected critical
 777 damage regions as a function of the loading periods (Omondi et al. 2016).

778 A review of recent advancements achieved in the use of ultrasound-based automated monitoring
 779 systems for rails was given by Santa-aho et al. (2017) along with examples of current field
 780 implementations and specific properties of the ultrasonic monitoring methods for use in railway
 781 tracks.

782

783 4.2.4 Image Analysis

784 Although miscellaneous algorithms for object detection problems have been designed by the
 785 computer vision society for industrial inspection processes, only a few amount of works exist on the
 786 use of computer vision technology in the specific area of rail inspection (Malar and Jayalakshmy
 787 2015). Since visual inspection are slow, laborious and subject to the interpretation of the operator, a
 788 more effective vision-based automatic rail inspection system was proposed (using computer vision
 789 based technologies). Purpose of the system was to detect presence/absence of sleepers and/or
 790 fasteners, by inspection of real images collected by a digital camera installed under a diagnostic train
 791 (Malar and Jayalakshmy 2015).

792 Mazzeo et al. (2006) developed a system for automatic detection of potential foreign material in the
793 ballast region. Outcomes were achieved by processing the images collected by a digital line scan
794 camera mounted under a train. Ballast patches were identified by neural classifiers and images were
795 processed using the edge-histogram method. The acquired detection system was verified on a set of
796 experiments carried out on real images that proved to accurately identify the ballast region and the
797 foreign materials therein.

798 In addition to the above, a warning system for tram drivers to perceive obstacles from the front view
799 of the trams was fostered via image analysis (Miyayama et al. 2010).

800 Advanced image improvement techniques, such as gamma adjustment, histogram equalisation, and
801 bi-lateral image filtering, combined with image segmentation techniques, including a watershed
802 algorithm and image thresholding, were used to successfully extract size and shape properties of
803 individual ballast particles as a tool for quantification of the level of ballast deterioration (Tutumluer
804 et al. 2016) .

805

806 4.2.5 *Ground Penetrating Radar (GPR)*

807 GPR is a non-destructive sensing technique that uses discrete pulses of EM energy to detect
808 alterations of the electrical properties of the subsurface (Neal 2004) in a dominant frequency range
809 from 10 MHz to 2.5 GHz. The system is capable to identify the size and position of electrically
810 dissimilar layers and objects (Saarenketo 2006). The GPR technique is mainly based on the emission
811 of EM energy into the ground or another medium by means of short EM pulses. Part of the
812 transmitted energy is reflected due to changes in: i) the electrical properties between the reflector
813 and the surrounding host material; ii) the material composition iii) the water content (Annan and
814 Davis 1997). Main features of the materials can be predicted by a number of parameters in the
815 reflected signal such as the time delay, the amplitude of the reflection peaks and the modulation of
816 frequency (Tosti et al. 2017). The physics of EM fields are mathematically given by Maxwell's
817 equations, whereas the constitutive equations quantify material properties. Integration of these two
818 elements allows for a quantitative description of GPR signals (Jol 2009). The EM behaviour of a
819 material is governed by its dielectric properties i.e., the relative dielectric permittivity (RDP)
820 (influencing the wave velocity), the electric conductivity (affecting the wave attenuation) and the
821 magnetic permeability (Benedetto et al. 2017 Ia).

822 Within this context, the travel time of a GPR signal is a direct measurement that can be collected in
823 the field. The signal velocity, however, is variable and dependent on the physical properties of the
824 materials among which RDP is the most significant one. Once the RDP is known, the relative EM
825 wave velocity can be computed from equation (2):

$$v_r = \frac{c}{\sqrt{\epsilon_r}} \quad (2)$$

826 where v_r is the relative velocity of the EM wave, c is the speed of light, and ϵ_r is RDP (Daniels
827 2004). Once the EM wave velocity is known, the depth of the object or interface can be computed
828 from equation (3):

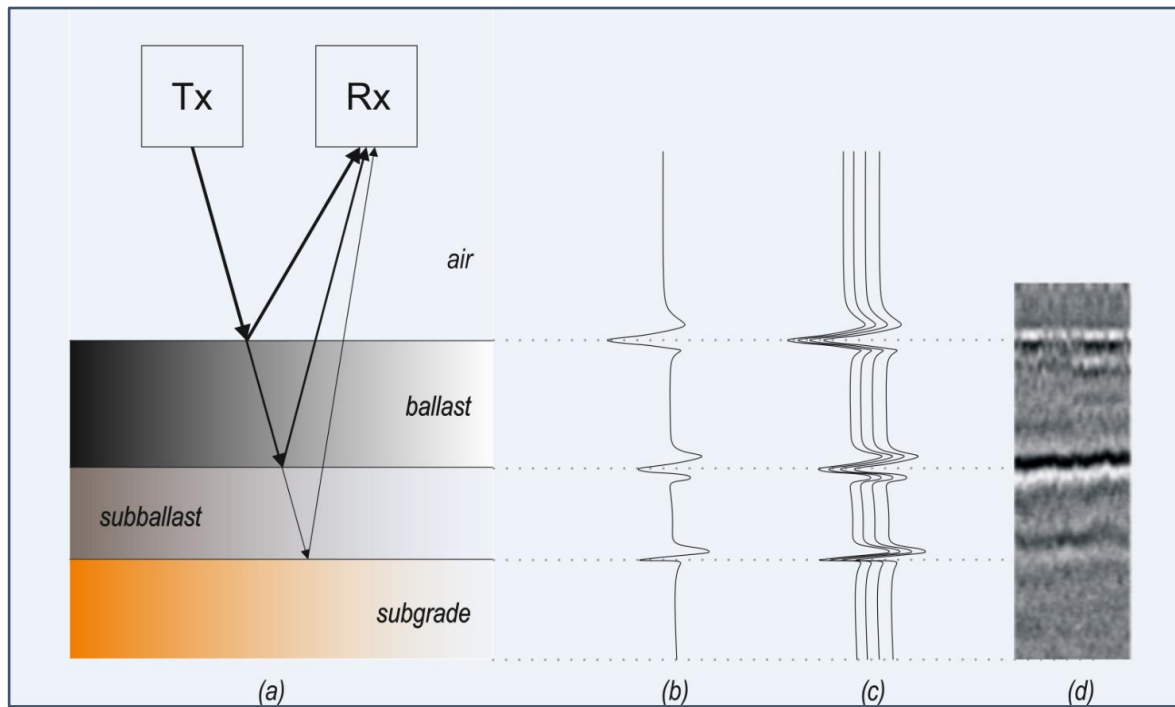
$$d = v_r \cdot \frac{t}{2} \quad (3)$$

829 where d is the depth of the object or layer of interest and t is the two-way radar travel time to and
830 from the target (Daniels 2004).

831 As expressed in Roberts et al. (2006), first GPR applications in railway engineering date back to the
832 eighties. Initial work was limited to ground-coupled antennas operating with center frequencies
833 below 500 MHz. It is worthy of mention that the railway industry has initiated use of GPR
834 technology in mid-nineties in Europe (mainly in Switzerland, UK, Finland), and North America
835 (Saarenketo 2006). GPR has been used in a wide range of applications for railway infrastructure
836 monitoring including the determination of layer thicknesses (Fernandes et al. 2008), investigation of
837 the embankment stability (Sussmann et al. 2003; Donohue et al. 2011), localisation of trapped water
838 areas (Hyslip et al. 2003), indirect estimation of track modulus from GPR (Narayanan et al. 2004),
839 detection of permafrost sections (Saarenketo et al. 2003; Du et al. 2011; Nurmikolu 2012; Guo et al.
840 2015). A repetition of GPR measurements over time allows to predict the deterioration rate of a track
841 substructure (especially ballast) and to control the effectiveness of maintenance activities. This fact
842 can help with an effective scheduling of the required maintenance works on a short, medium and
843 long-term base with notable cost and time savings (Maturana et al. 2011). A schematic
844 representation of a GPR profile generation on a ballasted track substructure is given in Fig. 14
845 (Hyslip 2007).

846 GPR was utilised to assess the level of ballast deterioration and identify the interface between the
847 ballast and the subgrade (Gallagher et al. 1999). Jack and Jackson (1999) qualitatively diagnosed
848 the variations of conditions in a ballast layer to classify the GPR profile into sections (Jack and
849 Jackson 1999). According to Hugenschmidt (2000), use of GPR compared to other traditional
850 inspection methods in ballast condition assessment lead to a substantial reduction in the number of
851 trenches as well as it allowed to identify regions where subsoil material penetrated into the ballast.
852 GPR has been successfully used in many studies for assessment of ballast quality and thickness
853 determination. De Bold (2011) has demonstrated that GPR can be used in ballast characterisation,
854 finding a high correlation between the Ionescu fouling index in the area scanned by GPR. In order
855 to address a main limitation related to the loss of reflectors at the base of the ballast layer, use of

856 radar detectable geosynthetics was introduced during the construction of railways. This allowed to
857 identify more precisely depth of ballast measurements after the construction (Carpenter et al. 2004).



858

859 **Fig. 14 The generation of a GPR profile with an air-coupled antenna on a track bed. a) The**
860 **transmitted energy is reflected from the boundaries in the substructure, b) A single trace with**
861 **reflection amplitudes for the reflection interfaces in (a), c) A sequence of multiple scans, d) Adjacent**
862 **scans combined to build a B-scan (adapted from Hyslip (2007))**

863

864 Sussmann et al. (2003) presented an investigation of a railway subgrade using GPR, where condition
865 indicators were used to ease the data interpretation process. In a recent paper, a GPR investigation
866 for the EM characterisation of railway ballast aggregates was performed with the use of different
867 GPR antennas (ground-coupled and air-coupled) and various frequency systems (600 MHz, 1000
868 MHz, 1600 MHz and 2000 MHz) within a unique experimental (laboratory) setup and critical factors
869 as well as antennas and central frequencies most suited for the investigation of ballast were presented
870 (Tosti et al. 2017).

871 Saarenketo (2006) indicated the importance of optimising the central frequencies of the antennas
872 used in railway surveys according to the type of inspection. Also, the antenna configuration was
873 optimised in a multiple-frequency GPR system (composed of two 2 GHz and one 500 MHz antenna)
874 for railroad substructure assessment (Al-Qadi et al. 2010a).

875 The assessment of railway ballast fouling using GPR has gathered the attention of many researchers
876 and found relatively-satisfactory solutions to the issue (Clark et al. 2001; Roberts et al. 2006, 2007;
877 Al-Qadi et al. 2008a, b, 2010a; Suits et al. 2010; De Bold 2011; Maturana et al. 2011; Zhang et al.

878 2011; Anbazhagan et al. 2011, 2016; Anbazhagan 2013; De Chiara et al. 2014b; Kashani et al. 2015;
879 Faghihi Kashani 2017; Benedetto et al. 2017 Ia; Benedetto et al. 2017 II).

880 Clark et al. (2001) presented the outcomes of a research carried out in a laboratory environment on
881 the electrical properties of ballast. In more detail, a comparative investigation of relative dielectric
882 permittivity values of clean against fouled ballast and wet against dry ballast was carried out. The
883 propagation velocity of EM waves through ballast is of utmost importance in converting the time
884 scale of GPR data into a depth scale. To this effect, numerous studies (Göbel et al. 1994; Jack and
885 Jackson 1999; Hugenschmidt 2000; Clark et al. 2001; Maturana et al. 2011; Tosti et al. 2016) have
886 attempted to attain the EM wave velocity for “time to depth GPR data conversion” purposes.

887 In a recent study, Benedetto et al. (2017 Ia) assessed clean and fouled ballast using GPR by means
888 of extensive laboratory experiments, signal processing and numerical modelling.

889 A scattering amplitude envelope method based on the energy scattered from the voids between
890 ballast aggregates was developed and used to distinguish between clean and fouled ballast using air-
891 coupled GPR antennas. (Roberts et al. 2006; Al-Qadi et al. 2008a; Roberts et al. 2007; Al-Qadi et
892 al. 2008b). Estimation of moisture in the railway substructure using GPR data is a research subject
893 area of major interest across the GPR community (Maturana et al. 2011; Khakiev et al. 2014).

894 Within this context, Artagan (2018) confirmed the viability of the GPR method to diagnose the
895 conditions of railway ballast by means of extensive laboratory and field measurements (limestone
896 and two types of granite). Parameters of interest were the fouling level and type, and the moisture
897 content (Artagan 2018).

898 In terms of frequency-based investigations of ballast, Bianchini Ciampoli et al. (2017b) reported an
899 increasing interest from the scientific community. In regard to this, a time-frequency method was
900 developed by Al-Qadi et al. (2010b). The authors removed the interference and the noise inherent to
901 the railway environment to improve the quality of GPR data (Al-Qadi et al. 2010b). The Short-time
902 Fourier transform methodology has been used in order to monitor variations of features in ballast at
903 both the time and the frequency domain level (Al-Qadi et al. 2010b; Leng and Al-Qadi 2010; Al-
904 Qadi et al. 2010a; Shihab et al. 2002). In addition, an automatic classification system of GPR traces
905 for ballast fouling was developed based on magnitude spectrum analysis and support vector
906 machines (Shao et al. 2011).

907 Trend of using numerical simulation to generate synthetic GPR data and allow for a better
908 interpretation of real-life and experimental conditions for railway ballast assessment purposes is
909 gaining momentum nowadays. This is supported by a significant reduction in cost and time
910 (Benedetto et al. 2017 Ib, Bianchini Ciampoli et al. 2017b). To this effect, many studies can be
911 mentioned where the finite-difference time-domain (FDTD) technique was used to simulate the GPR
912 signal (Zhang et al. 2011; Brancadoro et al. 2017; Bianchini Ciampoli et al. 2017a).

913 A main challenge exists for the collection of GPR data on the ballast material underneath concrete
914 sleepers and rails, as reinforcement bars have significant masking effects on the GPR signal. A
915 solution to this is to minimise or remove these effects to attain clearer images of the ballast. Optimum
916 surveying procedures and antenna configurations were also considered in order to account for the
917 presence of ties and rails (Olhoeft and Selig 2002; Manacorda et al. 2002; Hyslip et al. 2003; Al-
918 Qadi et al. 2010a). Surveying between the cribs in early stages (regions between the sleepers)
919 provided the GPR profile by overcoming the effects of sleeper (Gallagher et al. 1999). Nevertheless,
920 the information under the sleepers could be more important than the information beneath the cribs
921 (Roberts et al. 2006; Eriksen et al. 2006).

922 In terms of signal processing methods, Hugenschmidt (2000) proposed a series of post-processing
923 steps namely, migration, horizontal scaling, stacking and background removal in order to minimise
924 the impact of sleepers. Donohue et al. (2011) applied a 40-trace running average to the collected
925 data in order to remove ringing effect of the sleepers (Donohue et al. 2011). Geraads et al. (2002)
926 used the uniform spacing between sleepers and designed a wavenumber notch filter. The resulting
927 image was filtered from the backscattering from the concrete sleepers and allowed for clearer
928 reflections (Geraads et al. 2002). Liao et al. (2008) used a parabolic random transform in order to
929 eliminate the effects of railway sleepers on the ballast. Bianchini Ciampoli et al. (2018b) developed
930 a dedicated data processing scheme and spectral-based processing method to mitigate the effects
931 caused by the sleepers on the GPR signal (Bianchini Ciampoli et al. 2018b). A time-space filter
932 screen with interference information was developed by Zhu et al. (2013) and used to suppress the
933 multiple waves and diffractions caused by the sleepers. This led to an improvement of the signal-to-
934 noise ratio of the GPR records (Zhu et al. 2013). More recently, a research by Bianchini Ciampoli
935 et al. (2018a) has found interesting results on the subject with respect to the use different antenna
936 frequencies and orientations of air –coupled antenna systems. Two main findings were reported, i.e.,
937 i) a transverse orientation of the antenna systems (i.e., antenna oriented along the axis parallel to the
938 sleeper direction) over the sleepers was found to allow collection of GPR data more similar to the
939 signals acquired on the ballast material only. This was verified regardless of the frequency of the
940 antenna; ii) it was observed that the presence of sleepers caused a higher attenuation of the EM
941 waves (Bianchini Ciampoli et al. 2018a).

942

943 **5 Conclusion and Final Remarks**

944 This paper reports past and state-of-the-art research on the use of non-destructive testing (NDT)
945 methods for assessment and health monitoring of railway infrastructures. An overview of the
946 diagnosis and maintenance issues as well as the track deformations is first given. In more detail,
947 main deformations occurring in a railway substructure and superstructure are here discussed. In

948 regard to the substructure, it was emphasised that fouling is one of the primary causes of failure and
949 an early detection may be crucial to reduce future cost of intervention as well as likelihood of
950 derailment. Deformations in the superstructure were sorted into geometry-related and surface-
951 related, both of which are important factors to provide lower maintenance cost. Discussion on
952 maintenance activities required for a railway track has identified a relatively complex list of actions
953 to carry out across different time spans. In this regard, a comprehensive number of inspection
954 methods as well as use of geometry cars and measured parameters have been reported across several
955 different international countries.

956 Use of NDT methods for assessment of track geometry and components was observed to have gained
957 momentum over the past two decades mostly. The assessment of the track geometry has been sorted
958 into the measurement of stiffness and the detection of deformations. Stiffness is mostly estimated
959 by vibration-based techniques, whereas deformations are assessed using optical-based methods,
960 such as laser scanning and remote sensing. On the other hand, inspection of track components can
961 rely on use of many different NDT methods, such as optical-based methods, inertial methods,
962 acoustic and ultrasonic techniques, image analysis and ground penetrating radar (GPR).

963 Within this context, GPR has emerged as the most flexible and reliable technique for assessment of
964 railway infrastructures. Research has shown that different GPR antenna frequencies can be used to
965 assess several different rail track parameters. In addition, it was emphasised how GPR can be
966 relatively easily integrated to a number of NDT methods. To this effect, future research could task
967 itself to merge multi-scale information from different NDT methods. This is crucial to cover
968 information gaps and improve target detectability.

969

970 **References**

971 Al-Qadi I, Xie W, Roberts R (2010a) Optimization of antenna configuration in multiple-frequency
972 ground penetrating radar system for railroad substructure assessment. *NDT E Int* 43:20–28.
973 doi: 10.1016/j.ndteint.2009.08.006

974 Al-Qadi IL, Xie W, Roberts R (2008a) Scattering analysis of ground-penetrating radar data to
975 quantify railroad ballast contamination. *NDT E Int* 41:441–447. doi:
976 10.1016/j.ndteint.2008.03.004

977 Al-Qadi IL, Xie W, Roberts R (2008b) Time-Frequency Approach for Ground Penetrating Radar
978 Data Analysis to Assess Railroad Ballast Condition. *Res Nondestruct Eval* 19:219–237. doi:
979 10.1080/09349840802015107

980 Al-Qadi IL, Xie W, Roberts R, Leng Z (2010b) Data analysis techniques for GPR used for assessing
981 railroad ballast in high radio-frequency environment. *J Transp Eng* 136:392–399

982 Anbazhagan P (2013) Characterization of Rail Track Ballast Fouling Using Ground Penetration
983 Radar and Field Sampling

- 984 Anbazhagan P, Dixit PSN, Bharatha TP (2016) Identification of type and degree of railway ballast
985 fouling using ground coupled GPR antennas. *J Appl Geophys* 126:183–190. doi:
986 10.1016/j.jappgeo.2016.01.018
- 987 Anbazhagan P, Lijun S, Buddhima I, Cholachat R (2011) Model track studies on fouled ballast using
988 ground penetrating radar and multichannel analysis of surface wave. *J Appl Geophys*
989 74:175–184. doi: 10.1016/j.jappgeo.2011.05.002
- 990 Annan AP, Davis JL (1997) Ground penetrating radar—coming of age at last. In: proceedings of
991 Exploration. pp 515–522
- 992 Arastounia M (2015) Automated Recognition of Railroad Infrastructure in Rural Areas from LIDAR
993 Data. *Remote Sens* 7:14916–14938. doi: 10.3390/rs71114916
- 994 Artagan SS (2018) Use of Ground Penetrating Radar in Condition Assessment of Railway Ballast.
995 Ph.D., University of Pardubice
- 996 Artagan SS, Borecky V (2015) Applicability of GPR on Turkish Railways. *Electron J Occup Improv*
997 Res 162–174
- 998 Auer F (2013) Multi-function track recording cars. *RTR* 34 32–36
- 999 Aursudkij B (2007) A Laboratory Study of Railway Ballast Behaviour under Traffic Loading and
1000 Tamping Maintenance. University of Nottingham
- 1001 Barrias A, Casas J, Villalba S (2016) A Review of Distributed Optical Fiber Sensors for Civil
1002 Engineering Applications. *Sensors* 16:748. doi: 10.3390/s16050748
- 1003 Beben D (2011) Application of the interferometric radar for dynamic tests of corrugated steel plate
1004 (CSP) culvert. *NDT E Int* 44:405–412. doi: 10.1016/j.ndteint.2011.04.001
- 1005 Benedetto A, Pajewski L (2015) *Civil Engineering Applications of Ground Penetrating Radar*.
1006 Springer
- 1007 Benedetto A, Tosti F, Bianchini Ciampoli L, et al (2017) Railway ballast condition assessment using
1008 ground-penetrating radar – An experimental, numerical simulation and modelling
1009 development. *Constr Build Mater* 140:508–520. doi: 10.1016/j.conbuildmat.2017.02.110
- 1010 Berggren E (2009) *Railway Track Stiffness Dynamic Measurements and Evaluation for Efficient*
1011 *Maintenance*
- 1012 Berkovic G, Shafir E (2012) Optical methods for distance and displacement measurements. *Adv Opt*
1013 *Photonics* 4:441. doi: 10.1364/AOP.4.000441
- 1014 Bianchini Ciampoli L, Artagan SS, Tosti F, et al (2018a) A comparative investigation of the effects
1015 of concrete sleepers on the GPR signal for the assessment of railway ballast. In: 17th
1016 International Conference on Ground Penetrating Radar (GPR 2018). Rapperswil,
1017 Switzerland, p 6
- 1018 Bianchini Ciampoli L, Artagan SS, Tosti F, et al (2018b) A comparative investigation of the effects
1019 of concrete sleepers on the GPR signal for the assessment of railway ballast. 6
- 1020 Bianchini Ciampoli L, Artagan SS, Tosti F, et al (2018c) A GPR Spectral-based Processing Method
1021 for Minimisation of Concrete Sleepers Effects in Railway Ballast Investigations. In: TSP

- 1022 2018 41st International Conference on Telecommunications and Signal Processing. Athens,
1023 p 4
- 1024 Bianchini Ciampoli L, Tosti F, Brancadoro MG, et al (2017a) A spectral analysis of ground-
1025 penetrating radar data for the assessment of the railway ballast geometric properties. *NDT*
1026 *E Int* 90:39–47. doi: 10.1016/j.ndteint.2017.05.005
- 1027 Bianchini Ciampoli L, Tosti F, Calvi A, et al (2017b) Efficient practices in railway ballast
1028 maintenance and quality assessment using GPR. In: *Aiit International Congress on*
1029 *Transport Infrastructure and Systems*. pp 419–424
- 1030 Bin Osman MH, Kaewunruen S, Jack A (2018) Optimisation of schedules for the inspection of
1031 railway tracks. *Proc Inst Mech Eng Part F J Rail Rapid Transit* 232:1577–1587. doi:
1032 10.1177/0954409717721634
- 1033 Bond LJ, Doctor SR, Griffin JW, et al (2011) Damage Assessment Technologies for Prognostics
1034 and Proactive Management of Materials Degradation. *Nucl Technol* 173:46–55. doi:
1035 10.13182/NT173-46
- 1036 Borecky V, Haburaj F, Artagan SS, Routil L (2019) Analysis of GPR and FWD Data Dependency
1037 Based on Road Test Field Surveys. *Mater Eval* 77:214–225
- 1038 Brancadoro MG, Ciampoli LB, Ferrante C, et al (2017) An Investigation into the railway ballast
1039 grading using GPR and image analysis. In: *Advanced Ground Penetrating Radar*
1040 *(IWAGPR), 2017 9th International Workshop on*. IEEE, pp 1–4
- 1041 Burrow MPN, Chan AHC, Shein A (2007) Deflectometer-based analysis of ballasted railway tracks.
1042 *Proc Inst Civ Eng - Geotech Eng* 160:169–177. doi: 10.1680/geng.2007.160.3.169
- 1043 Campanella CE, Cuccovillo A, Campanella C, et al (2018) Fibre Bragg Grating Based Strain
1044 Sensors: Review of Technology and Applications
- 1045 Carpenter D, Jackson PJ, Jay A (2004) Enhancement of the GPR method of railway trackbed
1046 investigation by the installation of radar detectable geosynthetics. *NDT E Int* 37:95–103.
1047 doi: 10.1016/j.ndteint.2003.06.003
- 1048 Chandra S, Agarwal MM (2008) *Railway Engineering*. Oxford University Press, Inc., New York,
1049 NY, USA
- 1050 Chang L, Dollevoet RPB, Hanssen RF (2017) Nationwide Railway Monitoring Using Satellite SAR
1051 Interferometry. *IEEE J Sel Top Appl Earth Obs Remote Sens* 10:596–604. doi:
1052 10.1109/JSTARS.2016.2584783
- 1053 Clark M, Gordon M, Forde MC (2004) Issues over high-speed non-invasive monitoring of railway
1054 trackbed. *NDT E Int* 37:131–139. doi: 10.1016/j.ndteint.2003.05.002
- 1055 Clark MR, Gillespie R, Kemp T, et al (2001) Electromagnetic properties of railway ballast. *NDT E*
1056 *Int* 34:305–311
- 1057 da Costa Marques Pimentel RM, Barbosa MCB, Costa NMS, et al (2008) Hybrid Fiber-
1058 Optic/Electrical Measurement System for Characterization of Railway Traffic and Its
1059 Effects on a Short Span Bridge. *IEEE Sens J* 8:1243–1249. doi: 10.1109/JSEN.2008.926519

- 1060 D.-B. Zhu, J.-N. Geng, M. Huang (2013) Algorithm for suppressing sleeper interferences in railway
1061 subgrade GPR signals. *J China Railw Soc* 5:75–79. doi: 10.3969/j.issn.1001-
1062 8360.2013.05.012
- 1063 De Bold RP (2011) Non-destructive evaluation of railway trackbed ballast
- 1064 De Chiara F, Fontul S, Fortunato E (2014a) GPR Laboratory Tests For Railways Materials Dielectric
1065 Properties Assessment. *Remote Sens* 6:9712–9728. doi: 10.3390/rs6109712
- 1066 De Chiara F, Fontul S, Fortunato E (2014b) GPR Laboratory Tests For Railways Materials Dielectric
1067 Properties Assessment. *Remote Sens* 6:9712–9728. doi: 10.3390/rs6109712
- 1068 Donohue S, Gavin K, Tolooiyan A (2011) Geophysical and geotechnical assessment of a railway
1069 embankment failure. *Surf Geophys* 9:. doi: 10.3997/1873-0604.2010040
- 1070 Du LZ, Zhang XP, Qiu JH, Liu WB (2011) Study on Ground Penetrating Radar in Detecting of
1071 Zero-Temperature Boundary under the Railway Bed. *Adv Mater Res* 255–260:3975–3978.
1072 doi: 10.4028/www.scientific.net/AMR.255-260.3975
- 1073 EN 13848-5 (2008) EN 13848-5:2008+A1:2010: Railway applications - Track - Track geometry
1074 quality - Part 5: Geometric quality levels - Plain line. 26
- 1075 Eriksen A, Venables B, Gascoyne J, Bandyopadhyay S (2006) Benefits of high speed GPR to
1076 manage trackbed assets and renewal strategies. In: *PWI Conference*, June
- 1077 ESA Radar Course 3 - Synthetic Aperture Radar - ERS Radar Course 3 - ESA Operational EO
1078 Missions - Earth Online - ESA. [https://earth.esa.int/web/guest/missions/esa-operational-eo-](https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers/instruments/sar/applications/radar-courses/content-3/-/asset_publisher/mQ9R7ZVkJg5P/content/radar-course-3-synthetic-aperture-radar)
1079 [missions/ers/instruments/sar/applications/radar-courses/content-3/-](https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers/instruments/sar/applications/radar-courses/content-3/-/asset_publisher/mQ9R7ZVkJg5P/content/radar-course-3-synthetic-aperture-radar)
1080 [/asset_publisher/mQ9R7ZVkJg5P/content/radar-course-3-synthetic-aperture-radar.](https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers/instruments/sar/applications/radar-courses/content-3/-/asset_publisher/mQ9R7ZVkJg5P/content/radar-course-3-synthetic-aperture-radar)
1081 Accessed 16 Nov 2018
- 1082 Esveld C (2001) *Modern Railway Track*, Second
- 1083 Faghihi Kashani H (2017) Evaluating the Influence of Breakdown Fouling and Moisture Content on
1084 Mechanical and Electromagnetic Properties of Ballasted Railroad Track
- 1085 Farritor S, Arnold R, Norman C (2008) Method and Apparatus for Noncontact Relative Rail
1086 Displacement, Track Modulus and Stiffness Measurement by a Moving Rail Vehicle. 17
- 1087 Fernandes F, Pereira M, Gomes Correia A, et al (2008) Assessment of layer thickness and uniformity
1088 in railway embankments with ground penetrating radar. In: Ellis E, Thom N, Yu H-S, et al.
1089 (eds) *Advances in Transportation Geotechnics*. CRC Press, pp 571–575
- 1090 Filograno ML, Corredera Guillen P, Rodriguez-Barrios A, et al (2012) Real-Time Monitoring of
1091 Railway Traffic Using Fiber Bragg Grating Sensors. *IEEE Sens J* 12:85–92. doi:
1092 10.1109/JSEN.2011.2135848
- 1093 Fontul S, Mínguez R, Solla M, Santos-Assunção S (2016) The Use of Geophysics for the Condition
1094 Assessment of Railway Infrastructure. In: *Non-Destructive Techniques for the Evaluation*
1095 *of Structures and Infrastructure*. CRC Press
- 1096 Fontul S, Paixão A, Solla M, Pajewski L (2018) Railway Track Condition Assessment at Network
1097 Level by Frequency Domain Analysis of GPR Data. *Remote Sens* 10:559. doi:
1098 10.3390/rs10040559

- 1099 Fortunato E, Fontul S, Paixão A, et al (2016) Geotechnical Aspects of the Rehabilitation of a Freight
1100 Railway Line in Africa. Cagliari, Sardinia, Italy, p 227
- 1101 Fumeo E, Oneto L, Anguita D (2015) Condition Based Maintenance in Railway Transportation
1102 Systems Based on Big Data Streaming Analysis. *Procedia Comput Sci* 53:437–446. doi:
1103 10.1016/j.procs.2015.07.321
- 1104 Gallagher GP, Leiper Q, Williamson R, et al (1999) The application of time domain ground
1105 penetrating radar to evaluate railway track ballast. *NDT E Int* 32:463–468
- 1106 Gary R. Olhoeft, Ernest T. Selig (2002) Ground-penetrating radar evaluation of railway track
1107 substructure conditions. pp 4758–6
- 1108 Göbel C, Hellmann R, Petzold H (1994) Georadar-model and in-situ investigations for inspection of
1109 railway tracks
- 1110 Güler H (2017) Optimisation of railway track maintenance and renewal works by genetic algorithms.
1111 *J Croat Assoc Civ Eng* 68:979–993. doi: 10.14256/JCE.1458.2015
- 1112 Guo Z, Dong H, Xiao J (2015) Detection of Permafrost Subgrade Using GPR: A Case Examination
1113 on Qinghai-Tibet Plateau. *J Geosci Environ Prot* 03:35–47. doi: 10.4236/gep.2015.35005
- 1114 He R, Ai B, Wang G, et al (2016) High-Speed Railway Communications. *IEEE Veh Technol Mag*
1115 11:49–58. doi: 10.1109/MVT.2016.2564446
- 1116 Huang Q, Crosetto M, Monserrat O, Crippa B (2017) Displacement monitoring and modelling of a
1117 high-speed railway bridge using C-band Sentinel-1 data. *ISPRS J Photogramm Remote Sens*
1118 128:204–211. doi: 10.1016/j.isprsjprs.2017.03.016
- 1119 Hugenschmidt J (2000) Railway track inspection using GPR. *J Appl Geophys* 43:147–155
- 1120 Hunt GA (2005) Review of the Effects of Track Stiffness on Track Performance. *RSSB Research P*:
- 1121 Hyslip JP (2007) *Substructure_Maintenance_Management_2007.pdf*
- 1122 Hyslip JP, Smith SS, Olhoeft GR, Selig ET (2003) Assessment of railway track substructure
1123 condition using ground penetrating radar. In: 2003 Annual Conference of AREMA
- 1124 Jack R, Jackson P (1999) Imaging attributes of railway track formation and ballast using ground
1125 probing radar. *NDT E Int* 32:457–462
- 1126 Jol HM (ed) (2009) *Ground penetrating radar: theory and applications*, 1. ed. Elsevier Science,
1127 Amsterdam
- 1128 Kashani HF, Ho CL, Oden CP, Smith SS (2015) Model Track Studies by Ground Penetrating Radar
1129 (GPR) on Ballast With Different Fouling and Geotechnical Properties. *ASME*, p
1130 V001T01A006
- 1131 Kerr AD (2000) On the determination of the rail support modulus k. *Int J Solids Struct* 37:4335–
1132 4351. doi: 10.1016/S0020-7683(99)00151-1
- 1133 Kerrouche A, Leighton J, Boyle WJO, et al (2008) Strain Measurement on a Rail Bridge Loaded to
1134 Failure Using a Fiber Bragg Grating-Based Distributed Sensor System. *IEEE Sens J* 8:2059–
1135 2065. doi: 10.1109/JSEN.2008.2006704

- 1136 Khakiev Z, Shapovalov V, Kruglikov A, Yavna V (2014) GPR determination of physical parameters
1137 of railway structural layers. *J Appl Geophys* 106:139–145. doi:
1138 10.1016/j.jappgeo.2014.04.017
- 1139 Khouy IA (2013) Cost-effective maintenance of railway track geometry a shift from safety limits to
1140 maintenance limits. Luleå University of Technology, Luleå
- 1141 Kim H, Roberts C, Saade L, Weston P (2014) Measuring the deflection of a sequence of sleepers at
1142 a transition zone. In: 6th IET Conference on Railway Condition Monitoring (RCM 2014).
1143 Institution of Engineering and Technology, Birmingham, UK, pp 6.2.2-6.2.2
- 1144 Kojima T, Tsunashima H, Matsumoto A (2010) Fault detection of railway track by multi-resolution
1145 analysis. In: *WIT Transactions on State of the Art in Science and Engineering*, 1st edn. WIT
1146 Press, pp 99–108
- 1147 Labropoulos KC, Moundoulas P, Moropoulou A (2010) Methodology for the monitoring, control
1148 and warning of defects for preventive maintenance of rails. In: *WIT Transactions on State
1149 of the Art in Science and Engineering*, 1st edn. WIT Press, pp 89–98
- 1150 Leng Z, Al-Qadi I (2010) Railroad Ballast Evaluation Using Ground-Penetrating Radar: Laboratory
1151 Investigation and Field Validation. *Transp Res Rec J Transp Res Board* 2159:110–117. doi:
1152 10.3141/2159-14
- 1153 LIAO Lijian, YANG Xinan, DU Panfeng (2008) Processing GPR Detection Data of Railway
1154 Subgrade. *China Railw Sci* 03:
- 1155 Lichtberger B (2007) *The Track System and Its Maintenance*. RTR Spec
- 1156 Lidén T (2015) Railway Infrastructure Maintenance - A Survey of Planning Problems and
1157 Conducted Research. *Transp Res Procedia* 10:574–583. doi: 10.1016/j.trpro.2015.09.011
- 1158 Lyngby N, Hokstad P, Vatn J (2008) RAMS Management of Railway Tracks. In: Misra KB (ed)
1159 *Handbook of Performability Engineering*. Springer London, London, pp 1123–1145
- 1160 Malar R, Jayalakshmy S (2015) Detection of Cracks and Missing Fasteners in Railway lines Using
1161 Structure Topic Model. 2:7
- 1162 Manacorda G, Morandi D, Sarri A, Staccone G (2002) Customized GPR system for railroad track
1163 verification. In: *Ninth International Conference on Ground Penetrating Radar (GPR2002)*.
1164 International Society for Optics and Photonics, pp 719–723
- 1165 Maturana RM, Bautista BD, Aguacil AA, et al (2011) Preventive Maintenance of Railway
1166 Infrastructures using GPR–Ground Penetrating Radar
- 1167 Mazzeo PL, Stella E, Nitti M, Distanto A (2006) Potential dangerous object detection on railway
1168 ballast using digital image processing. In: *Computers in Railways X*. WIT Press, Prague,
1169 Czech Republic, pp 157–166
- 1170 Miura S, Takai H, Uchida M, Fukada Y (1998) *The Mechanism of Railway Tracks*. 8
- 1171 Miyayama H, Ohya T, Katori T, Izumi T (2010) Obstacle recognition from forward view images
1172 from trams. In: *WIT Transactions on State of the Art in Science and Engineering*, 1st edn.
1173 WIT Press, pp 137–147

- 1174 Morant A, Larsson-Kråik PO, Kumar U (2016) Data-driven model for maintenance decision
1175 support: A case study of railway signalling systems. *Proc Inst Mech Eng Part F J Rail Rapid*
1176 *Transit* 230:220–234. doi: 10.1177/0954409714533680
- 1177 Moretti M, Triglia M, Maffei G (2004) ARCHIMEDE - the first european diagnostic train for global
1178 monitoring of railway infrastructure. In: *IEEE Intelligent Vehicles Symposium, 2004*. IEEE,
1179 Parma, Italy, pp 522–526
- 1180 Nålsund R (2014) *Railway Ballast Characteristics, Selection Criteria and Performance*. Norwegian
1181 University of Science and Technology
- 1182 Narayanan RM, Jakub JW, Li D, Elias SEG (2004) Railroad track modulus estimation using ground
1183 penetrating radar measurements. *NDT E Int* 37:141–151. doi:
1184 10.1016/j.ndteint.2003.05.003
- 1185 Neal A (2004) Ground-penetrating radar and its use in sedimentology: principles, problems and
1186 progress. *Earth-Sci Rev* 66:261–330. doi: 10.1016/j.earscirev.2004.01.004
- 1187 Nurmikolu A (2012) Key aspects on the behaviour of the ballast and substructure of a modern
1188 railway track: research-based practical observations in Finland. *J Zhejiang Univ Sci A*
1189 13:825–835. doi: 10.1631/jzus.A12ISGT1
- 1190 Papaelias MP, Roberts C, Davis CL (2008) A review on non-destructive evaluation of rails: State-
1191 of-the-art and future development. *Proc Inst Mech Eng Part F J Rail Rapid Transit* 222:367–
1192 384. doi: 10.1243/09544097JRRT209
- 1193 Peng F (2011) *Scheduling of Track Inspection and Maintenance Activities in Railroad Networks*.
1194 180
- 1195 Peralta D, Bergmeir C, Krone M, et al (2018) Multiobjective Optimization for Railway Maintenance
1196 Plans. *J Comput Civ Eng* 32:04018014. doi: 10.1061/(ASCE)CP.1943-5487.0000757
- 1197 Pfeifer N, Briese C (2007) *Laser scanning – principles and applications*. Novosibirsk, Russia
- 1198 Picoux B, Takarli M, Petit C (2011) Non-destructive testing of an experimental pavement. In:
1199 *Proceedings of the 13th International Conference on Civil, Structural and Environmental*
1200 *Engineering Computing*
- 1201 Pieraccini M (2013) Monitoring of Civil Infrastructures by Interferometric Radar: A Review. *Sci*
1202 *World J* 2013:1–8. doi: 10.1155/2013/786961
- 1203 Pieraccini M, Fratini M, Parrini F, et al (2004) High-speed CW step-frequency coherent radar for
1204 dynamic monitoring of civil engineering structures. *Electron Lett* 40:907. doi:
1205 10.1049/el:20040549
- 1206 Pinto N, Ribeiro CA, Gabriel J, Calçada R (2015) Dynamic monitoring of railway track
1207 displacement using an optical system. *Proc Inst Mech Eng Part F J Rail Rapid Transit*
1208 229:280–290. doi: 10.1177/0954409713509980
- 1209 Ponnuswamy S (2012) *Railway Transportation: Engineering, Operation and Management*. Alpha
1210 Science International
- 1211 Prasad A (2016) *Various Cost Effective Maintenance Practices for Conventional Track Structure*

- 1212 Priest JA, Powrie W (2009) Determination of Dynamic Track Modulus from Measurement of Track
1213 Velocity during Train Passage. *J Geotech Geoenvironmental Eng* 135:1732–1740. doi:
1214 10.1061/(ASCE)GT.1943-5606.0000130
- 1215 Profillidis VA (2006) *Railway Management and Engineering*. Ashgate
- 1216 Pyrgidis C (2016) *Railway Transportation Systems: Design, Construction and Operation*. CRC Prss,
1217 Boca Raton, FL.
- 1218 Quiroga L, Schnieder E (2013) *Railway Systems*. In: Czichos H (ed) *Handbook of Technical*
1219 *Diagnostics*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 519–537
- 1220 Real J, Salvador P, Montalbán L, Bueno M (2011) Determination of Rail Vertical Profile through
1221 Inertial Methods. *Proc Inst Mech Eng Part F J Rail Rapid Transit* 225:14–23. doi:
1222 10.1243/09544097JRRT353
- 1223 RFI (2018) *Diagnostics Services Catalogue 2018*
- 1224 Roberts R, Al-Qadi I, Tutumluer E Track Substructure Characterization Using 500 MHz and 2 GHz
1225 Ground Penetrating Radar: Results from over 250 Miles of Track in Wyoming and Alaska.
1226 *Urbana* 51:61801
- 1227 Roberts R, Al-Qadi IL, Tutumluer E, Kathage A (2007) Ballast fouling assessment using 2 GHz
1228 horn antennas-GPR and ground truth comparison from 238 km of track. In: *9th International*
1229 *Railway Engineering Conference*
- 1230 Roberts R, Rudy J, GSSI S (2006) Railroad ballast fouling detection using ground penetrating radar.
1231 A new approach based on scattering from voids. *ECNDT 2006–Th 45 1*:
- 1232 Rosen PA, Hensley S, Joughin IR, et al (2000) Synthetic aperture radar interferometry. *Proc IEEE*
1233 88:333–382. doi: 10.1109/5.838084
- 1234 Saarenketo T (2006) *Electrical properties of road materials and subgrade soils and the use of Ground*
1235 *Penetrating Radar in traffic infrastructure surveys*. University of Oulu
- 1236 Saarenketo T, Silvast M, Noukka J (2003) USING GPR ON RAILWAYS TO IDENTIFY FROST
1237 SUSCEPTIBLE AREAS. *Proc Int Conf Exhib Railw Eng 2003 HELD Lond UK 30 APRIL*
1238 *- 1 MAY 2003 - CDROM*
- 1239 Salvador P, Naranjo V, Insa R, Teixeira P (2016) Axlebox accelerations: Their acquisition and time–
1240 frequency characterisation for railway track monitoring purposes. *Measurement* 82:301–
1241 312. doi: 10.1016/j.measurement.2016.01.012
- 1242 Selig ET, Waters JM (1994) *Track Geotechnology and Substructure Management*. Thomas Telford
- 1243 Shao W, Bouzerdoum A, Phung SL, et al (2011) Automatic Classification of Ground-Penetrating-
1244 Radar Signals for Railway-Ballast Assessment. *IEEE Trans Geosci Remote Sens* 49:3961–
1245 3972. doi: 10.1109/TGRS.2011.2128328
- 1246 Sharma S, Cui Y, He Q, et al (2018) Data-driven optimization of railway maintenance for track
1247 geometry. *Transp Res Part C Emerg Technol* 90:34–58. doi: 10.1016/j.trc.2018.02.019
- 1248 Shihab S, Zahran O, Al-Nuaimy W (2002) Time-frequency characteristics of ground penetrating
1249 radar reflections from railway ballast and plant. *IEEE*, p 8

- 1250 Soleimanmeigouni I, Ahmadi A, Letot C, et al (2016) Cost-Based Optimization of Track Geometry
1251 Inspection. 7
- 1252 Solomon B (2001) Railway Maintenance: The Men and Machines That Keep the Railroads Running.
1253 MBI Publishing Company
- 1254 Soni A, Robson S, Gleeson B (2014) Extracting Rail Track Geometry from Static Terrestrial Laser
1255 Scans for Monitoring Purposes. ISPRS - Int Arch Photogramm Remote Sens Spat Inf Sci
1256 XL-5:553–557. doi: 10.5194/isprsarchives-XL-5-553-2014
- 1257 Sophie Geraads, Bruno Charachon, Olivier Loeffler, Gildas Omnes (2002) Applying a wavenumber
1258 notch filter to remove interferences caused by railway sleepers from a GPR section. In:
1259 Proceedings of SPIE - The International Society for Optical Engineering. pp 715–718
- 1260 Suits LD, Sheahan TC, Su L-J, et al (2010) An Evaluation of Fouled Ballast in a Laboratory Model
1261 Track Using Ground Penetrating Radar. Geotech Test J 33:103045. doi:
1262 10.1520/GTJ103045
- 1263 Sussmann TR, Selig ET, Hyslip JP (2003) Railway track condition indicators from ground
1264 penetrating radar. NDT E Int 36:157–167
- 1265 Sussmann TR, Thompson II HB (2017) Track structural design for maintenance and rehabilitation
1266 with automated track inspection data. Sout Africa, Cape Town
- 1267 Tosti, F., Benedetto, A., Calvi, A., and Bianchini Ciampoli, L. (2016). Laboratory Investigations for
1268 the Electromagnetic Characterization of Railway Ballast through GPR. In: Proc. of the 16th
1269 International Conference on Ground Penetrating Radar, Hong Kong, June 13–16, 2016.
1270 DOI: 10.1109/ICGPR.2016.7572605
- 1271 Tosti F, Bianchini Ciampoli L, Calvi A, et al (2017) An investigation into the railway ballast
1272 dielectric properties using different GPR antennas and frequency systems. NDT E Int. doi:
1273 10.1016/j.ndteint.2017.10.003
- 1274 Trampus P (2014) NDT Challenges and Responses – an Overview. E-J Nondestruct Test 19:11
- 1275 Tsunashima H, Naganuma Y, Matsumoto A, et al (2012) Condition Monitoring of Railway Track
1276 Using In-Service Vehicle. Reliab Saf Railw 27
- 1277 Turner C, Thoppur Ravi P, Tiwari A, et al (2017) A software architecture for autonomous
1278 maintenance scheduling: Scenarios for uk and european rail. Int J Transp Dev Integr 1:371–
1279 381. doi: 10.2495/TDI-V1-N3-371-381
- 1280 Tutumluer E, Moaveni M, Hart JM, et al (2016) Field_Imaging_Based_Assessment_of_In-
1281 Service_Ballast_Condition.pdf. Orlando, Florida
- 1282 Tzanakakis K (2013) The railway track and its long term behaviour: a handbook for a railway track
1283 of high quality. Springer, Heidelberg ; New York
- 1284 UIC (2002) UIC leaflet 712, Rail defects
- 1285 UIC (2010) Final Report - INNOTRACK (Innovative Track Systems)
- 1286 Varandas JN, Hölscher P, Silva MAG (2011) Dynamic behaviour of railway tracks on transitions
1287 zones. Comput Struct 89:1468–1479. doi: 10.1016/j.compstruc.2011.02.013

- 1288 Villarejo R, Galar D, Johansson C-A, et al (2014) Context Awareness And Railway Maintenance.
 1289 In: Proceedings of the 3rd international workshop and congress on eMaintenance. Luleå,
 1290 Sweden, pp 17–24
- 1291 Wang P, Wang L, Chen R, et al (2016) Overview and outlook on railway track stiffness
 1292 measurement. *J Mod Transp* 24:89–102. doi: 10.1007/s40534-016-0104-8
- 1293 Wei C, Xin Q, Chung WH, et al (2011) Real-Time Train Wheel Condition Monitoring by Fiber
 1294 Bragg Grating Sensors. *Int J Distrib Sens Netw* 8:409048. doi: 10.1155/2012/409048
- 1295 Woodward PK, Kennedy J, Laghrouche O, et al (2014) Study of railway track stiffness modification
 1296 by polyurethane reinforcement of the ballast. *Transp Geotech* 1:214–224. doi:
 1297 10.1016/j.trgeo.2014.06.005
- 1298 Xiong Z, Li Q, Mao Q, Zou Q (2017) A 3D Laser Profiling System for Rail Surface Defect
 1299 Detection. *Sensors* 17:1791. doi: 10.3390/s17081791
- 1300 Yan L, Zhang Z, Wang P, et al (2011) Fiber Sensors for Strain Measurements and Axle Counting in
 1301 High-Speed Railway Applications. *IEEE Sens J* 11:1587–1594. doi:
 1302 10.1109/JSEN.2010.2086058
- 1303 Yang LA, Powrie W, Priest JA (2009) Dynamic Stress Analysis of a Ballasted Railway Track Bed
 1304 during Train Passage. *J Geotech Geoenvironmental Eng* 135:680–689. doi:
 1305 10.1061/(ASCE)GT.1943-5606.0000032
- 1306 Ye XW, Su YH, Han JP (2014) Structural Health Monitoring of Civil Infrastructure Using Optical
 1307 Fiber Sensing Technology: A Comprehensive Review. *Sci World J* 2014:1–11. doi:
 1308 10.1155/2014/652329
- 1309 Zakeri J-A, Rezvani FH (2012) concrete sleepers construction; sleeper defects; sleeper failure. *Int J*
 1310 *Constr Eng Manag* 5
- 1311 Zhang Q, Gascoyne J, Eriksen A (2011) Characterisation of ballast materials in trackbed using
 1312 ground penetrating radar: Part 1. In: *Railway Condition Monitoring and Non-Destructive*
 1313 *Testing (RCM 2011)*, 5th IET Conference on. IET, pp 1–8
- 1314