Non-destructive Assessment and Health Monitoring of Railway Infrastructures

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Abstract:

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

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

1 Introduction

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

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

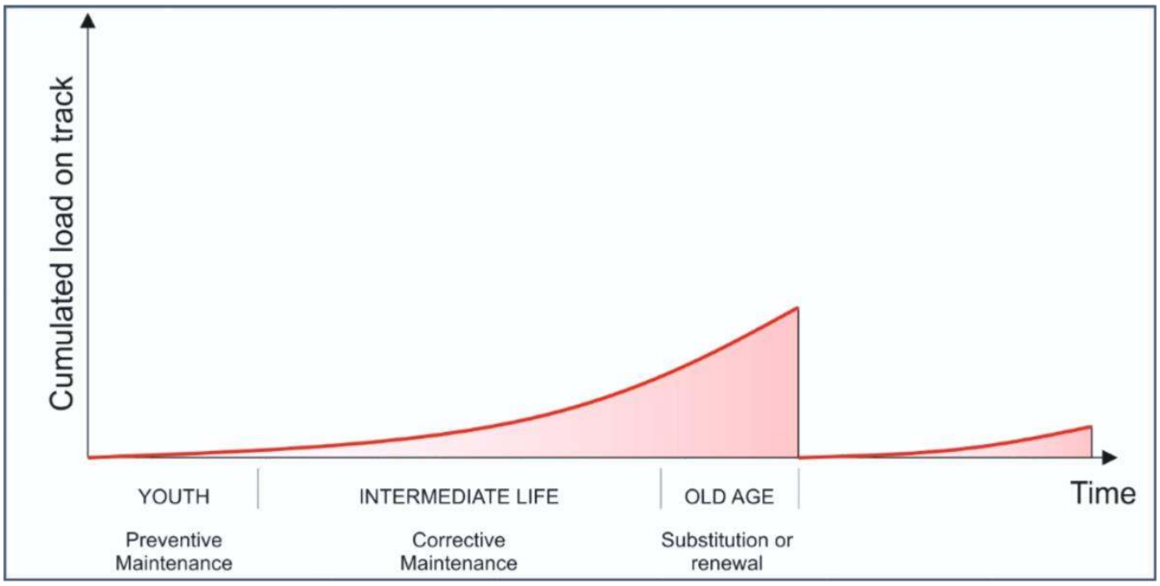

Fig. 1 Deterioration process of a railway track: life periods and corresponding maintenance actions versus cumulated loads exterted on the track (adapted from (Tzanakakis 2013))

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

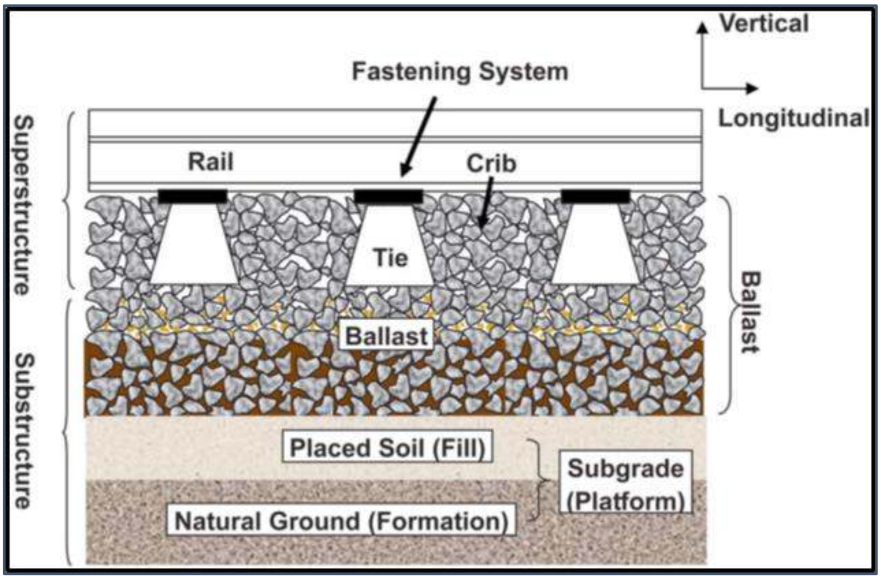

Fig. 2 Track structure (Selig and Waters 1994; Al-Qadi et al. 2010b)

1.1 Diagnosis & Maintenance Issues

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

Various approaches exist for the track inspection scheduling problem which can be formulated as a function of the track, available equipment, labor and time (Bin Osman et al. 2018). In a recent study, a multi-objective optimisation approach (i.e., maintenance cost and train delays set as objective functions) is proposed to handle the track maintenance scheduling problem together with a developed track degradation model. This model considers also the deformations caused by the maintenance operations (Peralta et al. 2018). A railway track inspection process includes a considerable volume of short-duration diagnosis tasks (e.g., visual inspections, vehicle-based inspections, and measurements by varying methods etc.) each of which occurs at disparate frequencies and time intervals (Bin Osman et al. 2018). A number of studies about railway track inspection scheduling were reviewed under an optimisation point of view for inspection scheduling and a gap analysis was undertaken (Bin Osman et al. 2018). These include an elaborated discussion of various ways in consideration of objective functions and constraints. Identification of the optimised cost-effective inspection interval as one of the several alternatives to minimise the overall track maintenance cost is crucial as the inspection of a track has a larger impact on the total maintenance cost. To that effect, in a lately published paper, track degradation, shock events, and recovery models were developed to propose an integrated long-term model for estimation of the track geometry conditions. Aim of the research was to properly identify optimal cost-based inspection intervals (Soleimanmeigouni et al. 2016). Attaining the trend for the forthcoming development of the track geometry conditions (diagnosis forecasting) plays a key role in the effective and proper planning of maintenance interventions (Quiroga and Schnieder 2013). Lidén (2015) provided an extensive analysis of the railway infrastructure maintenance area with a specific focus on the planning issues. The author presented an archive of planning issues in Sweden and a thorough literature review on the use of mathematical methods and optimisation approaches for solution-related purposes. Attempts were taken to provide an autonomous platform for maintenance planning by developing a model based on the exchange of information between prototype components and related systems (Turner et al. 2017).

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

Enormous budget is required for maintenance of railway infrastructures with miscellaneous challenging organisational and planning problems (particularly, coordination with train trafficking). However, the most of the research focus has been directed to investigate train traffic operations as opposed to the infrastructure maintenance operations (Lidén 2015). It is also noteworthy that the conditions of the track has an influence on the running dynamics of rail vehicles and the mutual interaction between the track and the rolling stock. To this effect, insecure occurrences depend both on the track and the vehicles along with their wear conditions (RFI 2018). Besides direct track maintenance costs, secondary costs such as those related to rolling stock maintenance, train and shipment delays, and train accidents are also closely connected to track maintenance activities and should be borne in mind (Peng 2011). Cost factors of track construction and maintenance, and also mathematical formulations of maintenance cost modeling including i) materials, equipment, labor, ii) condition monitoring and inspection and, iii) track possession time are discussed in a recently published research by Tzanakakis (2013). Coverage of various cost-efficient maintenance strategies for conventional track structure with an emphasis on effective planning and critical factors for track maintenance cost were recently presented by Prasad (2016).

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

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

2 Degradation Modes of Railways

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

2.1 Railway Substructure Deformations

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

Maintenance actions require a partial replacement of the track elements with the substructure being often maintained at its original layout. This occurrence does not allow to identify the actual reasons for the overall structural deformations, which are often related to issues in the substructure, such as fouled ballast, poor drainage, ballast pockets and subgrade settlements (De Chiara et al. 2014; Riveiro and Solla 2016). In other words, many superstructure faults may originally generate from decay at the substructure level. A general trend observed in railway asset management when limited funds are available, is to reduce the budget allocated for maintenance tasks such as ballast cleaning and renewal. This approach seems reasonable in a first instance in the shorter term (Solomon 2001). However, the approach could be regarded as a gamble jeopardising the long-term cost-effectiveness of the overall track assets. Overlooking a timely maintenance of a track-bed infrastructure could in fact cause more severe consequences and increase costs (Solomon 2001). A poor track substructure can increase decay of the track geometry leading to higher levels of wear or even failures of rails, sleepers, and fasteners. These occurrences may eventually lead to dramatic consequences such as derailments (Li et al. 2010).

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

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

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

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

2.2 Railway Superstructure Deformations

Rails are exposed to extensive wear and fatigue particularly when traffic load is close to the infrastructure capacity. Main rail faults are abrasive wear, plastic flow, corrugation, fatigue cracking and creep (Tzanakakis 2013). More details on the recognition, notification, and classification of rail defects can be found in UIC (2002).

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

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

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

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

3 Maintenance Activities and Inspection Methods

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

3.1 Common Track Maintenance Activities

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

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

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

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

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

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

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

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

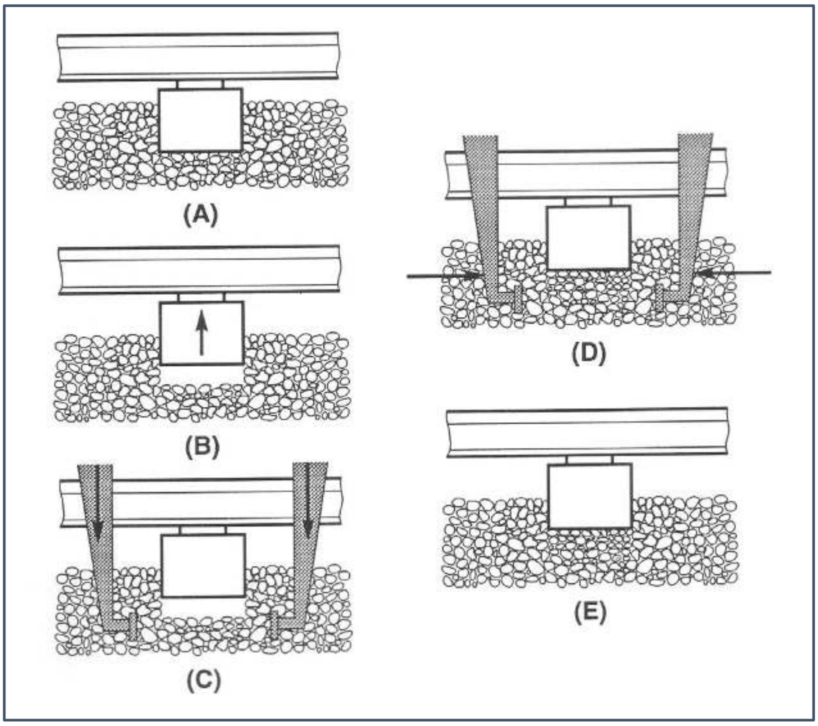

Fig. 3 Tamping progression (Adapted from (Selig and Waters 1994)).

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

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

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

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

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

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

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

3.2 Common Inspection Methods for Track Substructures

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

In regard to the rehabilitation of an existing railway track, a set of assessment destructive and NDT techniques can be mentioned. NDT methods include geophysics/remote sensing, reflection and refraction seismic surveys, magnetic surveys, gravity surveys, resistivity surveys, continuous surface wave tests, electromagnetic (EM) surveys, ground penetrating radar (GPR) surveys, infrared, radiometric and light detection and ranging (LiDAR) surveys. Destructive testing methods include various types of penetrometer tests (including DCP/DPSH/SPT/CPT & CPTU) and test holes/auger holes/geotechnical drilling/percussion drilling (Van Vreden et al. 2012).

3.3 Common Inspection Methods for Track Superstructures

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

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

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	

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

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

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

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

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

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

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)

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

4 Non-destructive Inspection of Track Geometry and Track Components

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

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

4.1 Non-destructive Assessment of Track Geometry

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

4.1.1 Stiffness measurements

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

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

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

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

$$k_d = \frac{|P|}{|Z|} \tag{1}$$

with $P = P_0e^{jwt}$ being the vertical harmonic force applied by a passing train on the rails, and $Z = Z_0e^{j(wt+f)}$ being the displacement at the point of application of the force.

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

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

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

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

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

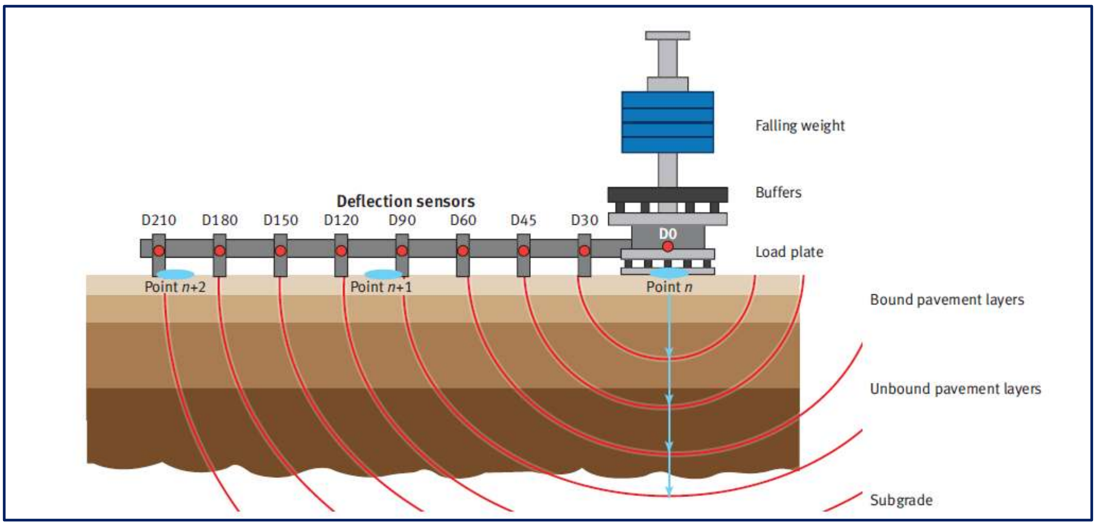

Fig. 5 Schematic presentation of the operation principles of a falling weight deflectometer (FWD) (Borecky et al. 2019)

4.1.2 Deformation detection

Optical-based methods:

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

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

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

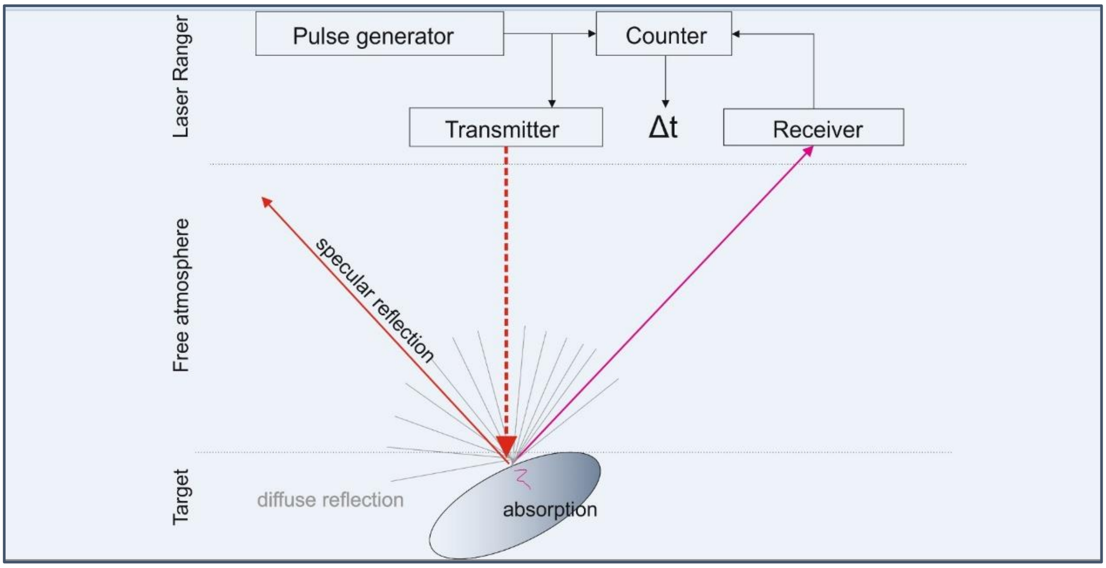

Fig. 6 Working principles of a pulse laser ranger (adapted from (Pfeifer and Briese 2007))

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

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

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

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

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

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

Remote Sensing:

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

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

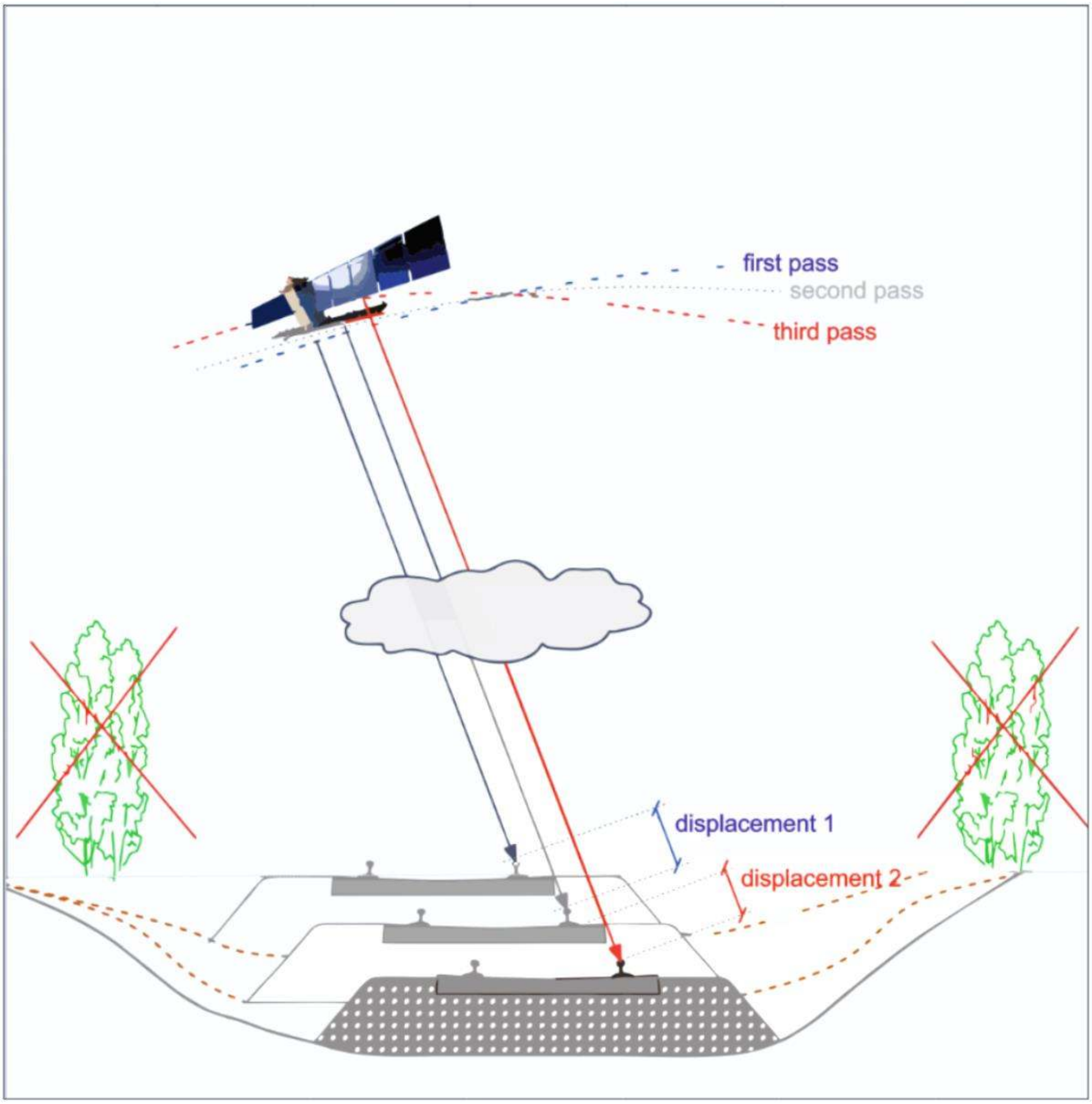

Fig. 8 Principles of Interferometric Synthetic Aperture Radar (In-SAR) where satellite-emitted EM signals are employed to measure phase differences from displacement along the surface.

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

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

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

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

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

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

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

A comprehensive review of NDT methodologies in practice around Europe and North America for rail defect detection is given by Papaelias et al. (2008), together with an overview of the background theory and the techniques used to integrate condition data into maintenance actions. The paper gives an elaborated list of non-destructive techniques and corresponding systems available, sorts of rail flaws diagnosed and performance (Papaelias et al. 2008).

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

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

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

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

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

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

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

4.2.1 Optical-based methods

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

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

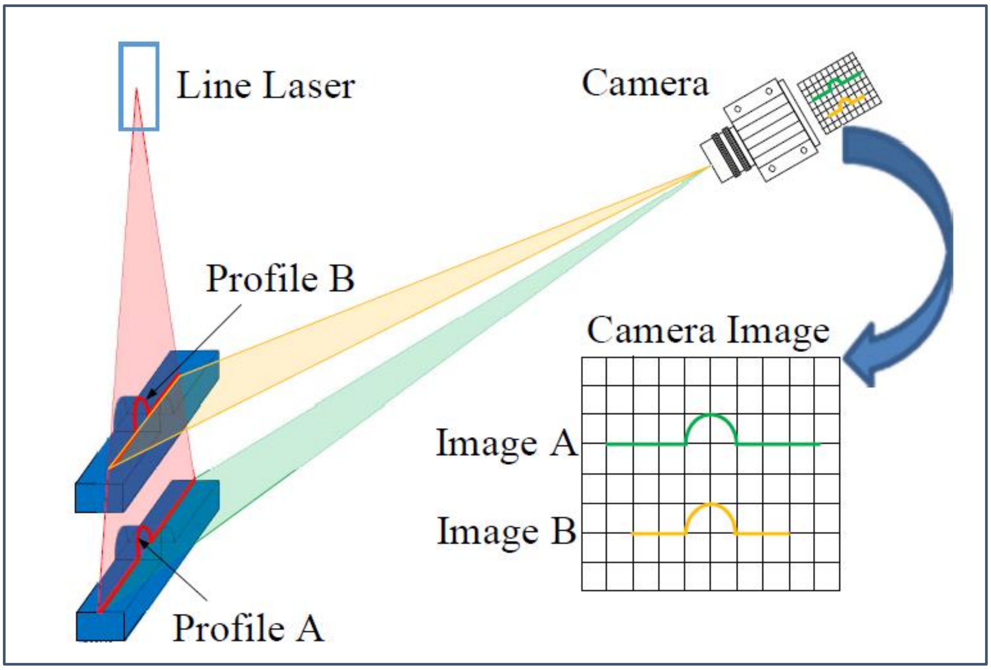

Fig. 9 Measurement principles of the system proposed in Xiong et al. (2017) for capturing the rail surface profile.

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

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

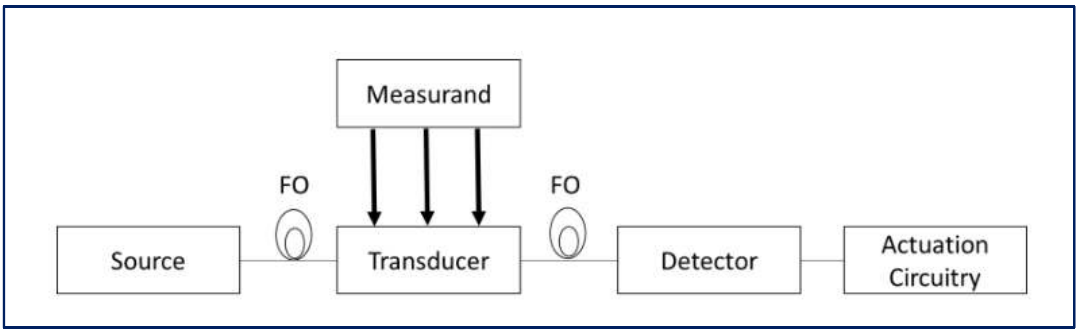

Fig. 10 A schematic system of OFSs (Campanella et al. 2018)

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

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

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

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

Traffic impacts on a short span railway bridge in Northern Portugal was demonstrated. To this purpose, a new hybrid platform deploying the synchronous assessment of signals generated by a sensing network, including both electrical and FBG-based sensors, was presented (da Costa Marques Pimentel et al. 2008). A bridge weight-in-motion algorithm was used to develop a commercial fiber-optic-based train characterisation system and the tested system provided an on-motion acquisition of train speed and weight distribution by using only three FBG sensors (da Costa Marques Pimentel et al. 2008).

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

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

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

4.2.2 Inertial methods

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

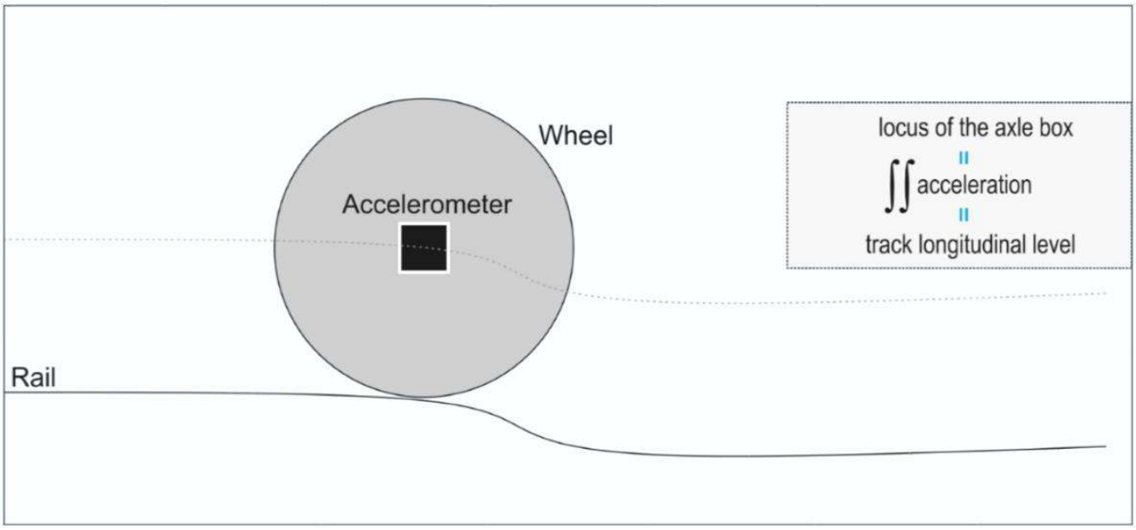

Fig. 11 Inertial track measurement in longitudinal level (adapted from (Tsunashima et al. 2012))

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

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

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

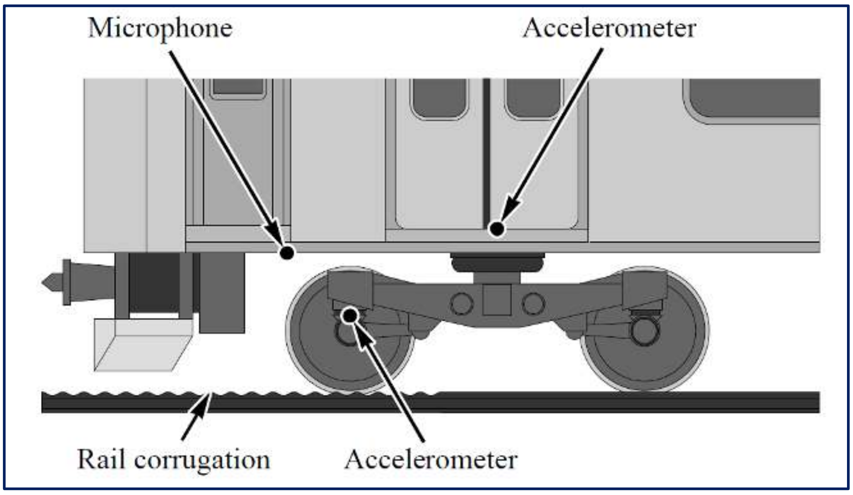

Fig. 12 Layout of the investigation equipment and position of sensors used in Kojima et al. (2010)

4.2.3 Acoustic and ultrasonic techniques

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

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

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

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

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

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

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

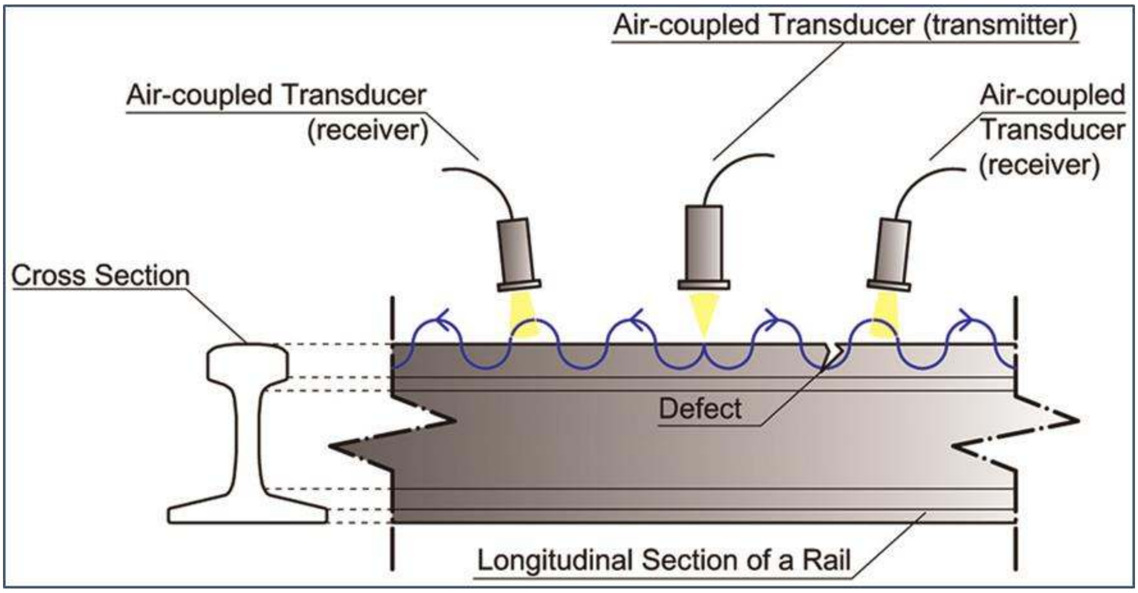

Fig. 13 Illustration of of the air-coupled guided wave transducers (Mariani et al. 2013)

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

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

4.2.4 Image Analysis

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

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

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

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

4.2.5 Ground Penetrating Radar (GPR)

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

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

$$v_r = \frac{c}{\sqrt{\varepsilon_r}} \tag{2}$$

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

$$d = v_r \cdot \frac{t}{2} \tag{3}$$

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

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

GPR was utilised to assess the level of ballast deterioration and identify the interface between the ballast and the subgrade (Gallagher et al. 1999). Jack and Jackson (1999) qualitatively diagnosed the variations of conditions in a ballast layer to classify the GPR profile into sections (Jack and Jackson 1999). According to Hugenschmidt (2000), use of GPR compared to other traditional inspection methods in ballast condition assessment lead to a substantial reduction in the number of trenches as well as it allowed to identify regions where subsoil material penetrated into the ballast. GPR has been successfully used in many studies for assessment of ballast quality and thickness determination. De Bold (2011) has demonstrated that GPR can be used in ballast characterisation, finding a high correlation between the Ionescu fouling index in the area scanned by GPR. In order to address a main limitation related to the loss of reflectors at the base of the ballast layer, use of radar detectable geosynthetics was introduced during the construction of railways. This allowed to identify more precisely depth of ballast measurements after the construction (Carpenter et al. 2004).

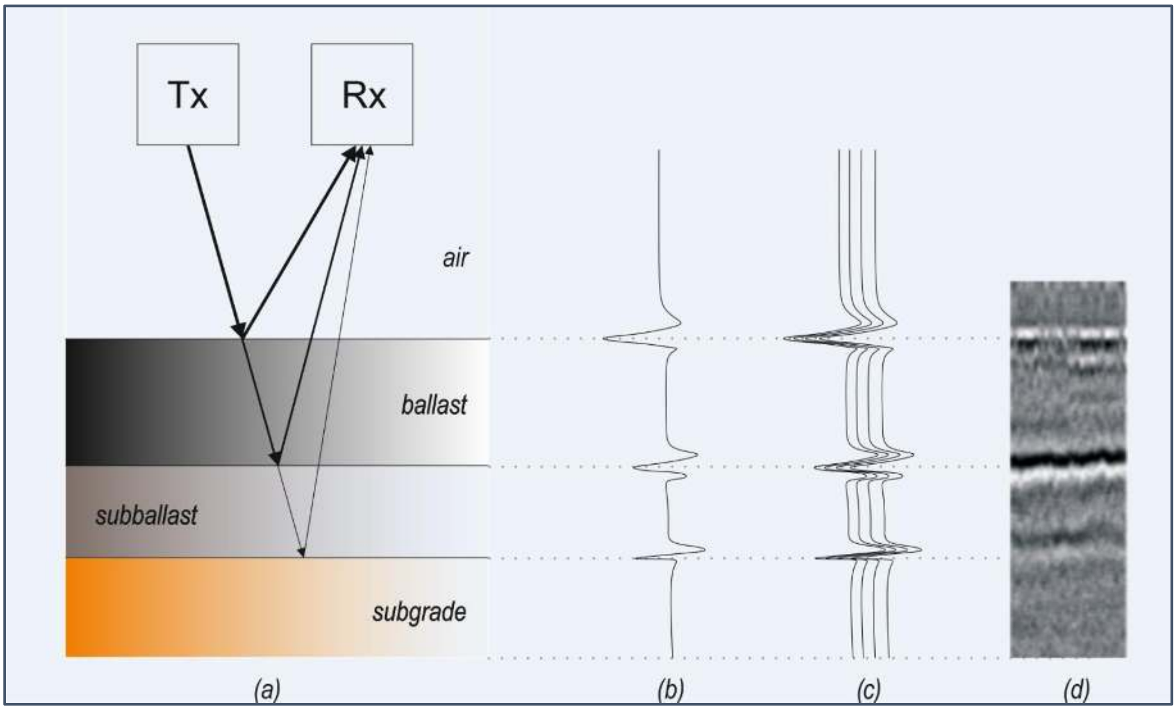

Fig. 14 The generation of a GPR profile with an air-coupled antenna on a track bed. a) The transmitted energy is reflected from the boundaries in the substructure, b) A single trace with reflection amplitudes for the reflection interfaces in (a), c) A sequence of multiple scans, d) Adjacent scans combined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

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

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

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

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

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

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

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

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

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

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

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

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

5 Conclusion and Final Remarks

This paper reports past and state-of-the-art research on the use of non-destructive testing (NDT) methods for assessment and health monitoring of railway infrastructures. An overview of the diagnosis and maintenance issues as well as the track deformations is first given. In more detail, main deformations occurring in a railway substructure and superstructure are here discussed. In regard to the substructure, it was emphasised that fouling is one of the primary causes of failure and an early detection may be crucial to reduce future cost of intervention as well as likelihood of derailment. Deformations in the superstructure were sorted into geometry-related and surface-related, both of which are important factors to provide lower maintenance cost. Discussion on maintenance activities required for a railway track has identified a relatively complex list of actions to carry out across different time spans. In this regard, a comprehensive number of inspection methods as well as use of geometry cars and measured parameters have been reported across several different international countries.

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

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

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