

## 1

## Introduction

### 1.1 General

Currently, railroads collect enormous quantities of data through vehicle-based inspection cars, trackside (or wayside) monitoring systems, hand-held gauges, and visual inspections. In addition, these data are located geographically using the global positioning system (GPS). The data from these inspection systems are collected electronically by hand or using various sensors, video inspections, machine visions, and many other sources. Furthermore, the data are growing both in quantity and quality and are more precise and diverse. Data of extremely large sizes are difficult to analyze using traditional approaches since they may exceed the limits of a typical spreadsheet. The railway track data are present in diverse forms, including categorical, numerical, or continuous values. The general characteristics of the data dictate which type of method is appropriate for analysis. For example, categorical and nominal values are unsorted, while numerical and continuous values are assumed to be sorted or to represent ordinal data (Ramírez-Gallego et al., 2016).

The development of advanced sensors and information technology in railway infrastructure monitoring and control has provided a platform for the expansive growth of data. This has created a new paradigm in the processing, storing, streaming, and visualization of data and information. Furthermore, changes in technology include the possibility of installing sensors and smart chips in critical infrastructure to measure system performance, current condition, and other indicators of imminent failures. Many of the railway infrastructure components have communication capabilities that allow data to be uploaded on demand.

Big data is about extremely large volumes of data originating from various sources: databases, audio and video, millions of sensors, and other systems. The sources of data in some cases provide structured outputs, but most are unstructured, semi-structured, or poly-structured. These data are streaming in some cases with high velocity, and the data exposes at a higher speed or some speed as it is generated.

This chapter presents a general overview, basic description, and properties of deterministic and random data that are encountered in railway track engineering data and relies heavily on the data output based on the advances in sensors, information technology, high information technology, and development that has led to extremely massive data sets. These large data sets have made the traditional analytical techniques used for railway track maintenance and safety issues somewhat obsolete.

The data obtained in railway track monitoring are collected by different sensors, at different times and environmental conditions, at different frequencies, and at different resolutions. The outputs of these data have different characteristics: discrete or continuous, spatial or temporal, signal and images, and categorical and objective, among others. All these characteristics, properties, and the extreme volume of data collected have made traditional analytical techniques very inefficient; issues like visualization and data streaming, which are very critical in railway track maintenance and safety, are not adequately addressed. The traditional statistical techniques fail to scale up to the extremely large volumes of data collected by railway inspection vehicles and trackside monitoring devices. Therefore, the growing amount of data generated by railway track inspection activities is outpacing the current capacity to explore and interpret these data and hence appropriately addresses maintenance and safety issues.

## 1.2 Track Components

The term “tracks” includes superstructure, substructure, and special structures (Figure 1.1). The superstructure is made of rails, ties, fasteners, turnouts, and crossings, while the substructure consists of ballast, subballast, the subgrade, and other drainage facilities. The superstructure and substructure are separated by the tie–ballast interface.

The main purpose of the railway track structure is to provide a safe and economical train transportation system through guiding the vehicle and transmitting loads through the track components to the subgrade. The carrying

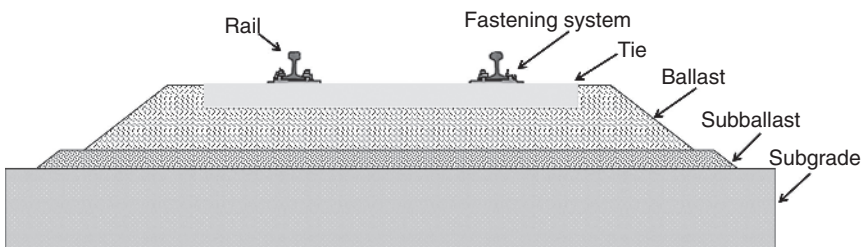


Figure 1.1 Track structure components

capacity and long-term durability of the track structure highly depend on how the superstructure and substructure respond to and interact with each other when subjected to moving trains and environmental factors (Selig and Waters, 1994; Kerr, 2003).

The function of different rail components has been presented by various authors, such as Hay (1982), Selig and Waters (1994), Esveld (2001), Kerr (2003), Sadeghi (2010), and Tzanakakis (2013). The aim of this section is to summarize this function. The rails are the longitudinal steel members that are placed on spaced ties to guide the train wheels evenly and continuously. Their strength and stiffness must be sufficient to maintain a steady shape and smooth track configuration and to resist various forces (vertical, lateral, and longitudinal) by vehicles. The rails also in some cases serve as electrical conductors for the signal circuit and also as a groundline for the electric locomotive power circuit. The profile of the rail surface (transverse and longitudinal) and wheel surface has a major influence on the operation of the vehicles on the track, and track defects may in some instances create and cause large dynamic loads that lead to derailment and safety issues, as well as accelerated degradation.

Most steel rail sections are connected either by bolted joints or by welding. The bolted joints create several problems, including rough riding track, undesirable vibration, and additional impact loads, among others; hence, the use of continuous welded rail (CWR) has been the better solution. CWR attempts to address some of the disadvantages of the bolted joints, which have its own set of maintenance requirements.

The rail fastener systems, or fastenings, include all the components that connect the rail to the tie, with the tie plate, spike, and anchor for wood ties and clip, insulator, and elastic fasteners for concrete ties. The function of the fastenings is to retain the rail against the ties and resist vertical, lateral, longitudinal, and overturning movements of the rail. They also serve as wheel load impact attenuation, increasing track elasticity, as well as electrical isolation between rails.

For concrete tie tracks, rail pads are installed on rail supporting points to reduce and transfer the stress and dynamic forces from the rail to the ties, and they reduce the interaction force between the rail and the ties (Choi, 2014). The pads also provide adequate resistance to longitudinal and rotational movement of the rail and provide a conforming layer between the rail and tie to avoid contact areas of high pressure. From a dynamic point of view, the rail pads tend to influence overall track stiffness.

Ties are transverse beams resting on ballast and support. They span below and tie together two rails. The main functions of ties are as follows:

- Uniformly transfer and distribute loads from the rail to the ballast
- Hold the fastening system to maintain proper track gage
- Restrain the lateral, longitudinal, and vertical rail movement by anchorage of the superstructure to the ballast

- Provide a cant to the rails to help develop proper wheel–rail contact by matching the inclination of the conical wheel shape
- Provide an insulation layer
- Allow fast drainage of fluid
- Allow for proper ballast maintenance

Ballast is the layer of crushed stone placed at the top layer of the substructure in which the tie is embedded. It is an elastic support and transfers forces from the rail and tie to the subballast. As some of its functions, it

- Distributes load from ties uniformly over the subgrade
- Anchors the track in place against lateral, vertical, and longitudinal movements
- Absorbs shock from the dynamic load
- Allows suitable global and local track settlement
- Avoids freezing and melting (thawing) problems by frost action
- Allows for proper drainage
- Allows for maintenance of the track geometry

The subballast is the layer between the ballast and the subgrade. As some of its functions, it

- Reduces the stress at the bottom of the ballast layers to a reasonable level to protect the subgrade
- Migrates fines from the subgrade to the upper layer of the ballast
- Protects the subgrade from the ballast
- Permits drainage of water that might otherwise flow upward from the subgrade

The subgrade is the last support of the track systems and, in some cases, is the existing soil at the location, unless the existing formation is very weak. In the case of a weak existing formation, techniques like stabilization and modification of the existing elevation use more appropriate soil. The addition of geosynthetic material has been used to improve the subgrade performance and bearing capacity. Its main functions are the following:

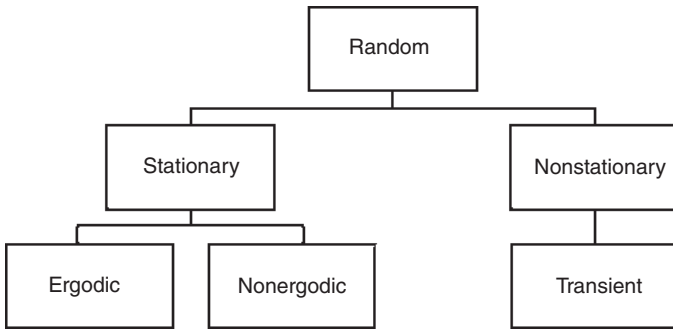
- Provide support to the track structure
- Bear and distribute the resultant load from the train vehicle through the track structure
- Provide sufficient drainage

### 1.3 Characteristics of Railway Track Data

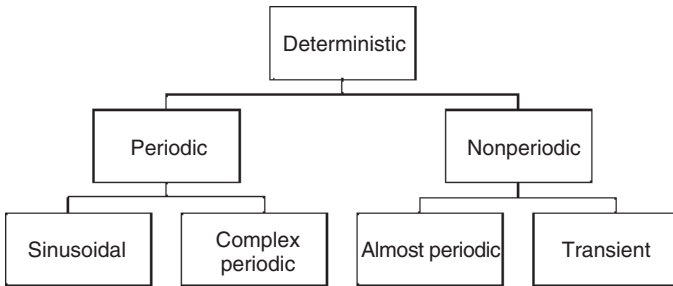
Railway track data are similar to data from other infrastructures. Its characteristics include the following:

- *Massive Data Sets.* Railway track data collection and monitoring has resulted in extremely large data sets for infrastructure monitoring. In some cases, the actual data are processed and only the reduced version is stored, while in most cases smaller amounts of data are stored for further analysis.
- *Unstructured Data, Heterogeneous Databases.* Some of the railway track data are stored in databases. In most cases, different agencies and countries have different data formats, different database management systems, and different data manipulation algorithms. Most of these databases are evolving, which in some cases makes analysis and data mining across them challenging. Some of the databases include unstructured images, plots, and tables, as well as links to other transportation and infrastructure documents of the agency. This can be challenging in terms of both analysis and reporting.
- *Information in the Form of Images.* The analysis of railway track, in terms of both rail and geometry defects, by its very nature deals with issues associated with the extraction of meaningful information from massive amounts of railway track images, thus opening a new direction in railway track analysis.
- *Poor Quality of Data.* Railway track data analysis, especially the image data, in most cases is of poor quality due to the railway track environment and sensor noise. In some cases, data are missing or input incorrectly. Furthermore, the data from different sources can vary in terms of quality. Also, the railway inspectors may in some cases have incomplete knowledge about the mechanism and initiation of different defects. This may lead to inconclusive reporting and analysis.
- *Multiresolution and Multisensor Data.* Several different sensors are used to collect different information and data. This may create a situation where several images may have different resolutions over time. Therefore, care must be taken so that the change in resolution can be included.
- *Noisy Data.* Noisy data cannot be avoided in railway track data collections. Methods of reducing the noise in data need to be implemented during the preprocessing of the data for further analysis. For example, shadows and orientations of the vehicle collecting the data can have an impact on the images. Therefore, poor illumination can have a major impact on the obtained image.
- *Missing Data.* The risk of missing data is always present in railway track data collection; this is mostly due to sensor malfunction. Filling the gaps can be a daunting task. Again care must be taken with how missing data is included.
- *Streaming Data.* Some of the data sets collected during railway monitoring can be streaming in nature; that is, a constant stream of data is being collected and received. This requires a specialized set of analyses different from the chunk data methods used in traditional analysis.

More broadly, the data can either be random or deterministic. The random data is shown in Figure 1.2, and the deterministic data is shown in Figure 1.3, as presented by Bendat (1998).



**Figure 1.2** Classification of random data (Bendat (1998). Reproduced with their permission of John Wiley & Sons)



**Figure 1.3** Classification of deterministic data (Bendat (1998). Reproduced with their permission of John Wiley & Sons)

Table 1.1 shows the general taxonomy of big data methods in railway engineering.

## 1.4 Railway Track Engineering Problems

Generally, railway track engineering problems can be classified into two groups according to Santamarina and Fratta (1998): (a) forward problems and (b) inverse problems. Table 1.2 shows the group of problems that fall under the two categories. For forward problems, the major objective is to design systems to satisfy predefined performance criteria. Also, convolution forms part of the forward problems. In convolution, the input is known, the type of system is known, and the only unknown is the output.

Inverse problems can either be (a) system identification where the input and output are known but the system is unknown or (b) deconvolution where the input is unknown, while the system and output are known. Figure 1.4 shows a generic representation of general civil engineering problems, including railway

**Table 1.1** Taxonomy of big data in railway engineering.

Analysis domain	Sources	Characteristics	Approaches	Comments
Structured data	Field data collection, sensors, data from scientific experiments	Structured records, real time	Data mining, statistical analysis	All infrastructure systems need field data
Unstructured data	Extreme events, sensors	Unstructured records, mixture of variables	Anomaly detection	Infrastructure inspection reports, specification updates
Text analytics	Logs, email, corporate documents, government rules and regulations, text content of web pages, citizen feedback and comments	Unstructured, rich textual, context, semantic, language dependent	Document presentation, NLP, information extraction, topic model, summarization, categorization, clustering, question answering, option mining	Early detection
Multimedia analytics	Corporation-produced multimedia, user-generated multimedia, surveillance	Image, audio, video, massive, redundancy, semantic gap	Summarization, annotation, indexing and retrieval, recommendation, event detection	Early detection
Mobile analytics	Mobile apps, RFID sensors		Monitoring, location-based mining	

Table 1.2 Engineering problems.

Forward problems		Inverse problems	
System design	Convolution	System identification	Deconvolution
The system is designed to satisfy performance criteria (controlled output for estimated input)	Input: known System: known Output: unknown	Input: known System: unknown Output: known	Input: unknown System: known Output: known

(Santamarina and Fratta., 1998) Reproduced with the permission of ASCE.

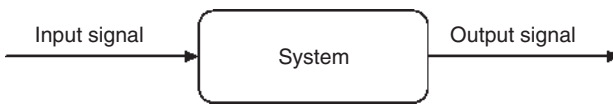


Figure 1.4 Engineering signals

track problems. But there can be different situations, including (a) single-input–output relationships as shown on the generic representation and (b) multiple-input–output relationships. Therefore, depending on the structural and objective analyses, there are different assumptions and analyses. Systems can be divided into two broad groups, (a) linear and (b) nonlinear. The linear systems can be further divided into constant parameter and time-varying systems (Bendat, 1998).

Major parts of railway track data are in the form of signals and images; therefore, a deeper understanding of analytical issues for signals and images is needed to analyze and interpret railway track data. A major issue related to track images is the presence of noise, which tends to affect the overall images if it is not properly reduced or accounted for. Therefore, efficient algorithms are needed to reduce noise in railway track images before further analysis can be done.

Table 1.3 shows examples of different track inspection technologies and their level of maturity. Railway track conditions are, in most cases, evaluated using the characteristics of track geometry wave form and vehicle dynamic response to the track. Also, in some cases, images from high definition cameras are also collected. It is apparent that to obtain the true picture of the railway track condition, there should be methods that can go beyond traditional statistical analysis. An efficient method is one that can perform the mining of the data, reduce noise from the wave forms, and combine data and information from different sources to provide a clear understanding of what maintenance activities to perform and how to satisfy all safety requirements.



**Table 1.3** Track inspection technologies.

Component	Inspection	Base technology	Maturity	Measurement	Maintenance activity	Level of automation
Rail	Profile	Laser/camera	Mature	Wear, cant, lip, GF angle, profile/contact	Wear, grinding, cant, lip	Very high
	Corrugation	Inertial or chord	Moderate	Wavelength and amplitude	Grinding	High
	Internal fatigue	Ultrasonic	Mature	Location and size of flaw	Replacement	High
	Surface fatigue	High definition camera	New	Location and size of flaw	Grinding	Moderate
Joint bars	Surface cracks	Eddy current	New	Location, length, and density of cracks	Grinding	Low
	Cracks, bolts	High definition camera	New	Location of failure	Replacement	Moderate
	Cracks, plate cut	High definition camera	New	Length, width, and density of cracks	Replacement	Low
Ties	Rot	Back scatter X-ray	Very new	Internal density	Replacement	Low
	GRMS	Force/displacement	Mature	Tie/fastener interface strength/stiffness	Replacement	High
Fasteners	Condition, existence	High definition camera	New	Missing or damaged	Replacement	Low
	GRMS	Force/displacement	Mature	Tie/fastener interface strength/stiffness	Replacement	High
Turnouts/ diamonds	Rail geometry	Laser/camera	New	Relative heights and dimensions, points, frog	Replacement, grinding, welding	Moderate
	Track geometry	Inertial	Mature	Relative rail-to-rail relationship	Tamping	High
	Component condition	High definition camera	New	Missing or damaged	Replacement, tighten	Low

(Continued)

**Table 1.3** (Continued)

Component	Inspection	Base technology	Maturity	Measurement	Maintenance activity	Level of automation
Geometry	Geometry car	Inertial or contact	Mature	Relative rail-to-rail relationship	Tamping	High
	Absolute geometry	Inertial	New	Absolute rail-to-rail relationship	Tamping	Low
	Vertical track interaction	Inertial	New	Vertical vehicle response to track	Tamping	High
Ballast/subballast/subgrade	Ground-penetrating radar	Radar	Moderate	Ballast depth and condition	Tamping, undercutting	Low
	Cone penetrometer	Force/displacement	Moderate	Ballast/subballast depth, condition, and strength	Tamping, undercutting	Low
	Vertical track deflection	Force/displacement	New	Track stiffness	Tamping, undercutting	Moderate
	Profile	Lidar	New	Ballast profile	Add ballast and tamp	Moderate
Clearance	Envelope	Lidar/laser	Moderate	Surrounding clearance and obstructions		Moderate

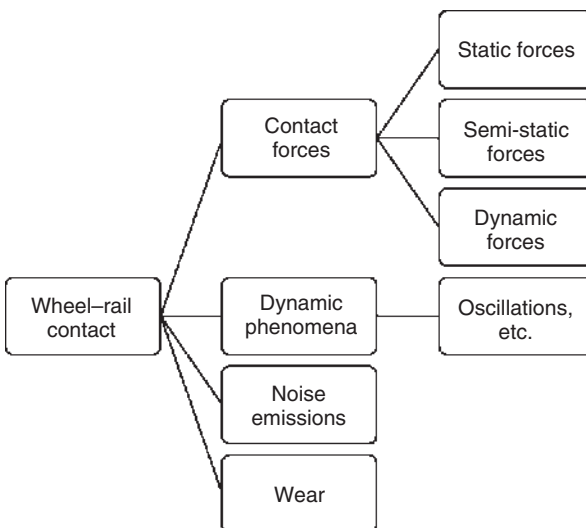
## 1.5 Wheel–Rail Interface Data

The wheel–rail contacts at the interface between the wheel and rail determine in part the reliability of railway systems. Tzanakakis (2013) presented in Figure 1.5 the different outcomes and effects of wheel–rail contact. The rail vehicles are supported, accelerated, and decelerated by contact forces acting on extremely small wheel–rail contact areas (around  $1 \text{ cm}^2$ ).

Meymand et al. (2016) presented a comprehensive survey on the topic. The paper discusses well-known theories for modeling normal contacts based on Hertzian and non-Hertzian methods and tangential contacts based on Kalker’s linear theory and Polach theory.

Track irregularities tend to produce different magnitudes of force on the track. These forces on the track can result in three types of loads: (a) vertical, (b) lateral, and (c) longitudinal. Lateral loads are transverse to the track, while longitudinal loads are parallel to the track. Depending on their nature, loads can be (a) static loads, (b) quasi-static loads, and (c) dynamic loads. The dynamic loads may cause

- Irregularities in the track geometry
- Wear of the running surface
- Discontinuities on the running surface, which includes switches and frogs
- Dynamic forces, which appear in two categories: P1 and P2 forces. Frequencies of P1 forces range between 100 and 2000 Hz, are mainly impact forces.



**Figure 1.5** Wheel–rail contact impacts (Tzanakakis (2013). Reproduced with the permission of Springer)

P1 forces can cause, among other things, bolt hole failure and cracking of concrete ties and have minimal effects on the ballast or subgrade. P2 forces contribute to the degradation of track geometry and are classified in the frequency range between 30 and 100 Hz.

The contact between the wheel and the rail is the basic constitutive element of the railway dynamics (Table 1.4). For modeling purposes, two aspects are considered (Trzaska, 2012): (a) the geometric or kinematical relations of the wheel–rail contact and (b) the contact mechanical relations for the calculation of the contact forces. The wheel–rail contact provides insight into the formation of corrugation and other rail defects, like wear, crack growth, and others. The wear depends on tangential forces and creep age at the contact patch. Using mathematical analysis, it is possible to build a comprehensive and functional understanding of wheel–rail interaction, suspension and suspension component behavior, simulation, and experimental validation. This is beyond the scope of the current analysis.

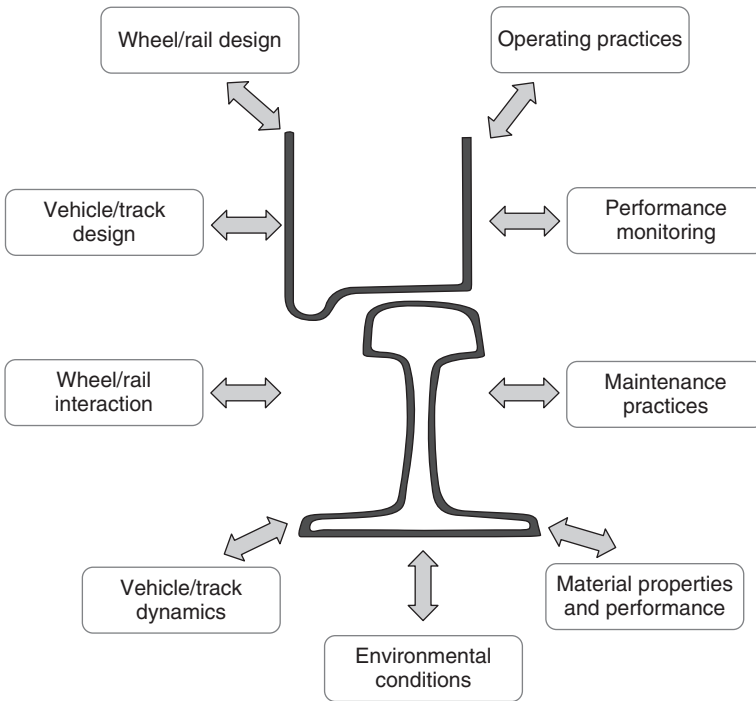
Figure 1.6 shows various wheel–rail interfaces and their effects.

In wheel–rail contact there are three “zones” of contact, namely, Region A, Region B, and Region C, as shown in Figure 1.7. Region A is the contact between the central region of the rail crown and the wheel thread (conicity, hollow wear, and thermal loads), Region B is the extreme reference gage corner contact of the two-point contact, and, finally, Region C is the field side contact. At Region A,

**Table 1.4** Vertical track forces.

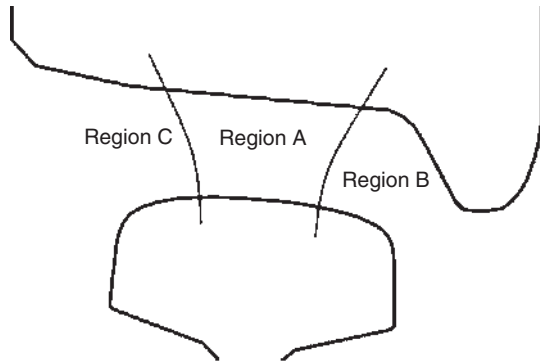
Cause	Force	Symptom
Impact at rail welds	Rail: P1+P2	Rail fatigue failure Corrugations Pad degradation Tie cracking/movement Ballast degradation Weld fatigue
Vehicle/track interaction	Quasi-static Dynamic forces	Track geometry deterioration Rail failure/fatigue Ballast failure/degradation Subgrade failure/degradation
Wheel irregularities	Wheel: P1+P2	Tie cracking Rail breaks Wheel cracks Ballast deterioration

Tzanakakis (2013). Reproduced with the permission of Springer.



**Figure 1.6** Wheel–rail interface

**Figure 1.7** Regions of wheel/rail contact (Harris et al., 2001)



contact stresses are the lowest, lateral creepages and creep forces are low, and longitudinal creepages and forces are high, with reference to the wheel tread. In Region B, with reference to the wheel flange and gage corners, the contact between gage corner and flange fillet contact patch is small, with highest contact stresses, and there are three types of possible contact: (a) two-point contact, (b) single-point contact, and (c) conformal contact. In two-point contact,

there is excessive creep relative to slip, high wear rates and material flaws, and less damage to the rail than the wheel. In the single-point contact, there are high longitudinal forces, the contact is most damaging to wheel and track, and head cracks are initialized and gage corners are broken out. During the conformal contact, gage corner and wheel flange wear to a common profile. In Region C, the field side contact, it is very difficult to optimize contact between wheel and rail due to the presence of high contact stresses.

Charles et al. (2008) developed a model-based condition monitoring applied to wheel–rail interaction parameter estimation, using the Kalman filter. The results appear to be very promising. The model was also capable of determining low adhesion detection and lateral track irregularities. Charles et al. (2008) in previous publications had used linear least square and other identification methods. Various techniques, including acoustic emission, have been used to monitor the continuous intensity of wheel–rail interaction. Also, various types of sensors are employed for this objective.

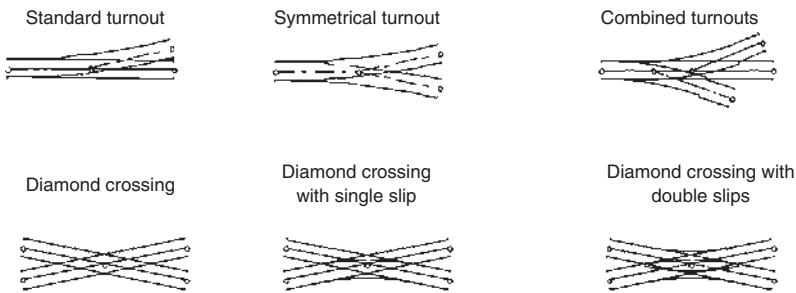
The current book will only attempt to use data science methods to address some of the output from wheel–rail experimental data. Thus, the approach will be more focused on probabilistic and statistical methods.

The derailment coefficient, the ratio between the lateral and vertical contact forces on the outside rail, has been shown to vary according to wheel–rail contact conditions, such as lubrication, time interval of train operation, rail temperature, and climate (Matsumoto et al., 2012). Currently, there are new systems that are used to collect data for that purpose. For example, data from wheel load sensors are sampled every 8 ms.

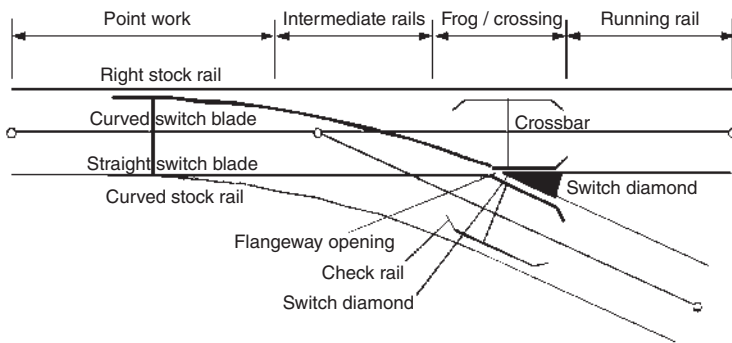
### 1.5.1 Switches and Crossings

Railway track switches and crossings (S&C) represent important components of the railway infrastructure. Generally, the S&C are referred to as turnouts, and their main function is to enable trains to change tracks. Train–track interaction at the turnouts is a major issue for both the design and maintenance of railway track systems (Bruni et al., 2009). Figure 1.8 shows the different types of S&C and Figure 1.9 shows the general structure of a crossing/switch. The nature of S&C makes them more expensive to maintain than regular straight and curved tracks (Zwanenburg, 2006):

- S&C have special components, like switch tongues, frogs, and slide plates, which are exposed to relatively high static and dynamic forces, making them experience high wear rates and specific deterioration.
- S&C have moving parts, which require extra regular inspections and maintenance actions.
- S&C form a potential safety hazard because of their moving parts and discontinuities that can create additional problems for failure, especially if they are not functioning well. This is a major safety issue.



**Figure 1.8** Different types of switches and crossings (Zwanenburg (2007). Reproduced with the permission of EPFL tous droits réservés)



**Figure 1.9** Schematized standard turnout and its components (Zwanenburg (2007). Reproduced with the permission of EPFL tous droits réservés)

The wheel and rail profiles have a major influence on the deterioration of S&C. S&C degradation has an additional parameter compared with regular track parameters. Zwanenburg (2006) discussed the statistical approach, where analyses are based on loads, and directions of trains over specific S&C. Again, the author summarized specific factors that influence the degradation of the geometry of S&C. These are organized into three groups: (a) train parameters (e.g., axle load, speed, and number of axles); (b) track parameters (e.g., quality of the frog, quality of rail fasteners, tie type, ballast quality, and soil quality); (c) usage parameters (e.g., million gross tons (MGT), braking or acceleration, speed, and number of throws). Generally, based on the availability of data, different machine learning techniques can be used to model the deterioration of S&C.

## 1.6 Geometry Data

It is very important to distinguish between monitoring and inspection. Railway track inspection addresses safety concerns, while monitoring focuses on faults

and supports efficient maintenance (Weston et al., 2015). Track geometry usually describes the position of each rail or track center line in space, in particular one rail with reference to the other. Therefore, the track geometry is a variation of lateral and vertical track positions in relation to the longitudinal plane or length parameter. The track consists of elements such as tangents, curves, transitions, S-shaped features, switches, and track irregularities (Haigermoser et al., 2015).

Track geometry consists of several parameters that have a major influence on ride quality and derailment risk. The Federal Railroad Administration (FRA) defines track geometry as the following geometry elements (FRA, 2014b):

- *Alignment*. Alignment is the projection of the track geometry of each rail or the track center line onto the horizontal plane. In other words, it is the relative position of the rails in its horizontal plane, and it is measured at the midpoint of a 62-ft chord. For tangent track, the alignment is equal to zero. For curved track the mid-chord offset of a 62 ft chord (in inches) is equal to the degree of curvature.
- *Crosslevel*. Crosslevel is the difference in elevation between the top surfaces of the two rails at any point of railroad track.
- *Gage*. Gage is the distance between to rail heads at right angles to the rails in a plane five-eighths of an inch below the top of the rail head. In the United States, the distance used is standard gage that is equal to 56.5 in for tracks containing up to 12° of curvature.
- *Profile*. Profile (also known as longitudinal leveling or surface) relates to the elevation along the longitudinal axis, which is an adherence to an established grade and the incidence of dips and humps. That is, it provides the elevation of the two rails along the track. The profile measurement is carried out in the midpoint of the 62-ft mid-chord.
- *Superelevation*. Superelevation (or cant) is the designed difference in the elevation between two rails in order to compensate for the effect of centrifugal forces in a curve. When that difference in the elevation does not fulfill the design requirements, it is called crosslevel.
- *Twist*. The difference in the crosslevel between two points of a fixed distance.
- *Warp*. The difference in the crosslevel between any two points within the specified chord length.

Track geometry is measured using automated systems and processed to give exceptions where measured parameters exceed a defined threshold. The current advances in the development of sensors have made track inspection systems that can compact and can be mounted underneath in-service vehicles possible. The large quantity of data collected by the sensors can be both advantageous and disadvantageous. Useful information can be obtained from the data, but at the same time there is the potential to lose critical information



after the reduction of the data. Signal and processing techniques are used to derive important information from the output that can be used for maintenance planning and budgeting. In most cases, the track geometry defects should be within certain limits, which can be a function of maximum permissible speed. One example is the European Standard EN 13848-5, which provides limits for each type of defect. There are three main levels: (a) the immediate action limit (IAL) refers to the value that, if exceeded, requires imposing speed restrictions or immediate correction of the track geometry; (b) the intervention limit (IL) is the value that, if exceeded, requires corrective maintenance before the IAL is reached; and (c) the alert limit (AL) is the value that, if exceeded, requires that the track geometry condition be analyzed and considered in the regularly planned maintenance operations. The International Union of Railways (UIC) standard 518 (UIC 2005) designates three levels as follows: (a) QN1 quality level, which is the value that necessitates monitoring or taking maintenance actions as part of regularly planned maintenance operations; (b) QN2 quality level, which refers to the value that requires short-term maintenance action; and (c) QN3 quality level, which refers to the value above which it is no longer desirable to maintain the scheduled traffic speed. North American track safety standards (FRA, 2014a) present example of the geometry criteria.

The foot-by-foot track geometry condition is quantified using an index to represent the track geometry numerically, in order to reduce the data for practical analysis techniques. The provided overall qualities are referred to as the track quality indices (TQIs). The TQIs provide an aggregate level picture and do not identify individual defects very well. The standard deviation appears to be the most common track quality indicator, and in most cases it is calculated as the combination of various parameters. The following formula shows an example of a TQI:

$$\text{TQI} = \sqrt{w_{Al}\sigma_{Al}^2 + w_G\sigma_G^2 + w_{Cl}\sigma_{Cl}^2 + w_{T_p}\sigma_{T_p}^2}, \quad (1.1)$$

where

*Al*: mean alignment

*G*: track gage

*Cl*: crosslevel

*T<sub>p</sub>*: mean of the longitudinal level of both rails

*w*: weighting factor of the geometry parameters

$\sigma$ : standard deviation of the individual parameters

The weighting factor is determined by the asset Management Manager.

Haigermoser et al. (2015) highlighted that the track quality is generally characterized by deviations of rail positions in three-dimensional space in terms of gage, crosslevel, longitudinal levels, alignment, and twist. Sometimes they are referred to as track irregularities.

Liu et al. (2015) presented the following definitions:

- *SD Index*. The SD index is associated with a track quality parameter and is calculated from measurement values for the parameter over a track segment (Equation 1.2). The larger the SD index is, the worse the track segment is in some aspect represented with the quality parameter.

$$\sigma_i = \sqrt{\frac{1}{n} \sum_{j=1}^n (x_{ij}^2 - \bar{x}_i^2)}, \quad \bar{x}_i = \sum_{j=1}^n \frac{x_{ij}}{n}, \quad (1.2)$$

where

- $\sigma_i$ : standard deviation of a quality parameter in millimeter
- $x_{ij}$ : measurement value in millimeter for the parameter at the  $j$ th sampling point in the track segment
- $n$ : number of sampling points in the track segment
- *Q Index*. ProRail of the Netherlands converts the SD index into a more universal form across different classes of tracks (Equation 1.3).

$$N = 10 * 0.675^{\sigma_i / \sigma_i^{80}}, \quad (1.3)$$

where

- $N$ :  $Q$  index for a quality parameter over a 200 m long track segment
- $\sigma_i$ : standard deviation for the quality parameter
- $\sigma_i^{80}$ : the 80th percentile of standard deviations for 200 m long segments in a maintenance section with length ranging from 5 to 10 km.

The  $Q$  index ranges from 10 to 0. The larger the  $Q$  index, the better the track quality.

- *P Index*. The  $P$  index is adopted by Japanese railroads and is the ratio of the number of sampling points whose quality parameter measurements fall outside  $\pm 3$  mm to the number of all sampling points in a track segment. It is applied to track segments of 100–500 m.
- *Track Roughness Index*. The track roughness index is used by Amtrak. In general, it presents the track roughness as the sum of squares of the amount of deviation measured over 20 m mid-chord offset ( $d^2$ ), divided by the total number of measures ( $n$ ) as shown in Equation 1.4.

$$R^2 = \sum_{i=1}^n \frac{d^2}{n} \quad (1.4)$$

- *Track Geometry Index*. The track geometry index  $TGI_i$  uses the measurement value space curve length  $L_i$  as shown in Equation 1.5.

$$TGI_i = \left( \frac{L_i}{L_0} - 1 \right) * 10^6 \quad L_i = \sum_{j=1}^{n-1} \sqrt{(x_{i(j+1)} - x_{ij})^2 + (y_{j+1} - y_j)^2}, \quad (1.5)$$

where

- $L_i$ : measurement value space curve length for a quality parameter over a track segment
- $L_0$ : length of the track segment
- $y_j$ : mile point of the  $j$ th sampling point on the track segment
- *CN's Track Quality Index*. The Canadian National Railway Company (CN) uses a second-order polynomial equation of the standard deviation  $\sigma_i$  of measurement values for a quality parameter over a track segment to assess its partial quality (Equation 1.6). The overall quality assessment is achieved by averaging six partial quality indices for gage, crosslevel, and left or right surface and alignment.

$$\text{TQI}_i = 1000 - C * \sigma_i^2, \quad (1.6)$$

- $C$ : constant
- $\sigma_i$ : standard deviation of measurement values

A larger track quality index implies the track segment has a better quality.

- *Overall Track Geometry Index (OTGI)*. A variation of the TGI was developed by Sadeghi and Askarinejad (2010). Called the overall track geometry index (OTGI), it considers a normal distribution for each of the track geometry parameters (profile, alignment, gage, and twist). The authors combined individual geometry indices into a single expression presented in Equation 1.7.

$$\text{OTGI} = \frac{\frac{a}{2} \times \text{GI}^+ + \frac{a'}{2} \text{GI}^- + b \times \text{AI} + c \times \text{PI} + d \times \text{TI}}{\frac{a+a'}{2} + b + c + d}, \quad (1.7)$$

where

- $\text{GI}^+$  and  $\text{GI}^-$ : positive and negative gage indices, respectively
- $\text{AI}$ : alignment index
- $\text{PI}$ : profile index
- $\text{TI}$ : twist index
- $a, a', b, c,$  and  $d$ : model coefficients
- *Sweden TQI*. The Sweden National Railway assesses track geometry conditions as shown in Equation 1.8:

$$Q = 150 - 100 \left[ \frac{\sigma_H}{\sigma_{Hlim}} + 2 \times \frac{\sigma_S}{\sigma_{Slim}} \right] / 3, \quad (1.8)$$

where

- $\sigma_H$ : standard deviation of the left and right profiles
- $\sigma_S$ : standard deviation of the crosslevel, gage, and horizontal deviation
- $\sigma_{Hlim}$ : standard deviation of the allowable  $\sigma_H$
- $\sigma_{Slim}$ : allowable value of  $\sigma_S$

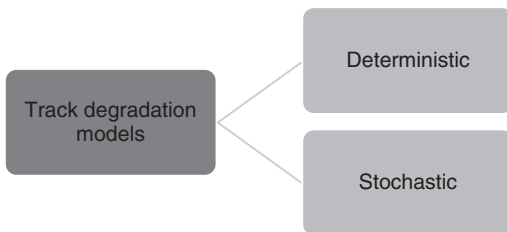
Table 1.5 shows indicators of different types of geometry defects

**Table 1.5** Indicators for each type of defect according to EN 13848-5 (Teixeira and Andrade, 2014) Reproduced with the permission of Springer.

Type of defect	Indicators
Track gage	Nominal track gage to peak value Nominal track gage to mean track gage over 100 m Minimum value of mean value over 100 m (on tangent track and in curves of radius $R > 10,000$ )
Longitudinal leveling	Mean to peak value (filtered in wavelength range 3–25 m) Mean to peak value (filtered in wavelength range 26–70 m) (only for train permissible speeds above 160 km/h) Standard deviation over a defined length, typically 200 m (filtered in wavelength range 3–25 m)
Horizontal alignment	Mean to peak value (filtered in wavelength range 3–25 m) Mean to peak value (filtered in wavelength range 26–70 m) (only for train permissible speeds above 160 km/h) Standard deviation over a defined length, typically 200 m (filtered in wavelength range 3–25 m)
Crosslevel	–
Twist	Zero to peak value (base length $l = 3$ m)

## 1.7 Track Geometry Degradation Models

Based on the existing literature, track geometry degradation models can be classified into two groups (Figure 1.10): deterministic and stochastic models. There are many contributions in this area in which different statistical techniques have been used in order to predict the track geometry degradation, which can be used as an input for determining the optimal schedule for maintenance activities. In this section, an overview of the contributions in literature regarding these track degradation models is presented, highlighting the main characteristics of each model and data collection technologies as well as discussing the findings and trends regarding track degradation models.



**Figure 1.10** Classification of track geometry models based on parameters' uncertainty

### 1.7.1 Deterministic Models

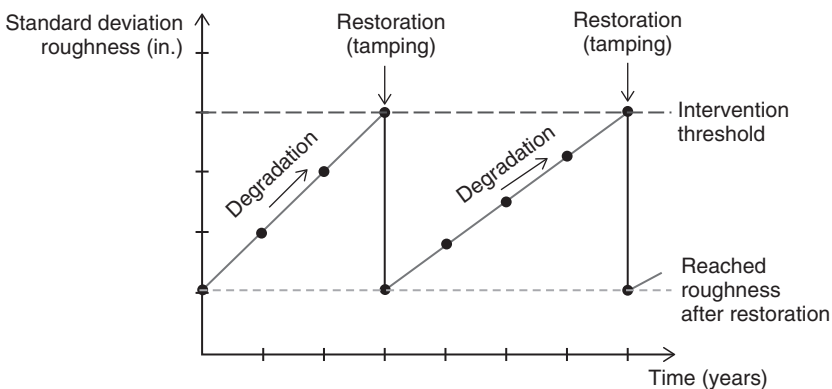
In general, a deterministic model assumes that both the input and the output of a system are constant values, so there is no uncertainty involved. That means that the output of the model only depends on the initial condition of the system and the parameter values. In track geometry degradation, those deterministic models can be linear or nonlinear (polynomial, exponential, etc.), and they are created with the assumption that model parameters are fixed values. There are literature reviews that address deterministic models for track geometry degradation, in which the works of Oberg (2006), Guler (2013), and Dahlberg (2001) are highlighted. In this section, a review of the contributions of track geometry degradation models is presented.

#### 1.7.1.1 Linear Models

In terms of linear track geometry degradation models, it is assumed that the model is linear in its parameters and that track degrades in a constant rate usually referred to in terms of in./MGT. Once it reaches a specified intervention threshold, maintenance activities are performed, such as tamping in order to achieve the desired roughness level (Figure 1.11). Usually, the intervention thresholds are determined based on railroads. In the United States, the FRA establishes the tolerances in terms of track safety requirements.

There exist in the literature several contributions of a linear representation of track geometry degradation, as presented below.

Chang et al. (2010) incorporated multilinear components in the track degradation model. The authors highlight the characteristics of the track geometry degradation in terms of three elements: (a) periodicity, which means that track geometry defects change patterns over the same track section and are the same between two adjacent track maintenance; (b) multistage, which means



**Figure 1.11** Linear representation of track geometry degradation and restoration based on the standard deviation of roughness

that the track geometry degradation rate varies from beginning to the end; and (c) experimental, which refers to the fact that track geometry degradation rate increases as passing tonnage increases. The multilinear model is presented in Equation 1.9 as follows:

$$\sigma_{TLD} = a_n + b_n T, \quad (1.9)$$

where

- $\sigma_{TLD}$ : standard deviation of longitudinal leveling defects
- $b_n$ : slope of line  $n$
- $a_n$ : intercept of line  $n$
- $T$ : cumulative passing tonnage from last maintenance to the present day

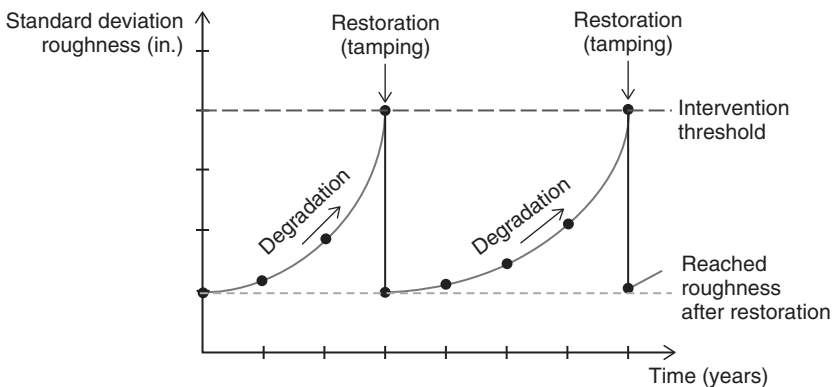
### 1.7.1.2 Nonlinear Models

Nonlinear models, on the other hand, assume that the degradation model is not linear in its parameters, so, in counterpart to linear models, the track roughness can be either a polynomial or exponential function, among others (Figure 1.12).

### 1.7.2 Stochastic Models

In general, a stochastic model assumes uncertainty in the model analysis.

Andrade and Teixeira (2012) implemented Markov chain Monte Carlo (MCMC) to estimate track geometry deterioration model parameters. The objective is to evaluate the uncertainty behavior of the infrastructure through its life cycle. The data was taken from the railway Lisbon–Porto in Portugal. In terms of modeling purposes, the authors considered the standard deviation of the longitudinal leveling defects. The track geometry deterioration model



**Figure 1.12** Nonlinear representation of track geometry degradation and restoration based on the standard deviation of roughness

follows the linear relationship using 200 m of track section, as shown in Equation 1.10.

$$\sigma_{LD} = c_1 + c_0 T, \quad (1.10)$$

where

- $\sigma_{LD}$ : standard deviation of the longitudinal leveling defects (mm)
- $c_1$ : initial standard deviation of the longitudinal leveling defects right after upgrade actions (mm)
- $c_0$ : deterioration rate (mm/100 MGT)
- $T$ : cumulative tonnage after track upgrade (100 MGT)

In terms of the Bayesian analysis, the authors assumed informative prior distribution by using elicitation. For the prior estimation of parameters  $c_1$  and  $c_0$  at the design stage, the authors used inspection data from the railroad Lisbon–Porto. By using a hypothesis test, the deterioration rate  $c_0$  followed a log-normal distribution, and the initial standard deviation of the longitudinal leveling defects  $c_1$  followed a bivariate log-normal distribution. In terms of the MCMC, the simulations were run considering the track sections divided into four groups: plain track, bridges, stations, and switches. The MCMC convergence was controlled by using a burn-in period length of 2000 values. The thinning consisted of 10,000 values with a lag  $L = 500$ ; it was made in order to eliminate the autocorrelation of the time series.

Andrade and Teixeira (2013) considered a hierarchical Bayesian approach where they assumed that the standard deviation of longitudinal level defects was normally distributed and where the mean was composed of the following elements: (a) the constant linear evolution with MGT, (b) the initial standard deviation of longitudinal defects, (c) the disturbance effect of the initial standard deviation of longitudinal level defects after each tamping operation, and (d) the differentiate of renewed track and nonrenewed track sections. In addition, the authors assumed non-informative priors using inverse gamma distributions.

Likewise, the work of Andrade and Teixeira (2011) defined track geometry defects in terms of the elements described above, as well as the linear representation of the standard deviation of the longitudinal leveling defects. For parameter estimation, the authors used the Kolmogorov–Smirnov goodness-of-fit test. In addition, a Monte Carlo simulation was performed in order to assess the uncertainty regarding the tamping cycle for each track section group and specific quality level, concluding that ballasted deck bridges and switches require far more frequent tamping actions compared with stations and plain track.

Audley and Andrews (2013) also present a linear degradation model as the relationship presented in Equation 1.11. For parameter estimation, the authors utilized a maximum likelihood estimation method.

$$\sigma = A + Bt, \quad (1.11)$$

where

- $\sigma$ : vertical alignment (mm)
- $A$ : intercept (mm)
- $B$ : deterioration rate (mm/day)

In terms of Markov models, Yousefikia et al. (2014) presented a Markov model in order to assess tram track condition and predict maintenance actions for Melbourne tram track data. For that purpose, the authors defined seven states for track condition named as follows:

- Normal
- Maintenance limit – degraded failure undetected
- Maintenance limit – degraded failure inspected
- Action limit – degraded failure undetected
- Action limit – degraded failure inspected
- Safety limit
- Repaired

On the other hand, He et al. (2013) considered a stochastic track geometry degradation model, considering factors such as the monthly traffic MGT traveling through track lot  $k$  ( $X_{1t}(t)$ ), the monthly total number of cars ( $X_{2t}(t)$ ), the monthly total number of trains ( $X_{3t}(t)$ ), and the number of inspection runs in sequence since the last observed red tag geometry defect ( $X_{4t}(t)$ ). Equation 1.12 shows the representation of the model.

$$\log \left( \frac{Y_k(t + \Delta t) - Y_k(t)}{\Delta t Y_k(t)} \right) = \alpha_0 + \alpha_1 X_{1k}(t) + \dots + \alpha_p X_{pk}(t) + \varepsilon_k(t),$$

$$\forall k = 1, \dots, N \quad (1.12)$$

where

- $Y_k(t)$ : aggregated geometry defect amplitude of the track lot  $k$  at inspection time  $t$
- $N$ : total number of track lots
- $X_{pk}(t)$ :  $p$ th external factor or predictor for  $k$ th track lot at inspection time  $t$
- $\alpha_0$ : model intercept
- $\alpha_i$ : coefficients for  $i$ th  $X$  factor.  $i = 1, \dots, p$
- $\varepsilon_k(t)$ : random error.  $\varepsilon_k(t) \sim N(0, \sigma^2)$

In addition, Vale and Lurdes (2013) performed a stochastic model based on Dagum distribution, which is used for describing the track geometry degradation process over time. Dagum distribution is a function of the input data and the model parameters. For parameter estimation, the authors used the maximum likelihood method.

Meier-Hirmer et al. (2006) presented a gamma process for track degradation and a classification method based on regression trees using environmental



variables, such as type and height of ballast, maximum speed, weather conditions, type of rail, and accumulated tonnage since ballast renewal, among others. In the paper, the authors considered longitudinal leveling defects as the track failure mechanism for track geometry defects.

Oyama and Miwa (2006) developed a model for measuring track surface irregularities and predicting track maintenance operation effects based on a logistic distribution. The transition process of surface irregularities model is composed of two processes: degradation and restoration. For the degradation model, the exponential smoothing method was used to predict the increasing trend of parameter  $b$  (standard deviation of logistic distribution) and expresses the typical characteristics of the track surface irregularities. For the restoration model, the  $\beta$  values before and after tamping operations were compared.

Table 1.6 attempts to summarize various models and the authors based on the work presented by Galvan-Nunez (2017).

### 1.7.3 Discussion

Based on the literature review (Table 1.6), the following conclusions are made:

- Most deterministic models focus on the study of differential ballast settlement as the main track geometry failure mechanism.
- There is no uniqueness in the used terminology with regard to track geometry degradation.
- Although the research trend suggests to consider uncertainty in track geometry degradation models, there is still no consensus in literature about such models. This is verified with the wide number of publications in the area that use different track geometry parameters. Based on that, it can be seen that the study of track geometry degradation is an open field that needs to be improved.

## 1.8 Rail Defect Data

Rail defects are almost always caused by fatigue from wheel–rail interactions and the presence of defective materials. Cannon et al. (2003) noted that fatigue failure in rail develops in three basic phases: first a fatigue crack initiates, and then it grows in size, and finally in the absence of control or maintenance, the rail breaks. The authors presented three broad groups of rail failure as follows:

- Those originating from rail manufacture – for example, tache or kidney defect
- Inappropriate handling, installation, and use – for example, wheel burn defects
- Those caused by exhaustion of rail steel’s inherent resistance to fatigue damage – for example, head checking, squats, and others.

**Table 1.6** Summary of literature review<sup>a)</sup>.

Author	Degradation model	Model parameters
Iyengar and Jaiswal (1995)	Random field	Absolute vertical profile, unevenness data
Meier-Hirmer et al. (2006)	Gamma process	$NL$ : longitudinal leveling, $\alpha$ : Gamma parameter (constant), $\beta$ : Gamma parameter (constant)
Oyama and Miwa (2006)	Exponential smoothing	$b$ : standard deviation of logistic distribution/track surface irregularities
Veit (2007)		
Chang et al. (2010)	Multi-stage linear regression	$\sigma_{TLD}$ : standard deviation of longitudinal level irregularity, $b_n$ : slope of line $n$ , $a_n$ : intercept of line $n$ , $T$ : cumulative passing tonnage from last maintenance to the present day
Xu et al. (2011)	Linear regression	
Berawi et al. (2010)	Linear regression	
Quiroga and Schnieder (2012)	Exponential function	$NL$ : longitudinal leveling, $NL_{init}$ : initial longitudinal leveling, $t$ : time, $t_n$ : time at which the last tamping operation took place, $b_n$ : log-normally distributed variable, $en(t)$ : measurement noise/normally distributed variable, $n$ : number of tamping interventions
Andrade and Teixeira (2011)	Linear regression	$c_1$ : Initial standard deviation after renewal or tamping operations, $c_0$ : Deterioration rate (mm/100 MGT), $T$ : Cumulative tonnage between tamping operations (100 MGT)
Andrade and Teixeira (2012)	Linear regression	$c_1$ : initial standard deviation after renewal or tamping operations, $c_0$ : Deterioration rate (mm/100 MGT), $T$ : cumulative tonnage between tamping operations (100 MGT)

Table 1.6 (Continued)

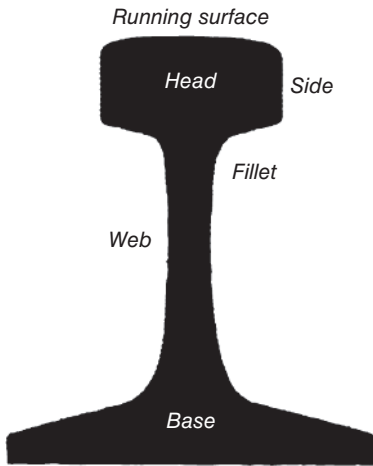
Author	Degradation model	Model parameters
Andrade and Teixeira (2013)	Hierarchical Bayesian	$Y_{svkl}$ : standard deviation of longitudinal level defects, $T_{svkl}$ : accumulated tonnage since last tamping or renewal operations, $b_{svk}$ : deterioration rate (constant linear), $a_{svk}$ : initial standard deviation of longitudinal level defects, $d_{sv}$ : initial standard deviation of longitudinal level defects after each tamping operations, $N_{svkl}$ : number of tamping operations performed since last renewal
Vale and Lurdes	Dagum model	Standard deviation longitudinal level, Dagum distribution shape and scale parameters
Audley and Andrews (2013)	Linear regression	
Yousefikia et al. (2014)	Markov chain	Markov chain states: normal, maintenance limit. Degraded failure undetected, maintenance limit. Degraded failure inspected, action limit. Degraded failure undetected, action limit. Degraded failure inspected, safety limit. Repaired
Guler (2013)	Artificial neural networks	–Gradient (%) curvature (1/R) (1/m), crosslevel (mm), speed (km/h), age (years), rail type (kg/m), rail length (m), tie type

a) Galvan-Nunez (2017).

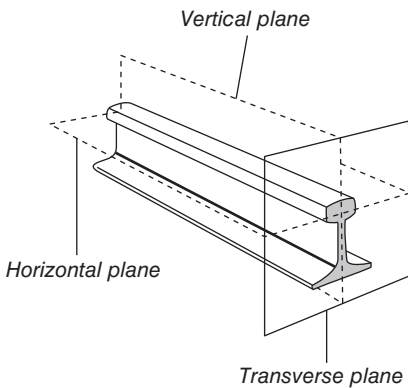
Rail defect management is one of the most important tasks in ensuring the reliable and safe operation of rail transport. Two major objectives of rail defect management are to (a) detect and rectify rail defects before they cause rail breaks and to (b) reduce and eliminate rail defects. Now with large amounts of data available from different railway agencies, the use of traditional statistical methods to address these objectives may not be adequate. The defect management systems include reporting and classifying rail failures, inspection and

actions, rail failure statistics, and other important information. The FRA (FRA, 2015) presented an extensive catalog of different rail defects and their nomenclatures. Broken rails occurring when traffic is at track speed can be costly present other safety issues (Zarembski and Palese, 2005).

Figures 1.13 and 1.14 show cross sections of rail and different planes. Tables 1.7–1.13 show different rail defects.



**Figure 1.13** Cross-section of a rail



**Figure 1.14** Transverse, vertical, and horizontal planes of track

**Table 1.7** Rail defects classification.

Defect name	Characteristics
Plastic deformation	<p>Will always be present in rail–wheel contact</p> <p>On a microscopic scale – close to the rail surface</p> <p>On a macroscopic scale – change of profile shape</p> <p>Work hardening and adaption to loading condition</p>
Wear	<p>Interaction between two surfaces results in dimensional loss of one solid</p> <p>Continuous material removal from the rail surface due to interaction between wheel and rail</p> <p>Several empirical wear laws do exist</p> <p>Types of wear (in the wheel–rail contact): adhesive wear, abrasive wear, fatigue wear, corrosive wear</p>
Corrugation	<p>Wave structure on the rail surface (tangent/curve)</p> <p>Short wave (25–80 mm wavelength) or long wave (100–300 mm) corrugation</p> <p>More detailed classification possible</p> <p>Combination of wear and plastic deformation</p> <p>Damage of other track components possible</p>
Head checks/gage corner cracking	<p>Periodic cracks at the gage corner</p> <p>Sometimes also cause periodic cracks on the running surface</p> <p>Grade-dependent crack spacing</p> <p>Can cause detail fracture if not treated</p>
Flaking and spalling	<p>Head checks can combine, causing material to break out of the rail surface</p> <p>Head checks – flaking – spalling</p>
Shelling	<p>Originates underneath the rail surface</p> <p>Delamination of rail material – crack will surface at gage corner and cause material to break out</p> <p>High loading conditions favor formation</p>
Squats	<p>Widening of running band</p> <p>Typical kidney-like shape and V-crack</p> <p>Three different classes (light, medium, severe)</p> <p>Difficult to detect in early stages by automated means</p> <p>Singular event or epidemic occurrence</p> <p>Can cause detail fracture</p> <p>Mixed traffic to low load conditions (low wear)</p>
Detail analysis – severe squat	<p>V-crack with opposite surfacing crack on running band</p> <p>Strong widening of running band and extended longitudinal extension</p> <p>Point of crack origin at tip of V</p> <p>Bowl-like growth of subsurface crack</p> <p>Break outs on rail surface</p>
Wheel burn	<p>Occurs in pairs directly opposite to each other (both rails)</p> <p>Continuous slipping of locomotive wheel set</p> <p>High temperature input to rail surface</p> <p>Formation of hard and brittle martensite layers (thick layers)</p> <p>Massive damage to rail surface</p>

**Table 1.8** Transverse defects.

Defect type	Detection	Comments
Transverse fissure	Can be detected by 70° transducer beams	Growth is initially slow, until defect 20–25% Failure almost occurs before defect becomes visible
Compound fissure	Can be detected by 70° transducer beams	Growth is normally slow until the defect reaches 30–35% Failure occurs before defect is visible Complete break of the rail across head, web, and base
Detail fracture Shelling Head check	Can be detected by 70° transducer beams	Growth is slow until defect reaches 15% Failure occurs before defect is visible
Engine burn fracture	Can be detected by 70° transducer beams	Growth is normally slow until the defect reaches 10–15% Failure occurs before defect is visible
Welded burn fracture	Can be detected by 70° transducer beams	Growth is normally slow until the defect reaches 15–20% Failure occurs before defect is visible

**Table 1.9** Longitudinal defects.

Defect type	Detection	Comments
Horizontal split head	0° and 45° transducer beams	May develop into a compound fissure
Vertical split head	0° and 45° transducer beams	Initially not visible Widening of the head for the length of the split
Shear break	0° and 45° transducer beams	Growth is sudden Initially not visible

**Table 1.10** Web defects.

Defect type	Detection	Comments
Head and web separation	0° and 45° transducer beams	Growth is rapid Entire length of the rail is usually weakened
Split web	0° and 45° transducer beams	Growth is rapid Entire length of the rail is usually weakened
Piped rail	0° and 45° transducer beams	Growth is usually slow Heavy loads may accelerate growth Rail is weakened for the distance of the pipe
Web and head separation	0° and 45° transducer beams	Growth usually occurs in gradual stages Rail is weakened for a distance in excess of the progressive separation

**Table 1.11** Base defects.

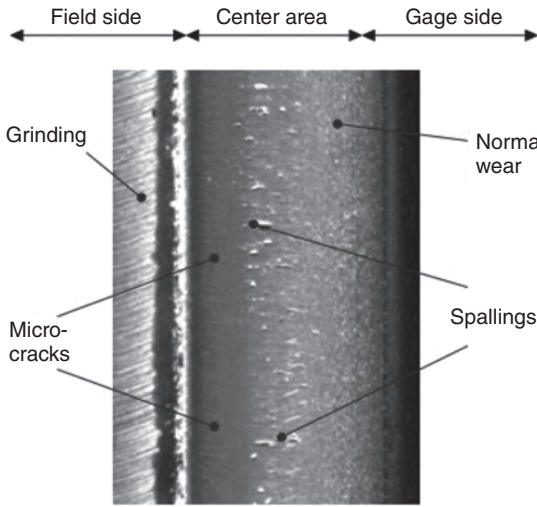
Defect type	Detection	Comments
Broken base	0° and 45° transducer beams	Weakened section
Base fractures	0° and 45° transducer beams	Growth relatively slow until the defect progresses from the edge of the base into the rail

**Table 1.12** Surface defects.

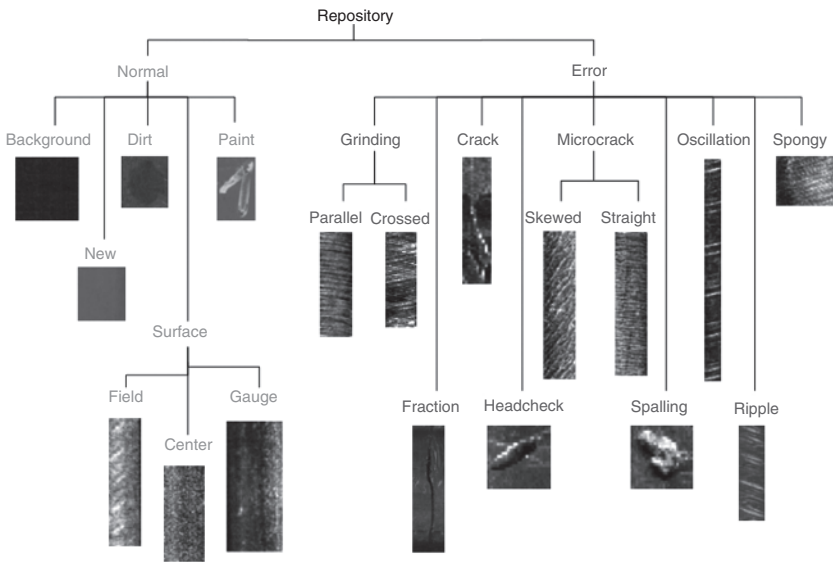
Defect type	Detection	Comments
Corrugation Short pitch Long pitch	Visual inspection	Not a serious hazard Short pitch between 30 and 90 mm wavelength Long pitch between 150 and 200 mm wavelength Can be rectified by grinding
Rolling contact fatigue	Visual inspection	Cracks initiate close to rail surface Cracks can spread across the rail head Can be rectified by grinding
Shelling	Visual inspection	Occurs frequently in curve territory Transverse representation may occur
Squats Running surface Gage corner	Visual inspection	Type of rolling contact fatigue Cracking when in moderate to severe stages Can develop in track with either timber or concrete ties Often develops in switches and turnouts Rail replacement needed in severe cases

**Table 1.13** Wheel burns.

Defect type	Detection	Comments
Wheel burns	Visual inspection	Does not grow Damage may cause roughening of traffic Can cause transverse separation May develop into thermal cracks



**Figure 1.15** Surface regions of rail head (Huber-Mörk et al. (2010). Reproduced with the permission of Springer)



**Figure 1.16** Repository of rail head surface classes: normal or noncritical surface (Huber-Mörk et al. (2010). Reproduced with the permission of Springer)

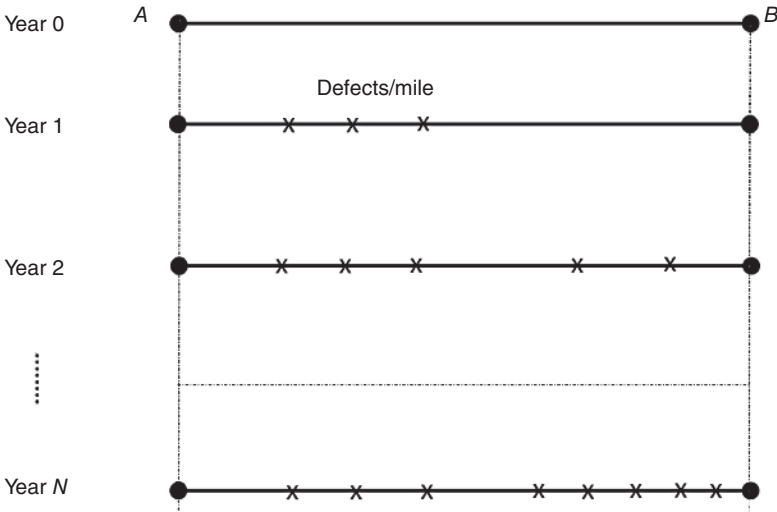
Figure 1.15 shows the surface regions of the rail head. Figure 1.16 shows different surface classes.

Figure 1.17 shows an example of defects per mile for track section AB. The defect rate is nonlinear. Figure 1.18 shows the percentage of all defects per mile.

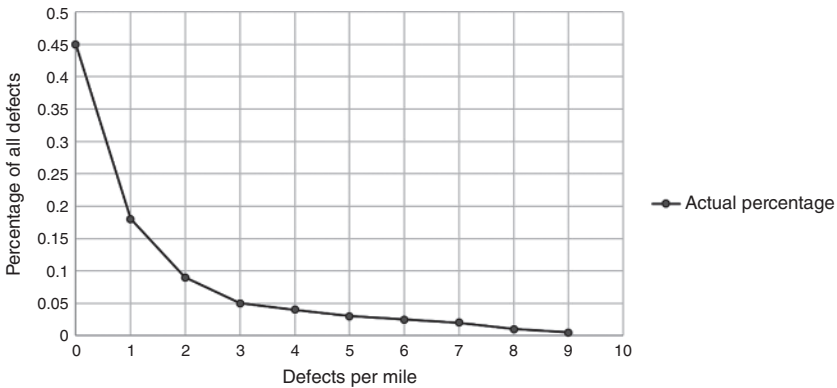
Rail track defects per mile or defect initiation grows with age but the growth rate is not linear. The crack also grows nonlinearly from initiation to failure. Figure 1.17 is a section of rail track.

The Weibull distribution has been the method used in the probabilistic analysis of rail defect occurrences within the rail track. It has been shown that





**Figure 1.17** Rail defects per mile



**Figure 1.18** Rail defects distribution

the past defect history appears to be important for the prediction of future rail defects (Palese and Wright, 2000). Figure 1.18 demonstrates statistical rail defect distribution.

## 1.9 Inspection and Detection Systems

There are various methods used to detect defects; these include the following:

- Ultrasonic testing from non-destructive test vehicle.
- Visual inspection methods by the track maintenance team. They also involve the use of ultrasonic equipment.
- Dye penetration and magnetic particle method. This is usually used for surface defects.

- Eddy current testing. This is a noncontact method of identifying surface-breaking or near-breaking defects.
- Radiography. This is used for the examination of aluminothermic welds that contain irregular, nonplanar defects and defects that are very difficult to detect using ultrasonic methods.

There are other new technologies, which include the following:

- Low frequency eddy current sensors to locate deeply buried defects. This type of detection makes the application of deep neural networks a viable technique in analyzing the data.
- Laser generation and reception of ultrasonic waves to enable noncontacting inspection (Allipi et al., 2000).
- Longitudinal guided waves, which allow locomotives to scan the track ahead.
- High-speed ultrasonic testing.
- Automated vision systems – their application is restricted to surface defects.
- Machine vision and profilometer technology.
- Ultrasonic rail flaw testing (Sawadisavi, 2010).
- Radiographic inspection or X-ray diffraction measurements for rolling contact fatigue layer (Matsui, 2014).
- Ground-penetrating radar (GPR) applications. The GPR inspection is focused on the thickness of rail track ballast, subsoil materials penetrating the ballast, and properties of the subgrade materials.

Currently there are also hybrid systems, combinations of human inspection and automated inspection devices. The general rationale is that human inspectors can (a) perform more detailed inspection but not necessarily objective, (b) provide better decision-making on the found defect, and (c) search for a larger variety of defects. The automated inspection, on the other hand, can (a) operate at a higher speed, (b) better locate small variations from the normal pattern, (c) limit human errors and bias, and (d) be very objective, consistent, and precise.

Carr (2014) discussed the application of autonomous track inspection technology that inspects the track from revenue service trains using unattended instrumentation. For example, the autonomous track geometry measurement systems (ATGMS) are mounted on the rail car and have remote access. They provide efficient inspections at a much lower cost and can identify changes in patterns very early through frequent inspections. Carr (2014) presented various inspection systems that are in operation and those that will be in operation soon. Table 1.14 shows the various inspection systems. There are systems available that can automatically detect visible anomalies on the surface of the rail, a missing fastener element, or a cracked or damaged tie and measure the ballast profile and hence the volume of the ballast. There are also other technologies, like the acoustic bearing detector (ABD) that uses sound

**Table 1.14** NDT techniques for the rail industry.

<b>NDT technique</b>	<b>Systems available</b>	<b>Defects detected</b>	<b>Performance</b>
Ultrasonics	Manual and high-speed systems (up to 70 km/h)	Surface defects, rail head internal defects, rail web, and foot defects	Reliable manual inspection but can miss rail foot defects. At high speed can miss surface defects smaller <4 mm as well as internal defects, particularly at the rail foot
Magnetic flux leakage (MFL)	High-speed systems (up to 35 km/h)	Surface defects and near-surface internal rail head defects	Reliable in detecting surface defects and shallow internal rail head defects but cannot detect cracks smaller than <4 mm. MFL performance deteriorates at higher speeds
Pulsed eddy current (including field gradient imaging)	Manual and high-speed systems (up to 70 km/h)	Surface and near-surface internal defects	Reliable in detecting surface-breaking defects. Adversely affected by grinding marks and lift-off variations
Automated Visual Inspection	Manual and high-speed systems (up to 320 km/h)	Surface-breaking defects, rail head profile, corrugation, missing parts, defective ballast	Reliable in detecting corrugation, rail head profile missing parts, and defective ballast at high speeds. Cannot reliably detect surface-breaking defects at speeds >4 km/h. Cannot assess the rail for internal defects
Radiography	Manual systems for static tests	Welds and known defects	Reliable in detecting internal defects in welds difficult to inspect by other means. Can miss certain transverse defects
Electromagnetic acoustic transducers	Low-speed hi-rail vehicle (<10 km/h)	Surface defects, rail head, web, and foot internal defects	Reliable for surface and internal defects. Can miss rail foot defects. Adversely affected by lift-off variations

*(Continued)*

**Table 1.14** (Continued)

<b>NDT technique</b>	<b>Systems available</b>	<b>Defects detected</b>	<b>Performance</b>
Long-range ultrasonics	Manual systems and low-speed hi-rail vehicle systems (<10 km/h)	Surface defects, rail head internal defects, rail web, and foot defects	Reliable in detecting large transverse defects (>5% of the overall cross-section)
Laser ultrasonics	Manual and low-speed hi-rail vehicle systems (<15 km/h)	Rail head, web and foot defects	Reliable in detecting internal defects. Can be affected by lift-off variations of the sensors, difficult to deploy at high speeds
Alternating current field measurement	Manual systems (hi-speed system under development)	Surface-breaking defects	Reliable in detecting and quantifying surface-breaking defects. Cannot detect subsurface defects. Very good tolerance to lift-off variations
Multifrequency eddy current sensors	Manual system. Static and slow speed.	Surface and near-surface defects.	Limited experiments conducted. Has the potential to reliably quantify defects detected
MAPS	Manual system. Static and walking speed tests	Residual stresses	Results comparable to X-ray diffraction. Commercially available

(Papaelias et al., 2008)

properties generated by specific component defects, the hot box detector (HBD) that evaluates the bearing temperature history and other defect issues based on temperature outliers, and the cracked wheel/axle detector that consists of rail-mounted sensors detect different tones generated by normal versus flawed wheel axles (Rose, 2015).

The Alliance for Innovation and Infrastructure (AIL, 2015) noted the following technologies for improving track integrity:

- *Track Integrity Sensors.* These can be used in both the rail and the ballast. It broadcasts anomalies to monitoring stations, and it is useful for maintenance in demand.
- *Ballast Integrity Sensors.* These provide continuous, real-time monitoring of subgrade movement in reference to the track structure.
- *Autonomous Track Geometry Measurements.* These measure and record track geometry remotely from an autonomous rail car in a regular train service.
- *Gage Restraint Measurement Systems (GRMS).* These are systems that measure rail motion under a combined vertical and lateral load to detect weak ties and fasteners. Their use allows inspectors to identify specific conditions at a specific location of tracks.
- *Ultrasonic and Induction Rail Testing.* Ultrasonic uses waves sent in angles that are reflected back to transducers and analyzed.

## 1.10 Rail Grinding

Zarembski and Palese (2005) presented a comprehensive overview and detailed technical description of rail grinding. The authors defined railway grinding as the removal of small amounts of metal from the top of the rail through the use of abrasive grinding materials with the rotating properties of the grinding motors. Rail grinding is an integral part of railway track routine maintenance. Some reasons for rail grinding are controlling (a) surface fatigue, (b) weld dipping, (c) plastic flow, (d) rail wear, (e) wheel wear and fatigue, (f) truck hunting, and (g) wheel/rail noise and (h) improving reliability of ultrasonic rail test. The success of the grinding operations depends on the characteristics and condition of the abrasive wheel, the applied pressure, and the speed of and angle between the grinding stones and the rail (Cuervo et al., 2015; Hartsough et al., 2016). There are four principal types of rail grinding (Elaina, 2015):

- *Corrective or Defect Grinding.* This is primarily the removal of the rail defects that have developed, which include (a) corrugations, (b) gross plastic flow, and (c) rolling contact fatigue defects. This involves aggressive grinding procedures that aim to remove a considerable amount of metal between 0.5 and 6 mm at long intervals determined by the severity and cluster.

- *Transitional Grinding.* This is less intensive than corrective grinding. The main objective is to provide a partial corrective grind to prepare the tracks for a preventive grind.
- *Preventative or Cyclic Grinding.* The objective of this type of grind is to eliminate or at least control rail defects and maintain the surface condition and preferred rail profiles. It usually involves removing about a minimum of 0.2 mm at more frequent and controlled intervals. The frequency is often determined by estimation and experience, so there is a fair amount of subjectivity. Preventative grinding can prolong rail life.
- *Special Grinding.* This involves the use of grinding to achieve a specific objective, for example, establishing the rail profiles to reduce the rate of wheel hollowing or to provide a very smooth rail contact surface to reduce noise and other dynamic effects generated by wheel–rail contact.

There are quite a number of optimization issues encountered in preventive maintenance metal removal because the optimal metal removal rate is dependent on different factors, including (a) tonnage since the last grinding cycle, (b) axle load, (c) traffic type, (d) rail metallurgy, (e) track grade, (f) track superelevation, (g) track curvature, (h) track gage, (i) track support structure, (j) friction management, and (k) environmental factors.

Bremsteller (2014) depicted critical defect depth and MGT. It was concluded that surface defects do not develop linearly and that doubling MGT results can result in triple damage depth. Figure 1.19 shows the graph of critical depth

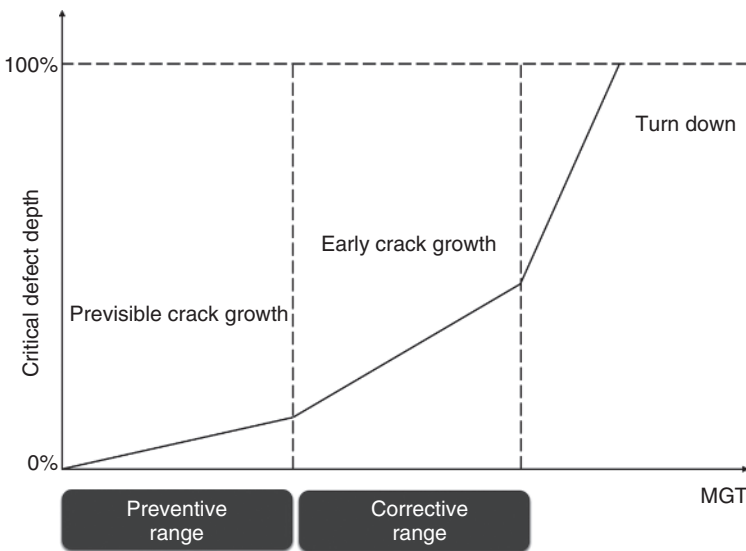
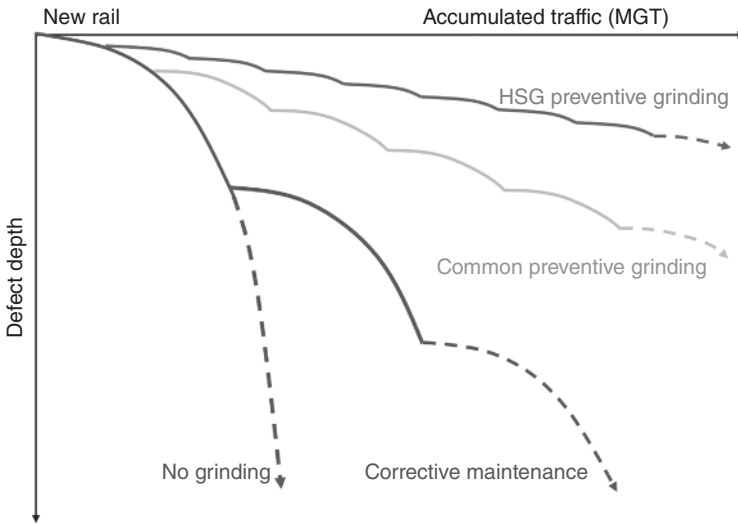


Figure 1.19 Rolling contact fatigue. Courtesy: Johannes Bremsteller



**Figure 1.20** Different rail maintenance strategies. Courtesy: Johannes Bremsteller

and MGT. Again the authors presented a graph comparing different rail maintenance strategies and defect depth (Figure 1.20). One major analytical issue based on the frequency curves is how effective the grinding process is at eliminating certain types of defects.

Palese et al. (2004) developed the grinding quality index (GQI) to evaluate the effectiveness of rail profile grinding and to check the difference between ground rail profile and the desired profile. By calculating the GQI before and after grinding, the effectiveness of the grinding operation can be assessed. The accuracy of GQI depends on the following:

- a) Method of profile captured
- b) Quality of rail image
- c) Calibration process
- d) Train speed during measurement
- e) Environmental conditions and factors

Mathematically, the grinding process can be expressed as follows:

$$y_{p_i} = p_i(x), \quad (1.13)$$

$$y_{R_i} = r_i(x), \quad (1.14)$$

where  $y_{p_i}$  is the measure profile,  $y_{R_i}$ ,  $y_p \geq y_R, \forall x$ .

The area between profile and template can be expressed as follows:

$$\text{Area} = [P_i(x) - r_i(x)]\Delta x \quad (1.15)$$

The GQI

$$G_i = 100 \frac{A_b}{A_a + A_b}, \quad (1.16)$$

where

- $A_a$ : Area difference profile above acceptable envelope
- $A_b$ : Area difference profile below acceptable envelope
- $G_i$  is between 0 and 100

## 1.11 Traditional Data Analysis Techniques

Various data analytical techniques have been used to analyze the output of rank inspection systems. Table 1.15 shows some of the techniques that have been used. Some cases are hybrid methods that involve the combination of different analytical techniques, like traditional neural network and wavelets application. Other hybrid applications include edge detection methods and the support vector machine (SVM). Bhaduri (2013) used a wavelength intensity algorithm as an extraction algorithm and used the SVM as a classifier. Arivazhagan et al. (2015) discussed various automatic crack detection techniques based on morphological operations, fractal analysis, and edge detection schemes.

**Table 1.15** Automated visual railway component inspection methods.

Components	Defects	Features	Decision methods
Fasteners	Missing	DWT	Three-layer NN
Fasteners	Missing	Edge density	Threshold
Fasteners	Broken	DWT	Threshold
Joint bars	Cracks	Edges	SVM
Fasteners	Missing/defective	Intensity	OT-MACH corr.
Fasteners	Broken	Haar	Adaboost
Fasteners	Missing	Direction field	Correlation
Ties/turnouts	–	Gabor	SVM
Tie plates	Missing spikes	Lines/haar	Adaboost
Fasteners	Missing/defective	Haar	PGM
Concrete ties	Cracks	DST	Iterative shrinkage
Fasteners	Defective	Harris-Stephen, Shi-Tomasi	Matching errors
Fasteners	Missing/defective	HOG	SVM
Concrete ties	Tie condition	Intensity	Deep CNN

Gibert et al. (2015). Reproduced with the permission of IEEE.



Gibert et al. (2015) discussed how multitask learning, an inductive transfer learning method in which two or more machine learning techniques are trained, can be applicable in track output data analysis. The main idea of this approach is that each task can benefit from reusing knowledge that has been learned while training for other tasks.

GPR data analysis involves analysis of images and signal processing tools to address the information obtained. Novel multivariate signal and image processing techniques are currently used to automatically detect and quantify various anomalies in the ballast and other subsurface conditions. Li et al. [Evaluation of GPR Technologies for Assessing Track Substructure Conditions] presented the results of GPR railway track applications. Li et al., attempted to tie the geometrical characteristics of the track with the GPR results. Ibrek (2015) used GPR to detect subsurface track body anomalies like ballast pockets and animal burrows and to map the distribution of water in the track body. Also, Ibrek (2015) discussed some GPR studies and railway applications: (a) measuring ballast layer thickness; (b) determining the degree of ballast fouling; (c) locating hidden objects; (d) detecting ballast anomalies that include subgrade penetration, ballast pockets, and mud pumping; and (e) detecting frost susceptibility and ice lens formations. In GPR analysis, sources of unwanted signal noise, or any abnormal signal, should be identified and removed from the output before initiating any analysis. The short-time Fourier transform has been used in ballast fouling surveys. SVM and  $k$ -neural network were also used in GPR ballast applications (Shao et al., 2011).

Recently, Einbinder (2015) used multivariate adaptive regression splines (MARS) to develop models that connect rail defects in terms of MGT to geometry defect variables. One major characteristic of the models developed by Einbinder (2015) is that the models were able to develop a set of equations between specific MGT ranges.

### 1.11.1 Emerging Data Analysis

Table 1.16 compares big data and traditional data. Most of the current analysis falls under traditional data analysis. As data becomes extremely large, different properties of the data will change, and hence one needs to devise new methods, like ABC algorithms, to handle and solve problems emerging from railway track monitoring and control output. Critical questions need to be addressed including how one can use the MapReduce architecture to solve problems.

## 1.12 Remarks

Most of the current data analysis techniques may not be appropriate in cases where there are large amounts of data present. It is also not clear if the current

**Table 1.16** Big data versus traditional data.

	Traditional data	Big data
Volume	GB	Constantly updated (TB or PB currently)
Generated rate	Per hour, day, ...	More rapid
Structure	Structured	Semi-structures or unstructured
Data source	Centralized	Fully distributed
Data integration	Easy	Difficult
Data store	RDBMS	HDFS, NoSQL
Access	Interactive	Batch or near real time

techniques will be efficient in solving problems on streaming data. Therefore, there is a need to develop a framework to analyze track data. As noted from the previous paragraphs, all the data, geometry or rail defect data, have most of the following characteristics:

- Massive data sets
- Unstructured data and heterogeneous databases
- Information in the form of images
- Poor quality of data
- Multiresolution and multisensor data
- Spatiotemporal data
- Noisy data
- Missing data
- Streaming data

## References

- AII. Back on track: bringing rail safety to the 21st century. Technical report, Alliance for Innovation and Infrastructure, 2015.
- C. Alippi, E. Casagrande, F. Scotti, and V. Piuri. Composite real-time image processing for railways track profile measurement. *IEEE Transactions on Instrumentation and Measurement*, **49**(3):559–564, 2000.
- A. R. Andrade and P. F. Teixeira. Uncertainty in rail-track geometry degradation: Lisbon-Oporto line case study. *Journal of Transportation Engineering ASCE*, **687**:193–200, 2011. doi: 10.1061/(ASCE)TE.1943-5436.0000206.
- A. R. Andrade and P. F. Teixeira. A Bayesian model to assess rail track geometry degradation through its life-cycle. *Research in Transportation Economics*, **36**(1):1–8, 2012. doi: 10.1016/j.retrec.2012.03.011.

- A. R. Andrade and P. F. Teixeira. Hierarchical Bayesian modelling of rail track geometry degradation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **227**(4):364–375, 2013. doi: 10.1177/0954409713486619.
- S. Arivazhagan, R. N. Shebiah, J. S. Magdalene, and G. Sushmitha. Railway track derailment inspection system using segmentation based fractal texture analysis. *Journal on Image and Video Processing*, **6**(1):1060–1065, 2015. [http://ictactjournals.in/paper/IJIVP\\_Paper\\_2\\_pp\\_1060\\_1065.pdf](http://ictactjournals.in/paper/IJIVP_Paper_2_pp_1060_1065.pdf).
- M. Audley and J. Andrews. The effects of tamping on railway track geometry degradation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **227**(4):376–391, 2013. doi: 10.1177/0954409713480439.
- J. S. Bendat. *Nonlinear System Techniques and Applications*. John Wiley & Sons, Inc., 2nd edition, 1998. ISBN: 9780471165767.
- A. R. B. Berawi, R. Delgado, R. Calcada, and C. Vale. Evaluating track geometrical quality through different methodologies. *International Journal of Technology*, **1**:38–47, 2010.
- S. Bhaduri. *Algorithm to enable intelligent rail break detection*. PhD thesis, Virginia Polytechnic Institute and State University, 2013. [https://theses.lib.vt.edu/theses/available/etd-12242013-094021/unrestricted/Bhaduri\\_S\\_T\\_2013\\_1.pdf](https://theses.lib.vt.edu/theses/available/etd-12242013-094021/unrestricted/Bhaduri_S_T_2013_1.pdf).
- J. Bremsteller. High Speed Grinding, 2014. ISSN: 10417958. <http://www.szdc.cz/soubory/konference-a-seminare/zdc-2014/b03-bremsteller-vossloh.pdf>.
- S. Bruni, I. Anastasopoulos, S. Alfi, A. Van Leuven, and G. Gazetas. Effects of train impacts on urban turnouts: modelling and validation through measurements. *Journal of Sound and Vibration*, **324**(3):666–689, 2009. doi: 10.1016/j.jsv.2009.02.016.
- D. F. Cannon, K.-O. Edell, S. L. Grassie, and K. Sawley. Rail defects: an overview. *Fatigue & Fracture of Engineering Materials & Structures*, **26**(10):865–886, 2003. doi: 10.1046/j.1460-2695.2003.00693.x.
- G. Carr. Embracing Technology for Railroad Track Inspection, 2014. [http://railtec.illinois.edu/cee/William W. Hay/Spring2014presentations/HaySeminar2014\\_GCarr\\_Final.pdf](http://railtec.illinois.edu/cee/William%20W.%20Hay/Spring2014presentations/HaySeminar2014_GCarr_Final.pdf).
- H. Chang, R. Liu, and Q. Li. A multi-stage linear prediction model for the irregularity of the longitudinal level over unit railway sections. In *Computers in Railways XII*, 2010. ISSN 17433509.
- G. Charles, R. Goodall, and R. Dixon. Vehicle system dynamics model-based condition monitoring at the wheel-rail interface. *Vehicle System Dynamics*, **46**:415–430, 2008. doi: 10.1080/00423110801979259.
- J. Choi. *Qualitative analysis for dynamic behavior of railway ballasted track*. PhD thesis, TU Berlin, 2014.
- S. Chrismer and E. T. Selig. Computer model for ballast maintenance planning. *Proceedings of 5th International Heavy Haul Railway*, 1993. [https://scholar.google.com/scholar\\_lookup?title=Computer%20model%20for%20ballast](https://scholar.google.com/scholar_lookup?title=Computer%20model%20for%20ballast)

- %20maintenance%20planning&author=S%20Chrismer&author=ET%20Selig&publication\_year=1993#%230.
- P. A. Cuervo, J. F. Santa, and A. Toro. Correlations between wear mechanisms and rail grinding operations in a commercial railroad. *Tribology International*, **82**:265–273, 2015. doi: 10.1016/j.triboint.2014.06.025.
- T. Dahlberg. Some railroad settlement models—a critical review. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **215**(4):289–300, 2001. doi: 10.1243/0954409011531585.
- D. Einbinder. *The development of rail defects due to the presence of geometry defects in class 1 railroads*. Master thesis, University of Delaware, 2015. [http://dspace.udel.edu/bitstream/handle/19716/17394/2015\\_EinbinderDaniel\\_MCE.pdf?sequence=1&isAllowed=y](http://dspace.udel.edu/bitstream/handle/19716/17394/2015_EinbinderDaniel_MCE.pdf?sequence=1&isAllowed=y).
- H. Elaina. Track engineering standard rail grinding. Technical report, Metro. MTST 033100-08, 2015.
- C. Esveld. *Modern Railway Track*. MRT-Productions, 2001. ISBN: 9080032433.
- FRA. Track safety standards: improving rail integrity. Technical report, Federal Railroad Administration, 2014a. <https://www.fra.dot.gov/eLib/Details/L04920>.
- FRA. Automated track inspection program (ATIP) geometry car operation. In *Track and Rail Infrastructure Integrity Compliance Manual*, Chapter 3, pages 1–22. Federal Railroad Administration, 1st edition, 2014b.
- FRA. Track inspector rail defect reference manual. Technical report, Federal Railroad Administration, 2015. <https://www.fra.dot.gov/Elib/Details/L03531>.
- S. Galvan-Nunez. *Hybrid Bayesian-Wiener Process in Track Geometry Degradation Analysis*. Ph.D. Thesis, 2017.
- X. Gibert, V. M. Patel, and R. Chellappa. Deep Multi-Task Learning for Railway Track Inspection, 2015. <http://arxiv.org/abs/1509.05267>.
- H. Guler. Prediction of railway track geometry deterioration using artificial neural networks: a case study for Turkish state railways. *Structure and Infrastructure Engineering*, **10**(5):1–13, 2013. doi: 10.1080/15732479.2012.757791.
- A. Haigermoser, B. Lubert, J. Rauh, and G. Gräfe. Road and track irregularities: measurement, assessment and simulation. *Vehicle System Dynamics*, **53**(7):878–957, 2015. doi: 10.1080/00423114.2015.1037312.
- A. Hamid, K. Rasmussen, M. Baluja, and T.-L. Yang. Analytical descriptions of track geometry variations. Technical report, Report No. DOT/FRA/ORD-83/03.1, 1983.
- C. M. Hartsough, J. W. Palese, G. Schmitzer, J. C. Espindola, and T. G. Viana. Optimized rail grinding through dynamic positioning and powering of grinding motors. In *2016 Joint Rail Conference*, page V001T01A005. ASME, 2016. ISBN: 978-0-7918-4967-5.
- W. J. Harris, W. Ebersöhn, J. Lundgren, H. Tournay, and S. Zakharov, *Guidelines to Best Practices for Heavy Haul Railway Operations: Wheel and Rail Interface Issues*, International Heavy Haul Association, 2001.
- W. W. Hay. *Railroad Engineering*. Wiley, 1982. ISBN: 9780471364009.

- Q. He, H. Li, D. Bhattacharjya, D. P. Parikh, and A. Hampapur. Railway track geometry defect modeling: deterioration, derailment risk, and optimal repair. In *Transportation Research Board 92nd Annual Meeting*, pages 1–20, 2013. <http://trid.trb.org/view.aspx?id=1242877>.
- R. Huber-Mörk, M. Nölle, A. Oberhauser, and E. Fischmeister. Statistical rail surface classification based on 2D and 21/2D image analysis. In *Advanced Concepts for Intelligent Vision Systems*, Volume 6474, pages 50–61. Springer, Berlin Heidelberg, 2010. [http://link.springer.com/10.1007/978-3-642-17688-3\\_6](http://link.springer.com/10.1007/978-3-642-17688-3_6).
- P. A. Y. Ibrekk. *Detecting anomalies and water distribution in railway ballast using GPR*. Master thesis, Norwegian University of Science and Technology, 2015. <https://brage.bibsys.no/xmlui/handle/11250/2381904>.
- R. N. Iyengar and O. R. Jaiswal. Random field modeling of railway track irregularities. *Journal of Transportation Engineering*, 121:303–308, 1995. doi: 10.1061/(ASCE)0733-947X(1997)123:3(245.2).
- S. Jovanovic. Railway track quality assessment and related decision making. In *AREMA 2006 Annual Conferences*, 2006.
- A. D. Kerr. *Fundamentals of Railway Track Engineering*. SimmonBoardman Books, Inc., 2003. ISBN: 0911382402, 9780911382402.
- I. A. Khouy, H. Schunnesson, U. Juntti, A. Nissen, and P.-O. Larsson-Kråik. Evaluation of track geometry maintenance for heavy haul railroad in Sweden - a case study. *Proceedings of the Institution of Mechanical Engineers*, Part F: Journal of Rail and Rapid Transit, 496–503, 2013. doi: 10.1177/0954409713482239.
- R.-K. Liu, P. Xu, Z.-Z. Sun, C. Zou, and Q.-X. Sun. Establishment of track quality index standard recommendations for Beijing metro. *Discrete Dynamics in Nature and Society*, 2015:1–9, 2015. ISSN 1026-0226. doi: 10.1155/2015/473830. URL <http://www.hindawi.com/journals/ddns/2015/473830/>.
- M. Matsui. Application of X-Ray Fourier Analysis to Rolling Contact Fatigue Layer of Rail, 2014. <http://www.rtri.or.jp/eng/publish/newsletter/pdf/48/RTN-48-283.pdf>.
- A. Matsumoto, Y. Sato, H. Ohno, M. Shimizu, J. Kurihara, M. Tomeoka, T. Saitou, Y. Michitsuji, M. Tanimoto, and M. Mizuno. Continuous observation of wheel/rail contact forces in curved track and theoretical considerations. *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility*, 50(1):349–364, 2012. doi: 10.1080/00423114.2012.669130.
- C. Meier-Hirmer, A. Senée, G. Riboulet, F. Sourget, and M. Roussignol. A decision support system for track maintenance. In *Computers in Railways X, WIT Transactions on The Built Environment*, Volume 1 and 88, pages 217–226. WIT Press, Southampton, UK, 2006. ISBN: 1845641779.
- S. Z. Meymand, A. Keylin, and M. Ahmadian. A survey of wheel-rail contact models for rail vehicles. *Vehicle System Dynamics: International Journal of*

- Vehicle Mechanics and Mobility*, **54**(3):386–428, 2016. doi: 10.1080/00423114.2015.1137956.
- J. Oberg. *Track Deterioration of Ballasted Tracks: Marginal Cost Models for Different Railway Vehicles*. Rail Vehicles, Aeronautical and Vehicle engineering, Royal Institute of Technology, 2006. ISBN: 917178537X, [https://books.google.com/books/about/Track\\_deterioration\\_of\\_ballasted\\_tracks.html?id=9hSUNAAACAAJ](https://books.google.com/books/about/Track_deterioration_of_ballasted_tracks.html?id=9hSUNAAACAAJ).
- T. Oyama and M. Miwa. Mathematical modeling analyses for obtaining an optimal railway track maintenance schedule. *Japan Journal of Industrial and Applied Mathematics*, **23**(2):207–224, 2006. doi: 10.1007/BF03167551.
- J. W. Palese, T. Euston, and A. M. Zarembski. Use of profile indices for quality control of grinding. In *Annual Conference and Exposition, AREMA*. AREMA, 2004. [https://scholar.google.com/scholar?hl=en&q=Use+of+profile+indices+for+quality+control+of+grinding&btnG=&as\\_sdt=1%2C8&as\\_sctp=](https://scholar.google.com/scholar?hl=en&q=Use+of+profile+indices+for+quality+control+of+grinding&btnG=&as_sdt=1%2C8&as_sctp=)
- J. W. Palese and T. W. Wright. Risk based ultrasonic rail test scheduling on Burlington Northern Santa Fe. In *AREMA Proceedings of the 2000 Annual Conference*, pages 1–35, 2000. <https://trid.trb.org/view.aspx?id=675467>.
- M. Papaalias, C. Roberts, and C. L. Davis. A review on non-destructive evaluation of rails: state-of-the-art and future development. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **222**(4):367–384, 2008. doi: 10.1243/09544097JRR209.
- L. M. Quiroga and E. Schnieder. Monte Carlo simulation of railway track geometry deterioration and restoration. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, **226**(3):274–282, 2012. doi: 10.1177/1748006X11418422.
- S. Ramírez-Gallego, S. García, H. Mouriño-Talín, D. Martínez-Rego, V. Bolón-Canedo, A. Alonso-Betanzos, J. M. Benítez, and F. Herrera. Data discretization: taxonomy and big data challenge. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, **6**(1):5–21, 2016. doi: 10.1002/widm.1173.
- M. Rose. *Shaping the Future of Rail Through Technology*, 2015.
- J. Sadeghi. Development of railway track geometry Indexes based on statistical distribution of geometry data. *Journal of Transportation Engineering*, **136**(8):693–700, 2010. doi: 10.1061/(ASCE)0733-947X(2010)136:8(693).
- J. Sadeghi and H. Askarinejad. Development of improved railway track degradation models. *Structure and Infrastructure Engineering*, **6**(6):675–688, 2010. doi: 10.1080/15732470801902436.
- J. C. Santamarina and D. Fratta. *Introduction to Discrete Signals and Inverse Problems in Civil Engineering*. ASCE Press, 1998. [https://books.google.com/books/about/Introduction\\_to\\_Discrete\\_Signals\\_and\\_Inv.html?id=GIVRAAAAMAAJ&pgis=1](https://books.google.com/books/about/Introduction_to_Discrete_Signals_and_Inv.html?id=GIVRAAAAMAAJ&pgis=1).

- Y. Sato. Japanese studies on deterioration of ballasted track. *Vehicle System Dynamics*, **24**(sup1):197–208, 1995. doi: 10.1080/00423119508969625.
- S. V. Sawadisavi. *Development of Machine-vision technology for inspection of railroad track*. PhD thesis, University of Illinois at Urbana-Champaign, 2010.
- E. T. Selig and J. M. Waters. *Track Geotechnology and Substructure Management*. Thomas Telford, 1994. ISBN: 0727720139.
- W. Shao, A. Bouzerdoun, S. L. Phung, L. Su, B. Indraratna, and C. Rujikiatkamjorn. Automatic classification of ground-penetrating-radar signals for railway-ballast assessment. *IEEE Transactions on Geoscience and Remote Sensing*, **49**(10 Part 2):3961–3972, 2011. doi: 10.1109/TGRS.2011.2128328.
- M. Shenton. Ballast deformation and track deterioration. *Track technology*, 1985.
- I. Y. Shevtsov. *Wheel/rail interface optimisation*. Phd thesis, Delft University of Technology, 2008.
- R. Stock. Damage in the Rail-Wheel System - An Overview, 2012. <http://www.wheel-rail-seminars.com/downloads.php>.
- P. F. Teixeira and A. R. Andrade. Unplanned-maintenance needs related to rail track geometry. *Proceedings of the ICE - Transport*, **167**(6):400–410, 2014.
- Z. Trzaska. Modeling of energy processes in wheel-rail contacts operating under influence of periodic discontinuous forces. *Journal of Transportation Technologies*, **02**(02):129–143, 2012. doi: 10.4236/jtts.2012.22014.
- K. Tzanakakis. *The Railway Track and Its Long Term Behaviour*, Springer Tracts on Transportation and Traffic, Volume 2. Springer, Berlin Heidelberg, 2013. <http://link.springer.com/10.1007/978-3-642-36051-0>.
- C. Vale and S. M. Lurdes. Stochastic model for the geometrical rail track degradation process in the Portuguese railway Northern Line. *Reliability Engineering and System Safety*, **116**:91–98, 2013. doi: 10.1016/j.ress.2013.02.010.
- P. Veit. Track quality: luxury or necessity? Technical Report July, 2007.
- P. Weston, C. Roberts, G. Yeo, and E. Stewart. Perspectives on railway track geometry condition monitoring from in-service railway vehicles. *Vehicle System Dynamics*, **3114**(7):1063–1091, 2015. doi: 10.1080/00423114.2015.1034730.
- P. Xu, Q. Sun, R. Liu, and F. Wang. A short-range prediction model for track quality index. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, **225**(3):277–285, 2011. doi: 10.1177/2041301710392477.
- M. Yousefikia, S. Moridpour, S. Setunge, and E. Mazloui. Modeling degradation of tracks for maintenance planning on a tram line. *Journal of Traffic and Logistics Engineering*, **2**(2):86–91, 2014. doi: 10.12720/jtle.2.2.86-91.
- A. M. Zaremski and J. W. Palese. Characterization of broken rail risk for freight and passenger railway operations. In *2005 AREMA Annual Conference*, pages 1–25, Chicago, IL, 2005.

W.-J. Zwanenburg. Modeling degradation processes of switches and crossings for maintenance and renewal planning on the Swiss railway network. In *6th Swiss Transport Research Conference - STRC 06*, pages 1–11, Monte Verità / Ascona, 2006.

W.-J. Zwanenburg. The Swiss experience on the wear of railway switches & crossings. In *7th Swiss Transport Research Conference-STRC 07*, 2007.